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A global assessment of nitrogen and phosphorus generated in the waste streams of domesticated cats and dogs

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ABSTRACT

Domesticated livestock and their waste streams are considered a significant source of nitrogen (N) and phosphorus (P) pollution at the global scale; however, the waste generated (excreta) by domesticated cats and dogs, whose global numbers are estimated at 700 million and 900 million, respectively, is not included in any global inventories or models of N and P pollution sources. Based on parameters derived from a variety of literature sources, this study estimates the total global N and P excretion from domestic cats and dogs to be 4.32 (1.27–7.38) Tg N yr^{-1} and 0.76 (0.31–1.21) Tg P yr^{-1} which are equivalent to 3.3 (1.0–5.7)% of N and 3.3 (1.3–5.3)% of P waste produced by livestock at a global level. These estimates are in line with the combined mass of the animals (the total mass of cats and dogs is equivalent to 3.6% of the total mass of domesticated mammalian livestock). While there is a severe under reporting of waste streams for cat and dog waste deposition in literature, we infer from our estimates that global emissions of N_2O and NH_3 from cat and dog waste are in the region of 43 (13–74) Gg N_2O–N yr^{-1} and 864 ± 654 Gg NH_3–N, representing an unreported contribution that may exceed 17.7% of the carbon footprint associated with global pet food production (in the form of N_2O emissions).

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1. Introduction

Globally, more than 220 million cats and 500 million dogs are kept as pets (Dauphiné & Cooper, 2008; Hughes & Macdonald, 2013; Smith et al., 2019). A further 480 million cats and 200 million dogs are estimated to be feral (Bögel et al., 1990; Dauphiné & Cooper, 2008). Considering the difficulties in assessing feral populations, the true global populations are expected to be higher (Gompper, 2013). While exact population numbers are difficult to estimate, it is certain that worldwide pet ownership is growing, as indicated by the rapidly expanding pet food market, which has increased from $78 billion in 2011 to over $140 billion currently (Watson et al., 2023). Domestic cats and dogs have an estimated combined global biomass of approximately 24 megatons (Mt), which is greater than all wild terrestrial mammal mass combined (22 Mt) (Greenspoon et al., 2023). The majority of food consumed by domestic cats and dogs is meat-based, typically containing by-products of intensive livestock and fishing industries (though dog food can contain high fractions of cereal). However, as much of the materials that go into pet food are by-products of the meat industry, determining the true environmental impact of pet food is controversial. Alexander et al. (2020) estimated (based on an economic approach) that global annual pet food production accounts for 56–151 Mt CO_{2eq} (1.1–2.9% of the global agricultural total), 41–58 Mha of agricultural land-use (0.8–1.2% of the global agricultural total) and 5–11 km^3 freshwater use (0.2–0.4% of the global agricultural total). While the environmental impacts of food production for domestic cats and dogs have been examined in relation to these typical agricultural metrics (with noted uncertainty), less is understood about the waste generated by these animals as excreta, and the fate of resulting nutrient pollution in the form of nitrogen (N) and phosphorus (P).

Research investigating cat and dog waste streams is focussed almost entirely on veterinary research aspects. Unlike herbivorous livestock, which often have their waste (manure) recycled into agricultural soils (efficiencies vary drastically by region), pet waste and the waste of feral animals are typically not handled this way. The environmental consequences of cat and dog excreta will depend on a variety of factors. In terms of N pollution, the surface upon which excreta are deposited can influence its impact on the environment. Reactive N compounds applied to

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soils will behave differently than N applied to inert surfaces such as concrete or tarmac. Microbial activity in soils will begin to break down N compounds quickly (and mineralise organic N compounds), and the powerful greenhouse gas nitrous oxide (N_2O) will be released as a by-product of microbial nitrification and denitrification (Butterbach-Bahl et al., 2013). Where nitrogen is left on a relatively warm and inert surface (e.g. concrete), a greater quantity of ammonia (NH_3) will volatilise into the atmosphere (Groenestein et al., 2006), directly exposing urban populations to increased air pollution at ground level with resulting negative impacts on air quality and human health, primarily through the formation of fine-particulate matter ($PM_{2.5}$) which causes cardiovascular and pulmonary disease (Ali et al., 2018; Bourdrel et al., 2017). Thus, in cities where the majority of people and domesticated (as well as feral) cats and dogs reside, there will be a significant difference in behaviour and impact of deposited N and P in comparison to conditions associated with typical livestock deposition. Increasing N and P inputs to waterways through run-off and leaching can result in the eutrophication of aquatic systems (Malone & Newton, 2020). Eutrophication is a major global water quality issue leading to the formation of harmful algal blooms, coastal dead zones, mass mortalities of fish, closure of economically important fisheries and shell-fisheries, high rates of biodiversity loss, high rates of greenhouse gas emissions, and the loss of economic, societal, and cultural value associated with high-quality ecosystems (Johnes et al., 2022).

Many assessments have investigated nutrient flows through the livestock sector, both globally and nationally. However, few studies have examined the fate of nutrients from domestic cat and dog waste streams. A rare example of cat and dog inclusion in a national scale inventory is that of the UK, where NH_3 emissions from pets in the UK in 2021 are estimated to be 8.3 Gg NH_3–N yr^{-1} for dogs and 1.3 Gg NH_3–N yr^{-1} for cats, accounting for approximately 4.4% of total national NH_3 emissions in the UK in 2021 (NAEI, 2022). However, these estimates are based largely on a handful of studies where simple lab-based measurements and assumptions are made, rather than direct measurements. Thus, uncertainty in these estimates remains high (4.0–16.6 Gg NH_3–N yr^{-1}). No national or global scale inventories include N_2O emissions from excreted waste from domesticated cats and dogs.

