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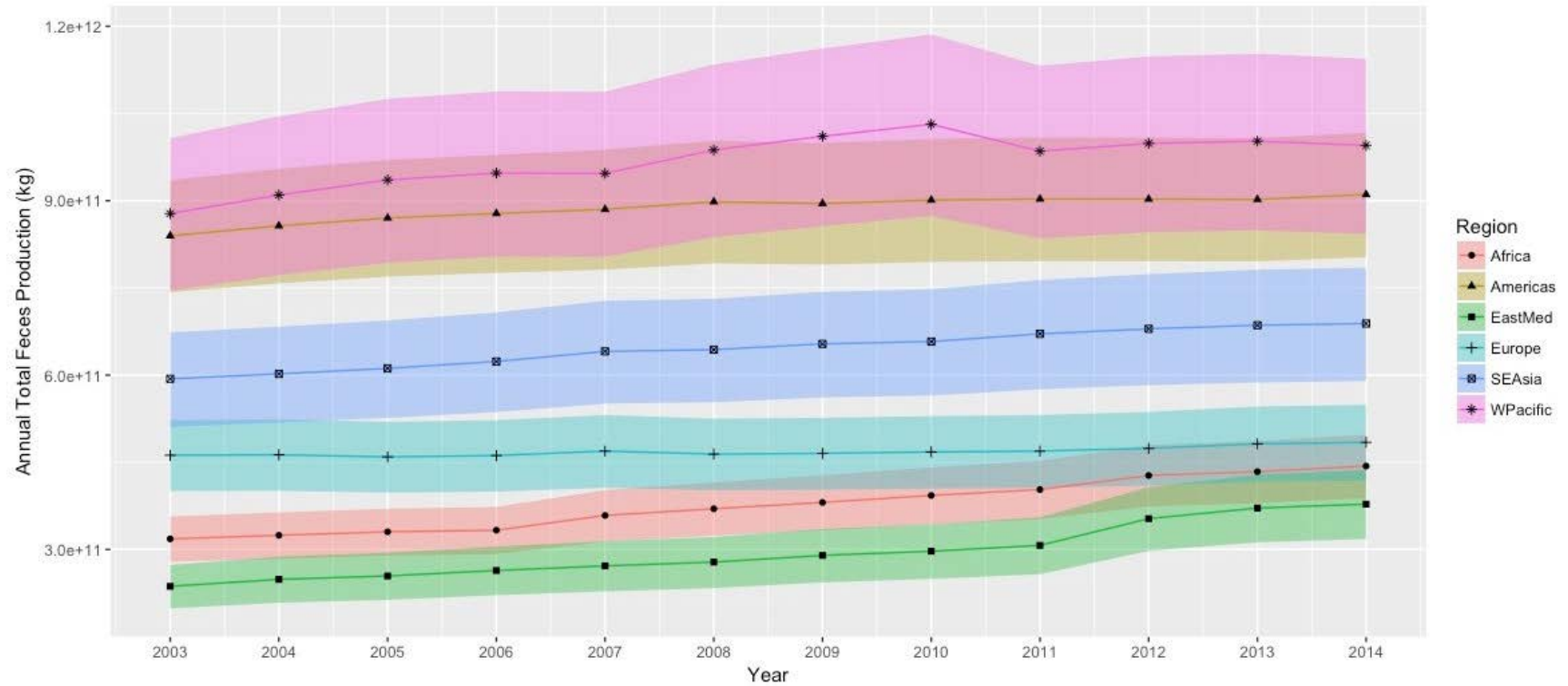
Estimation of global recoverable human and animal faecal biomass

