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RESEARCH ARTICLE

Urban scavengers as providers of ecosystem services: Waste management and carbon reduction in a rapidly urbanizing African City

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Abstract

1. Scavengers, such as spotted hyenas (*Crocuta crocuta*), African wolves (*Canis lupaster*), hooded vultures (*Necrosyrtes monachus*) and stray dogs (*Canis lupus familiaris*), are crucial for waste management in urban ecosystems, particularly in areas with poor waste management and sanitation.
2. This study quantifies their economic and carbon capture services by comparing the cost of their waste disposal with alternatives and estimating the CO_2 emissions avoided by consuming organic waste.
3. Through semi-structured interviews with 409 households in Mekelle, Ethiopia, we estimated the annual disposal of meat and organic waste and explored residents' perceptions of the ecosystem services.
4. Our results showed that approximately 1,058,200 animals (chickens, sheep and goats) were slaughtered annually at home, which is equivalent to 3286 animals per square kilometre. This generates approximately 1240.6 metric tons of meat waste (3.85 tons per square kilometre).
5. Scavenging of this meat waste could prevent an estimated 1063.34 metric tons of carbon emissions annually, which corresponds to an economic value of approximately $99,507. Furthermore, 32,656 metric tons of other organic food waste are produced each year (101.4 tons per square kilometre), which is sufficient to sustain an estimated population of 3051 spotted hyenas in Mekelle.
6. Predators/scavengers in our study area process approximately 5026 metric tons of organic waste annually, providing a waste disposal offset valued at around $100,510 per year. Spotted hyenas are the primary contributors, processing 4455 metric tons of human-generated organic waste, which translates to a value of approximately $89,100 annually. Stray dogs follow, processing 519 metric tons, valued at $10,380 per year, while African wolves process 51.5 metric tons, contributing a value of $1030 annually.
7. In conclusion, the main predators/scavengers in our study area provide essential urban ecosystem services, from waste management to CO_2 emissions

reduction. These species are highly specialized in the consumption of organic waste, and residents recognize the benefits they provide in waste removal, further highlighting the potential for beneficial co-existence between wildlife and humans.

8. *Practical implication*: Future research should explore diverse urban settings to understand how religious practices, cultural differences, and urbanization influence waste generation and human–wildlife interactions.

KEYWORDS
carbon emissions reduction, ecosystem services, food waste management, human–wildlife interactions, organic waste processing, urban scavengers, waste disposal

1 | INTRODUCTION

At the end of the next four decades, 60% of the projected 10.8 billion people on Earth will reside in urban areas, while predators are expected to lose an additional 10%–25% of their habitat (Rondinini & Visconti, 2015). Simultaneously, due to increasing human populations, climate change and political instability, many predator/scavenger species are projected to experience dramatic population declines over the next 25 years (Chapron & López-Bao, 2014; Di Minin et al., 2016; Ripple et al., 2014). The survival of some predator species will depend on their ability to adapt to human-altered landscapes and the willingness of humans to tolerate their presence (Bouyer et al., 2014; Odden et al., 2014). There is an urgent need to understand how predators and humans can co-adapt and to develop strategies that mitigate conflicts while fostering coexistence.

Predators/scavengers provide significant economic, health and environmental benefits in many urban ecosystems (Sonawane et al., 2021). They contribute to waste regulation by managing organic food waste (O'Bryan et al., 2018), accelerate nutrient recycling (Wilson & Read, 2003) and help reduce the risk of infectious disease transmission by removing carcasses (Ostfeld & Holt, 2004). However, despite these well-documented contributions, their role in urban environments has rarely been systematically quantified (Inger et al., 2016).

Predators/scavengers often have a negative public reputation due to real and perceived threats to humans (Penteriani et al., 2016), yet their benefits are rarely quantified. Traditionally, ecosystem services are classified as 'cultural', 'supporting', 'regulating' and 'provisioning' (Millennium Ecosystem Assessment, 2005), and predators/scavengers contribute to all these services, ultimately improving the well-being of residents within their ecosystems. Although the role of wildlife in ecosystem services is well-studied (Walther et al., 2002), less is known about the specific contributions of these species in urban landscapes and how they compare to their roles in natural ecosystems. Addressing this knowledge gap is critical, as global pressures on ecosystem services continue to rise due to increasing human populations and growing demands on natural resources (Newsome et al., 2014). Understanding the benefits predators/scavengers provide to human well-being is essential to strengthen conservation efforts and foster coexistence between people and wildlife.

Ethiopia has about 135 million people, making it the second most populous country in Africa. It also has the continent's largest livestock population, including 65 million cattle, 40 million sheep, 51 million goats, 8 million camels and 49 million chickens as of 2020 (Central Statistical Agency, 2020). Ethiopia's waste production is high by African standards, increasing from 9700 tons per day in 2015 to 12,200 tons per day in 2020. However, civic waste collection meets only 40% of the required removal, with less than 5% of waste being recycled (Habtom, 2022). Ecosystem services such as waste removal are especially important in developing countries such as Ethiopia, where waste disposal is often hindered by limited funds and infrastructure. Given these challenges, predators/scavengers play a crucial role in waste management by removing carcasses from livestock, thereby preventing the accumulation of toxins in the environment and reducing potential disease reservoirs prior to putrefaction (Inger et al., 2016).

In Mekelle, two-thirds of the solid waste generated by residents is disposed of in open areas and along roadsides, primarily due to the inadequacy of waste collection infrastructure, making waste management one of the city's most pressing public service challenges (Tadesse et al., 2008; Tadesse & Hadgu, 2007). The main components of household waste in the city are dust, ash, and organic matter (Tesfay, 2004, as cited in Tadesse et al., 2008). However, the production of meat waste is increasing in Mekelle due to the growing demand for meat, leading to an increase in the number of animals slaughtered. This trend provides a unique opportunity for scavengers to target available human waste.

In this study, we investigate the ecological role of the main predators/scavengers in Mekelle, focussing on spotted hyenas (*Crocuta crocuta*), African wolves (*Canis lupaster*), hooded vultures (*Necrosyrtes monachus*) and stray dogs (*Canis lupus familiaris*). Stray dogs were included in our study due to their significant presence in the city, with approximately 20,000 owned and ownerless dogs (Habtamu et al., 2017). We quantified the ecosystem service of waste removal provided by these species, assessing the amount of waste processed (kg), its financial value, and its carbon emissions reduction benefits. Furthermore, we explored the relationship between household

demographic data and this ecosystem service. Finally, we examine residents' perceptions of these predators/scavengers, assessing whether they are viewed as beneficial or not.

