

The Ecological Paw Print of Companion Dogs and Cats

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As an indicator of sustainable development, the ecological footprint has been successful in providing a basis for discussing the environmental impacts of human consumption. Humans are at the origin of numerous pollutant activities on Earth and are the primary drivers of climate change. However, very little research has been conducted on the environmental impacts of animals, especially companion animals. Often regarded as friends or family members by their owners, companion animals need significant amounts of food in order to sustain their daily energy requirement. The ecological paw print (EPP) could therefore serve as a useful indicator for assessing the impacts of companion animals on the environment. In the present article, we explain the environmental impact of companion dogs and cats by quantifying their dietary EPP and greenhouse gas (GHG) emissions according to primary data we collected in China, the Netherlands, and Japan and discuss how to reduce companion dietary EPP and GHG emissions in order to understand the sustainability of the relationship between companion animals and the environment.

Keywords: ecological paw print, greenhouse gas emissions, environment, dogs, cats

Companion animals are part of human societies around the world (Amiot et al. 2016). Pets provide a host of benefits to people including companionship, improved mental and physical health, expanded social networks, and even benefitting child and teenage development (Wood et al. 2005, Cutt et al. 2007, Beverland et al. 2008, Okin 2017). Statistics describing companion animal numbers worldwide are scarce, and they fluctuate, but according to the data from Vetnosis and the European Pet Food Industry Federation, there were 223 million registered companion dogs and 220 million registered companion cats in the world in 2014. Dogs and cats are often regarded as family members, and most owners show great concern for their pet's well-being, including the food and water requirements of their pet, their living spaces, their health conditions, and even their pet's emotions and feelings (Flynn 2000, Martens et al. 2016, Su et al. 2018a). Providing complete nutrition during all stages of their lives is a common and effective way for owners to have caring and loving relationships with their animals (Fleeman and Owens 2007). Many owners feed their animals more nutrients than minimum recommendations or give them ingredients that are suitable for human consumption (Fleeman and Owens 2007, Swanson et al. 2013). Given the sheer numbers of companion dogs and cats globally and their potentially nutrient-rich diets, we have ample reason to suspect that resource consumption by companion animals is more serious than has been heretofore imagined. However,

Okin (2017) indicated, "It could be argued that dogs and cats eat meat that humans cannot consume and [that] is simply a byproduct of production for human use and, therefore, should not be counted as consumption beyond that of humans." But this is only partly true. For bone meal, an ingredient in most food for cats and dogs, this is true; humans generally do not eat this. For other ingredients, it is more complex. Some byproducts could be made suitable, after processing, for human consumption. Therefore, it is of vital importance to identify companion animals' resource consumption and environmental impacts and to simultaneously investigate how current pet food production systems can sustainably support their nutritional requirements.

The ecological footprint (EF) is a popular natural resource accounting tool that is used to measure environmental sustainability. Specifically, it is the total area of productive land and water required to continuously produce all resources consumed and to assimilate all waste produced by a defined population wherever on Earth that land is located (Wackernagel and Rees 1998b, Csutora et al. 2009). The dietary ecological paw print (EPP) is based on the EF and measures how much biologically productive land is used for companion animals' food consumption. The diet of an animal greatly affects its EPP, according to the animals' particular metabolic needs or dietary preferences and the availability of resources (Swanson et al. 2013, Vale and Vale 2009). Meat-based diets require more energy and water

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and, therefore, have far greater environmental impacts than plant-based diets (Pimentel and Pimentel 2003, Reijnders and Soret 2003, Wirsenius et al. 2010, Okin 2017). For example, in China, commercial pet dry food has higher percentages of animal meat products than human foods. Therefore, the dietary EPP and greenhouse gas (GHG) emissions of companion dogs relying on commercial dry food was found to be much higher than the dogs relying on human leftover foods (Su et al. 2018b). If we look at differences between countries—assuming all companion dogs and cats eat commercial dry food—then the dietary EPP of all companion dogs and cats in China equals the dietary EF of between 70 million and 245 million Chinese people, in terms of home-made food (Su et al. 2018b). The carbon emissions resulting from the food consumption of these animals are equivalent to the emissions generated by the food consumption of between 34 million and 107 million Chinese people (Su et al. 2018b). Meanwhile, in Japan, companion dogs and cats may consume between 3.6% and 15.6% of the food eaten by Japanese people, and through their consumption, Japanese companions release between 2.5 million and 10.7 million tons of GHG per year (Su and Martens 2018). In the United States, the energy consumption of companion dogs and cats is approximately one-fifth of the US population's energy consumption, whereas animal meat product consumption by dogs and cats alone is responsible for up to 80 million tons of methane and nitrous oxide (Okin 2017). Therefore, the individual and cumulative environmental impacts of the commercial dry food consumption by companion animals and the industries behind its manufacture are significant, considering the sheer volumes of planetwide pet ownership (Hammerly and DuMont 2012).