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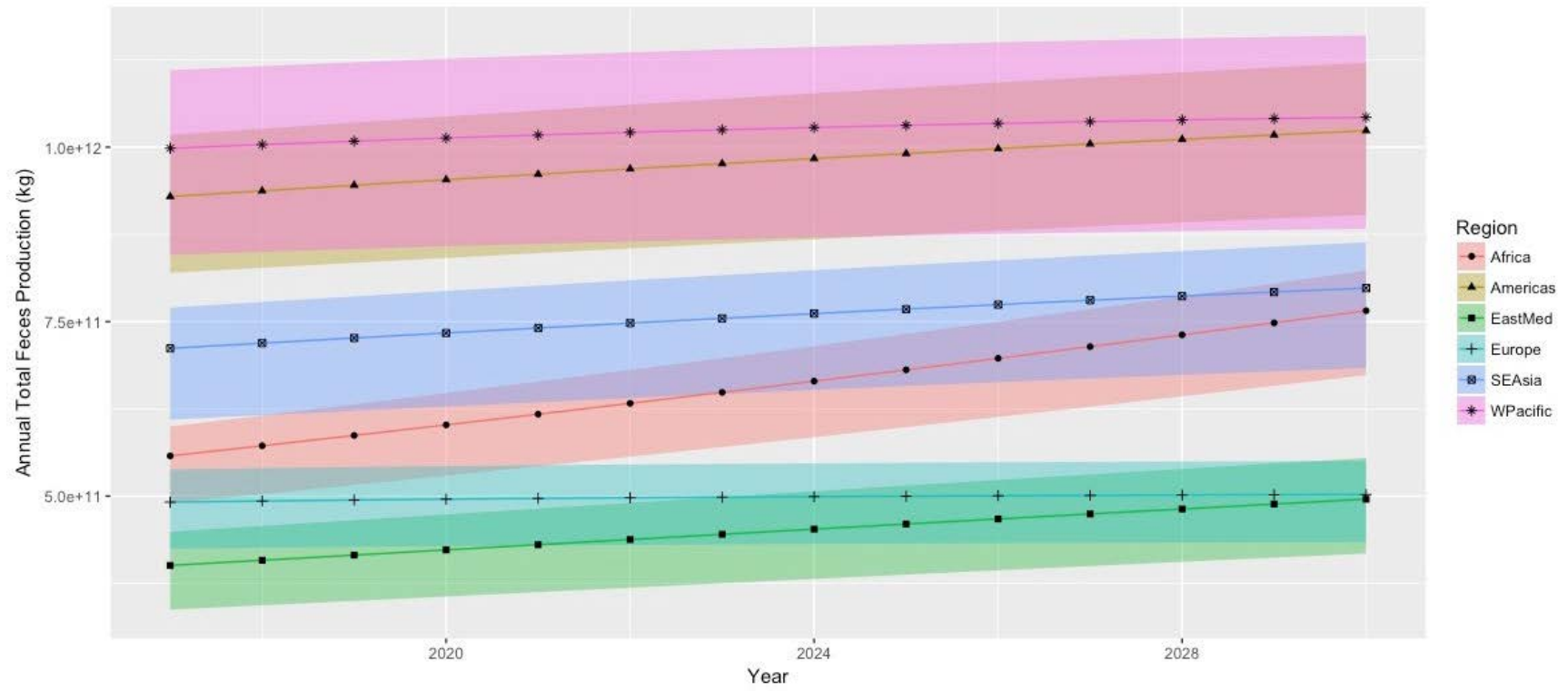
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Supplementary Figure 1: Annual estimates for total (human and animal) fecal biomasses by region from 2003-2014 (a) and 2017-2030 (b). Regions are denoted by symbols and colors in legend at right. Uncertainty bands around linear estimates, calculated as explained in methods, are denoted by colored ribbon.

a)

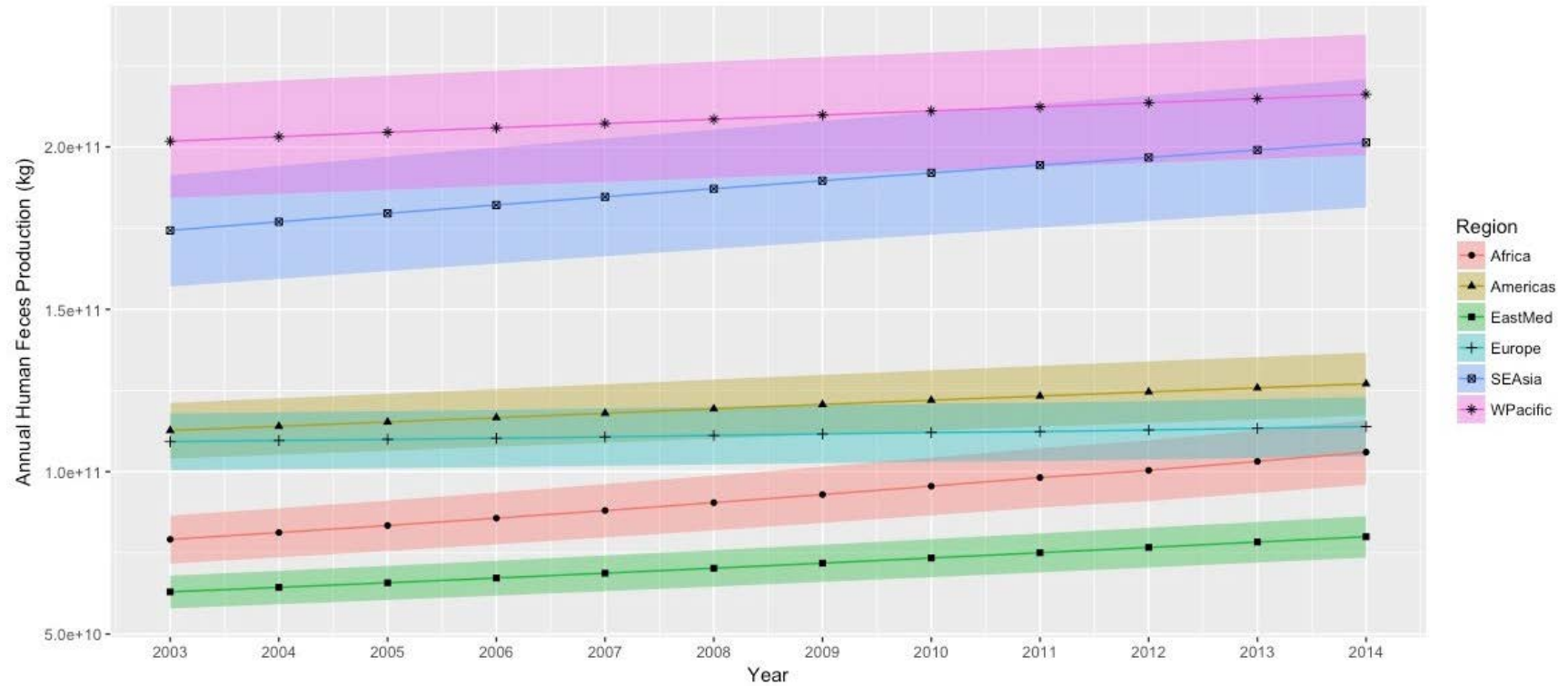


b)

