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Estimation of global recoverable human and animal faecal biomass

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Human and animal faeces present persistent threats to global public health and also opportunities for recovery of resources. We present the first global-scale accounting of recoverable faeces (livestock animal and human) from 2003 to 2030 using country-specific human and animal population estimates and estimated species-specific faeces production by human or animal body mass. We also examine global coverage of domestic livestock animals and sanitation facilities to describe the distribution of onsite versus offsite hazards from animal and human faeces. In 2014, the total mass of faeces was 3.9×10^{12} kg per year, increasing by $>52\times10^{9}$ kg per year since 2003 and anticipated to reach at least 4.6×10^{12} kg in 2030. Annual global production of faeces from animals (primarily cattle, chickens and sheep) was about four times that from humans. Ratios of animal faeces to human faeces continue to increase (geometric mean of 4.2:1 for 2003 versus 5.0:1 for 2014 versus a projected 6.0:1 for 2030). Low-income populations bear the greatest burden of onsite faeces, mostly from animals in or near the domestic environment. This analysis highlights the challenges of resource recovery from concentrated and dispersed sources of faeces, and the global public health policy needed for safe management of animal faeces.

By 2050, the global population is expected to increase by a third, from 7.2 to 9.6×10^{9} (ref. [1]), with the proportion of urban residents increasing from 50% to 66%[2]. Although supplying essential resources to support an expanding global population is critical, the waste generated from this growth also requires careful consideration. Faecal wastes from human and livestock animal populations present both potentially recoverable resources (nutrients, energy and metals[3]) as well as public health hazards, with increases in population density raising the stakes for waste management[4–6].

Opportunity costs associated with discarded, unmanaged faeces can be high, given resource limitations[7,8]. Yields from recovery of metals alone may reach $13 million from the waste of one million people[9]. Phosphorous, nitrogen and potassium in human faeces and urine could significantly contribute to future needs (for example, up to 22% of global demand for phosphorous[10]), especially with improved recovery from newer sanitation systems[10,11]. Animal faeces and urine have similar recovery potential and are commonly applied to agricultural lands[12,13].

Unsafe management and subsequent exposure to human faeces are associated with high burdens of enteric infections, stunting of growth and poor cognitive development[4,14–17]. Recent evidence indicates similar outcomes from exposure to animal faeces[5,18,19], changing our understanding of the potential impact of zoonoses on global public health. Safe management of human faeces is a priority for Sustainable Development Goals (SDG)[20], and may require decentralized sanitation solutions with faecal sludge management (FSM). This differs from the model of sanitation development in many wealthy countries[21], though onsite systems are also present (for example >20% of domestic waste is managed onsite in the United States)[22]. Containment and safe use of animal faecal wastes have not been priorities in global sanitation policy so far. Approaches that make use of animal faeces while reducing unsafe exposures are variable in practice[5], despite the critical role such wastes may play in enteric disease transmission. Integrated human and animal waste management is recognized in the One Health paradigm, which seeks holistic integration of human, animal and environmental systems underpinning current and emergent public health challenges[23,24].

In this study, we estimated for humans and livestock animals the annual global recoverable faeces production historically (2003–2014) and prospectively (2017–2030). We combine animal population data from the United Nations Food and Agricultural Organization (FAO), human population data from the World Bank and mass-based estimates of human- and animal-specific faecal production from research literature to produce global- and region-specific estimates of faecal biomass. We also estimate national percentages of faecal biomass representing household-level hazards versus percentages offsite, using data on household ownership of animals and sanitation facilities. This analysis provides a foundation for global estimates of resource recovery potential and risks associated with faeces using systematically derived estimates. Results can support global and regional planning for public health and resource recovery.

Results

Faecal production from animal and human populations. The 2014 global population of humans (7.2×10^{9}) and livestock animals (29.7×10^{9}) produced an estimated 3.9×10^{12} kg faeces (Table 1). Human faeces comprised only 810×10^{9} kg (21%) of the total faecal biomass, and was highest in Southeast (SE) Asia (1.9×10^{9} people, 201×10^{9} kg faeces) and the Western (W) Pacific (1.8×10^{9} people, 216×10^{9} kg faeces). The discrepancy in regional human faecal production versus population was due to smaller average body mass in Southeast Asia (58 kg) than in the Western Pacific (66 kg)[25].

Animal populations were greatest in the Western Pacific (8.9×10^{9} animals, 779×10^{9} kg faeces), the Americas (6.7×10^{9}, 784×10^{9} kg faeces) and Southeast Asia (4.3×10^{9}, 487×10^{9} kg faeces). Globally, chickens (21.4×10^{9}, 780×10^{9} kg faeces), cattle

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Table 1 | 2014 estimates of WHO (World Health Organization) regional animal population, animal faecal production, human population and human faecal production

Region	Animal population, 2014	Animal faeces ($kg\,yr^{-1}$)	Human population, 2014	Human faeces ($kg\,yr^{-1}$)	Total faeces ($kg\,yr^{-1}$)
Africa	2.34×10^{9}	4.01×10^{11}	9.62×10^{8}	1.06×10^{11}	5.07×10^{11}
Americas	6.74×10^{9}	7.84×10^{11}	9.75×10^{8}	1.27×10^{11}	9.11×10^{11}
EastMed	3.49×10^{9}	2.98×10^{11}	6.39×10^{8}	8.00×10^{10}	3.78×10^{11}
Europe	4.00×10^{9}	3.70×10^{11}	9.09×10^{8}	1.14×10^{11}	4.84×10^{11}
SEAsia	4.26×10^{9}	4.87×10^{11}	1.90×10^{9}	2.01×10^{11}	6.88×10^{11}
WPacific	8.91×10^{9}	7.79×10^{11}	1.83×10^{9}	2.16×10^{11}	9.95×10^{11}
World	2.97×10^{10}	3.12×10^{12}	7.22×10^{9}	8.10×10^{11}	3.93×10^{12}

(1.5×10^{9}, 1.3×10^{12} kg faeces) and sheep (1.4×10^{9}, 231×10^{9} kg faeces) were the largest animal populations and faeces producers (Supplementary Table 2). Despite having fewer animals, the Americas produced more faeces, compared with other regions, due to its livestock animals with high body masses (for example, cattle).