2 | MATERIALS AND METHODS

2.1 | Study area

Tigray, a region in northern Ethiopia with a population of approximately 9.3 million (Central Statistical Agency, 2023), supports a significant livestock population, including 5 million cattle, 2.1 million sheep, 4.9 million goats and 6.4 million chickens (Central Statistical Agency, 2020). The abundance of livestock provides scavengers in the area with carcasses and organic waste as food sources. In particular, a large population of spotted hyenas thrives in landscapes dominated by humans, especially around urban waste dumps, where they scavenge at night (Yirga, De Iongh, Leirs, Asmelash, et al., 2015). Despite their status as the main predator, spotted hyenas are widely tolerated in the region, mainly surviving on anthropogenic organic waste and animal remains (Yirga, De Iongh, Leirs, Asmelash, et al., 2015). Poor civic waste management exacerbates the accumulation of organic waste and carcasses in urban areas. Due to the inadequate waste-disposal infrastructure and the impacts of war (Yirga et al., 2025), waste collection remains insufficient in many cities in Tigray. As a result, livestock carcasses and organic waste are frequently seen along main streets and even near public service centres such as schools and health facilities, further sustaining scavenger populations.

The study was carried out in Mekelle, the capital and largest city of Tigray. The city is located at an elevation of 2200 to 2254 meters above sea level and covers an area of 322 km^2. It is an ideal city to investigate the dynamics between urbanization, waste management, and wildlife adaptation. Mekelle is a rapidly growing city with a dense population and a significant presence of livestock. During the study period, the city had an estimated population of 544,300 residents (UNICEF, 2021) and supported around 120,000 livestock animals (Sonawane et al., 2021). Mekelle experiences an average annual rainfall of 618 mm, mainly concentrated in the main rainy season (mid-June to mid-September), with mean temperatures ranging from 11 to 24°C. Geographically, it lies between 13° 24′ 30″ and 13° 36′ 52″ North Latitude, and between 39° 25′ 30″ and 39° 38′ 33″ East Longitude. Administratively, Mekelle is divided into seven sub-cities: Hawelti, Adihaki, Kedamay-Weyane, Hadnet, Ayder, Semen and Quiha (Figure 1). Despite its dense urban environment, patches of vegetation, mainly *Acacia* spp. and *Eucalyptus* spp., persist around public sites and churches. The wild prey base of the Tigray region is severely depleted, forcing predators to rely primarily on

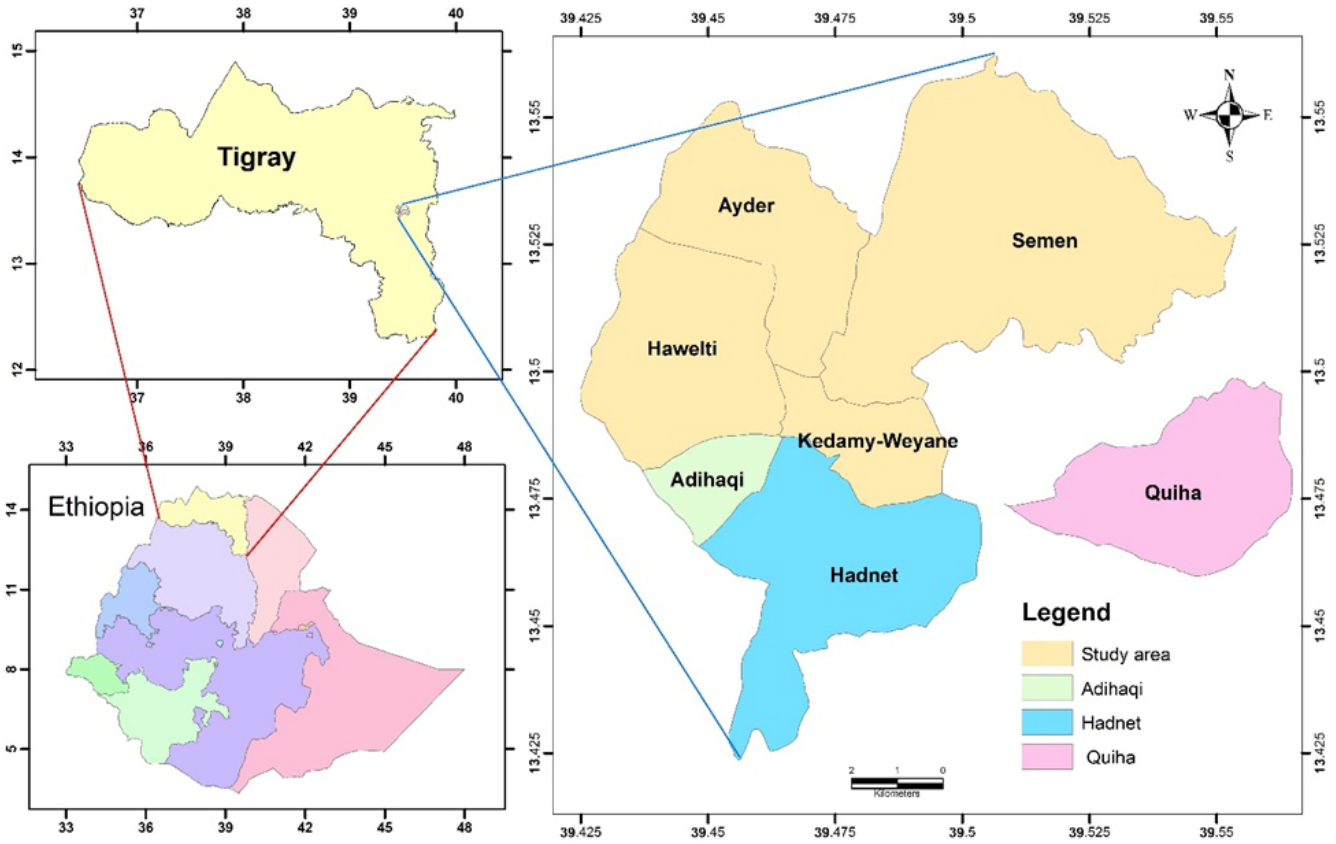

FIGURE 1 Sequential maps showing Ethiopia, the Tigray region, and Mekelle city, Mekelle is composed of seven sub-cities: Hawelti, Ayder, Semen, Kedamay-Weyane (highlighted in yellow as study area), as well as Adihaki, Hadnet, and Quiha. Sub-city boundaries are indicated by lines.

anthropogenic food sources (Yirga et al., 2013; Yirga, De Iongh, Leirs, Gebrehiwot, et al., 2015; Yirga et al., 2017). Spotted hyenas (hereafter referred to as hyenas) and African wolves (hereafter referred to as wolves) commonly roam the city at night, scavenging for food, while during the day, they hide in the surrounding agro-pastoral landscape. Mekelle was chosen as the study area due to its unique ecological and urban characteristics that provide an interesting setting to examine human–wildlife interactions.