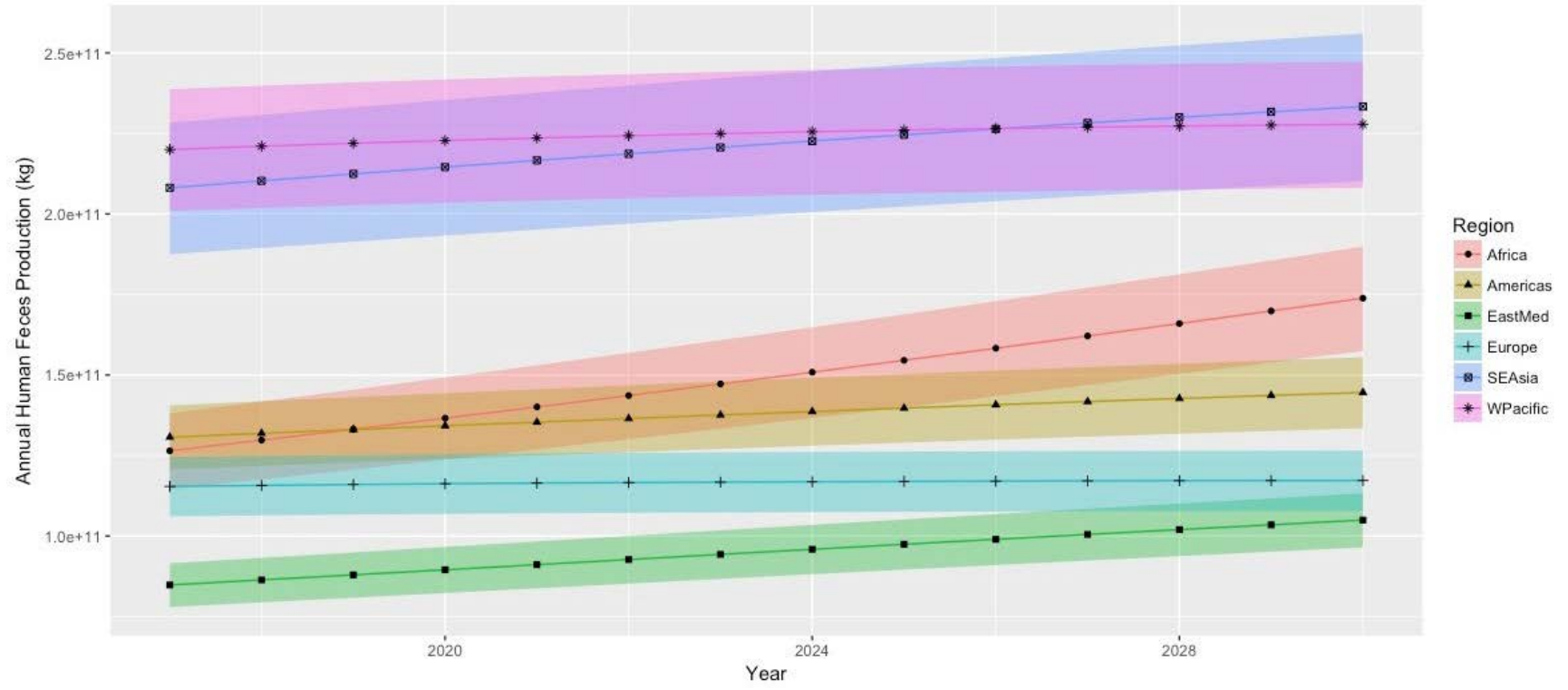


Supplementary Figure 2: Annual estimates for human-associated fecal biomasses by region from 2003-2014 (a) and 2017-2030 (b). Regions are denoted by symbols and colors in legend at right. Uncertainty bands around linear estimates, calculated as explained in methods, are denoted by colored ribbon.

a)