Commercial pet food has become one of the most popular feeds for companion animals in recent decades, replacing human leftover food. Pet food industry is no longer a niche market. As was demonstrated in previous studies, it has become an economic sector of substantial importance (Leenstra and Vellinga 2011), a commercial system of its own in many Western countries, and a growing sector in developing countries. Attention must therefore also be given to commercial pet food production if we wish to reduce the EPP of companion animals (of course, their impacts could be reduced via, e.g., changing pet ownership laws—limits to how many and types of pets people can own—and creating better guidelines on pet feeding; see also the next section). However, the pet food industry is unique with regard to sustainability, because commercial pet food formulations are based on consumer demand (e.g., sufficient energy, complete nutrition, functional and balanced food) and often provide an excess of nutrients (Hughes 1995). There is, furthermore, a growing obesity trend among companion animals in Western societies, because they are overconsuming and therefore potentially wasting resources. Both factors pose a significant barrier to the sustainable optimization of the pet food sector and to pet ownership in general (Swanson et al. 2013). Because the number of companion animal owners is

increasing, product sales are expected to grow in the near future, creating an increasing demand for pet food. Leenstra and Vellinga (2011) warned that this high demand is already beginning to exceed the offal available from human meat and fish consumption that is used to make pet food. Meat used in pet foods and other plant-based ingredients are now competing with food suitable for human consumption. The sustainability of pet food industries, as both food producers and polluters, should therefore be seriously considered, because they are now contributing significantly to global climate change (Swanson et al. 2013). Given the growing concern for environmental sustainable development, the pet food industry should consider how to promote technological progress in pet food production.

The goal of this research is to quantify the relationship between companion food consumption and associated environmental impacts. In the present study, we provide an overview of the individual and total companion dogs and cats' dietary EPP and GHG emissions in China, Japan, and the Netherlands, according to primary data we collected from companion dog and cat owners in these countries. The framework, findings, and recommendations in the present study can serve as a motivational platform for further research into the environmental impacts of companion animals from a global perspective.

Calculations of ecological paw prints

To measure the EPP of dogs, Vale and Vale (2009) analyzed the ingredients of one common UK dog food brand and assumed that the recommended portions indicated on the packaging represented the actual quantities fed to companion animals. Using the square meters (m^2) of land needed to generate the previously converted dry grams into whole chicken or grains present in the product (taking into account specific water content), they obtained an EPP of 0.27 hectares (ha) for an average medium-size dog (0.18 for small dogs and 0.36 for large dogs). They compared this to a dog having a completely omnivorous human diet and obtained an EPP of 0.48 ha per year. For cats, they used the same methodology to calculate the footprint of a 1-year supply of dry cat food and obtained 0.3 ha per year. Vale and Vale also assessed the footprint of the packaging but concluded that it was too small an amount to be significant. For tinned cat food, they assumed 80% moisture and converted the protein content into its raw meat equivalent. Assuming a cat is fed one 400-gram tin daily for a year, they calculated a paw print of 0.84 ha per year for beef, 0.13 ha per year for all other livestock meats, and 0.54 ha per year for fish meat.

Vale and Vale's (2009) results were published in numerous press articles (e.g., Alton 2009, Peoples 2009) and sparked an uproar among the media and from pet owners. The results of their study were later confirmed by John Barrett of the Stockholm Environment Institute (United Kingdom) in *New Scientist* magazine (Alton 2009). His calculations, based on his own data, showed essentially the same (relatively high) EPP results, mainly because of the high carbon footprint of

meat. Nevertheless, the accuracy of his and Vale and Vale's calculations was criticized on different aspects: the overestimation of the number of calories a dog requires daily; calculations being based on data for human-made meat instead of meat by-products; and the omission of the footprints produced by processing the ingredients, manufacturing it into food, packaging it, and transporting it (Ravilious 2009, William-Derry 2009, Rastogi 2010, Rushforth and Moreau 2013, Beynen 2015). Moreover, Vale and Vale (2009) assumed that owners fed their companions exactly as recommended by the pet food industry; however, many households choose noncommercial diets or supplement their pets' diets with table leftovers.

