Critical Review

Exposure to Animal Feces and Human Health: A Systematic Review and Proposed Research Priorities

Gauthami Penakalapati, Jenna Swarthout, Miranda J. Delahoy, Lydia McAliley, Breanna Wodnik, Karen Levy, and Matthew C. Freeman*

Department of Environmental Health, Emory University, Atlanta, Georgia 30322 United States

Ⓢ Supporting Information

ABSTRACT: Humans can be exposed to pathogens from poorly managed animal feces, particularly in communities where animals live in close proximity to humans. This systematic review of peer-reviewed and gray literature examines the human health impacts of exposure to poorly managed animal feces transmitted via water, sanitation, and hygiene (WASH)-related pathways in low- and middle-income countries, where household livestock, small-scale animal operations, and free-roaming animals are common. We identify routes of contamination by animal feces, control measures to reduce human exposure, and propose research priorities for further inquiry. Exposure to animal feces has been associated with diarrhea, soil-transmitted helminth infection, trachoma, environmental enteric dysfunction, and growth faltering. Few studies have evaluated control measures, but interventions include reducing cohabitation with animals, provision of animal feces scoops, controlling animal movement, creating safe child spaces, improving veterinary care, and hygiene promotion. Future research should evaluate: behaviors related to points of contact with animal feces; animal fecal contamination of food; cultural behaviors of animal fecal management; acute and chronic health risks associated with exposure to animal feces; and factors influencing concentrations and shedding rates of pathogens originating from animal feces.

INTRODUCTION

Nearly two-thirds of human pathogens and three-quarters of emerging pathogens are zoonotic in origin.[1,2] While research has focused on zoonotic transmission of respiratory and vector-borne pathogens, such as Ebola and West Nile Virus, less attention has been given to pathogens found in animal feces that are transmitted via water, sanitation, and/or hygiene (WASH)-related pathways, as illustrated by the classic "F-diagram" (Figure 1).[3] According to the Food and Agricultural Organization (FAO), "domestic animals such as poultry, cattle, sheep, and pigs generate 85% of the world's animal faecal waste, proportionally a far greater amount than the contribution by the human population"; the fecal production rate can total to 2.62×10^{13} kg/year.[4] Insufficient separation of animal feces from human domestic environments, common in low-income countries, can lead to fecal-oral transmission of zoonotic pathogens through direct contact with humans and/or fecal contamination of fingers, food, and water sources.

Several pathogens of zoonotic origin are associated with acute gastrointestinal symptoms that can arise from contact with animal feces.[5] Children may experience long-term growth shortfalls after exposure to these pathogens, and pregnant women and the immunocompromised may also experience severe and/or long-term adverse health effects after infection with pathogens carried in animal feces.[6−9] Approximately one-third of deaths among children under five years due to diarrhea in the Global Burden of Disease 2015 report are attributed to pathogens that can be found in animal feces.[10] While some studies seek to identify a relationship between animal contact and diarrhea, not all etiologies of diarrhea are transmitted through animal feces. While many important viral enteropathogens (e.g., rotavirus) have limited zoonotic transmission, animal feces may play an important role in the transmission of some important etiologies of childhood diarrhea, such as *Cryptosporidium*, which substantially contributes to the childhood burden of diarrheal disease and has been associated with severe acute and long-term clinical manifestations, including child growth faltering.[11] Unlike rotavirus, there is currently no vaccine for *Cryptosporidium* and treatment options are limited and often unavailable in developing countries. Thus, preventive measures for such zoonotic pathogens are important for reducing disease burden. Though the total contribution of zoonotic transmission is unknown, it may be substantial, and it may vary by the virulence and animal host(s) of the specific etiologic agent, geographic and cultural context, and environmental conditions.[12]