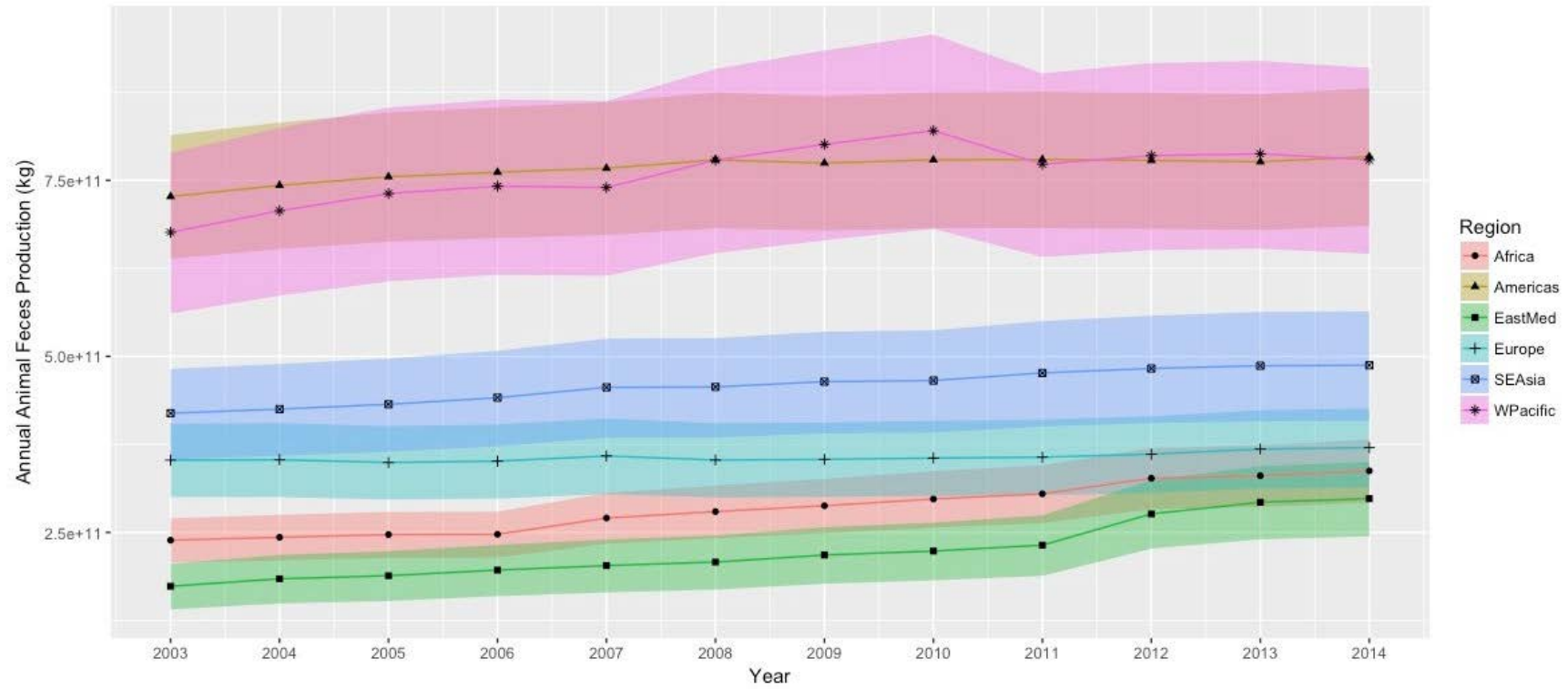


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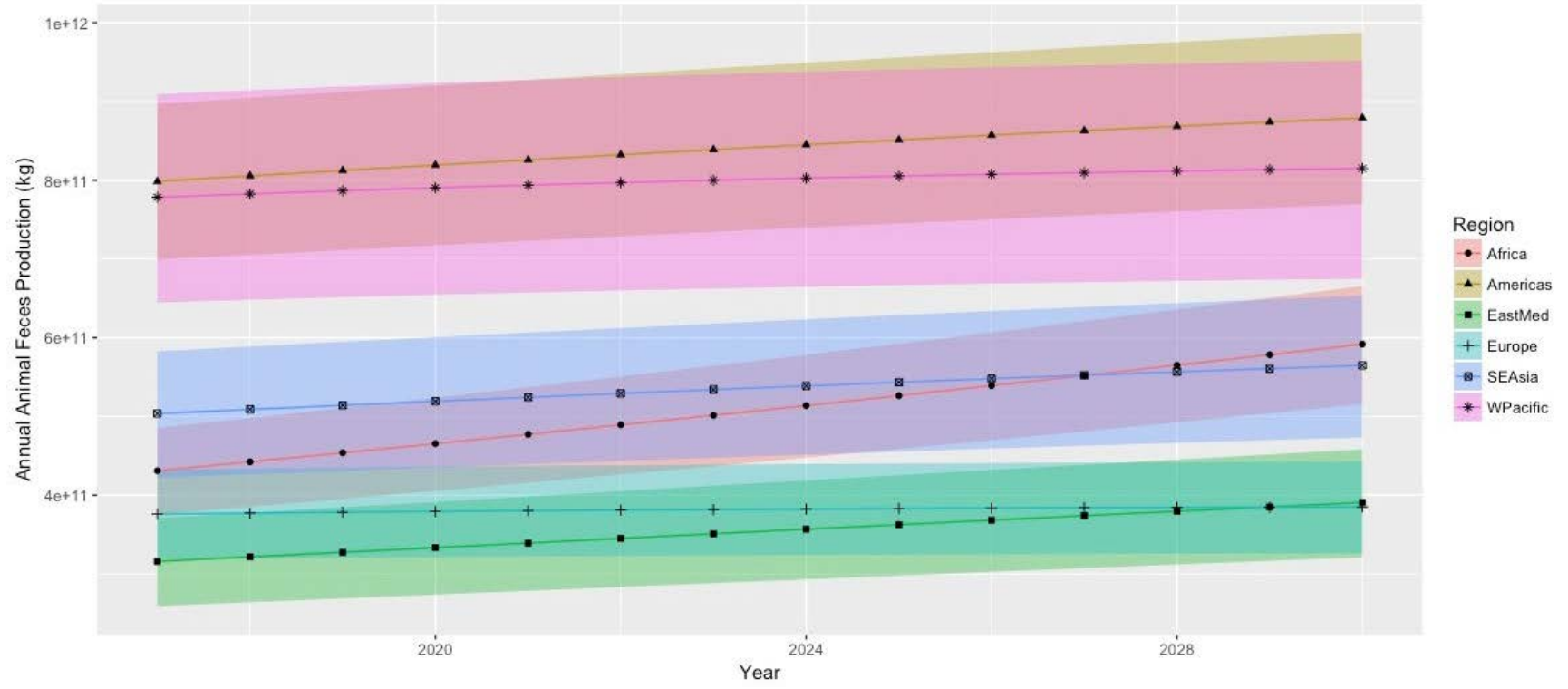


Supplementary Figure 3: Annual estimates for animal-associated fecal biomasses by region from 2003-2014 (a) and 2017-2030 (b). Regions are denoted by symbols and colors in legend at right. Uncertainty bands around linear estimates, calculated as explained in methods, are denoted by colored ribbon.

a)



b)



Supplementary Methods:

Total livestock-associated animal populations in each country were collected from FAO data ¹. In 25 countries, one or more groups of animals were not able to be reported or estimated. While other animal groups within these countries were included in the final dataset, these country/animal pairs with no data (representing 34/3190 lines of data or 1%) were excluded from analysis. WHO regions were used for all analyses (see <http://www.who.int/about/regions/en/> for regional definitions and map).