Countries with the largest human populations produced the greatest estimated faecal biomass in 2014 (Fig. 1). China (19%) and India (11%) accounted for >25% of the world's faeces, followed by Brazil (7.2%), the United States (6.1%), Pakistan (3.3%), Indonesia (2.9%) and Mexico (2.0%). Argentina, Australia, Bangladesh, France, Iran, Nigeria, Russia, Sudan and Turkey composed the remaining 9 of 16 countries that individually produced ≥1% of the world's faeces, and together produced >63% in 2014. Ratios of animal faeces to human faeces in 2014 (kg animal faeces/kg human faeces) varied from <1 to >20 by country (Fig. 2). Regional geometric mean animal to human faeces ratios were highest in the Western Pacific (26) and Americas (11), compared with other regions (3.2–4.2). From 2003 to 2014, annual animal to human faeces ratios increased significantly by country and overall (Fig. 3). The overall geometric mean increased from 4.2 (95% confidence interval, CI: 3.6–5.0) to 5.0 (95% CI: 4.2–6.0). Projecting current trends results in a geometric mean of 6.0 (95% CI: 4.8–7.6) by 2030. Full descriptions of human and animal populations and faeces production are available in Figs. 1–3, Table 1, Supplementary Table 2 and the Supplementary Discussion.

Onsite (household-level) hazards from human and animal faeces. Worldwide, 56% of households had a sanitation facility with onsite containment (that is, unsewered, representing 456×10^{9} kg faeces), while 29% were connected to sewerage networks (235×10^{9} kg faeces) and 12% had no facility (97×10^{9} kg faeces) (Table 2). Onsite containment was most prevalent in the Western Pacific (70%, 152×10^{9} kg faeces), Southeast Asia (69%, 140×10^{9} kg faeces) and Africa (61%, 65×10^{9} kg faeces). Conversely, sewerage was most prevalent in Europe (68%, 78×10^{9} kg faeces), the Eastern Mediterranean (40%, 32×10^{9} kg faeces) and the Americas (33%, 42×10^{9} kg faeces). Further data are in Table 2 and the Supplementary Discussion.

Globally, 30% of households had domestic livestock animals in 2014 (933×10^{9} kg faeces: more than twice that of onsite human faeces, Table 3). These animals were chickens (44%), cattle (22%) and goats (18%). Southeast Asia (53%), Africa (48%) and the Western Pacific (33%) had the largest proportions of domestic livestock animals. Further global and regional estimates are in Table 3, Supplementary Table 3 and the Supplementary Discussion.

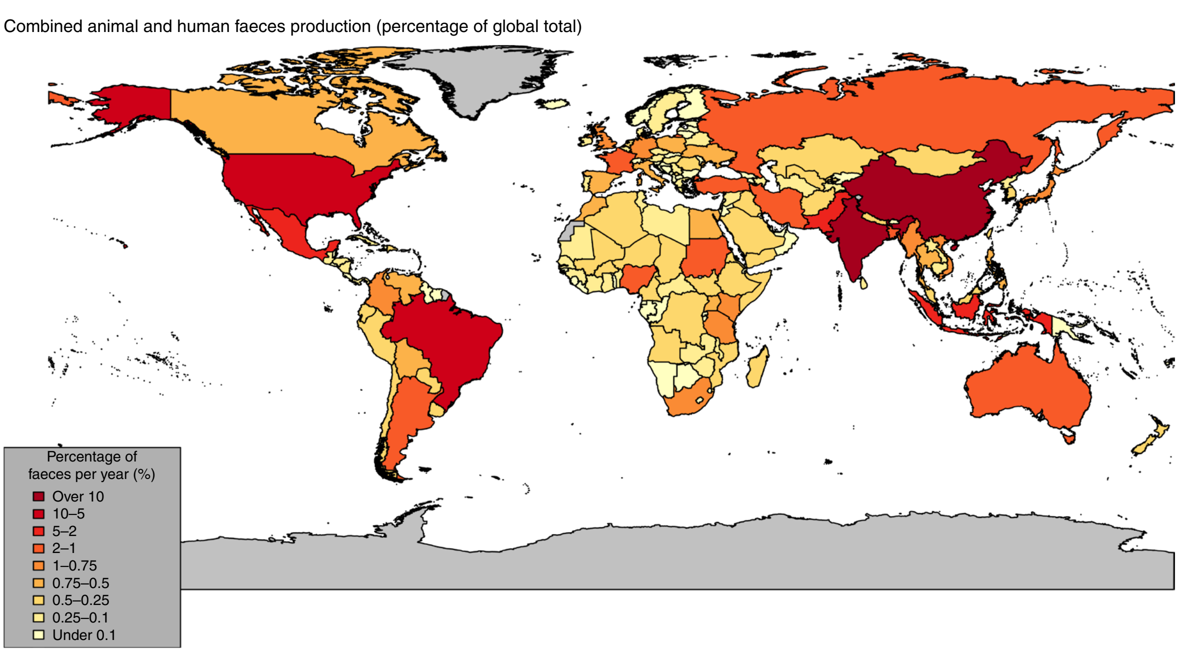

Fig. 1 | Country-level estimates for percentage of the world's faeces production in 2014. Darker red indicates larger production of faeces annually. Country borders are in black, while countries/regions in grey have no data.