2.2 | Semi-structured interviews

We conducted semi-structured interviews (see Supporting Information—Interview Guide for details) focused on collecting data on sociodemographic characteristics, organic waste production patterns and the perceptions of the participants of predators/scavengers and the ecosystem services they provide. The survey assessed 409 randomly selected households in four sub-cities in Mekelle. The sub-cities, Hawelti, Kedamay-Weyane, Semen and Ayder, were randomly selected using a lottery method from the existing seven sub-cities (Figure 1). The interviews were conducted in Tigrinya, the local language, and each interview lasted between 30 and 45 min, allowing sufficient time for the participants to offer detailed and thoughtful responses.

2.3 | Quantification of the mass of organic food and meat waste

All data used in this analysis were obtained through household interviews. Respondents were asked to report (i) the average mass of organic food waste discarded per week (in kilograms), (ii) the number of animals slaughtered at home per year and (iii) the mass of meat waste discarded per slaughtered animal. Using these data, we first calculated weekly organic food waste and annual meat waste per household. To estimate the total organic food waste for each sub-city, we multiplied the average per-household waste by the total number of households in that sub-city. A similar method was applied to estimate total meat waste. These figures were then extrapolated to the city level to estimate the annual volume of organic food waste, the number of animals slaughtered, and total meat waste for Mekelle. The total number of households in the city ($n = 130{,}000$) was estimated by dividing the population of Mekelle during the study period (544,300) by the average household size (4.2) as determined from our survey. The sampling approach was designed to ensure adequate representation of different household types.

The combined total of organic food waste and meat waste represents the food available to scavengers in Mekelle and was used to estimate the city's potential hyena population. The carrying capacity was calculated using the formula by Carbone and Gittleman (2002), which estimates 90 kg of predator biomass for every 10,000 kg of prey biomass.

We estimated the annual amount of organic waste removed by hyenas, stray dogs and wolves in Mekelle using species-specific food consumption rates from existing literature. Hyenas consume approximately 3.8–4.0 kg of meat per day to maintain body condition (Henschel & Tilson, 1988). Adult dogs typically consume 2%–3% of their body weight daily, which translates to 500–700 g for a medium- to large-sized dog (Dog Feeding Chart, 2021). For stray dogs, we applied an average consumption rate of 0.6 kg per day. Wolves have only recently been identified as distinct from golden jackals, and in the absence of specific data for wolves, we used the average daily food intake of golden jackals (0.85 kg) for ecosystem service calculations (Ćirović et al., 2016).

The total population of owned and ownerless dogs in Mekelle was estimated at 20,000, corresponding to a human population of 300,000 (Habtamu et al., 2017), a dog-to-human ratio of approximately 1:15. Using this ratio conservatively to the updated human population of Mekelle during the study period (544,300; UNICEF, 2021) leads to an estimated dog population of nearly 36,300, which includes owned and ownerless dogs. Furthermore, Habtamu et al. (2018) recorded 1606 free-roaming dogs in Mekelle, when the city's human population was approximately 369,087 (World Population Review, 2023). Since our research focussed on stray dogs, we used this ratio to estimate the stray dog population during the study period. Based on this, we estimate that the stray dog population increased to approximately 2368 by the time the human population reached 544,300 (UNICEF, 2021).

2.4 | Quantification of economic benefit of waste removal

To assess the economic value of waste removal services provided by predators/scavengers, we interviewed six horse cart owners involved in waste transport for disposal. Each was asked how much they charged to dispose of 100 kg of waste at the city dump. On average, the fee was 100 ETB (approximately USD 2 at the time of the study).

2.5 | Quantification of carbon emissions

To estimate the amount of carbon emissions prevented by the main predators/scavengers, we used established emission factors. According to Gerretsen (2022), the decomposition of 1 kg of carcass meat results in approximately 0.86 kg of carbon dioxide equivalent (CO_2e) emissions. This value was used to quantify the emissions avoided through the consumption of organic waste by scavengers. To assess the economic value of these avoided emissions, we referenced the World Bank's Carbon Pricing Dashboard, which reports CO_2e prices ranging from USD 73 to USD 114 per tonne (World Bank, 2024). For this analysis, we used the average value of USD 93.573 per ton of CO_2e to estimate the monetary benefit of carbon

emission reductions facilitated by scavenger activity in the study area.

2.6 | Residents' perception and ranking scavengers involved in waste clearing service

We evaluated residents' perceptions of the ecosystem services provided by predators/scavengers using a 5-point Likert scale, ranging from 'very harmful' (1) to 'very beneficial' (5). Additionally, respondents ranked four predator/scavenger species—hyenas, wolves, stray dogs, and hooded vultures—according to their perceived importance in removing livestock carcasses, with 1 representing the most important and 4 the least. This approach captures both the perceived ecological value and the functional significance of each species.

All statistical analyses were conducted using the JMP software. A one-way ANOVA was performed to compare the mass of organic waste processed by hyenas, stray dogs, and wolves. A chi-square test of independence was used to evaluate whether there was a significant difference in the number of respondents who rated animals as 'beneficial' or 'very beneficial' versus those who rated them as 'harmful' or 'very harmful'. Furthermore, we used a chi-square goodness-of-fit test to assess whether the distribution of slaughtered animal types (chickens, sheep and goats) differed significantly. Figures were generated using fully scripted data processing and analytical workflows in R (v4.3.2) to ensure transparency and reproducibility. Error bars represent ±1 standard error (SE) of the mean for each group, calculated as the standard deviation divided by the square root of the sample size.

All fieldwork, including wildlife observations and household surveys, was conducted with the approval of Mekelle University, Ethiopia. No additional licences or permits were required. Household surveys were carried out in private households with the informed consent of participants, in accordance with national regulations and institutional ethical standards.