Three studies were carried out in response to these criticisms. The first was conducted by Arizona State University, investigating the EPP for dry dog food. Rushforth and Moreau (2013) used a hybrid economic input–output life cycle assessment to examine the supply chain and energy production associated with pet food manufacturing, within a particular factory. The goal of this study was to respond to criticism of Vale and Vale's methodology. Using the protein content values for different livestock meats, they calculated the meat needed in order to match the protein levels required in a certain number of tons of pet food per year, then estimated land-use requirements and the carbon and water footprints for this quantity of meat. An interesting finding from Rushforth and Moreau (2013) is that using lean meat in dog food was better—in terms of environmental impacts—than using offal, because its protein content more easily satisfies a dog's protein requirements. In addition, they found dog food manufacturing processes to have significantly high carbon footprints among all pet food manufacturers. Along with careful selection of meat sources, they recommended alternative energy systems as possible methods to reduce the carbon footprint of industrially manufactured pet foods (Rushforth and Moreau 2013). In their results, they reported a value of 1.06 ha of land required for a pet food manufacturer to produce 1 ton of dog food, which is 11.72 m² per kilogram.

The second study was published by Wageningen Livestock Research (WUR) and was focused on competition for food and space of cats, dogs, and horses in the Netherlands. WUR's calculations were based on human-edible products, which might overestimate the EPP (Leenstra and Vellinga 2011). However, the researchers did not include spillage or overfeeding, which usually compensates for these overestimations. Using data from relatively high crop yields of North Western Europe, Leenstra and Vellinga (2011) estimated a cat paw print of 0.1 ha and a dog paw print of 0.2 ha. They extrapolated these figures to pet ownership in the Netherlands and found that approximately 40% of all Dutch arable lands would be needed to produce the 82,000 ha required for these pets' diets (Leenstra and Vellinga 2011).

The third study was conducted by the authors of the present article. We assessed the dietary EPP, as derived from the EF, and greenhouse gas (GHG) emissions of cats and dogs in China and Japan (Su and Martens 2018, Su et al. 2018b).

The key determining factors influencing these paw prints included the average weight of cats and dogs in the sample, their diets (based on chicken and cereal), and the daily quantities they were fed. We assessed the environmental impacts linked to pet ownership while improving further understanding of the nutritional requirements for cats and dogs, pet food production, and its impacts on the environment. The results of these studies showed that companion dogs (in particular, large dogs) in China and Japan consumed more food resources than their actual needs and, therefore, had a relatively high dietary EPP and huge GHG emissions. These findings indicate that overfeeding and food waste are a common phenomenon among companion animal (especially dog) owners in China and Japan.

In the present study, the method used to calculate the dietary EPP of average-size companion dogs and cats in China, the Netherlands, and Japan (see the supplemental material) was also derived from the EF, often used to measure humanity's overall impact on nature, by analyzing six main categories of ecologically productive land areas: arable, grazing, forest, fishing, built-up, and energy (Wackernagel and Rees 1998a, Fu et al. 2015). Each of these six land types has its own annual productivity and equivalence factor. In order to estimate and quantify the dietary EPP of companion animals regarding their commercial dry food, two materials of consumption (chicken and cereal) were identified as relevant in this study, and as a result, only the arable and grazing land categories are included (see the supplemental material). In this research, we focus primarily on commercial dry food consumption and on the environmental impacts of average-size companion dogs and cats. Individual and total companion dogs and cats' dietary EPP and GHG emissions in the Netherlands, together with the comparison of findings from China and Japan, were included in the present study (see box 1).

Reducing companion animals' dietary ecological paw print

The majority of studies in the literature that were intended to analyze animal energy consumption and make policy recommendations often regard animal health as a key indicator (Nutrition 1971, Fleeman and Owens 2007, Bermingham et al. 2010, Linder and Freeman 2010, Fowler et al. 2013, Bermingham et al. 2014, Okin 2017). They generally confirm a positive correlation between energy consumption and an animal's health condition. These studies imply that animals consume a lot of energy (i.e., through meat consumption), and therefore, more attention should be paid to reduce their energy intake and to simultaneously safeguard their health and nutritional well-being (Collier et al. 1982, Mullis et al. 2015). The present study establishes a clear relationship between companion animal food consumption and environmental impacts by reviewing the data from three countries. In it, we highlight a neglected predictor of environmental damage and develop novel approaches not only to the relationship between a companion's energy intake and health

Box 1. Three cases: China, Japan, and the Netherlands.