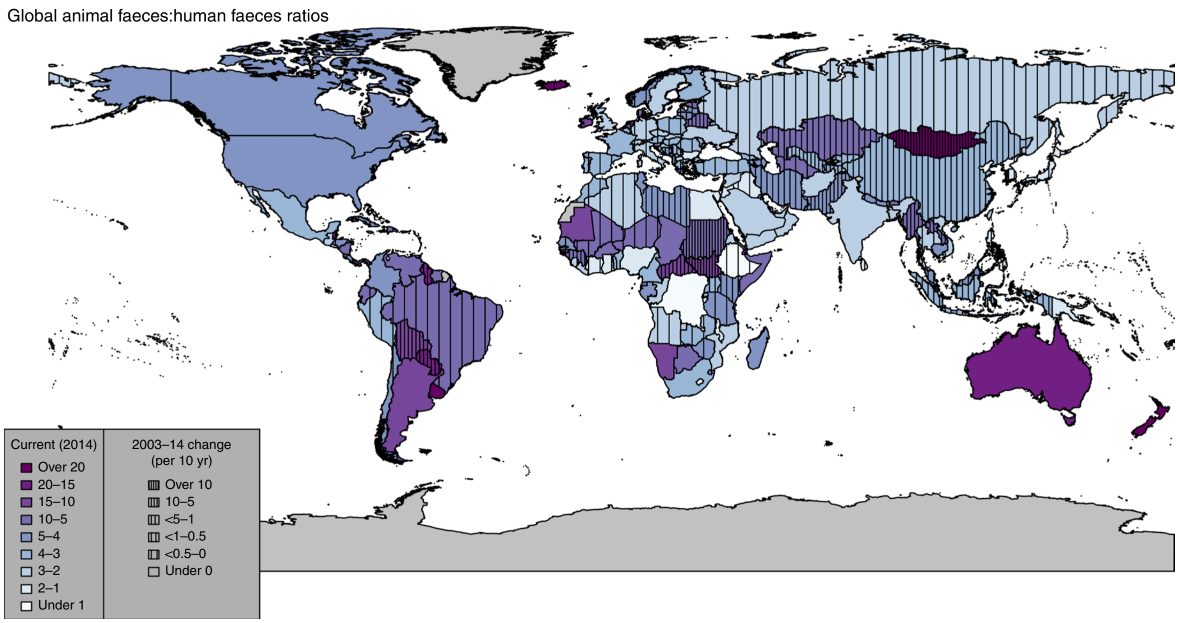

Fig. 2 | Country-level animal faeces to human faeces ratios. Colours represent 2014 ratios (darker purple indicates countries with larger ratios, while countries in white have ratios close to 1). Line density varies with the average change in ratios from 2003 to 2014 (presented per 10 years for ease of interpretation). Higher line density indicates larger, positive average changes in the ratio, while absence of lines indicates a negative change in ratio (with the exception of one country, all negative ratios were between −1 and 0). Countries in grey have no data available.

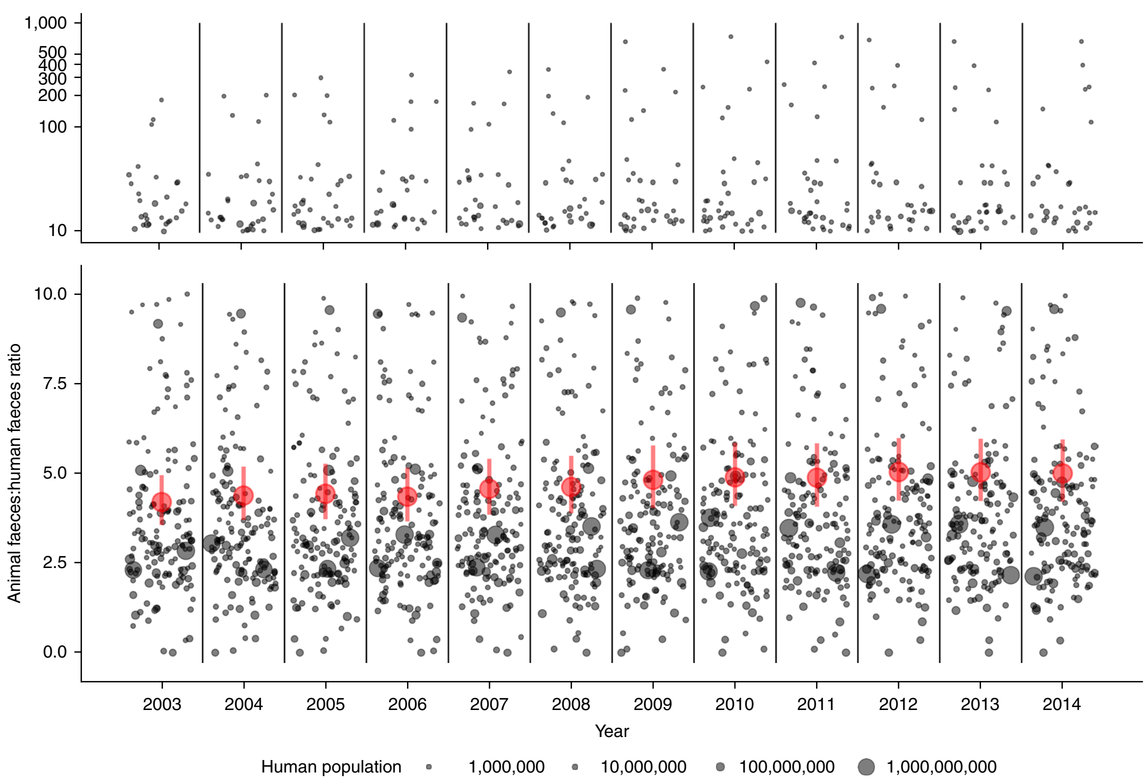

Fig. 3 | Country-level animal faeces to human faeces ratios, 2003–2014. Grey dots represent countries, with dot size varying by population. Dots are jittered for visualization only: all dots within the designated lines belong to the same year. Annual geometric means and 95% confidence intervals are indicated by red circles and lines, respectively. Graph is split into ratios between 0 and 10 (bottom, linear scale) and 10 and 1,000 (top, logarithmic scale) for visualization. Linear mixed-effects models estimating ratios by year, with a random effect for each country, were significant at $P < 0.001$.