To inform future environmental assessments of the proportion of the contribution from cat and dog excreta, this study details a method of estimating and constraining the magnitude of nutrient waste streams produced by cats and dogs. We provide the first global estimate of N and P production in the excreta of dogs and cats using data collated from the available literature. As well as to provide evidence of the magnitude of typical cat and dog waste streams, these data are interpreted to discuss realistic ranges of the resulting N pollution in the form of NH_3 and N_2O emissions released at a global scale, as well as the magnitude of the deposition of P in urban areas and drainage streams.

2. Method

2.1. Global cat and dog populations

Global domesticated cat and dog populations are difficult to estimate due to the number of unregistered and feral animals (feral defined in this study as animals which can be classed as stray, semi-wild, or mostly free-roaming in nature). There is no official agency that monitors cat and dog populations at a global scale, and while some nations have reasonably good estimates due to pet registration requirements and low feral populations, any attempt to establish a global population is highly uncertain. The WHO estimated a dog-to-human ratio of approximately one dog for every 6–10 humans in western nations in 1990 (Bögel et al., 1990) which in modern-day terms would approximate to 800 million to 1.3 billion dogs if extrapolated to the current global population. However, cat and dog populations are dynamic in nature and numbers vary drastically between nations, depending on factors such as environmental suitability (survival of feral animals) and economic barriers to pet ownership, for which significant decadal shifts are observed at national scales (Xiao et al., 2021). Based on numbers reported in the literature (Table 1), we estimate populations of approximately 700 million cats and 900 million dogs in this study, with a 95% CI ranging approximately ±200 million for each animal, which we believe is justified as realistic considering the limited available evidence (which may be replicated across studies), the likelihood of global accounting to underestimate feral populations and recent global trends in pet ownership.

2.2. Cat and dog body mass

The food consumed and excreta generated by cats and dogs depend heavily on the consumption rates of the animals (e.g. diet) and thus are dependent on mass. While there are large numbers of recognised breeds of domestic cats globally (Lipinski et al., 2008), the vast majority of domestic cats (>90%) are a class of mixed breed. Domestic cats typically weigh between 2.8 and 5.5 kg each (Kienzle & Moik, 2011) with females of the same breed typically weighing approximately 70–80% of a male. While behaviour, diet, and neutered status can

Table 1. A summary of global populations of cats and dogs reported in the literature

Source	Cats Cat_{Pop} (Million)	Dogs Dog_{Pop} (Million)
Bögel et al. (1990)		800–1,300
Wandeler et al. (1993)		700
Dauphiné and Cooper (2008)	600	
Lord et al. (2013)		1,000+
Hughes and Macdonald (2013)		700
Gompper (2013)		900
Smith et al. (2019)		700
Mori et al. (2019)	600–1,000	
Sykes et al. (2020)		700–1,000
Greenspoon et al. (2023)	600	1,000
This study	**700 ± 200**	**900 ± 200**

all affect the weight of domesticated cats (Nguyen et al., 2004), the default clinical expectation for a pet cat is to weigh approximately 4 kg, and between 3.5 and 4.5 kg, this being consistent across most domesticated breeds in good health. Feral cats are typically slightly smaller than pet cats and weigh between 2.8 and 4.0 kg on average (Fleming et al., 2020; Scott et al., 2002). Due to our approximation of mean mass being similar to the 3.75 kg value used for the mass of an individual cat by Greenspoon et al. (2023) in their global assessment, we define the global mean mass of a cat as 3.75 ± 1.0 kg in this study for consistency between studies.

Generally, dogs are classed into groups of small (smaller than 10 kg), medium (10–26 kg), and large (greater than 26 kg); though these definitions vary between countries. An investigation carried out by Householdquotes in 2021 (householdquotes.co.uk/most-popular-dog-breed) identified 27 dog breeds that were the most popular in all countries where data were available. The average mass of these breeds is approximately 26 ± 2 kg per animal, though smaller dog breeds may be more common than this analysis suggests. In the UK, 22 dog breeds account for over 75% of dog registrations between 2013 and 2023 (thekennelclub.org.uk). The average full adult weight of all registered dogs in this bracket is approximately 17.3 ± 1.4 kg (Table S1). We also consider the large contingent of feral dog populations at a global scale, such as the Indian pariah dog (*Canis lupus familiaris*) which weighs between 15 and 30 kg, the Ghanaian street dog (a.k.a. avuvi) which weighs between 9 and 21 kg, and the South American street dog (a.k.a. callejero), which weighs between 10 and 30 kg. While the data are not available to map dog size globally, we estimate a mean individual mass of approximately 19–24 kg based on the evidence available. Again, due to our approximation of mean mass being similar to the mass of an individual dog used by Greenspoon et al. (2023) in their global assessment, we define the global mean mass of a dog as 21.6 ± 5.0 kg in this study for consistency, with a conservative estimate of uncertainty.

In terms of animal age and development, the majority of cats and dogs reach full size by 12–18 months, meaning they should spend approximately 95% of their life at full size. While this assumption may not include the shorter lifespans of stray animals and the larger proportion of younger animals in this category, we also ignore the number of pregnant or overweight animals, and thus, having a large degree of uncertainty of 3.75 ± 1.0 kg per cat and 21.6 ± 5.0 kg per dog in the analysis should cover a realistic range. Based on these estimates, 700 ± 200 million cats and 900 ± 200 million dogs would weigh approximately (Cat_{Mass}) 2.6 ± 1.3 Tg and (Dog_{Mass}) 19.4 ± 6.3 Tg, respectively.