Basic information about the nutrients and calorie content of companion animals' commercial dry food in China, Japan, and the Netherlands is presented in table 1.

According to the data we collected from these three countries, we quantified individual and total companion dog and cat food consumption (table 2).

The environmental impacts of companion dogs and cats in the Netherlands, Japan, and China

We quantified companion dogs and cats' dietary EPP, GHG emissions and energy consumption according to their food consumption of commercial dry food in these three countries (i.e., the Netherlands, Japan, and China). The dietary EPP of an average-size dog in China was between 0.82 and 4.19 ha per year, whereas for a cat, it was between 0.36 and 0.63 ha per year. Given that China has a large companion dog and cat population; their total environmental impacts are undoubtedly significant. Specifically, if we assume that all companion dogs and cats eat commercial dry food in China, their dietary EPP is calculated to be between 43.4 million and 151.4 million ha per year, which is equivalent to the dietary EF of between 72.3 million and 252.3 million Chinese people in a year. GHG emissions from this dry-food consumption are between 16.7 million and 57.4 million tons per year. The dietary EPP of an average-size dog in Japan was between 0.33 and 2.19 ha per year, whereas for a cat, it was between 0.32 and 0.56 ha per year. The dietary EPP of all companion dogs and cats in Japan lies between 6.6 million and 28.3 million ha per year, equivalent to the dietary EF of between 4.62 million and 19.79 million Japanese people. The GHG emissions from Japanese dog and cat food consumption were between 2.52 million and 10.70 million tons, which is equivalent to the GHG emissions resulting from the food consumption of between 1.17 million and 4.95 million Japanese people. With regard to companion dogs and cats in the Netherlands, our results showed that the dietary EPP of an average-size dog was between 0.90 and 3.66 ha per year, whereas for a cat, it was between 0.40 and 0.67 ha per year. The dietary EPP of all companion dogs and cats in the Netherlands was between 2.9 million and 8.7 million ha per year, which was equivalent to the whole EF of between 0.50 million and 1.51 million Dutch people. The GHG emissions from Dutch dog and cat food consumption was in the range of between 1.09 million and 3.28 million tons, which is equivalent to between 94,000 and 284,000 Dutch peoples' GHG emissions regarding their total resource consumption (table 3, table 4).

Our results show that the dietary EPP of one companion dog relying on commercial dry food in the Netherlands or in China was around two times that of a dog relying on commercial dry food in Japan. Consequently, their GHG emissions and energy consumption were higher than their Japanese equivalents. China has the largest number of companion dogs among the three countries, and the Netherlands has the least. Therefore, the dietary EPP, carbon emissions, and energy consumption of all companion dogs in China were the largest, whereas these values in the Netherlands were the smallest (table 3). With regard to cats, our results show that dietary EPP, GHG emissions, and energy consumption per capita for companion cats are similar across the three countries. However, although the per capita environmental impacts were similar, their total environmental impacts were quite different. The total number of companion cats in China, because of their greater numbers, consumed more resources and, to a large extent, contributed to greater environmental impact than companion cats in the Netherlands and Japan (table 4).

In addition, we also found that many companion dogs in the Netherlands and China consumed more energy than their actual needs, whereas in all three countries, the calorie intake of companion cats was sufficient to offset their energy requirements.

condition but also to the relationship between their food consumption and environmentally sustainable development.

However, in contrast to human diets, pet food products present a limited set of options, especially if companion animal owners' choices are limited to the predetermined blends of ingredients used by manufacturers (Rushforth and Moreau 2013). Reducing the dietary EPP of companion animals becomes highly dependent on selecting which recipes and ingredients require less land, produce the least emissions, and provide sufficient nutrients (Rushforth and Moreau 2013). This requires pet food industries to take responsibility for producing more sustainable pet food through product design and manufacturing processes (e.g., production facilities running on renewable energy or green supply chains; Rushforth and Moreau 2013, Swanson et al. 2013, Beynen 2015). Moreover, increasing the bioavailability and digestibility

of pet foods may also help to reduce food waste (Swanson et al. 2013).