Past and projected animal and human faeces production. From 2003 to 2014, total annual faecal biomass increased by 52.1×10^9 kg per year, on average: 9.5×10^9 kg per year from humans and 42.6×10^9 kg per year from animals (data not shown). Using projected human population increases with 2014 human to animal population ratios, the total annual faecal biomass would increase

Table 2 | WHO region-level distribution of sanitation and amount of human faeces (kg) served by types of sanitation, based on 2014 population estimates

Region	Percentage of population with sanitation					Faeces production (kg yr^{-1}) of population served by sanitation				
	EcoSan[a]	FSM[b]	Sewered	No facility	Other	EcoSan[a]	FSM[b]	Sewered	No facility	Other
Africa	0.4	61.4	9.3	27.7	1.3	3.82×10^{8}	6.51×10^{10}	9.82×10^{9}	2.93×10^{10}	1.37×10^{9}
Americas	0.0	57.0	33.3	3.0	1.2	3.03×10^{7}	7.24×10^{10}	4.23×10^{10}	3.78×10^{9}	1.50×10^{9}
EastMed	0.2	48.0	40.1	10.4	1.0	1.37×10^{8}	3.84×10^{10}	3.20×10^{10}	8.35×10^{9}	7.88×10^{8}
Europe	0.1	31.4	68.3	0.1	0.1	1.09×10^{8}	3.58×10^{10}	7.78×10^{10}	7.40×10^{7}	9.22×10^{7}
SEAsia	0.2	69.4	10.0	18.8	1.6	4.50×10^{8}	1.40×10^{11}	2.00×10^{10}	3.78×10^{10}	3.13×10^{9}
WPacific	0.3	70.3	13.5	12.0	4.1	7.14×10^{8}	1.52×10^{11}	2.91×10^{10}	2.59×10^{10}	8.91×10^{9}
World	0.2	56.3	29.1	12.0	1.5	1.63×10^{9}	4.56×10^{11}	2.35×10^{11}	9.71×10^{10}	1.24×10^{10}

[a]Ecological Sanitation (EcoSan): systems by which human faecal waste is collected for composting to generate fertilizer, either onsite (in-the-pit or toilet) or offsite. [b]FSM indicates any form of onsite containment of faeces that must be emptied, covered or otherwise dealt with by the user (that is containment that is not sewered nor part of an Ecological Sanitation system). We note that not all faeces processed via FSM may be potentially recovered or extracted for reuse, including for example rural areas where dug pits are covered once full and the latrine is moved elsewhere.

by 13% from 4.09×10^{12} kg (2017) to 4.63×10^{12} kg (2030), on average by 41.5×10^{9} kg per year. This estimate is more conservative than (1) projecting the 2003–2014 trend to 2030 (4.73×10^{12} kg) or (2) applying projected animal to human faeces ratios to country-level human faecal production estimates in 2030 (5.03×10^{12} kg). Regardless of estimate, humans would produce $>1\times10^{12}$ kg faeces per year by 2030.

Under the most conservative estimates, total faecal biomass in the Western Pacific and the Americas would be about equal in 2030 (1.04×10^{12} versus 1.02×10^{12} kg, Supplementary Fig. 1b). By 2030, the human faecal biomass in Southeast Asia would approximate that of the Western Pacific (233×10^{9} versus 228×10^{9} kg, Supplementary Fig. 2b), while the animal faecal biomass in the Americas would still be the largest (879×10^{9} kg, Supplementary Fig. 3b). Through 2030, Africa has the largest average change in total (18×10^{9} kg per year, Supplementary Fig. 1b), human (4.1×10^{9} kg per year, Supplementary Fig. 2b) and animal (14×10^{9} kg per year, Supplementary Fig. 3b) faecal biomass. More information on past and projected faeces production is in Supplementary Figs.1–3.

Table 3 | Percentage of households, by WHO region, with animals onsite

Region	Cattle	Chickens	Goats	Horses, donkeys, mules	Sheep	Any animal[a]
Africa	21.5	46.5	29.2	10.3	15.5	47.5
Americas	12.5	49.5	8.0	8.8	5.6	15.4
EastMed	19.3	36.0	22.6	16.7	27.8	16.8
Europe	16.8	25.0	5.1	6.5	7.4	14.3
SEAsia	45.2	62.2	28.0	9.6	7.9	52.7
WPacific	16.6	44.8	17.7	9.3	20.1	32.8
World	22.0	44.0	18.4	10.2	14.1	29.9

[a]Percentage of households with at least one animal onsite, regardless of type.

Discussion

A baseline accounting of the faecal biomass associated with the growing global human and livestock animal populations can motivate and inform the establishment of global policies to maximize resource recovery while effectively mitigating public health hazards from both sources. This analysis highlights the differences required for safe management of human and animal faeces in high-income versus low- and middle-income countries (LMIC), but also underscores the large and generally under-appreciated burden of animal faeces management, especially in and near the domestic environment in LMICs. Our analysis may be useful in integrating policies to address the SDG around food production (SDG 2), public health (SDG 3), water and sanitation (SDG 6) and sustainable production (SDG 12)[20].

Although estimates of annual human faeces produced in LMICs, animal and human populations, and human-specific population growth and biomass, have been generated previously[3,25–28], this analysis is the first to comprehensively estimate global and regional faecal biomass from human and animal sources. Our estimates of faecal biomass (that include animal faeces) are 10 to 40 times larger than previous human-specific estimates limited to LMICs[3]. Studies highlighting the need for onsite management of faecal wastes have not accounted for animal faeces[21,29], the contribution of which to health risk is only beginning to be examined critically[5].

Interdisciplinary efforts to 'close the loop' (understand faecal waste from both a resource and a public health perspective) have rarely been extensively implemented, despite the need to safely maximize resource efficiency[30]. This may be due to challenges in monitoring the impacts of resource recovery, and concomitant public health hazards, from human and animal faecal biomass, which must generally be assessed at global (and not local) scales, as is common in measuring sustainability[30,31]. Although nutrient content and recoverability vary by source, scale, diet and other factors related to management, almost 4×10^{12} kg faeces represent significant potential value for recovery, especially if accompanied by urine recovery (not included in our calculations but often present in the same waste streams). Such biomasses could provide large, low-cost quantities of phosphorous (21–91×10^{9} kg per year), potassium (7–28×10^{9} kg per year), calcium (15–17×10^{9} kg per year), magnesium (4–5×10^{9} kg per year) and iron (786×10^{9} kg per year)[3,32]. At the household level, the type of sanitation facility, and its associated ability to recover waste in efficient ways that limit microbial exposures, is also an important factor and area of recent research[13,33].

However, translating the potential value of these resources into real benefits will require multiscale solutions with sustained investment, including in approaches to limit exposure risks associated with faecal waste streams. Although technology and processes for both onsite (household-level) and offsite (for example, concentrated animal feeding operations (CAFOs)) storage, treatment and use of animal and human waste exist, the management options are variable and frequently challenging. In most high-income countries, sewerage enables rapid, centralized treatment of concentrated wastewater and sludge for agricultural use[34,35], which supplement the small global percentage of EcoSan (0.2%). Similarly, CAFOs produce concentrated animal waste, facilitating treatment and subsequent use, but also potentially magnifying public health hazards. As 'point sources' of human and animal waste treatment, centralized paradigms present challenges in optimizing the geographic supply and demand for nutrients from faeces, and to a larger extent urine, but also improve efficiency and regulation of treatment given high throughput[7,36].