Estimation of animal feces onsite: Questions about the type and quantities of animals owned (DHS questions HV246A-F, MICS questions HC14A-E) were used to estimate the proportion of the national population with that particular type of animal at the household (see Table S1 for classification of animals between surveys). Survey data were averaged (in the event that both DHS and MICS data was available for a country) and used to assess these household-level exposures. Among households with animals onsite, the number of a particular type of animal onsite was grouped by approximate \log_{10} -order (animal quantities greater than 95 are not quantified specifically in DHS or MICS surveys, thus the $2\text{-}\log_{10}$ cutoff for animals was at 95, and not 100): Category 0 (1-10 animals present), 1 (>10-95 animals present), or 2 (>95 animals present). “Proportion of fecal exposures at the household” and “weighted fecal exposures” were calculated from these estimates, combined with FAO data on country-level animal populations, as described in Table S1. Briefly, the proportion of households in a country with any amount of a given type of animal multiplied by the total number of animals of that type in that country was used to estimate the “proportion of fecal exposures at the household.” “Weighted fecal exposures” were similarly calculated, but weighted by the proportion of households in Categories 0, 1, or 2 (and using the

midpoint number of animals in each category to estimate fecal production). Pigs, camelids, camels, rabbits, and small rodents were not estimated at the household-level due to their exclusion from either/both DHS or MICS data, and thus only contributed to the country-level and world-level fecal production estimates. For high-income countries, where data on household-level ownership of animals was not available, the order of magnitude of animals was assumed to follow a log-scale: it was assumed that 90% of households with animals fell into Category 0, 9% fell into Category 1, and 1% fell into Category 2.

Estimating human exposures to human feces: DHS and MICS questions on the type of household sanitation facility present were used to group households in two ways: 1) households with any onsite facility or public facility used vs. those open defecating; and 2) among households with sanitation facilities, households with sewerated sanitation facilities vs. those with facilities containing waste onsite (and thus requiring some form of fecal sludge management (FSM)).² Definitions for (2) are described elsewhere.² Briefly, household sanitation facilities that lead to sewerage were classified as “sewerated”, while those that retain waste onsite (e.g. septic tanks, traditional pit latrines) were classified as “in need of FSM in order to continue to function.” Households using Ecological Sanitation (EcoSan) or composting toilets were excluded from the analysis of human exposure to human feces in onsite waste, but are examined specifically as examples of nutrient recovery from human fecal waste. As above, high-income countries were assigned data based on IPUMS-I and best estimates of fate and transport of fecal waste (e.g. connected to sewerage, in need of FSM) were used. All households not specifically designated as using FSM were assumed to have sewerage in these countries. Countries without estimates were assigned the average from their WHO region and income category.

Total human feces production was estimated from the total population multiplied by the estimated daily production of feces per human. The weighted proportion of households with sewerage, onsite, or no sanitation facilities in a given country were multiplied, respectively, by 1) the estimated population of the country; and 2) the estimated daily production of feces; in order to estimate total feces moving through sewers, retained onsite at households, and/or entering the environment from open defecation specifically.

Supplementary Discussion:

Worldwide, a large human fecal biomass remains onsite and requires FSM to be managed, beyond the portion that is discharged directly to the environment without a facility (Table 2b). About 456 billion kg of human feces remain in onsite sanitation facilities that must be emptied each year, while another 97 billion kg are discharged directly into the environment without a facility. Sewered sanitation facilities process 235 billion kg each year. Regionally, 152 billion kg and 140 billion kg of feces are discharged into onsite facilities that require some form of FSM in the Western Pacific and Southeast Asia each year. Those regions also have 38 billion kg and 26 billion kg, respectively, discharged without a facility present. While only 65 billion kg of feces are discharged into onsite facilities in Africa each year, another 29 billion kg are discharged without a facility present.

Chickens (44% of households), cattle (22%), and goats (18%) were the most common animals found at households (Table 3). Chickens were common as onsite animals throughout all regions (range: 25-62% of households). Southeast Asia had the highest prevalence of onsite chickens (62%), cattle (45%) and goats (28%), while the Eastern Mediterranean had the highest prevalence of onsite horses, donkeys, or mules (17%) and sheep (28%).

Households generally had 10 or fewer animals onsite (Supplementary Table 3). Depending on the type of animal, 80-93% of households with animals fell into Category 0, while 7-19% of household with animals were in Category 1 (11-95 animals onsite), and 0.5-2% of households with animals were in Category 2 (more than 95 animals onsite). Total annual biomass of feces that was estimated to remain onsite at the household was 456 billion kg from humans (Table 2b, human biomass going into facilities requiring FSM) and

933 billion kg from animals (Tables 1 and Supplementary Table 3, percent of households with animals onsite multiplied by total animal fecal biomass), or 1.39 trillion kg per year.