Previous research has demonstrated that the protein content in animal-based products is around 11 times higher than that of plant-based products, meaning that pet food manufacturers can reach required protein content levels more efficiently if they use more animal products in pet food production (Swanson et al. 2013). However, the proteins found in meat also have a higher environmental impact than those found in plants and cereals (Swanson et al. 2013), so consuming fewer animal proteins or replacing them with plant-based proteins would lower GHG emissions (Westhoek et al. 2011). Therefore, the first and most evident solution for dramatically reducing companion animals' dietary EPP is to adopt vegetarian or vegan diets. This alternative diet has generated an ongoing and divisive debate, because it may not be the best possible path for

Table 1. The percentage of nutrients and calorie contents in commercial dry dog and cat food.

	Dog			Cat		
	China	Japan	The Netherlands	China	Japan	The Netherlands
Protein (in percent)	25.21	25.67	24.70	29.15	26.00	33.18
Fat (in percent)	13.80	14.67	8.33	13.17	7.50	12.76
Ash (in percent)	9.23	8.00	6.25	8.39	8.00	7.70
Fiber (in percent)	3.72	3.83	2.33	4.66	6.25	3.58
Moisture (in percent)	10.44	10.00	13.44	8.75	10.00	10.12
Carbohydrates (in percent)	37.60	37.83	44.95	35.88	42.25	32.66
Calories (in kilocalories per kilogram)	3371.35	3533.3	3145.80	3395.50	3445.0	3389.00

Table 2. Companion animal numbers and their commercial dry food consumptions in three countries.

	Dog			Cat		
	China	Japan	The Netherlands	China	Japan	The Netherlands
Per capita food consumption (in kilograms per year)	48–243	19–123	61–247	20–34	18–31	20–33
Total numbers (in millions)	27.4	10.35	1.8	58.1	9.96	3.2
Total food consumption (in millions of kilograms per year)	1308–6656	194–1271	109–445	1168–1954	178–311	64–106

Table 3. The dietary ecological paw print (EPP) and greenhouse gas (GHG) emissions of companion dogs in the Netherlands, Japan, and China.

Cat size	Country	EPP (in hectares)	GHG emission (in tons)
Per capita average-size dog	The Netherlands	0.90–3.66	0.349–1.424
	Japan	0.33–2.19	0.127–0.831
	China	0.82–4.19	0.313–1.592
Lifetime of one dog	The Netherlands	10.77–43.93	4.188–17.087
	Japan	4.01–26.28	1.522–9.972
	China	9.89–50.32	3.756–19.104
Total dogs	The Netherlands	1.62 million–6.59 million	0.608 million–2.480 million
	Japan	3.40 million–22.70 million	1.312 million–8.596 million
	China	22.5 million–114.8 million	8.576 million–43.621 million

Note: An average-size dog weights 10–20 kilograms.

maintaining an animal's health (or may be impossible, given certain dietary needs—e.g., cats, which are obligate carnivores) while significantly reducing its dietary EPP. However, alternative diets do not have to mean a complete abstention from meat. The choice of the sources of protein offers a large potential for reductions depending on the selection of high- or low-impact meat (Nijdam et al. 2012). By preferring poultry or fish sources over beef, for instance, desirable protein quality and content can be achieved while lowering both the EPP and GHG emissions (Schwartz 2014, Vale and Vale 2009).

It has been shown that the prevalence of companion animal obesity increases in line with human obesity (German

2006, Morrison et al. 2014). Most large companion dogs in China, Japan, and the Netherlands consume more energy than their actual needs to maintain normal activity, suggesting that overfeeding and food waste is commonplace among their owners. Maintaining ideal body weight and avoiding overfeeding nutrients in excess could diminish food waste and reduce dietary EPP and GHG emissions (Swanson et al. 2013, Schwartz 2014). Besides veterinarians, the pet food industry and relevant retailers could try to promote awareness of this salient fact by providing informative labeling. Improving the uniformity of food labels and providing insight to customers as to the meaning of indications on labels are strongly emphasized and could improve owners'

Table 4. The dietary ecological paw print (EPP) and greenhouse gas (GHG) emissions of companion cats in the Netherlands, Japan, and China.