3 | RESULTS

We first report on demographic characteristics, calculations of average organic waste production and estimate of hyena abundance. Using these data, we then further report on the economic benefits of scavenging hyenas defined financially and in carbon offsets. We then link these financial and carbon calculations to demographic characteristics.

3.1 | Demographic characteristics of the sample respondents

In our study, 88% of the sample population was between 21 and 50 years old, with 148 individuals aged 21–35 and 213 aged 36–50, and 41 respondents were aged 51–65, and 7 were over 65 years. Nearly 60% of the respondents were female. Most families (68.9%) had between 4 and 6 members, while 16.6% had 1 to 3 members, and 14.4% had 7 or more members. Approximately 7.6% of respondents were illiterate, 21.5% completed primary school, 32.3% secondary school, and 38.6% held a diploma or higher qualification. Most of the respondents (83%) were Orthodox Christians, followed by Muslims (16.4%) and Protestants (0.5%). These proportions are consistent with the broader religious demographics of the Mekelle region and the Tigray region.

3.2 | Waste production and hyena abundance estimates

On average, households surveyed in the four sub-cities slaughtered 8.14 animals per year, for a total of 3328 animals in 409 households. Aggregated by sub-city, the mean number of animals slaughtered was 832 ± 251.75 (SD) per sub-city, with a standard error of approximately 125.88 and a 95% confidence interval of 585.35 to 1078.65. Most slaughtered animals were chickens (57.3%), followed by sheep (29.6%) and goats (13.1%). The average meat waste discarded per animal, based on the surveyed sample households, was 2.61 kg for sheep, 2.16 kg for goats and 0.20 kg for chickens. This corresponds to a total of approximately 3894 kg of meat waste per year among the surveyed households, with sheep contributing 2568 kg (66.0%), goats 944 kg (24.2%) and poultry 382 kg (9.8%). Using extrapolation based on household slaughter rates, we estimated that approximately 1,058,200 animals are slaughtered annually in Mekelle, corresponding to 3286 animals per km^2. This home-based slaughter is estimated to generate 1240.6 metric tons of meat waste per year, or approximately 3.85 tons per km^2. The mean mass of organic food waste discarded per household in Mekelle was 4.83 ± 1.39 kg per week (mean ± SD), with a standard error of 0.069 kg and a 95% confidence interval of 4.70–4.96 kg. This corresponds to an estimated 251.2 kg annually per household, or approximately 59.8 kg per capita per year, equating to 0.16 kg of organic food waste discarded per person per day. By extrapolation, this leads to an estimated 32,656 metric tons of organic food waste discarded annually in Mekelle, or 101.4 metric tons per km^2, with an SE of 1294.2 metric tons and a 95% CI of 30,117.2–35,194.8 metric tons, corresponding to 101.4 metric tons per square kilometre. When combined with an estimated 1240.6 metric tons of meat waste, the total volume of anthropogenic organic waste available to scavengers is approximately 33,897 metric tons per year, or 105.3 tons per km^2. Based on this availability, the estimated carrying capacity for hyenas in Mekelle is approximately 3051 individuals. The estimated amount of organic waste processed by hyenas was significantly greater than that processed by stray dogs and wolves ($p < 0.001$), with hyenas removing approximately 8.6 times more waste than stray dogs and 86.5 times more than wolves. A significant difference was observed in the proportions of slaughtered animals ($\chi^2 = 306.14$, df = 2, $p < 0.001$), with chickens comprising the majority, followed by sheep and goats. Additionally, the distribution of goats, sheep, and chickens slaughtered varied

significantly across sub-cities ($\chi^2 = 96.91$, df = 6, $p < 0.0001$). Among the four sub-cities, Semen reported the highest total number of slaughtered animals (1165), followed by Hawelti (878), Ayder (694), and Kedamay-Weyane (591).

3.3 | Economic benefits of waste removal

Translating our waste estimates into economic terms using current cart-based waste disposal costs, scavengers are offsetting the disposal of approximately 5026 metric tons of organic waste annually, resulting in an estimated economic benefit of $100,510 per year. This benefit is primarily attributed to hyenas, which process around 4455 metric tons of organic waste, equivalent to $89,100 annually. Stray dogs are processing 519 metric tons, valued at $10,380 per year, while wolves process 51.5 metric tons, which is equivalent to $1030 annually. In spatial terms, this results in offset removal costs of $276.70 per km^2 per year for hyenas, $32.20 per km^2 for stray dogs, and $3.20 per km^2 for wolves—a combined total of $312.10 per km^2 annually. The estimated offset amounts to approximately $0.19 per capita annually. Specifically, scavengers process 15.61 metric tons of waste per km^2 annually, generating an offset value of $312.10 in an area with an average income of $296,205 per km^2 per year. In addition, these scavengers contribute to carbon emissions reduction, with an estimated 3.3 metric tons of CO_2e avoided.

3.4 | Carbon emissions per household

Carbon emissions from the decomposition of slaughtered animal waste varied considerably among the four sub-cities surveyed, with the Semen sub-city having the highest emissions at 1.197 tons per year (35.2%), followed by Hawelti (0.842 tons, 24.8%), Ayder (0.797 tons, 23.4%) and Kedamay-Weyane (0.565 tons, 16.6%). The average carbon emissions across the study sites were 0.85 ± 0.26 (mean ± SD) tons per year, with a standard error (SE) of 0.13 tons per year and a 95% confidence interval (CI) of 0.59–1.11 tons per year. This translates to 2.08 kg of carbon emissions per household and 0.495 kg per capita per year. Across all sub-cities, sheep contributed the largest proportion of emissions, followed by goats and chickens. Based on our conversions and the World Bank (2024) carbon price, scavenging meat waste in Mekelle potentially prevents approximately 1063.34 metric tons of CO_2 emissions annually, which is valued at approximately $99,507.

3.5 | Carbon emissions among demographic characteristics

In our study sites, households with 4–6 members, Muslim households, and those headed by individuals with secondary education had the highest estimated average annual CO_2 emissions (Table 1). Muslim households emitted significantly more carbon compared to Orthodox households ($t = 2.51$, df = 88, $p = 0.014$). Moreover, households headed by individuals with secondary education had significantly higher emissions than those headed by illiterate individuals ($t = 9.56$, df = 75, $p < 0.001$). Additionally, families with 4–6 members produced significantly more carbon emissions than smaller families of 1–3 members ($t = 5.25$, df = 120, $p < 0.001$). There were significant variations in carbon emissions among demographic characteristics (Figure 2). Semen sub-city had the highest mean household carbon emissions (11.08 kg CO_2), followed by Ayder (7.97 kg), Hawelti (7.25 kg) and Kedamay-Weyane (6.64 kg). The differences across sub-cities were statistically significant ($p < 0.001$), with Semen also exhibiting the highest total emissions.