Supplementary Table 1: Classification of animals between country-level data (FAO) and household-level data (DHS and MICS).

FAO category	DHS/MICS category	Calculations
Donkeys (Asses) Horses Mules	DHS: Horses, donkeys, or mules MICS: Horses, donkeys, or mules	<p>Feces produced: [Average daily fecal production per ass] x [total asses (FAO)] + [average daily fecal production per horse] x [total horses (FAO)] + [average daily fecal production per mule] x [total mules (FAO)]</p> <p>Proportion of fecal hazard at household: [Total feces] x [Weighted proportion of population responding “Yes” to MICS/DHS question about owning horses, donkeys, or mules]</p> <p>Total feces per animal (used only in “weighted hazards by household” calculation below): [Total feces] / [Total asses, horses, and mules]</p> <p>Weighted hazards by household: Category 0: [Total feces per animal] x 5 x [Weighted proportion of population responding “1-10” to MICS/DHS] Category 1: [Total feces per animal] x 53 x [Weighted proportion of population responding “>10-95” to MICS/DHS] Category 2: [Total feces per animal] x 100 x [Weighted proportion of population responding “>95” to MICS/DHS]</p>
Buffaloes Cattle	DHS: Questions about “cattle” and “cows, bulls” combined MICS: Cattle, milk cows, or bulls	<p>Feces produced: [Average daily fecal production per buffalo] x [total buffaloes (FAO)] + [average fecal production per cow/bull] x [total cattle (FAO)]</p> <p>Proportion of fecal hazard at household: [Total feces] x [Weighted proportion of population responding “Yes” to MICS/DHS question about owning cattle, milk cows, or bulls]</p> <p>Total feces per animal (used only in “weighted hazards by household” calculation below): [Total feces] / [Total buffaloes and cattle]</p> <p>Weighted hazards by household: Category 0: [Total feces per animal] x 5 x [Weighted proportion of population responding “1-10” to MICS/DHS] Category 1: [Total feces per animal] x 53 x [Weighted proportion of population responding “>10-95” to MICS/DHS] Category 2: [Total feces per animal] x 100 x [Weighted proportion of population responding “>95” to MICS/DHS]</p>
Chickens Ducks	DHS: Chickens MICS: Chickens	<p>Feces produced: [Average daily fecal production per chicken] x [total chickens (FAO)] + [average fecal production per duck] x [total ducks (FAO)] + [average daily fecal production per</p>

Geese and guinea fowl
Pigeons, other birds
Turkeys

goose] x [total geese or guinea fowl (FAO)] + [average daily fecal production per pigeon] x [total pigeons (FAO)] + [average daily fecal production per turkey] x [total turkeys (FAO)]

Proportion of fecal hazard at household: [Total feces] x [Weighted proportion of population responding “Yes” to MICS/DHS question about chickens]

Total feces per animal (used only in “weighted hazards by household” calculation below): [Total feces] / [Total chickens, ducks, geese and guinea fowl, pigeons and other birds, and turkeys]

Weighted hazards by household:

Category 0: [Total feces per animal] x 5 x [Weighted proportion of population responding “1-10” to MICS/DHS]

Category 1: [Total feces per animal] x 53 x [Weighted proportion of population responding “>10-95” to MICS/DHS]

Category 2: [Total feces per animal] x 100 x [Weighted proportion of population responding “>95” to MICS/DHS]

Goats

DHS: Goats
MICS: Goats

Feces produced: [Average daily fecal production per goat] x [total goats (FAO)]

Proportion of fecal hazard at household: [Total feces] x [Weighted proportion of population responding “Yes” to MICS/DHS question about goats]

Total feces per animal (used only in “weighted hazards by household” calculation below): [Total feces] / [Total goats]

Weighted hazards by household:

Category 0: [Average daily fecal production per goat] x 5 x [Weighted proportion of population responding “1-10” to MICS/DHS]

Category 1: [Average daily fecal production per goat] x 53 x [Weighted proportion of population responding “>10-95” to MICS/DHS]

Category 2: [Average daily fecal production per goat] x 100 x [Weighted proportion of population responding “>95” to MICS/DHS]

Sheep

DHS: Sheep
MICS: Sheep

Feces produced: [Average daily fecal production per sheep] x [total sheep (FAO)]

Proportion of fecal hazard at household: [Total feces] x [Weighted proportion of population responding “Yes” to MICS/DHS question about sheep]

Total feces per animal (used only in “weighted hazards by household” calculation below): [Total feces] / [Total sheep]

Weighted hazards by household:

Category 0: [Average daily fecal production per sheep] x 5 x [Weighted proportion of population responding "1-10" to MICS/DHS]

Category 1: [Average daily fecal production per sheep] x 53 x [Weighted proportion of population responding ">10-95" to MICS/DHS]

Category 2: [Average daily fecal production per sheep] x 100 x [Weighted proportion of population responding ">95" to MICS/DHS]

Pigs	DHS: None (most recent MICS survey data used for country if available, otherwise household pig ownership assigned as the WHO regional average of all countries with MICS data) MICS: Pigs	Feces produced: [Average daily fecal production per pig] x [total pigs (FAO)] Proportion of fecal hazard at household: [Total feces] x [Weighted proportion of population responding "Yes" to MICS question about pigs]
Camelids	None	Feces produced: [Average daily fecal production per camelid] x [total camelids (FAO)] Proportion of fecal hazard at household: No calculation Weighted hazards by household: No calculation
Camels	None	As above for camelids
Rabbits and hares	None	As above for camelids
Rodents, other	None	As above for camelids

Supplementary Table 2: Estimates of WHO regional animal populations and feces production by animal type, 2014.