In contrast, managing human and animal waste in LMICs may present challenges not yet anticipated in high-income settings (sewerage/CAFO paradigm) because decentralized approaches may be required. Treatment of geographically diffuse animal and human waste requires methods appropriate for smaller volumes of higher-strength waste with greater solids and pathogen content, including onsite systems; these characteristics affect design, treatment efficiency and regulatory control[37]. Despite advances in regulatory capacity in LMICs, direct use or discharge of sewage or wastewater from animal and human sources remains common[37,38] and national and local guidelines or regulations for reuse of faecal wastes are challenging to develop, implement and enforce[37]. The responsibility of management, including any treatment, may fall to households or small communities.

Increased user-borne costs are also associated with decentralized systems. Aggregation of small volumes of waste into large, usable quantities (as at Wastewater Treatment Plants; WWTPs) may face significant, financial hurdles in the emptying and transport costs for faecal sludges, potentially threatening the economic viability of these services[39]. In contrast to centralized treatment paradigms that may be supported with public funds, costs are predominantly passed on to the user (household), potentially limiting sustainability and affordability, and therefore scale[40]. Growing urban LMIC populations require new management systems for onsite sanitation that economize space[41], minimize costs[21] and safely sequester faecal wastes from human contact. Although localized agriculture presents opportunities for immediate onsite use not generally present in high-income settings, such opportunities may be absent in urban and urbanizing areas. LMIC waste management paradigms will probably shift with growing populations, population densities and wealth. Further, there is a need to ensure that existing onsite sanitation systems are properly designed, installed and maintained to prevent contamination of local water resources throughout the world[42].

From a public health perspective, the hazards associated with unsafe management of onsite human and animal faeces accrue at localized scales, where humans and animals live in close proximity. Common livestock animals, which are also large producers of onsite faeces (for example chickens, cattle, goats and sheep), present significant risks for paediatric enteric infections in LMICs[5,43]. Poor treatment of applied wastes may also result in significant disease burdens from faecal contamination (and subsequent consumption) of raw, unwashed or undercooked produce beyond the household[44].

In addition to the responsibility for onsite management of human faeces recognized in decentralized sanitation paradigms[21,45], households in LMICs also bear the greatest burden of managing onsite animal faeces and associated exposure risks[5]. Despite decades of focus on preventing contact with human faeces and associated enteric pathogens[46] and substantial knowledge of zoonotic hosts of many of these same enteric pathogens, the water, sanitation and hygiene (WASH) sector has yet to focus substantively on safe management of animal faeces[5,43]. This analysis shows animal faeces are of immediate and growing concern, comprising 80% of the global faecal biomass and almost 1×10^{12} kg onsite (more than twice that of human faeces) with increasing animal faeces to human faeces ratios over time.

We note limitations in the scope and precision of this analysis, which includes both direct and imputed national estimates for countries without available data. This approach provides a valuable first estimate of recoverable faecal biomass, but does not account for country- and subcountry-level uncertainty and relies on some assumptions of unknown validity. Variability in subnational infrastructure coverage prevents generalization of national-scale estimates to subnational scales[47,48].

Estimates of mammalian faeces production based on primary analyses of mammalian faeces to body mass relationships[49] are more accurate than point estimates for single species. However, we had to use literature estimates for avian faeces production, which generally comprised 'excreta' (urine and faeces) and not faeces alone. Given data limitations, we were unable to account for within-species variation in body mass by age and assumed estimates for adults. Although we assumed that the 2014 ratios of human to animal populations remained constant when projecting faecal biomass production, these ratios may increase following recent trends in faeces ratios (Fig. 3), and therefore probably underestimate the growth of livestock animal populations (and their faeces) as demand for meat and dairy increases with wealth[50]. Sparse estimates of sanitation coverage and animal ownership in high-income countries represent an area where expanded household-level data could improve accuracy and highlight locations without access to safely managed sanitation systems (for example in countries like the United States)[51].

Current and projected estimates of faecal biomass indicate that the world's poorest regions have not only the largest onsite hazards from human faeces but also from animal faeces, amplifying exposure risks associated with unsafe management and opportunities for productive use. This analysis highlights the ever-growing burden of animal faeces in the recent past, present and future. Given potential disease burdens, there is an urgent need to develop, test and scale innovations that improve safe management of animal faecal wastes (in addition to human faecal wastes), especially among the world's poorest people where the potential risks and benefits are greatest.

Methods

Data sources. We collected human and livestock animal population data from World Bank estimates for the period 2003–2030[26,27] and from the FAO for the period 2003–2014[28] (when the most recent data was available), respectively. We analysed data by country, WHO region and globally. We describe the derivation of FAO estimates of country-level animal populations in the Supplementary Discussion and Supplementary Table 1.

We obtained data for 112 LMICs on household ownership of animals and types of household sanitation facilities from the Demographic and Health Survey (DHS, phase 5 (2003–2008), 6 (2008–2013) and 7 (2013–2018: most recent survey from 2015)) and Multiple Indicator Cluster Survey (MICS, rounds 3 (2005–2009), 4 (2009–2013) and 5 (2013–2017, most recent survey from 2016)). For an LMIC without these data, we assigned it the average proportion of households with animals and/or average sanitation coverage of all countries in its WHO region and income level (low, low-middle, middle, middle-high or high), with the exception of China, given the proportion of the global population it occupies. We collected data for China from the 2009 China Health and Nutrition Survey (CHNS)[52].

We obtained data on sanitation coverage in middle-high and high income countries from the Integrated Public Use Microdata Series-International (IPUMS-I)[53], which included seven countries. Therefore, we assigned all other middle-high and high-income countries to the average sanitation coverage by region and income level, as described for LMICs. Owing to sparse country-level data on household livestock animal ownership, we generated estimates for these countries from the American Veterinary Medical Association[54], which was corroborated by previous American and European literature[55–61]. We conducted all analyses and generated all figures in R version 3.4.0 (R Foundation for Statistical Computing)[62].