TABLE 1 Socio-demographic factors influencing household carbon emissions: mean carbon emissions (kg) from slaughtered animal meat waste by family size, education level, and religion, based on a survey of 409 households in four sub-cities in Mekelle, Ethiopia.

Category	Group	*n*	Mean	SE	CI (±2 SE)
Family S.	1–3	68	7.2	0.262	(6.69, 7.71)
	4–6	282	8.8	0.157	(8.49, 9.11)
	>6	59	7.2	0.281	(6.65, 7.75)
Religion	Orthodox	340	8.2	0.133	(7.94, 8.46)
	Muslim	67	9.1	0.334	(8.45, 9.75)
	Protestant	2	2.1	0.446	(1.23, 2.97)
Education	Illiterate	31	5.3	0.285	(4.74, 5.86)
	Primary	88	7.5	0.240	(7.03, 7.97)
	Secondary	132	8.8	0.229	(8.35, 9.25)
	Diploma+	158	7.9	0.189	(7.53, 8.27)

3.6 | Order of scavengers involved in waste clearance services

In the survey, stray dogs were perceived as the most important scavengers for removing livestock carcasses, with 83.6% of respondents ranking them first. They were followed by hyenas (12%), hooded vultures (4.2%) and wolves (0.2%). Stray dogs consistently received the highest rankings, while wolves were most frequently ranked last (Figure 3). Overall, stray dogs and hyenas were considered the most effective scavengers, ranked first and second, respectively, while hooded vultures and wolves were ranked third and fourth.

3.7 | Resident attitude towards ecosystem services

A majority of residents (72%) perceived predators/scavengers as 'beneficial' or 'very beneficial' while only 19.3% considered them harmful or very harmful. The most frequently cited benefit was waste removal (61.5%), followed by reductions in house fly populations (17%), fetid odours (16%), and disease transmission (5.5%). In contrast, the main concerns included livestock predation by hyenas and wolves (50.4%),

dog bites and rabies transmission from stray dogs (44.6%), and chicken predation by vultures (5%). Residents widely recognized hooded vultures and wolves as the most important scavenger species in terms of ecosystem services, particularly for their role in waste removal (Figure 4). However, perceptions varied across sub-cities. In Semen and Ayder, wolves were more frequently rated as beneficial or very beneficial, whereas in Kedamay-Weyane and Hawelti, hooded vultures and stray dogs, respectively, received the highest positive ratings. Overall, perceptions of the four focal species, hyenas, stray dogs, hooded vultures, and wolves, were largely consistent. No statistically significant differences were found between the 'beneficial' and 'very beneficial' categories (Figure 4), and the overall distribution of responses (very harmful, harmful, neutral, beneficial and very beneficial), did not differ significantly among species. When broken down by category, hyenas and stray dogs received similarly high combined harmful ratings (95 and 98, respectively), yet both were also considered beneficial by a large portion of respondents (283 each). Hooded vultures had fewer harmful responses (72 combined) and the highest number of beneficial ratings (306 combined), while wolves had the lowest harmful rating (62 combined) and a comparable beneficial rating (299 combined). Overall, positive perceptions (ratings of 'beneficial' and 'very beneficial') significantly outweighed negative perceptions (ratings of 'harmful' and 'very harmful') across all species ($\chi^2 = 20$, df = 4, $p = 0.022$).

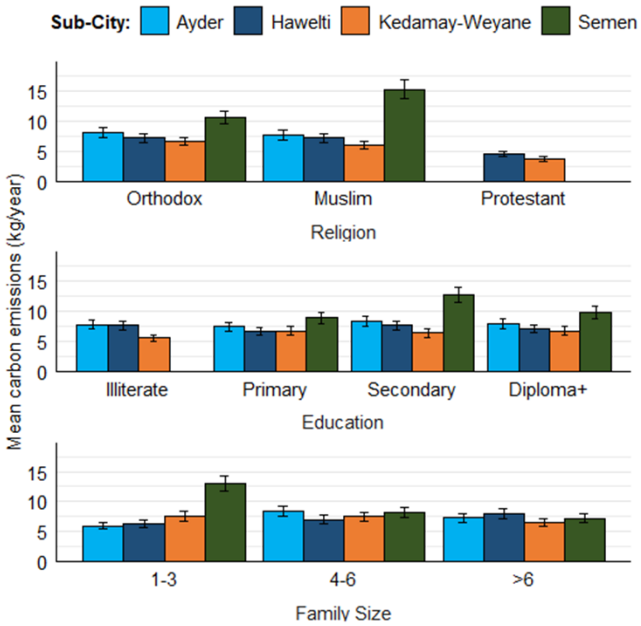

FIGURE 2 Mean carbon emissions from meat waste (kg/year) ±1 SE by religion, education level, and family size among respondents ($n = 409$) from four sub-cities in Mekelle, Ethiopia. Empty gaps indicate groups that were absent in the surveyed population ($n = 0$), including Protestants in Ayder and Semen, and illiterate respondents in Semen.

4 | DISCUSSION

The role of predators/scavengers in urban environments has often been overlooked, particularly given the growing proportion of the global population living in cities, the persistence of poverty and subsistence living in urban areas, and the ongoing loss of natural habitats for predators. These factors typically indicate an increased risk of human–wildlife conflict. However, our study suggests that certain scavengers, such as hyenas and stray dogs, could provide unexpected ecological, financial, climate-related and civic benefits to urban communities. This research from the Tigray region of Ethiopia highlights the material and financial contributions of scavengers, their role in reducing carbon emissions, and the positive civic benefits they offer. Our findings also reveal a strong positive association between people and these scavengers, along with insights into how demographic factors such as religion, education and family size influence perceptions of these species and their ecosystem services.