Region	Buffalo		Camelids		Camels		Cattle		Chickens	
	Total	Feces (kg/yr)	Total	Feces (kg/yr)	Total	Feces (kg/yr)	Total	Feces (kg/yr)	Total	Feces (kg/yr)
Africa	2.67 x 10 ³	1.82 x 10 ⁶	NA		1.64 x 10 ⁷	1.03 x 10 ¹⁰	2.68 x 10 ⁸	2.35 x 10 ¹¹	1.29 x 10 ⁹	4.72 x 10 ¹⁰
Americas	1.33 x 10 ⁶	9.09 x 10 ⁸	8.89 x 10 ⁶	1.38 x 10 ⁹	6.16 x 10 ⁶	3.87 x 10 ⁹	5.14 x 10 ⁸	4.50 x 10 ¹¹	5.42 x 10 ⁹	1.98 x 10 ¹¹
EastMed	3.88 x 10 ⁷	2.66 x 10 ¹⁰	NA		1.55 x 10 ⁷	9.75 x 10 ⁹	1.01 x 10 ⁸	8.85 x 10 ¹⁰	2.78 x 10 ⁹	1.01 x 10 ¹¹
Europe	8.15 x 10 ⁵	5.58 x 10 ⁸	NA		6.98 x 10 ⁶	4.39 x 10 ⁹	1.63 x 10 ⁸	1.43 x 10 ¹¹	2.59 x 10 ⁹	9.46 x 10 ¹⁰
SEAsia	1.23 x 10 ⁸	8.41 x 10 ¹⁰	NA		1.92 x 10 ⁶	1.21 x 10 ⁹	2.55 x 10 ⁸	2.23 x 10 ¹¹	3.30 x 10 ⁹	1.21 x 10 ¹¹
WPacific	2.81 x 10 ⁷	1.93 x 10 ¹⁰	NA		4.09 x 10 ⁶	2.57 x 10 ⁹	1.94 x 10 ⁸	1.70 x 10 ¹¹	6.00 x 10 ⁹	2.19 x 10 ¹¹
World	1.92 x 10 ⁸	1.31 x 10 ¹¹	8.89 x 10 ⁶	1.38 x 10 ⁹	5.11 x 10 ⁷	3.21 x 10 ¹⁰	1.50 x 10 ⁹	1.31 x 10 ¹²	2.14 x 10 ¹⁰	7.80 x 10 ¹¹
Region	Donkeys		Ducks		Geese/guinea fowl		Goats		Horses	
	Total	Feces (kg/yr)	Total	Feces (kg/yr)	Total	Feces (kg/yr)	Total	Feces (kg/yr)	Total	Feces (kg/yr)
Africa	3.17 x 10 ⁷	1.13 x 10 ¹⁰	2.75 x 10 ⁷	1.51 x 10 ⁹	3.66 x 10 ⁷	1.06 x 10 ¹⁰	3.17 x 10 ⁸	2.72 x 10 ¹⁰	7.66 x 10 ⁶	5.37 x 10 ⁹
Americas	1.83 x 10 ⁷	6.54 x 10 ⁹	3.62 x 10 ⁷	1.98 x 10 ⁹	1.04 x 10 ⁷	3.00 x 10 ⁹	3.56 x 10 ⁷	3.06 x 10 ⁹	3.32 x 10 ⁷	2.32 x 10 ¹⁰
EastMed	1.68 x 10 ⁷	5.99 x 10 ⁹	3.49 x 10 ⁷	1.91 x 10 ⁹	1.77 x 10 ⁷	5.13 x 10 ⁹	1.73 x 10 ⁸	1.49 x 10 ¹⁰	2.40 x 10 ⁶	1.68 x 10 ⁹
Europe	3.08 x 10 ⁷	1.10 x 10 ¹⁰	9.52 x 10 ⁷	5.21 x 10 ⁹	2.91 x 10 ⁷	8.41 x 10 ⁹	5.28 x 10 ⁷	4.54 x 10 ⁹	8.34 x 10 ⁶	5.85 x 10 ⁹
SEAsia	8.96 x 10 ⁶	3.20 x 10 ⁹	1.66 x 10 ⁸	9.10 x 10 ⁹	5.24 x 10 ⁶	1.52 x 10 ⁹	2.28 x 10 ⁸	1.96 x 10 ¹⁰	1.64 x 10 ⁶	1.15 x 10 ⁹
WPacific	3.12 x 10 ⁷	1.11 x 10 ¹⁰	8.23 x 10 ⁸	4.50 x 10 ¹⁰	2.84 x 10 ⁸	8.22 x 10 ¹⁰	2.47 x 10 ⁸	2.12 x 10 ¹⁰	1.09 x 10 ⁷	7.61 x 10 ⁹
World	1.38 x 10 ⁸	4.91 x 10 ¹⁰	1.18 x 10 ⁹	6.48 x 10 ¹⁰	3.83 x 10 ⁸	1.11 x 10 ¹¹	1.05 x 10 ⁹	9.06 x 10 ¹⁰	6.41 x 10 ⁷	4.49 x 10 ¹⁰
Region	Mules		Pigeons/other small birds		Pigs		Rabbits/hares		Rodents/small mammal	
	Total	Feces (kg/yr)	Total	Feces (kg/yr)	Total	Feces (kg/yr)	Total	Feces (kg/yr)	Total	Feces (kg/yr)
Africa	1.38 x 10 ⁶	5.59 x 10 ⁸	1.34 x 10 ⁵	1.47 x 10 ⁶	3.46 x 10 ⁷	7.49 x 10 ⁹	2.59 x 10 ⁷	1.40 x 10 ⁸	NA	
Americas	6.13 x 10 ⁶	2.47 x 10 ⁹	NA		1.70 x 10 ⁸	3.68 x 10 ¹⁰	2.25 x 10 ⁷	1.21 x 10 ⁸	1.89 x 10 ⁷	6.33 x 10 ⁷
EastMed	1.13 x 10 ⁶	4.55 x 10 ⁸	2.03 x 10 ⁷	2.22 x 10 ⁸	1.76 x 10 ⁶	3.81 x 10 ⁸	2.30 x 10 ⁷	1.24 x 10 ⁸	NA	
Europe	1.10 x 10 ⁶	4.45 x 10 ⁸	3.56 x 10 ⁶	3.90 x 10 ⁷	1.88 x 10 ⁸	4.06 x 10 ¹⁰	4.82 x 10 ⁸	2.60 x 10 ⁹	NA	
SEAsia	3.27 x 10 ⁵	1.32 x 10 ⁸	7.00 x 10 ⁵	7.67 x 10 ⁶	4.28 x 10 ⁷	9.28 x 10 ⁹	3.91 x 10 ⁷	2.11 x 10 ⁸	NA	
WPacific	2.87 x 10 ⁶	1.16 x 10 ⁹	7.60 x 10 ⁶	8.32 x 10 ⁷	5.51 x 10 ⁸	1.19 x 10 ¹¹	2.47 x 10 ⁸	1.33 x 10 ⁹	NA	
World	1.29 x 10 ⁷	5.22 x 10 ⁹	3.23 x 10 ⁷	3.53 x 10 ⁸	9.87 x 10 ⁸	2.14 x 10 ¹¹	8.39 x 10 ⁸	4.53 x 10 ⁹	1.89 x 10 ⁷	6.33 x 10 ⁷
Region	Sheep		Turkeys							
	Total	Feces (kg/yr)	Total	Feces (kg/yr)						
Africa	2.63 x 10 ⁸	4.31 x 10 ¹⁰	1.90 x 10 ⁷	1.91 x 10 ⁹						
Americas	1.26 x 10 ⁸	2.06 x 10 ¹⁰	3.17 x 10 ⁸	3.18 x 10 ¹⁰						
EastMed	2.32 x 10 ⁸	3.80 x 10 ¹⁰	3.09 x 10 ⁷	3.10 x 10 ⁹						
Europe	2.23 x 10 ⁸	3.67 x 10 ¹⁰	1.24 x 10 ⁸	1.24 x 10 ¹⁰						