Estimating annual per-animal and per-human faecal production. We estimated annual mammalian (including human) faeces production by type using an equation for daily mammalian faeces production from Yang et al. (2017):[49]

[Global population of the given animal (or humans)] × [Average adult (per-animal or per-human) body mass in kg]$^{0.83}$ × [0.01] × [365 days per year] = [Faeces produced by a given animal (or by humans) in kg per year]

where average mammalian animal body mass was estimated, assuming all animals were adults, from the University of Michigan Museum of Zoology[63] and peer-reviewed literature[64–71]. We accounted for regional variation in diet and body mass by estimating human body masses by WHO regions from previous literature[25]. The equation represents the study of daily production of faeces by individual mammals at the Atlanta Zoo by mass and species, plotted together[49]. In total, the equation explained 86% of the variance in daily faeces production ($R^2 = 0.86$), the most of any characteristic measured on mammals[49].

For avians, we estimated faeces production by animal type from literature[72–74], with the exception of guinea fowl, which were assumed to produce faeces at the same rate as geese, but proportional to mass (the 'geese/guinea fowl' FAO group was assumed to be composed of half of each species).

For all estimates, we constructed uncertainty bands by: (1) using high and low values from 95% CI for animal body mass (for animals with more than two body mass estimates and for humans using regional estimates[25]); or (2) inputting the two body masses (for animals with only two body mass estimates); or (3) using a 14% estimate of uncertainty, based on residual variability in the model from Yang et al[49]. (for animals with only one body mass estimate available). More information about classification of animals by type can be found in the Supplementary Discussion and Supplementary Table 1.

Estimating onsite (household-level) hazards from animal and human faeces. As a measure of the potential onsite (household-level) hazards of faecal biomass, we estimated the proportions of animal and human faeces located at the household versus 'offsite' (at other locations) from previous data sources combined with surveys of household animal ownership and sanitation facilities (for example DHS, MICS, IPUMS-I). For animal faeces, we also combined FAO country-level estimates of animal populations with data on household animal ownership to apportion numbers of animals, and thereby animal faeces, by location. For human faeces, we combined World Bank national estimates of human populations with data on household sanitation type—divided into sewered versus onsite (non-sewered)—to apportion human faeces by location. We include further information on estimation methods and assumptions for these data in the Supplementary Materials and Methods.

Projected human and animal faecal production. We projected human faecal production for 2017–2030 based on the World Bank Population Estimates and Projections Database[27] (for human populations) and previously described methods for human faeces production. We projected animal faecal production for 2017–2030 from current (2014) estimated ratios of animals:humans by country and FAO animal type[28], which we then applied to those World Bank human population projections for 2017–2030. We calculated uncertainty bands as described previously for these estimates. Additionally, we calculated alternative faeces production estimates by: (1) estimating the average annual growth in faecal production from 2003 to 2014 and applying that estimate to 2017–2030 data; and (2) projecting animal faeces to human faeces ratios for 2017–2030 and applying them to human faeces production estimates from World Bank human population projections (described earlier).

Analyses of animal faeces/human faeces ratios. We analysed trends in animal faeces to human faeces ratios, at country level, over time using mixed-effects linear regression with year as the predictor variable and a random intercept for country. We conducted analyses in R using the lme4 package[75].

Data availability

All data on animal sizes and population estimates were obtained from tables or figures in manuscripts listed and publicly available datasets (DHS data available from the DHS programme: https://dhsprogram.com/data/; MICS data available from UNICEF: http://mics.unicef.org/). A final dataset of the faeces estimates supporting this manuscript is available from the corresponding author upon request.