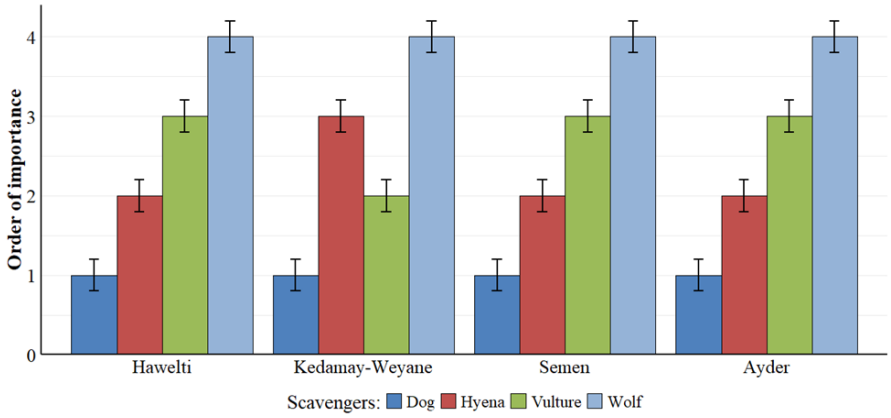

FIGURE 3 Order of importance of scavenger species involved in the removal of household waste across four sub-cities in Mekelle, Ethiopia. Respondents ($n = 409$) ranked the species on a scale from 1 to 4, where 1 represents the most important and 4 the least important species in household waste removal. Bars represent the mean rank, and error bars represent ±1 SE.

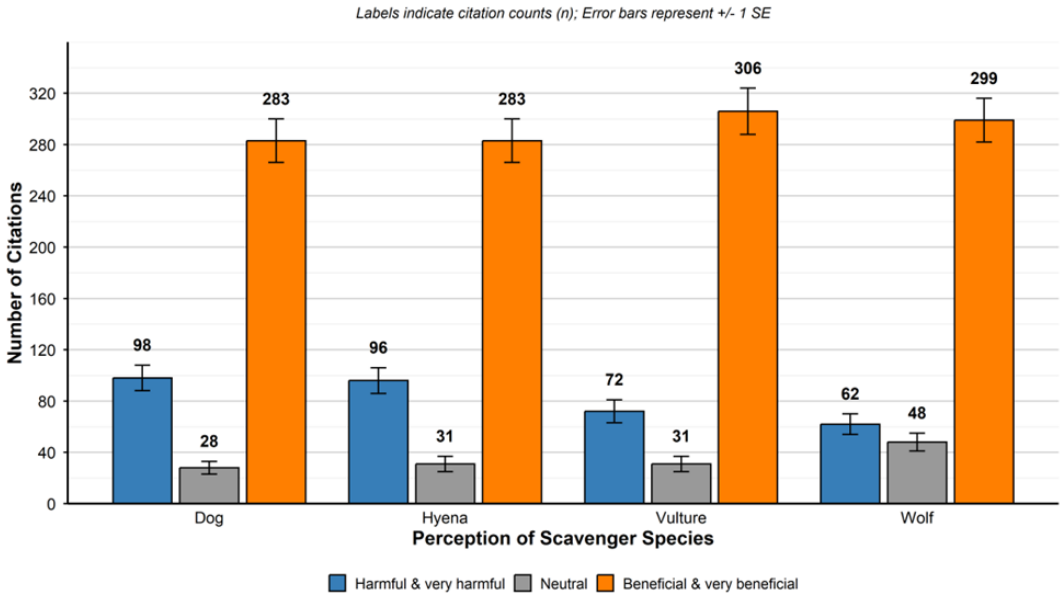

FIGURE 4 Perceptions of scavengers' importance in ecosystem services, rated on a five-point scale where 1 = very harmful, 2 = harmful, 3 = neutral, 4 = beneficial, and 5 = very beneficial.

4.1 | Demographic characteristics

In our study area, most of the residents perceived predators/scavengers as beneficial. Education, gender, age and religion are known to influence attitudes towards wildlife, particularly predators (Gamborg & Jensen, 2016; Makumbe et al., 2022; Myers et al., 2004; Yang et al., 2010). Our findings are particularly noteworthy considering that wildlife attitude surveys often show significant gender-based differences in perceptions. For example, in the Southeast Lowveld of Zimbabwe, males were found to be less likely to have negative views towards problem animals compared to females (Makumbe et al., 2022). In China, women were found to be more positive than men about wildlife conservation, with individuals who had higher levels of education and religious affiliations also showing more support for conservation efforts (Yang et al., 2010). This aligns with broader findings that suggest that females often form stronger emotional connections to animals, placing greater value on nonhuman species, and showing more concern for the welfare of individual animals and the conservation of populations (Leuschner et al., 1989). On the contrary, males tend to focus more on the practical utility of animals for human benefit (Gamborg & Jensen, 2016; Knight et al., 2004). Thus, our finding of a positive attitude towards predators/scavengers contrasts with some other studies. The literature presents a mixed picture regarding younger generations: some studies suggest that younger people are more positive towards wildlife conservation (Kellert, 1993; Su & Martens, 2017), while others indicate that age has little effect on attitudes (Learmonth, 2020; Wells & Hepper, 1997) or that younger individuals may have more fear and negative views toward species perceived as dangerous (Fredrikson et al., 1996; Myers et al., 2004). However, our data point to a positive link between younger generations and attitudes towards scavengers, suggesting that in our study area, younger people may be more open to the ecosystem services provided by scavengers.

4.2 | Organic food and meat waste

In this study, 'organic food waste' includes vegetable scraps, fruit peels, bones and household residues, while 'meat waste' refers to meat and offal from slaughtered sheep, goats, and chickens. Though both are organic, they are categorized separately to quantify distinct waste streams for management and scavenger ecology. Our findings underscore the important ecological services provided by predators/scavengers in Mekelle. Including both household meat and organic food waste, Mekelle generates approximately 33,897 metric tons of anthropogenic waste annually (105.3 tons/km^2), potentially supporting an estimated 3051 hyenas. Solid waste production in sub-Saharan Africa is estimated at 62 million tons per year, with daily per capita rates ranging from 0.09 to 3.0 kg (average 0.65 kg; Hoornweg et al., 2000). At the global scale, 30%–40% of food produced is wasted (Oro et al., 2013), with households contributing about 61% (UNEP, 2021). This equates to roughly 931 million tons of food discarded annually (World Economic Forum, 2021). Overall, worldwide waste generation averages 0.74 kg per person per day (World Bank, 2022). The actual quantity of meat waste in Mekelle is likely underestimated, as waste from the official municipal slaughterhouse was not included. The city hosts 110 registered butcher shops, 308 cafeterias and 292 restaurants (Haileselassie et al., 2013), in addition to higher education institutions and military camps. All of these obtain meat from the municipal abattoir, which contributes substantially to the city's overall meat waste. On a global scale, meat consumption has increased by 40% over the past decade (Brennan et al., 2021). In 2020 alone, global meat production reached 252.6 million tons, including 99.1 million tons of chicken (Wang

et al., 2021). While predator/scavenger abundance in natural ecosystems correlates with prey biomass (Karanth et al., 2004), in human-dominated landscapes, their populations often depend more heavily on anthropogenic food sources (Llaneza et al., 2011; Yirga et al., 2017).