SEAsia	8.33 x 10 ⁷	1.37 x 10 ¹⁰	3.02 x 10 ⁶	3.03 x 10 ⁸
WPacific	4.79 x 10 ⁸	7.85 x 10 ¹⁰	8.28 x 10 ⁶	8.31 x 10 ⁸
World	1.41 x 10 ⁹	2.31 x 10 ¹¹	5.02 x 10 ⁸	5.04 x 10 ¹⁰

NA: no animals reported in region

Supplementary Table 3: Proportion of households (overall), by WHO region, with animals onsite by quantity of animals.¹

Region	Cattle			Chickens			Goats			Horses, donkeys, or mules			Sheep		
	1-10	11-95	>95	1-10	11-95	>95	1-10	11-95	>95	1-10	11-95	>95	1-10	11-95	>95
Africa	16.7	3.0	0.2	34.6	10.7	0.2	24.3	3.2	0.1	9.8	0.5	0.1	12.6	1.9	0.1
Americas	9.9	2.2	0.1	35.4	13.5	0.3	7.1	0.8	0.1	8.3	0.5	0.1	4.5	1.0	0.1
EastMed	18.1	1.1	0.1	30.9	4.9	0.2	18.4	4.1	0.1	15.8	0.8	0.1	22.4	5.3	0.2
Europe	16.0	0.8	0.1	17.3	7.5	0.1	4.6	0.4	0.0	6.3	0.2	0.0	5.8	1.4	0.0
SE Asia	41.8	3.2	0.2	53.1	8.7	0.3	26.2	1.6	0.2	9.0	0.5	0.1	7.1	0.7	0.1
W Pacific	14.2	2.2	0.1	38.8	5.6	0.4	13.5	3.0	1.3	7.6	1.7	0.1	15.8	3.1	1.2
World	19.5	2.1	0.1	35.0	8.5	0.2	15.7	2.2	0.3	9.5	0.7	0.1	11.4	2.2	0.3
Relative percents (world) ²	88.6	9.5	0.6	79.6	19.3	0.5	85.0	11.9	1.6	92.6	6.8	0.7	80.8	15.9	1.9

¹Percentage of all households, with the exception of the bottom row; ²Percentage of households with animals of that type among all households with that type of animal

Supplementary Information Reference List:

- 1 Food and Agriculture Organization of the United Nations. FAOSTAT. Live Anim. 2017.
- 2 Berendes DM, Sumner TA, Brown JM. Safely Managed Sanitation for All Means Fecal Sludge Management for At Least 1.8 Billion People in Low and Middle Income Countries. *Environ Sci Technol* 2017; **51**: 3074–3083.