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References

1. Gerland, P. et al. World population stabilization unlikely this century. *Science* **346**, 234–237 (2014).
2. *World Urbanization Prospects, 2014 Revision* (United Nations, 2015).
3. Rose, C., Parker, A., Jefferson, B. & Cartmell, E. The characterization of feces and urine: a review of the literature to inform advanced treatment technology. *Crit. Rev. Environ. Sci. Technol.* **45**, 1827–1879 (2015).
4. Clasen, T. et al. *Interventions to Improve Disposal of Human Eexcreta for Preventing Diarrhoea (Review)* (2010); https://www.cochranelibrary.com/cdsr/doi/10.1002/14651858.CD007180.pub2/full
5. Penakalapati, G. et al. Exposure to animal feces and human health: a systematic review and proposed research priorities. *Environ. Sci. Technol.* **51**, 11537–11552 (2017).
6. Alirol, E., Getaz, L., Stoll, B., Chappuis, F. & Loutan, L. Urbanisation and infectious diseases in a globalised world. *Lancet Infect. Dis.* **11**, 131–141 (2011).
7. Wielemaker, R. C., Weijma, J. & Zeeman, G. Harvest to harvest: recovering nutrients with new sanitation systems for reuse in urban agriculture. *Resour. Conserv. Recycl.* **128**, 426–437 (2018).
8. Otoo, M. & Hanjra, M A. in *Wastewater: Economic Asset in an Urbanizing World* (eds P. Drechsel et al.) 247–268 (Springer, Netherlands, 2015).
9. Westerhoff, P. et al. Characterization, recovery opportunities, and valuation of metals in municipal sludges from U.S. wastewater treatment plants nationwide. *Environ. Sci. Technol.* **49**, 9479–9488 (2015).
10. Mihelcic, J. R., Fry, L. M. & Shaw, R. Global potential of phosphorus recovery from human urine and feces. *Chemosphere* **84**, 832–839 (2011).
11. Batstone, D. J., Hülsen, T., Mehta, C. M. & Keller, J. Platforms for energy and nutrient recovery from domestic wastewater: A review. *Chemosphere* **140**, 2–11 (2015).
12. Smith, L. W. & Wheeler, W. E. Nutritional and economic value of animal excreta. *J. Anim. Sci.* **48**, 144–156 (1979).
13. Stenström, T. A., Seidu, R., Nelson, E. & Christian, Z. *Microbial Exposure and Health Assessments in Sanitation Technologies and Systems* (Stockholm Environment Institute, Stockholm, 2011); http://www.ecosanres.org/pdf_files/Microbial_Exposure_&_Health_Assessments_in_Sanitation_Technologies_&_Systems.pdf
14. Prüss-Ustün, A. et al. Burden of disease from inadequate water, sanitation and hygiene in low- and middle-income settings: a retrospective analysis of data from 145 countries. *Trop. Med. Int. Health* **0**, 1–12 (2014).
15. Wolf, J. et al. Systematic review: assessing the impact of drinking water and sanitation on diarrhoeal disease in low- and middle-income settings: Systematic review and meta-regression. *Trop. Med. Int. Health* **19**, 928–942 (2014).
16. Berendes, D. et al. Household sanitation is associated with lower risk of bacterial and protozoal enteric infections, but not viral infections and diarrhea, in a cohort study in a low-income urban neighborhood in Vellore, India. *Trop. Med. Int. Health* **22**, 1119–1129 (2017).
17. Mbuya, M. N. N. & Humphrey, J. H. Preventing environmental enteric dysfunction through improved water, sanitation and hygiene: an opportunity for stunting reduction in developing countries.Matern. Child Nutr. (2015).
18. Mosites, E. M. et al. The relationship between livestock ownership and child stunting in three countries in eastern Africa using national survey data. *PLoS ONE* **10**, 1–10 (2015).
19. Kaur, M., Graham, J. P. & Eisenberg, J. N. S. Livestock ownership among rural households and child morbidity and mortality: an analysis of demographic health survey data from 30 Sub-Saharan African countries (2005–2015). *Am. J. Trop. Med. Hyg.* **96**, 16–0664 (2017).
20. *Transforming our World: The 2030 Agenda for Sustainable Development* (United Nations, 2015); https://doi.org/10.1007/s13398-014-0173-7.2.
21. Berendes, D. M., Sumner, T. A. & Brown, J. M. Safely managed sanitation for all means fecal sludge management for at least 1.8×10^9 people in low and middle income countries. *Environ. Sci. Technol.* **51**, 3074–3083 (2017).
22. *Septic Systems Overview* (United States Environmental Protection Agency, 2018); https://www.epa.gov/septic/septic-systems-overview.
23. Gebreyes, W.A. et al. The global One Health paradigm: challenges and opportunities for tackling infectious diseases at the human, animal, and environment interface in low-resource settings. PLoS Negl. Trop. Dis. 8, https://doi.org/10.1371/journal.pntd.0003257 (2014).
24. Atlas, R. et al. One Health—attaining optimal health for people, animals, and the environment. *Microbe* **5**, 383–389 (2010).
25. Walpole, S. C. et al. The weight of nations: an estimation of adult human biomass. *BMC Public Health* **12**, 439 (2012).
26. *Population Data* (The World Bank, 2017).
27. *Population Estimates and Projections* (The World Bank, 2017).
28. *FAOSTAT* (Food and Agriculture Organization of the United Nations, 2017); http://www.fao.org/faostat/en/#home
29. *Progress on Drinking Water, Sanitation and Hygiene* (UNICEF/ WHO, 2017); https://doi.org/10.1111/tmi.12329.
30. Seto, K. C., Golden, J. S., Alberti, M. & Turner, B. L. Sustainability in an urbanizing planet. *Proc. Natl Acad. Sci. USA* **114**, 201606037 (2017).
31. Seto, K. C., Guneralp, B. & Hutyra, L. R. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proc. Natl Acad. Sci. USA* **109**, 16083–16088 (2012).
32. Barnett, G. M. Phosphorus forms in animal manure. *Bioresour. Technol.* **49**, 139–147 (1994).
33. Orner, K. D. & Mihelcic, J. R. A review of sanitation technologies to achieve multiple sustainable development goals that promote resource recovery. *Environ. Sci. Water Res. Technol.* **4**, 16–32 (2018).
34. Van Loosdrecht, M. C. M. & Brdjanovic, D. Anticipating the next century of wastewater treatment. *Science* **344**, 1452–1453 (2014).
35. Fytili, D. & Zabaniotou, A. Utilization of sewage sludge in EU application of old and new methods—a review. *Renew. Sust. Energ. Rev.* **12**, 116–140 (2008).
36. Cordell, D., Rosemarin, A., Schröder, J. J. & Smit, A. L. Towards global phosphorus security: a systems framework for phosphorus recovery and reuse options. *Chemosphere* **84**, 747–758 (2011).
37. Jiménez, B. et al. in *Wastewater Irrigation and Health: Assessing and Mitigating Risk in Low-income Countries* (eds A., Bahri, P., Drechsel, L., Raschid-Sally. & M., Redwood). 1–27 (Routledge, 2010).