2.3. Quantifying nutrients in dog and cat excreta

2.3.1. Nitrogen

Domesticated cats and dogs are both considered carnivores, and the majority of their diet typically consists of meat or animal-derived ingredients. While dogs can be omnivorous in some respects and have developed digestive systems to cope with some plant materials and degraded proteins (Bhadra & Bhadra, 2014), there remains a strong carnivorous bias in their traits and behaviour. Cats, on the other hand, are obligate carnivores, meaning they need to eat meat to survive and depend more on protein sources for energy. Regardless of their meat or plant consumption, cats and dogs require protein to survive and maintain bodily functions. A study by Laflamme and Hannah (2013) calculated that the minimum daily protein requirement for adult cats appears to be at least 5.2 g kg^{-1} BM (body mass) which is higher than other studies (e.g. 2.7 g kg^{-1} BM, Riond et al., 2003) and the current recommendation by the Association of American Feed Control Officials (AAFCO), who recommend 3.25–3.9 g kg^{-1} BM of protein for adult cats, daily. While feral cats may have less consistent diets than those of household pets, they can consume up to twice as much crude protein in their diet in the form of prey animals (Plantinga et al., 2011). For adult dogs, protein should be supplied at approximately 2.55 g kg^{-1} BM (Holt, 2021), though older dogs may require up to 50% more to maintain optimal body condition (Churchill & Eirmann, 2021). Historically, protein to nitrogen conversion has been calculated by applying a ratio of 0.16 (protein is 16% N by mass), based on the work of Jones (1931); however, this ratio may be closer to 0.2 for meat and between 0.18 and 0.16 for fish (Krul, 2019). As the diets of domestic cats and dogs are highly variable and contain multiple sources of protein, we use a conversion ratio of 0.17 ± 0.02 to incorporate some uncertainty in this conversion. Based on dietary data, assumed daily protein ingestion rates of 5.0 ± 1.0 g kg^{-1} d^{-1} BM and 3.0 ± 1 g kg^{-1} d^{-1} BM result in an estimated N intake of 0.85 ± 0.20 g N kg^{-1} d^{-1} BM and 0.51 ± 0.18 g N kg^{-1} d^{-1} BM for cats and dogs, respectively.

Based on a review of nitrogen produced in cat and dog waste reported in the literature (Table S2), we estimate daily N excretion rates of 0.69 ± 0.17 g N kg^{-1} d^{-1} BM and 0.67 ± 0.24 g N kg^{-1} d^{-1} BM for cats and dogs, respectively. The majority of N excreted by the animals was in the form of urine, with a ratio of N in urine and faeces of 3.9 to 1 and 5.7 to 1 for cats and dogs, respectively. While these numbers differ from those initially calculated based on dietary intake, the 95% CIs do overlap, suggesting that both assessments are realistic in magnitude. For the purposes of this study, we use a balanced approach (Balanced Estimate) using both the intake and output data from the literature to establish realistic N excretion rates in the form of urine and faeces (Table 2).

2.3.2. Phosphorus

As with N, the quantity of P in the diets of cats and dogs is highly variable in nature, and nutritional requirements are closely linked to the quantity of calcium consumed. Requirements of P are linked to bone development, so needs vary throughout the life of an animal. A growing or pregnant cat may require 2–3 times the amount of P to help develop bone growth (Kienzle et al., 1998), though this need declines rapidly with age (Pérez-Camargo, 2004). American Association for Feed Control Officials (AAFCO) guidelines for phosphorus in foods for healthy cats is 1.25 g P per 1,000 kcal ME for maintenance. An average 4 kg domestic cat is expected to eat between 40 and 100 kcal ME kg^{-1} BM d^{-1} (Miller & Allison, 1958; Pérez-Camargo, 2004); thus P intake should be approximately 87.5 ± 37.5 mg P kg^{-1} BM d^{-1}. It has been reported that dietary phosphorus allowance in dogs is approximately 0.75 g day^{-1} for the average dog (minimum of 0.4 g d^{-1}) (National Research Council NRC, 2006). This would translate to approximately 37.5 mg P kg^{-1} BM d^{-1} (for a 20 kg dog). Böswald et al. (2018) recommend a calcium to phosphorus ratio of 1.4:1 in dog diets, which translates to approximately 43.9 mg P kg^{-1} BM d^{-1} according to their estimates.

As with N, data on P in pet excreta are under-reported for environmental purposes, and most available data come as a result of medical and diet trials (Table S3). While many trials on P excretion have been carried out, it is common in these studies to include groups where P ingestion is elevated (>100 mg P kg^{-1} BM d^{-1}) for experimental purposes (e.g. Dobenecker, Hertel-Böhnke, et al., 2018; Dobenecker, Webel, et al., 2018; Hofmann et al., 2022), but excretion ratios are still useful for reference (58–76% of P excreted from dogs is in the form of faeces). We use P contents reported in the meta-analysis carried out by De Frenne et al. (2022) to estimate excretion of P from dogs.