Cat size	Country	EPP (in hectares)	GHG emission (in tons)
Per capita average-size cat	The Netherlands	0.40–0.67	0.150–0.251
	Japan	0.32–0.56	0.121–0.211
	China	0.36–0.63	0.141–0.237
Lifetime of one cat	The Netherlands	5.62–9.39	2.102–3.511
	Japan	4.46–7.80	1.693–2.959
	China	5.04–8.82	1.974–3.318
Total cats	The Netherlands	1.28 million–2.14 million	0.480 million–0.803 million
	Japan	3.20 million–5.60 million	1.204 million–2.105 million
	China	20.90 million–36.60 million	8.192 million–13.770 million

Note: An average-size cat weights 2–6 kilograms.

knowledge on how to feed their animals (PBL 2013). Owners could be encouraged to check labeling claims of nutritional adequacy and to ask manufacturers what evidence they can provide in order to ensure nutritional soundness and consistency of their animals' diets (Knight and Leitsberger 2016). Aside from consumer choice, the selection of more sustainable suppliers for ingredient composition and selection may also increase pet food sustainability—for example, by opting for foods from crops using fewer fertilizers (Swanson et al. 2013, Beynen 2015).

Another option, raised by Rastogi (2010), is to recycle companion animal owners' (human) food that would otherwise be wasted, by processing it into pet food (providing it would entail the correct balance of nutrients). Broader efforts for reducing daily emissions—for instance, by cycling to work—may also constitute a personal trade-off for pet owners, to balance their EF against the EPP of their companion animals (Rastogi 2010), although this may seem rather artificial. Schwartz (2014) cited other simple solutions for reducing the environmental impacts of companion animals besides their diets. For example, disposing of a dog's excrement responsibly could prevent animal waste from polluting water sources. Vale and Vale (2009) noted that pet food packaging is not such a significant issue for a pet's EPP as their main recommendations: sharing a communal pet instead of owning an individual pet, adopting edible pets such as egg-laying hens, or simply owning smaller dogs and cats in general. All the solutions and strategies proposed by others and in this present study, some of them being more realistic than others, reaffirm the importance of the environmental impacts of pet food and any other resource consumption by companion animals.

Conclusions

The research shows that people with a pet are, in general, healthier than non-pet owners. Pets also increase the capacity for empathy and social contact among children (which

are useful characteristics for a healthy and happy life). Furthermore, people who are heavily involved in animal welfare appear to have more compassion for the problems of people (Amiot et al. 2016). However, on the other side, the negative environmental impacts of food consumption by companion animals are expected to grow worldwide in the near future (Okin 2017). Besides food, companion animals also need water, entertainment, healthcare, living space, and many other resources and services, all of which dramatically affect their environmental impact. Therefore, a broader quantification of all companion animal resource consumptions (e.g., water footprint, health footprint) and waste production (e.g., feces) should be considered in future studies. Furthermore, the environmental impact of other animal groups, such as farm animals, wild animals, zoo animals, working animals, and laboratory animals are also interesting areas for further research. The present study was conducted according to data from the Netherlands, China, and Japan; further studies into the environmental impacts of other animal groups from global or cross-cultural perspectives also deserve more attention.

Animal products have greater environmental impact than plant-based products, and some researchers have quantified the different carbon or GHG emissions of meat and cereal. Therefore, quantifying the different impacts of animal and plant-based products consumed by companion animals in different countries should also be considered. Besides commercial dry food, companion animal owners feed their animals with canned food, homemade food, and pure meat. Therefore, another interesting avenue for further research would be to quantify companion animals' dietary EPP regarding their exact daily food consumption. As Rushforth and Moreau (2013) suggested, further research might also include comparisons of the contributions of pet ownership to various activities associated with society (e.g., dogs versus cats).

Although animal companionship can benefit physiological, psychological, and social aspects of the quality of human life, further knowledge and awareness are needed to enable

cat and dog owners to acknowledge the environmental costs of owning pets. Providing a broader perspective, Swanson and colleagues (2013) argued that ensuring sustainable pet ownership includes meeting the current and future needs of pets in providing their appropriate nutrition. Consequently, assessing whether and how the pet food system as a whole can sustainably support the health and nutrition of the growing population of companion animals is of also significant importance in the near future (Swanson et al. 2013).

Supplemental material

Supplementary data are available at *BIOSCI* online.