38. Julian, T. R. Environmental transmission of diarrheal pathogens in low and middle income countries. *Environ Sci. Process Impacts* **18**, 944–955 (2016).
39. Kennedy-Walker, R., Holderness, T., Alderson, D., Evans, B. & Barr, S. Network modelling for road-based faecal sludge management. *Proc. Inst. Civ. Eng. Civ. Eng.* **167**, 157–165 (2015).
40. Dodane, P.-H., Mbéguéré, M., Sow, O. & Strande, L. Capital and operating costs of full-scale fecal sludge management and wastewater treatment systems in Dakar, Senegal. *Environ. Sci. Technol.* **46**, 3705–3711 (2012).
41. Chunga, R. M., Ensink, J. H. J., Jenkins, M. W. & Brown, J. Adopt or adapt: Sanitation technology choices in urbanizing Malawi. *PLoS ONE* **11**, 1–16 (2016).
42. Wright, Ja et al. A spatial analysis of pit latrine density and groundwater source contamination. *Environ. Monit. Assess.* **185**, 4261–4272 (2013).
43. Zambrano, L. D., Levy, K., Menezes, N. P. & Freeman, M. C. Human diarrhea infections associated with domestic animal husbandry: a systematic review and meta-analysis. *Trans. R. Soc. Trop. Med. Hyg.* **108**, 313–325 (2014).
44. Grace, D. Food safety in low and middle income countries. *Int. J. Environ. Res. Public Health* **12**, 10490–10507 (2015).
45. Koné, D. Making urban excreta and wastewater management contribute to cities' economic development: a paradigm shift. *Water Policy* **12**, 602–610 (2010).
46. Wagner, E. G. & Lanoix, J. N. *Excreta Disposal for Rural Areas and Small Communities* (WHO, 1958).
47. Pullan, R. L., Freeman, M. C., Gething, P. W. & Brooker, S. J. Geographical inequalities in use of improved drinking water supply and sanitation across Sub-Saharan Africa: mapping and spatial analysis of cross-sectional survey data. *PLoS Med.* **11**, e1001626 (2014).
48. Osgood-Zimmerman, A. et al. Mapping child growth failure in Africa between 2000 and 2015. *Nature* **555**, 41–47 (2018).
49. Yang, P. J., LaMarca, M., Kaminski, C., Chu, D. I. & Hu, D. L. Hydrodynamics of defecation. *Soft Matter* **13**, 4960–4970 (2017).
50. Godfray, H. C. J. et al. The challenge of food security. *Science* **327**, 812–818 (2010).
51. Izenberg, M., Johns-Yost, O., Johnson, P. D. & Brown, J. Nocturnal convenience: the problem of securing universal sanitation access in Alabamaas black belt. *Environ. Justice* **6**, 200–205 (2013).
52. *CHNS: China Health and Nutrition Survey* (UNC Carolina Population Center, 2009); http://www.cpc.unc.edu/projects/china
53. *Integrated Public Use Microdata Series, International: Version 6.5 [dataset]* (Minnesota Population Center, 2017); http://doi.org/10.18128/D020.V6.5
54. *U.S. Pet Ownership & Demographics Sourcebook* (American Veterinary Medical Association, 2012); https://www.avma.org/KB/Resources/Statistics/Pages/Market-research-statistics-US-Pet-Ownership-Demographics-Sourcebook.aspx.
55. *Pet Ownership Internationally: Global GfK Survey* (GfK, 2016); https://www.gfk.com/fileadmin/user_upload/country_one_pager/NL/documents/Global-GfK-survey_Pet-Ownership_2016.pdf
56. *The European Pet Food Industry. Key Facts & Figures* (FEDIAF, 2016); www.fediaf.org.
57. Kifle, Y. W. et al. Animal ownership and touching enrich the context of social contacts relevant to the spread of human infectious diseases. *PLoS ONE* **10**, 1–13 (2015).
58. Elkhoraibi, C., Blatchford, R. A., Pitesky, M. E. & Mench, J. A. Backyard chickens in the United States: a survey of flock owners. *Poult. Sci.* **93**, 2920–2931 (2014).
59. *Urban Chicken Ownership in Four U.S. Cities* (USDA, 2013); https://www.aphis.usda.gov/animal_health/nahms/poultry/downloads/poultry10/Poultry10_dr_Urban_Chicken_Four.pdf
60. Lowder, S. K., Skoet, J. & Raney, T. The number, size, and distribution of farms, smallholder farms, and family farms worldwide. *World Dev.* **87**, 16–29 (2016).
61. McClintock, N., Pallana, E. & Wooten, H. Urban livestock ownership, management, and regulation in the United States: an exploratory survey and research agenda. *Land Use Policy* **38**, 426–440 (2014).
62. *R: A Language and Environment for Statistical Computing* (R. Core Team, 2015); https://www.r-project.org/
63. *Animal Diversity Web* (University of Michigan Museum of Zoology, 2014); http://animaldiversity.org/
64. Salama, M. A. M. & Shalles, R. R. Growth of water buffalo, Bubalus arnee. *Trop. Agric.* **69**, 239–242 (1992).
65. Fabbriciani, C., Lucania, L., Milano, G., Schiavone Panni, A. & Evangelisti, M. Meniscal allografts: cryopreservation vs deep-frozen technique. An experimental study in goats. *Knee Surg. Sports Traumatol. Arthrosc.* **5**, 124–134 (1997).
66. Mishra, S. & Rai, S. N. Influence of varying RDP:UDP ratios in diets on digestion, nitrogen utilization and milk production efficiency in goats. *Small Rumin. Res.* **20**, 39–45 (1996).
67. Snyman, M. A. & Olivier, J. J. Genetic parameters for body weight, fleece weight and fibre diameter in South African Angora goats. *Livest. Prod. Sci.* **47**, 1–6 (1996).
68. Kugler, W., Grünenfelder, H.-P. & Broxham, E. *Donkey Breeds in Europe. Inventory, Description, Need for Action* Report 2007/2008 (Monitoring Institute for Rare Breeds and Seeds in Europe, 2008); http://www.save-foundation.net/pdf/donkey.pdf
69. Ruusunen, M. & Puolanne, E. Histochemical properties of fibre types in muscles of wild and domestic pigs and the effect of growth rate on muscle fibre properties. *Meat Sci.* **67**, 533–539 (2004).
70. Kafi, M., Safdarian, M. & Hashemi, M. Seasonal variation in semen characteristics, scrotal circumference and libido of Persian Karakul rams. *Small Rumin. Res.* **53**, 133–139 (2004).
71. Keller, D. G., Lawson, J. E. & Peters, H. F. Diameter of muscle fibers and composition of selected retail cuts from Cattalo and Hereford carcasses. *Can. J. Anim. Sci.* **57**, 509–517 (1977).
72. Johnston, R.F. in Rock Dove (*Columba livia*). (eds A., Poole, P., Stettenheim. & F., Gill).*The Birds of North America*. (The Academy of Natural Sciences: Washington DC, 1992.
73. Williams, C. *Poultry Waste Management in Developing Countries* (Food and Agriculture Organization of the United Nations, 2009): http://www.fao.org/docrep/013/al715e/al715e00.pdf
74. *Canada Geese Facts and Management Options. Environmental Fact Sheet* (New Hampshire Department of Environmental Services, 2012); https://www.des.nh.gov/organization/commissioner/pip/factsheets/bb/documents/bb-53.pdf
75. Bates, D., Maechler, M., Bolker, B. & Walker, S. Fitting linear mixed-effects models ssing lme4. *J. Stat. Softw.* **67**, 1–48 (2014).

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Authors contributions
D.B. and J.B. conceived of the analysis. D.B., P.Y., D.H. and J.B. planned the analysis. D.B. and P.Y. obtained data and conducted the analysis. D.B. wrote the initial manuscript and created all figures and tables. D.B., P.Y., A.L., D.H. and J.B. contributed edits and sections to the manuscript.

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The authors declare no competing interests.

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