Based on the available data, we estimate that cats produce 107 ± 37 mg P kg^{-1} BM d^{-1} and dogs produce 88 ± 20 mg P kg^{-1} BM d^{-1}. In cat waste, P tends to end up relatively evenly in the different fractions of the waste with a ratio of near 1 to 1. In dog waste, the ratio of P is highly skewed towards faeces, with a ratio of 7.8 to 1 which is similar in magnitude to those observed in the high P intake clinical trials. These estimates of P excretion exceed those of the recommended daily intake for maintenance, though there are plausible reasons for these discrepancies. There is evidence that manufactured pet food contains higher P content than is necessary for animals, likely as a result of the varying developmental needs of pets at various stages in their life (e.g. Brunetto et al., 2019). It is also likely that feral animals will overconsume P due to eating bones within small animals (birds, rodents, etc.) which results in increased phosphorus excretion for free-roaming animals (Böswald et al., 2018). As a result of these factors, it is likely that consumption and excretion of P from cats and dogs are often larger than the recommended veterinary guidelines. For the purposes of this study, we use a balanced approach using both the intake and output data from literature (leaning more towards the latter) to establish realistic P excretion rates in the form of urine and faeces (Table 3).

Table 2. A summary of N excretion rates for domesticated cats and dogs. Literature used to calculate excretion rates is presented in Table S2. Uncertainties represent the 95% CIs of the mean

	Species	Waste type	Daily N excretion (g N kg^{-1} BM d^{-1})
Dietary intake			
Total N intake	Cat	All	0.85 ± 0.20
Total N intake	Dog	All	0.51 ± 0.18
Measured excretion			
Cat urine N	Cat	Urine	0.55 ± 0.17
Cat faeces N	Dog	Faeces	0.14 ± 0.04
Dog urine N	Cat	Urine	0.57 ± 0.23
Dog faeces N	Dog	Faeces	0.10 ± 0.06
Balanced estimate			
$CatUrine_{N\_Excrete}$	Cat	Urine	0.60 ± 0.25
$CatFaeces_{N\_Excrete}$	Cat	Faeces	0.15 ± 0.05
$DogUrine_{N\_Excrete}$	Dog	Urine	0.50 ± 0.25
$DogFaeces_{N\_Excrete}$	Dog	Faeces	0.10 ± 0.05

2.4. Global nutrient waste estimates

Using reported values from literature and veterinary sources (See methods 2.1–2.3), each input parameter

Table 3. A summary of P excretion rates for domesticated cats and dogs. Literature used to calculate excretion rates is presented in Table S3. Uncertainties represent the 95% CIs of the mean

	Species	Waste type	Daily N excretion (mg P kg^{-1} BM d^{-1})
Dietary intake			
Total P intake	Cat	All	87.5 ± 37.5
Total P intake	Dog	All	>40
Measured excretion			
Cat urine P	Cat	Urine	52 ± 28
Cat faeces P	Dog	Faeces	55 ± 24
Dog urine P	Cat	Urine	18 ± 9
Dog faeces P	Dog	Faeces	70 ± 18
Balanced estimate			
$CatUrine_{P\_Excrete}$	Cat	Urine	55.4 ± 30.4
$CatFaeces_{P\_Excrete}$	Cat	Faeces	58.6 ± 32.2
$DogUrine_{P\_Excrete}$	Dog	Urine	22.0 ± 5.7
$DogFaeces_{P\_Excrete}$	Dog	Faeces	58.6 ± 4.9

for our calculations was assigned a mean and 95% confidence interval (95% CI), assuming a Gaussian distribution (Table 4). Using these parameters, Equation 1 was used to estimate global totals of annual N and P production, using the method of least squares (Tellinghuisen, 2015) to propagate error:

$$X_{Waste} = X_{Pop} * X_{Mass} * X_{Excrete} * 365 \quad (1)$$

where X represents cats or dogs, X_{Waste} is the total mass of waste (N/P) produced in one year, X_{Pop} is the estimated global population of animals (Cat_{pop}/Dog_{pop}), X_{Mass} is the estimated total body mass of the global population of the animal (Cat_{Mass}/Dog_{Mass}), and X_{Excrete} is the expected daily excretion rate of N or P for an individual animal per kg of body mass.

3. Results

The total global N and P excretion from domestic cats and dogs is estimated to be 4.32 (1.27–7.38) Tg N yr^{-1} and 0.76 (0.31–1.21) Tg P yr^{-1} (Table 5). These results highlight that urination is the primary route of N excretion in cats and dogs, and that faeces are the primary route of P excretion. The larger overall mass of dogs makes their contribution to both N and P waste considerably larger than that of cats despite the higher excretion rate per kg BM of cats. The majority of N is deposited from dogs (88%), with dog urine accounting for an estimated 74% of all N waste. Dogs also contribute approximately 91% of P excretion globally from both cats and dogs. While dog faeces contribute more to P waste than dog urine, our analysis suggests that P in dog urine (0.14 ± 0.12 Tg P yr^{-1}) is still a larger source of P waste than all cat excretion combined (0.08 ± 0.06 Tg P yr^{-1}), though uncertainties overlap substantially (Table 5). Uncertainties are relatively large for all sources accounting for 71% and 59% of the magnitude of the estimates for $Total_N$ and $Total_P$, respectively.