The high frequency of chicken slaughter in our study area likely reflects its affordability and accessibility for households. No household-level cattle slaughter was reported. Typically, only 45%–60% of an animal's weight is consumed, with the remainder classified as waste (Chowdhury et al., 2022). Such waste may harbour pathogens including prions, fungi, bacteria, viruses, yeasts and microbial toxins (Franke-Whittle & Insam, 2013). Residents therefore generate large amounts of organic waste and livestock carcasses annually. Sonawane et al. (2021) observed hyenas feeding at Mekelle dumpsites but focused exclusively on hyenas, excluding other scavengers. Their estimates, derived from literature and abattoir waste, did not assess household-level waste generation. In contrast, our study excluded abattoir waste and literature-based carcass estimates, emphasizing organic food and meat waste from city household categories overlooked by Sonawane et al. (2021). These methodological differences account for discrepancies between the studies and underscore how each provides distinct insights into the ecosystem services of urban scavengers in Mekelle.

4.3 | Economic benefit of waste removal

In Mekelle, a lack of waste infrastructure results in a significant amount of unmanaged organic waste. Predators/scavengers, including hyenas, hooded vultures and stray dogs, provide a crucial informal waste removal service. They consume organic and animal waste from household dumps, streets and official sites, offering notable economic and ecological benefits that often go unrecognized. These ecological services provide significant economic benefits to Mekelle, with an estimated annual value of $100,510. While this amount seems modest, it represents a substantial contribution to household well-being, equivalent to approximately 5.9% of Tigray's GDP per capita ($735) (OCHA, 2021). This highlights the crucial role informal waste actors play in both environmental sustainability and local economic resilience and suggests the need to formally recognize and support them. Previous work showed that hyena scavenging prevents roughly five human infections of anthrax and bovine tuberculosis annually, along with 140 livestock infections, saving about $20,000 in treatment and avoided losses (Sonawane et al., 2021). However, hyenas also prey on domestic animals (Abay et al., 2011). In Wukro district, 45 km from Mekelle, hyena predation averages 0.13 livestock per household annually (~$6.1), considerably lower than in Kenya, where annual losses reach $74,740 and about 1020 shoats (Koskey et al., 2021).

4.4 | Carbon emissions of households

Our study found significant variation in household carbon emissions across sites, family sizes, religions and educational levels. Muslim households showed higher emissions than Orthodox and Protestant households, likely due to Ethiopian Orthodox fasting practices, which prohibit meat, dairy and eggs for about 180 days annually, thereby reducing slaughter-related emissions. Families with four to six members and those with secondary education recorded the highest emissions. These estimates reflect differences in meat disposal patterns and do not capture other significant sources of household carbon emissions, such as electricity consumption, heating or other energy uses. Household emissions are known to correlate with income and size (Sumita et al., 2019); in the EU, households account for roughly 20% of greenhouse gas emissions (Eurostat, 2022). It is estimated that around 8%–10% of global greenhouse gas emissions are associated with food that is not consumed (UNEP, 2021). In our study sites, meat waste generated an average of 0.85 tons of carbon emissions annually, equivalent to 2.1 kg per household and 0.5 kg per capita. Scavengers play an important role in offsetting these emissions by consuming discarded meat waste. Religious practices in Ethiopian Orthodox and Muslim households significantly influence waste generation. Orthodox fasting periods reduce meat consumption and waste, while Muslim households produce more. Cultural and religious factors therefore play a significant role in waste production and co-existence of humans with nature. Predators/scavengers in the study area help reduce emissions by consuming carcasses and organic waste. This reduces the decomposition of waste and the subsequent release of greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4) into the atmosphere (Beasley et al., 2015; Bhattacharjee et al., 2024; Gerretsen, 2022).

4.5 | Species involved in waste clearing services

Our household survey identified stray dogs as the most efficient scavengers of household waste in Mekelle, although hyenas process the largest overall volume. Dogs' high efficiency likely reflects their frequent presence near residences and active engagement with easily accessible waste. Waste consumption generally increases with scavenger population size. Many households in Mekelle do not confine their dogs, contributing to this free-roaming population. While providing important waste removal services, stray dogs also pose serious public health risks. In Mekelle, the stray dog population may significantly contribute to rabies transmission, posing a serious public health threat. Additionally, their unburied faecal matter can contaminate soil and water, increasing the risk of pathogen spread. In contrast, hyenas, which primarily scavenge organic waste, are less likely to cause this type of environmental contamination. Despite stray dog abundance, they were generally not viewed negatively. Between 2003/4 and 2014/15, Tigray reported 11,041 dog bite cases, resulting in 53 deaths (Menghistu et al., 2018). Globally, dogs are responsible for 99% of rabies transmission, causing over 55,000 human deaths annually, primarily in developing countries (WHO, 2005). The global dog population ranges from 700 million to 1 billion, with roughly 75% classified as stray (Smith et al., 2019).

Hooded vultures provide effective waste removal services in Mekelle, although their population remains unknown, as no surveys

have assessed vulture abundance in Tigray. They are frequently observed feeding on carcasses along Mekelle's streets, highlighting their active role in organic waste removal. Literature shows vultures are specialized scavengers, removing large quantities of discarded animal waste annually (Sekercioglu, 2006; Şekercioğlu et al., 2004). In regions of Africa and Asia with limited waste infrastructure, vultures deliver long-term carcass removal services vital to the livestock industry (Dupont et al., 2012). Despite this, scientific evidence quantifying their effectiveness in removing potentially disease-carrying carcasses is limited (Van Den Heever et al., 2021). Further research is needed to clarify their contributions to disease control and broader ecological services.