References cited

- Alton R. 2009. Polluting pets: The devastating impact of man's best friend. *Independent* (25 December 2009).
- Amiot C, Bastian B, Martens P. 2016. People and companion animals: It takes two to tango. *BioScience* 66: 552–560.
- Birmingham EN, Thomas DG, Cave NJ, Morris PJ, Butterwick RF, German AJ. 2014. Energy requirements of adult dogs: A meta-analysis. *PLOS ONE* 9 (art. e109681).
- Birmingham EN, Thomas DG, Morris PJ, Hawthorne AJ. 2010. Energy requirements of adult cats. *British Journal of Nutrition* 103: 1083–1093.
- Beverland MB, Farrelly F, Lim EAC. 2008. Exploring the dark side of pet ownership: Status-and control-based pet consumption. *Journal of Business Research* 61: 490–496.
- Beynen AC. 2015. Green Pet Foods. *Creature Companion* (March): 54–55.
- Collier R, Beede D, Thatcher W, Israel L, Wilcox C. 1982. Influences of environment and its modification on dairy animal health and production. *Journal of Dairy Science* 65: 2213–2227.
- Csutora M, Mózner Z, Tabi A. 2009. Sustainable consumption: From escape strategies towards real alternatives. Sustainable Consumption Conference. Sustainable Consumption, Production, and Communication.
- Cutt H, Giles-Corti B, Knuijan M, Burke V. 2007. Dog ownership, health and physical activity: A critical review of the literature. *Health and Place* 13: 261–272.
- Du B, Zhang K, Song G, Wen Z. 2006. Methodology for an urban ecological footprint to evaluate sustainable development in China. *International Journal of Sustainable Development and World Ecology* 13: 245–254.
- Fleeman LM, Owens E. 2007. Applied animal nutrition. Pages 14–31 in McGowan C, Gott L, eds. *Animal Physiotherapy: Assessment, Treatment and Rehabilitation of Animals*.
- Flynn CP. 2000. Battered women and their animal companions: Symbolic interaction between human and nonhuman animals. *Society and Animals* 8: 99–127.
- Fowler V, Fuller M, Close W, Whittemore C. 2013. Energy requirements for the growing pig. Pages 151–156 in Mount LE, ed. *Energy Metabolism: Proceedings of the Eighth Symposium of the European Association of Animal Production*. Butterworths.
- Francke I, Castro J. 2013. Carbon and water footprint analysis of a soap bar produced in Brazil by Natura Cosmetics. *Water Resources and Industry* 1: 37–48.
- Fu W, Turner JC, Zhao J, Du G. 2015. Ecological footprint (EF): An expanded role in calculating resource productivity (RP) using China and the G20 member countries as examples. *Ecological Indicators* 48: 464–471.
- Gerber PJ, Steinfeld H, Henderson B, Mottet A, Opio C, Dijkman J, Falcucci A, Tempio G. 2013. Tackling Climate Change Through Livestock: A Global Assessment of Emissions and Mitigation Opportunities. Food and Agriculture Organization of the United Nations.
- German AJ. 2006. The growing problem of obesity in dogs and cats. *Journal of Nutrition* 136: 1940S–1946S.
- Hammerly T, DuMont B. 2012. The environmental impact of pets. *Green Teacher* 25.
- Hughes D. 1995. Animal welfare: The consumer and the food industry. *British Food Journal* 97: 3–7.
- Knight A, Leitsberger M. 2016. Vegetarian versus meat-based diets for companion animals. *Animals* 6: 57.
- Leenstra F, Vellinga T. 2011. Indication of the ecological foot print of companion animals: First survey, focussed on cats, dogs and horses in the Netherlands. Wageningen UR Livestock Research. Report no 410650.
- Linder DE, Freeman LM. 2010. Evaluation of calorie density and feeding directions for commercially available diets designed for weight loss in dogs and cats. *Journal of the American Veterinary Medical Association* 236: 74–77.
- Liu H, Wang X, Yang J, Zhou X, Liu Y. 2017. The ecological footprint evaluation of low carbon campuses based on life cycle assessment: A case study of Tianjin, China. *Journal of Cleaner Production* 144: 266–278.
- Martens P, Enders-Slegers M-J, Walker JK. 2016. The emotional lives of companion animals: Attachment and subjective claims by owners of cats and dogs. *Anthrozoös* 29: 73–88.
- Morrison R, Reilly J, Penpraze V, Pendlebury E, Yam P. 2014. A 6-month observational study of changes in objectively measured physical activity during weight loss in dogs. *Journal of Small Animal Practice* 55: 566–570.
- Mullis RA, Witzel AL, Price J. 2015. Maintenance energy requirements of odor detection, explosive detection and human detection working dogs. *PeerJ* 3: e767.
- Nemecek T, Weiler K, Plassmann K, Schnetzer J, Gaillard G, Jefferies D, García-Suárez T, King H, i Canals LM. 2012. Estimation of the variability in global warming potential of worldwide crop production using a modular extrapolation approach. *Journal of Cleaner Production* 31: 106–117.
- Nutrition NRCCoA. 1971. *Nutrient Requirements of Poultry*. National Academies Press.
- Okin GS. 2017. Environmental impacts of food consumption by dogs and cats. *PLOS ONE* 12 (art. e0181301).
- PBL. 2013. Netherlands Environmental Assessment Agency (PBL), in Agency NEA, ed.
- Peebles L. 2009. How big is a dog's eco-pawprint? Audubon (25 November 2009). www.audubon.org/news/how-big-dogs-eco-pawprint
- Pimentel D, Pimentel M. 2003. Sustainability of meat-based and plant-based diets and the environment. *American Journal of Clinical Nutrition* 78: 660S–663S.
- Rastogi NS. 2010. The trouble with kibbles: The environmental impact of pet food. *Slate* (23 February 2010). <https://slate.com/technology/2010/02/the-environmental-impact-of-pet-food.html>
- Ravilious K. 2009. How green is your pet? *New Scientist* 204: 46–47.
- Reijnders L, Soret S. 2003. Quantification of the environmental impact of different dietary protein choices. *American Journal of Clinical Nutrition* 78: 664S–668S.
- Rushforth R, Moreau M. 2013. Finding Your Dog's Ecological "Pawprint": A Hybrid EIO-LCA of Dog Food Manufacturing. Arizona State University.
- Schwartz L. 2014. The surprisingly large carbon paw print of your beloved pet. *Salon* (20 November 2014) www.salon.com/2014/11/20/the_surprisingly_large_carbon_paw_print_of_your_beloved_pet_partner
- Shanahan H, Carlsson Kanyama A. 2005. Interdependence between consumption in the North and sustainable communities in the South. *International Journal of Consumer Studies* 29: 298–307.
- Su B, Koda N, Martens P. 2018a. How Japanese companion dog and cat owners' degree of attachment relates to the attribution of emotions to their animals. *PLOS ONE* 13 (art. e0190781).
- Su B, Martens P. 2018. Environmental impacts of food consumption by companion dogs and cats in Japan. *Ecological Indicators* 93: 1043–1049.
- Su B, Martens P, Enders-Slegers M-J. 2018b. A neglected predictor of environmental damage: The ecological paw print and carbon emissions of food consumption by companion dogs and cats in China. *Journal of Cleaner Production* 194: 1–11.