4. Discussion

4.1. Contribution to global waste streams

This study provides the first global estimates of N and P produced in cat and dog waste. Our review of the literature highlights that this is a severely understudied nutrient stream at the global level. The value of the analysis carried out in this study is that the estimates within are constrained by real data, providing the best estimates to date of the waste streams described within. However, it must still be emphasised that many of the parameters of the calculations used in this analysis were highly uncertain with no immediate opportunity to verify global estimates or compare with other studies. Basic factors such as the number of domesticated cats and dogs in the world and their combined body mass are both highly uncertain and many countries have poor records of animal numbers. Our estimate of a total combined mass of cats and dogs of 22 Tg is slightly lower than that of Greenspoon et al. (2023), who estimated a mass of 24 Tg. If we have underestimated

Table 4. A summary of parameters used in Equation 1 to estimate global excretion of N and P from cats and dogs. Uncertainties represent the 95% CIs of the mean. Units refer to the mass of N or P per kg of animal body mass BM per day

Parameter	Scale	Unit	Mean	±95% CI
Cat_{Pop}	Global	Millions	700	200
Dog_{Pop}	Global	Millions	900	200
Cat_{Mass}	Global	Tg	2.6	1.3
Dog_{Mass}	Global	Tg	19.4	6.3
$CatUrine_{N\_Excrete}$	Individual	g N kg^{-1} BM d^{-1}	0.60	0.25
$CatFaeces_{N\_Excrete}$	Individual	g N kg^{-1} BM d^{-1}	0.15	0.05
$DogUrine_{N\_Excrete}$	Individual	g N kg^{-1} BM d^{-1}	0.50	0.25
$DogFaeces_{N\_Excrete}$	Individual	g N kg^{-1} BM d^{-1}	0.10	0.05
$CatUrine_{P\_Excrete}$	Individual	mg P kg^{-1} BM d^{-1}	55.4	30.4
$CatFaeces_{P\_Excrete}$	Individual	mg P kg^{-1} BM d^{-1}	58.6	32.2
$DogUrine_{P\_Excrete}$	Individual	mg P kg^{-1} BM d^{-1}	22.0	5.7
$DogFaeces_{P\_Excrete}$	Individual	mg P kg^{-1} BM d^{-1}	85.6	4.9

Table 5. A summary of the total global nitrogen ($Total_N$) and phosphorus ($Total_P$) produced in cat and dog waste (as calculated using Equation 1)Uncertainties represent the 95% CIs of the mean

Animal	Waste	$Total_N$	$Total_P$
		(Tg N)	(Tg P)
Cat	Urine	0.40 (0.01–0.79)	0.04 (0–0.08)
Cat	Faeces	0.10 (0.01–0.19)	0.04 (0–0.08)
Cat	**Total**	**0.50 (0.1–0.9)**	**0.08 (0.02–0.13)**
Dog	Urine	3.19 (0.22–6.16)	0.14 (0.02–0.26)
Dog	Faeces	0.64 (0.04–1.23)	0.55 (0.12–0.98)
Dog	**Total**	**3.82 (0.79–6.85)**	**0.69 (0.24–1.13)**
All	**Total**	**4.32 (1.27–7.38)**	**0.76 (0.31–1.21)**

animal mass in this study, then the true waste generated by cats and dogs may be higher than we report. However, there is no way to validate many of these parameters with current data; hence, we have used conservative estimates of uncertainty in our calculations to constrain a broad range of possibilities.

To put these nutrient streams into context, we compare, here, our values of N and P from cat and dog waste with those of livestock waste at the global scale. The annual content of global agricultural manure production is of the order of 130 Tg N yr^{-1} (Zhang et al., 2017) and 23 Tg P yr^{-1} (Q. Liu et al., 2017). Our estimates of production from cat and dog excreta of 4.32 ± 3.06 Tg N yr^{-1} and 0.76 ± 0.45 Tg P yr^{-1} indicate equivalent loss terms of 3.3 (1.0–5.7)% and 3.3 (1.3–5.3)% of global livestock nutrient losses for N and P, respectively. As the total mass of cats and dogs in this study (22.0 ± 6.4 Tg) is equivalent to 3.6% of the 604 Tg total mass of domesticated mammalian livestock (excluding cats and dogs as estimated in Greenspoon et al. (2023), we are confident that the magnitude of the estimates of N and P excreted that we report is realistic. Global anthropogenic nitrogen fixation is estimated to be in excess of 200 Tg N yr^{-1} (Fowler et al., 2013), so while the 4.32 ± 3.06 Tg N yr^{-1} of waste generated by cats and dogs is relatively small at the global scale in comparison to other domesticated animals (e.g. livestock), this is still a quantitatively large number. To put this in context, nutrient waste from cats and dogs can be equivalent to or larger than the agricultural nutrient requirements of an entire country (e.g. more than double the applied total of 2.1 Tg of N and 0.28 Tg of P to agricultural fields in the UK in 2021 (Soil nutrient balances UK, 2021)).

At current market prices (in excess of \$1,350 ton^{-1} N in the US and EU), the cost of an equivalent amount of N in the form of mineral fertiliser would be over \$5.8 billion a year. Unlike herbivorous livestock, which often have their waste (manure) recycled into agricultural soils, pet waste and the waste of stray animals are typically not handled this way. The solid waste of carnivorous animals is more odorous than that of herbivorous livestock due to the presence of sulphur-containing mercaptan compounds (rancid odour). Carnivorous mammalian faeces can also contain harmful pathogens (Penakalapati et al., 2017); thus, humans are less likely to accept direct interaction with these waste materials in large volumes and have not done so historically. While it may be possible to collect and utilise pet waste on a large scale for composting and crop fertiliser purposes (Nemiroff & Patterson, 2007), it is rarely done due to the dangers of pathogens surviving at low composting temperatures, the unpleasant nature of handling the waste and the difficulty of collecting such a diffuse waste source. Additionally, as the majority of the N streams from cats and dogs are in the form of urine, it becomes exponentially harder to collect and reuse for agricultural (or other) purposes than the collection and disposal of faeces. For many reasons, we cannot recommend that cat and dog waste is considered for future nutrient cycling. It is impractical, uneconomic, and potentially dangerous to do so. Therefore, we must accept that the majority of these waste streams will continue to be deposited into the natural and urban environments at the global scale.