In Mekelle, African golden wolves, formerly known as golden jackals, have been reported to remove substantial amounts of discarded animal waste. This adaptable species inhabits diverse habitats and thrives in human-dominated agricultural landscapes across Africa, Europe, and Asia (Sillero-Zubiri et al., 2004; Stoyanov, 2012). Like jackals, they often enter human settlements at night to scavenge organic waste (Jhala & Moehlman, 2008). In Serbia, golden jackals remove approximately 3700 tons of animal waste annually (Ćirović et al., 2016), while in European urban areas, jackals eliminate around 13,000 tons of organic waste per year, with an estimated economic value of $0.5 million (Barua et al., 2013). These observations underscore the critical role of wolves in urban waste management, reducing environmental pollution and contributing essential ecosystem services.

4.6 | The attitude of residents towards ecosystem services

Based on respondents' answers to the question, 'Could you order these species by their importance in the removal of your livestock carcasses?', stray dogs and hyenas were ranked first and second, respectively, in waste removal services. This is likely due to their larger populations, resulting in a higher total amount of waste consumed. Personal observational and local knowledge support the inference that stray dogs and hyenas are the most effective scavengers in terms of actual waste removal. However, public perception—as reflected in the survey responses—favoured hooded vultures and wolves as the most important species for waste removal. This contrast highlights the difference between actual scavenging efficiency and perceived importance. Despite the greater effectiveness of stray dogs and hyenas in removing carcasses, residents of the study area still consider hooded vultures to be the most important scavengers. Public perceptions of scavenger effectiveness are influenced by visibility bias: vultures are active during the day and easily observed, whereas nocturnal scavengers such as hyenas and dogs are less visible, which may lead to under recognition of their waste removal roles. As such, these perceptions may not accurately reflect actual ecological efficiency.

Most residents viewed predators and scavengers as beneficial, mainly for waste removal, while livestock depredation was the main concern. Understanding local attitudes is vital for effective human–wildlife coexistence (Basak et al., 2023). Not all human–wildlife interactions cause conflict; in our study area, they benefited both people and wildlife. However, negative perceptions often arise from the costs linked to wild animals (Störmer et al., 2019). Effective wildlife management must be grounded in public attitudes towards wildlife (Pooley et al., 2020). For the successful conservation of wildlife species, it is essential to assess and understand people's perceptions and attitudes towards these animals (Makumbe et al., 2022).

4.7 | Limitations and assumptions

Hyena populations in Mekelle may be limited by breeding sites, resting areas and inter-clan dynamics; thus, our density estimates are likely conservative approximations. Despite these potential constraints, hyena densities in Mekelle exceeded those of wild populations in sub-Saharan Africa, ranging from 0.82 to 1.10 individuals/km^2 in the Serengeti, Tanzania (Hofer & East, 1993), and about 1.65 individuals/km^2 in Amboseli, Kenya (Holekamp & Dloniak, 2010). Human-derived organic waste was treated as the primary prey resource, assuming household meat and food waste can be converted to prey biomass (Carbone & Gittleman, 2002) and that scavengers have full access to it. Yirga et al. (2017) recorded 562 hyenas and 63 wolves at 34 calling stations, estimating 1145 hyenas and 166 wolves in Enderta District (Mekelle surroundings), with a density of about 80 hyenas per 100 km^2. Our estimates excluded commercial meat waste from municipal abattoirs, likely underestimating total biomass available to scavengers, as measurements included only household-level livestock slaughter. Although cattle processed at the municipal abattoir are accessible to scavengers, they were excluded from this study. Haileselassie et al. (2013) reported that 40–65 male cattle are slaughtered daily at the official facility on non-fasting days, particularly Wednesdays and Fridays. Although scavengers process only about 14.8% of Mekelle's annual organic waste, they provide substantial ecological and economic benefits. At a waste removal cost of $2 per 100 kg, their activity offsets over $100,000 in municipal waste expenses, using average household-based meat waste conversion factors. Due to limited wolf-specific data, the golden jackal's food intake was used as a proxy. Given the similarity in size and feeding habits between golden jackals and wolves, this substitution provides a reasonable estimate of wolf food requirements. Similarly, the estimated stray dog population of 2368 was derived using proportional scaling rather than direct counts. This method is commonly used in urban wildlife studies, as human population size strongly correlates with free-roaming dog abundance (Hughes & Macdonald, 2013). While these approaches have inherent limitations, they provide practical, evidence-based approximations of scavenger populations and their contributions to Mekelle's urban ecosystem. Quantifying emissions from the faecal matter of dogs, wolves, hyenas, and vultures in terms of CO_2, CH_4, and N_2O is important, as these emissions can offset the reduction benefits gained from waste consumption. Future research that incorporates faecal

emission estimates would allow for a more comprehensive assessment of the net carbon balance.

5 | CONCLUSIONS

We conclude that the main predators/scavengers in our study area play a crucial role in regulating ecological processes and providing valuable urban ecosystem services, particularly in terms of the removal of human waste. These species are highly specialized in the consumption of organic waste, and residents of the area are aware of the significant benefits they provide in terms of waste removal. This creates a unique case of co-existence between wildlife and people. Although hyenas are often among the most disliked and persecuted species in Africa, in our study area, they are considered ecologically important. Therefore, the relationship between wild animals and humans in our study area is predominantly positive. Future research should explore similar dynamics in other urban settings to better understand the role of religious practices, cultural differences, and urbanization in waste generation and human–wildlife interactions. Future studies should use quantitative methods like weighing household waste at the source and monitoring it during consumption.

AUTHOR CONTRIBUTIONS

Gidey Yirga secured funding, conceived the study, collected and analysed the data, and drafted the manuscript. Robert P. Freckleton, Hans Bauer, and Andrew P. Beckerman contributed to data interpretation, led manuscript writing, and reviewed analyses. All authors critically revised the manuscript and approved the final version for publication.

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CONFLICT OF INTEREST STATEMENT

We declare no conflict of interest.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

Data available from the Dryad Digital Repository: https://doi.org/10.5061/dryad.0rxwdbsfw (Yirga et al., 2026).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Table S1. Average meat waste per animal and estimated annual totals from household slaughter: data from 409 surveyed households and extrapolation to Mekelle city.

Figure S1. Waste removal (A) Economic value (B) and CO_2 offsets (C) provided by scavenger species in Mekelle, Ethiopia.

Figure S2. Mean carbon emissions (kg) from animals slaughtered at the household level in four sub-cities of Mekelle, based on data from a sample of 409 households.

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