- Swanson KS, Carter RA, Yount TP, Aretz J, Buff PR. 2013. Nutritional sustainability of pet foods. *Advances in Nutrition: An International Review Journal* 4: 141–150.
- Vale, Vale. 2009. *Time to Eat the Dog? The Real Guide to Sustainable Living*. Thames and Hudson.
- Wackernagel M, Onisto L, Bello P, Linares AC, Falfán ISL, Garcia JM, Guerrero AIS, Guerrero MGS. 1999. National natural capital accounting with the ecological footprint concept. *Ecological Economics* 29: 375–390.
- Wackernagel M, Rees W. 1998a. *Our Ecological Footprint: Reducing Human Impact on the Earth*. New Society Publishers.
- Wackernagel M, Rees W. 1998b. *Our Ecological Footprint: Reducing Human Impact on the Earth*. New Society Publishers.
- Westhoek H, Rood T, van den Berg M, Janse J, Nijdam D, Reudink M, Stehfest E, Lesschen J, Oenema O, Woltjer G. 2011. *The Protein Puzzle: The Consumption and Production of Meat, Dairy and Fish in the European Union*. Netherlands Environmental Assessment Agency.
- William-Derry C. 2009. Dogs vs. SUVs. Sightline Institute (2 November 2009). www.sightline.org/2009/11/02/dogs-vs-cars
- Wirsenius S, Azar C, Berndes G. 2010. How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? *Agricultural Systems* 103: 621–638.
- Wood L, Giles-Corti B, Bulsara M. 2005. The pet connection: Pets as a conduit for social capital? *Social Science and Medicine* 61: 1159–1173.
- Xu X, Lan Y. 2017. Spatial and temporal patterns of carbon footprints of grain crops in China. *Journal of Cleaner Production* 146: 218–227.

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