4.2. Distribution of cat and dog waste

As waste from cats and dogs is rarely reused for agricultural purposes, any waste that is collected by humans is most likely to end up in municipal waste streams and eventually in landfill or incinerator facilities. Deposition into the environment or collection into municipal waste will primarily depend upon whether an animal is considered a pet. The majority of cats at the global scale are considered strays, and Lord et al. (2013) estimated that approximately 83% of dogs are "free-living" meaning that they have a large degree of autonomy (e.g. breeding and roaming), even if they are technically classed as "pets" and still rely on human engagement to survive (e.g. food source and medicine). For stray or free-roaming animals, it is unlikely that anyone will clean up any excreta immediately after deposition. It has been reported that approximately 41% of cat owners keep their cats solely indoors in some countries (Foreman-Worsley et al., 2021). While these excreta will not enter the natural environment directly as would be the case with a free-roaming cat, we can still expect microbial activity to occur in landfill resulting in emissions of N_2O and NH_3 (though these emissions are likely already accounted for in any national budget in "landfill" or "waste" categories). The behaviour of dog owners varies widely when it comes to picking up faeces. Overgaauw et al. (2009) suggested that 39% of dog owners do not pick up their waste, while Westgarth et al. (2008) reported owners will pick up after their dogs in streets and public areas approximately 90% of the time, but only 50% in the open countryside.

An assumption could be made that the deposition of cat and dog waste into the environment will closely follow cat and dog populations, but this will vary widely by region (Hughes & Macdonald, 2013). Numerous factors controlled by both nature and humans will alter the deposition of excreta (e.g. geography, diet, weather patterns, prey behaviour, human removal, etc.). There is evidence in some studies that there is a slightly higher prevalence of pet ownership in rural areas (Hawes et al., 2021; Lepczyk et al., 2004), but generally the distribution of pets in a given region is directly associated with the size of the human population (Asher et al., 2011). As with household pets, the prevalence of feral cats and dogs is also directly associated with the size of the human population and the rural/urban split is dependent upon the ratio of humans living in each (Gill et al., 2022). An estimated 56% of the world's human population now lives in urban settings (worldbank.org). Based on a global urban land coverage of 3.5 million km^2 (estimated for 2020 by Zhao et al. (2022)) and an urban deposition of 2.4 Tg N yr^{-1} and 0.43 Tg P yr^{-1}, it could be estimated that a global average of 6.9 kg N and 0.12 kg P is deposited per hectare in urban areas every year (though this would vary drastically by region).

The impact of relatively small quantities of N deposition on sensitive ecosystems is well documented (Payne et al., 2012; Stevens et al., 2018), and in the case of cat and dog waste streams a large amount of concentrated N can be applied to sensitive environments, especially in the form of dog urine which is the dominant N waste stream in this study. The impact of dog waste on urban grasslands may be less severe due to the already limited biodiversity in these regions and the adaptability of grass species to N and P loading (Buchholz et al., 2021). However, as dog walkers' frequent areas of natural beauty (e.g. parks, forests, beaches and nature reservations; George & Crooks, 2006; Rangel-Buitrago et al., 2024), N and P deposition can be concentrated in these sensitive areas, especially near foot paths (also observed in urban settings; Allen et al., 2020). De Frenne et al. (2022) estimated that 11 kg N was deposited per hectare to peri-urban forests every year from dogs and that this would have negative impact on sensitive ecosystems. However, these impacts are highly complex, with numerous cascading effects such as driving animals from their natural habitats or interfering with territorial markers (George & Crooks, 2006; Thomas et al., 2024). To effectively model and determine the true environmental impact of cat and dog waste in the environment at the global scale, much more explanatory data would be required in terms of the spatial distribution of animal population and their diets and behaviours, which makes local assessments and models more suitable for particular regions than a global effort.

4.3. Contribution to atmospheric emissions of nitrogen

Deposited N in the form of cat and dog excreta will inevitably contribute to emissions of N_2O and NH_3, though this is not an area of research that has been examined in detail, and no N_2O emissions from cat and dog waste are published in the literature. Emissions of N_2O come as a by-product of the natural microbial processes of nitrification and denitrification which occur in soils and aquatic bodies (Davidson et al., 2000). Microbes that consume available N from the breakdown of organic materials (e.g. animal waste) will convert it into unreactive nitrogen gas (N_2) but also generate a small fraction of N_2O during these processes which is released into the atmosphere. For N_2O from agricultural livestock, emission factors (EFs, the % of N emitted after deposition) in the literature vary widely but are generally limited to between 0.3 and 2% of deposited nitrogen. The global IPCC Tier 1 EF for N_2O emissions from animal urine is 0.4% to estimate direct emissions and another 0.27% for indirect emissions by leaching and volatilization (Michel et al., 2019). While N_2O EFs of livestock emissions for dung and urine are generally lower than 1%, the non-linear response of N_2O to N deposition (e.g. concentrated applications of N lead to higher N_2O emissions; Shcherbak et al., 2014) and expected emissions from N losses in wastewater drainage EF (1.6% reported in Michel et al., 2019) push toward higher EFs. Without any experimentation to refer to, the emissions of N_2O from cat and dog waste are highly speculative in nature and rely on comparisons with livestock waste. However, based on these experiments, at the global scale it could be realistic to assume an N_2O EF between 0.5 and 1.5% of deposited N. This would mean that cat and dog waste would emit in the region of 43 (13–74) Gg N_2O-N yr^{-1} at the global scale. This makes only a very small contribution (0.66%) to global anthropogenic emissions of N_2O, which are estimated to be 6.5 (3.2–10.0 Tg N yr^{-1}; Tian et al., 2020) but is still the same order of magnitude of emissions from an intensive developed agricultural nation such as the UK, which reports almost identical national scale emissions of N_2O from all sources in the region of 45 Gg

$N_2O–N\ yr^{-1}$ (70.4 Gg N_2O, reported in NAEI, 2022). Comparatively, hundreds of experiments have been carried out in the UK (and other developed nations with similar N_2O emissions) with aims to better understand and mitigate N emissions, while not a single experiment has been carried out in the world on the topic of N_2O emissions from cats and dogs. However, some of these emissions may already be accounted for in global inventories in landfill and sewage/drainage categories. Our global warming potential estimate of N_2O from cat and dog waste is the equivalent of 18.7 Tg $CO_{2eq}\ yr^{-1}$. Based on the assessment by Alexander et al. (2020) that the pet food industry accounts for approximately 106 Tg $CO_{2eq}\ yr^{-1}$, our study estimates that N_2O emissions from pet waste are equivalent to 17.7% of the carbon footprint of this industry, which has so far gone unaccounted in global calculations and carbon foot-printing of pet ownership.

Emissions of NH_3 occur due to the volatilisation of NH_3 and ammonium (NH_4^+) from soils and aquatic bodies. Emissions of NH_3 are complex and difficult to measure but are known to be dependent on several physical factors such as humidity, wind speeds, and soil pH (e.g. Kim et al., 2021; Yang et al., 2022). Where a large fraction of ammonia or urea is deposited in a small area (e.g. a urine patch), a large fraction of this N will be volatilised into the atmosphere before it is consumed by plants or microbes in the soil. Emission factors of NH_3 released from livestock urine are widely reported (Burchill et al., 2017; Fischer et al., 2016; Hristov et al., 2011), although large uncertainties persist with emissions reported in the literature ranging from near 0 to over 30% of deposited nitrogen depending on environmental conditions. Ammonia emissions are strongly affected by weather. Increasing temperature will significantly increase the volatility and thus emissions of NH_3 (Pedersen et al., 2021; Sutton et al., 2013). Therefore, similar quantities of nitrogen applied in different climates will behave differently depending upon the weather. Sutton et al. (2000) made an attempt to estimate NH_3 emissions from dogs, based on values derived by Cass et al. (1982) of 2.07 kg $NH_3–N\ dog^{-1}\ yr^{-1}$. This study makes the assumption that 36% of urinary N would be volatilised rather than the 90% assumed by Cass et al. (1982). However, there is no way to validate these estimates without measurements which have not been carried out to date. The surface upon which cats and dogs deposit waste will strongly impact NH_3 emissions. Urban streets with warm tarmac and concrete may see an order of magnitude higher NH_3 emissions than long damp grasses in cold rural regions. Without research activity to quantify any of these assumptions, uncertainty remains high in estimating this emission source. Assuming a highly speculative NH_3 EF of 20 ± 15% based on livestock waste experimentation, we make a very approximate estimate of 864 ± 654 Gg $NH_3–N$ from cat and dog waste, which accounts for approximately 1.3 (0.5–2.2)% of domestic livestock emissions at the global scale (64 Tg $NH_3\ yr^{-1}$ reported by Luo et al., 2022).

4.4. Phosphorus waste streams

As with N, the environmental and societal impacts of P deposition are highly dependent on spatial factors and human behaviour. Unlike N, P deposition is largely in the faeces of the animals which can be more readily handled by humans. Where stray numbers are low and pet owners are responsible, much of the P is removed from the environment and sent to municipal waste, thus greatly reducing any environmental impacts. However, it is expected that the majority of P deposited by cats and dogs remains in the urban and rural environment at the global scale due to the large number of stray animals, P concentration in urine, and the lack of responsibility among pet owners (varies by region). De Frenne et al. (2022) estimated that 5 kg of P was deposited per hectare in peri-urban forests every year from dogs and that this would have negative impact on sensitive ecosystems. In urban areas, the majority of animal waste is likely to sit on tarmac or compressed soils with little vegetation, which will lead to an increase in P deposition to drainage channels. Global urban discharge of P has been estimated at 1.0 Tg P yr^{-1} (Morée et al., 2013), though uncertainties are high. This value emphasises the importance of accounting from cat and dog waste in global models, especially urban regions which we estimate in this study to be in the region of 0.43 Tg yr^{-1}. While it has been reported that P in urban waste streams can be dominated by plant materials in some cases (Yang & Toor, 2018), Hobbie et al. (2017) conclude that the relationship between watershed P inputs and stormwater P exports indicates dog waste as one primary source of P in urban drainage.

Mihelcic et al. (2011) estimated that 3.4 Tg P yr^{-1} was produced in human urine and faeces and of this it is estimated that 0.3–1.5 Tg is recovered from human waste annually by wastewater reuse and reclamation and biosolids application (Liu et al., 2008; Senthilkumar et al., 2014). Where cat and dog faeces are sent to municipal landfill or leached (or flushed) into natural waterways P becomes unusable and is removed from human use. Sources of mined P which are adequate for use as agricultural fertiliser (e.g. low in heavy metal impurities such as cadmium) are a finite and in demand (Brownlie et al., 2022); thus, stripping P from the food chain adds to the rate at which global phosphorus supplies dwindle. Without further data on removal processes (i.e. wastewater reclamation of nutrients), it is difficult to estimate the final fate of much of this P and uncertainties in global inventories remain high with respect to cat and dog waste.

4.5. Future research and mitigation options for cat and dog waste

Reporting the environmental impacts of pet ownership is highly controversial due to the close ties that humans have with animal companions. Dogs are often referred to as "man's best friend" and are considered the first domesticated animal (Ahmad et al., 2020). Any attempt to quantify the environmental impact of cats and dogs, or to alter behaviour to mitigate environmental harm should be considered a sensitive topic due to the strong feelings that the public has for pets. However, pets such as cats and dogs do come with an environmental cost, and it is our responsibility as researchers to (i) establish and quantify to the best of our ability, our interactions with the environment via direct or indirect contribution, and (ii) to encourage mitigation of these impacts where it is prudent to do so.

The difficulty of collecting a diffuse source of waste such as cat and dog waste and the unpleasant nature of handling it drastically reduce the number of researchers who would seriously consider carrying out physical research on this topic. This (paired with the relatively small scale of waste streams in comparison to livestock) is likely the reason that trials have never been carried out to quantify these impacts. Regardless of the total quantity of waste generated at a global level (greater than the annual agricultural nutrient input of some nations), it is unlikely that experimentation will ever be carried out to accurately quantify these waste streams at a global level. As such, reviews like this one are necessary to attempt to characterise these waste streams for global inventories. Without terms for these waste streams, a variety of environmental models may either underestimate pollution generated by human activity, or wrongly associate measured pollution with other sources (e.g. human sewage or agriculture). While our estimates of cat and dog waste are relatively small at approximately 3.3% of the N and P in global livestock waste, this is still a large and significant number in environmental models, especially in the case of N pollution which cascades in various forms.

While it has been argued that areas with specific sensitivities to domesticated cats and dogs could be protected from domesticated cats and dogs, this is typically to prevent predation of native species rather than for nutrient deposition purposes (Parsons et al., 2016; Zamora-Nasca & Lambertucci, 2022). Without studies to determine the impact of N and P deposition to ecologically sensitive zones, we cannot truly assess the damage to these ecosystems or provide balanced policy recommendations for mitigation efforts. However, basic mitigation of the environmental impacts of cat and dog waste is relatively simple. Where possible faeces (and urine via cat litter) can be collected and disposed of into municipal waste. While this waste is still likely to contribute to emissions of N_2O and NH_3, this is an extremely small contribution to these gases in relation to other human activities such as sewage treatment, livestock farming, and general agricultural use of N fertilisers. Deposition of cat and dog waste into municipal waste streams such as landfill, incineration or sewage treatment has a significantly reduced impact on the natural environment and will not have a direct impact on biodiversity or nutrient-sensitive zones.

Changing the diet of cats and dogs may have an impact on the environmental cost of pet food, but due to the protein (and thus N) requirements of these animals, N waste streams will remain unchanged regardless of a meat- or plant-based diet. It has been reported that pet foods often contain higher amounts of P than is required (e.g. Brunetto et al., 2019), which may even be detrimental to animals. One potential step that could be taken to reduce P waste streams would be to better refine dietary P intake in pet food (where the health of the animal is not affected). As N and P waste is directly related to animal size, smaller animals will have a smaller impact on the environment. The results of this study have found that N and P waste streams from dogs are approximately nine times greater than those of cats, partly due to the larger mass of the animal and partly due to the larger global population. While the option of reducing the cat and dog population to reduce environmental impact is an obvious mitigation choice, the authors of this study stress that this is not a recommendation that we would make. The value of cat and dog ownership in terms of the benefits on mental health and the useful jobs that trained animals carry out (e.g. search and rescue, therapy and rodent control) should be taken into account in this instance. Many other sources of pollution should be a priority for policy makers (e.g. sewage run-off, inefficient fertiliser use, and poor manure storage practices) before any action to reduce the impact of cat and dog waste is considered.

5. Conclusions

While it has been known for a long time that cat and dog waste is a source of N and P pollution, which is associated with negative environmental impacts, this study is the first to report global estimates of N and P nutrient waste from cats and dogs. While these waste streams have been difficult to estimate and often overlooked for many decades, we provide a defensible method to allow for emission inventories and global models to include these relatively small waste streams. The total global N and P excretion from domestic cats and dogs is estimated to be 4.32 (1.27–7.38) Tg N yr^{-1} and 0.76 (0.31–1.21) Tg P yr^{-1} in the form of urine and faeces, the vast majority of which ends up in rural and urban environments. While these quantities are relatively small in terms of total N and P pollution, missing them from inventories and models results in a systematic underestimate of the impacts of these pollution streams, which are equivalent to 3.3 (1.0–5.7)% N and 3.3 (1.3–5.3)% of P produced by livestock at the global scale. For this reason, we argue that these waste streams should be included in global pollution accounting and modelling efforts. Due to the lack of data available in terms of spatial variation of deposition and the wide range of sensitivities in the natural environment to this additional nutrient input, we recommend that if any further studies investigating the environmental impacts of cat and dog waste are carried out, they focus on smaller regional models where sufficient data can be gathered that more adequately represents the complex interactions between nutrient input and any potential ecological impact.

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Author contributions

NC conceived and was primary author and analyst for this study. WB and BMS provided expertise and guidance on the aspects of phosphorus pollution. ST, EC, and UD provided expertise and guidance on the aspects of nitrogen pollution and global/national scale nitrogen models. PL and JD provided expertise and guidance on statistical methods and analysis of data collected data. All co-authors engaged in the literature review and manuscript writing.

Data availability statement

All data used are referenced and provided in the supplementary materials attached to this manuscript. All other information is available within reasonable request to the corresponding author (Nicholas Cowan).

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