Recent reviews, predominantly using observational data, suggest that improved WASH conditions are associated with better children's health outcomes.[13−15] Yet randomized controlled trials in low-income rural settings have demonstrated mixed effects of such interventions on diarrhea, soil-transmitted helminth (STH) infection, trachoma, and stunting.[16−23] Even comprehensive WASH interventions may be insufficient to
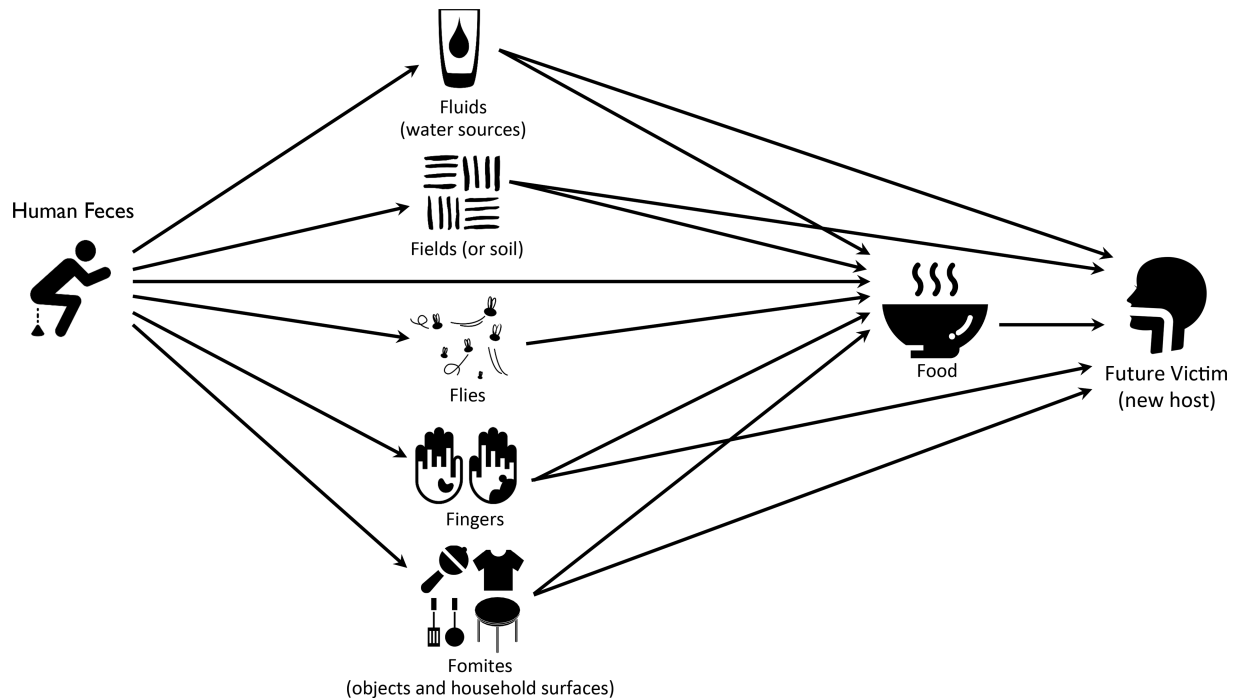
Figure 1. Traditional F-Diagram showing potential fecal-oral transmission pathways. Adapted from Wagner, E.; Lanoix, J., Excreta disposal for rural areas and small communities. *Monograph Series World Health Organization.* **1958**, *39*, 182. Copyright 1958, World Health Organization.

prevent growth faltering in rural settings.[24] One possible reason for the lack of health effects is suboptimal program fidelity and adherence, yielding less than universal coverage and use.[25] An alternative explanation is that because sanitation interventions have focused primarily on containment of *human* excrement, the lack of evidence for health effects in large intervention trials could be due to persistent exposure to fecal pathogens of *animal* origin among the study populations.[5,26,27] A recent systematic review and meta-analysis noted that domestic poultry and livestock exposure are associated with diarrheal illness in humans;[5] we expand on this review by exploring the risk of animal exposure on diarrhea, child growth outcomes, environmental enteric dysfunction (EED), pathogenic infection, trachoma, and STH infection.

Human exposure to animal feces is more common in developing countries where domestic animals and their animal feces may not be properly contained or separated from domestic environments. Though children and adults in high-income countries (HIC) can also be exposed to animals and/or their feces, potentially causing bacterial, helminth, and/or protozoan infections,[28−33] the risk may be greater in low- and middle-income countries (LMIC), where domestic animal ownership and middle- and small-scale animal production is more common in both rural and urban households[34] compared to households in HIC.

The primary objective of this systematic review was to examine what is known about human health impacts of exposure to poorly managed animal feces transmitted via WASH-related pathways in LMIC. We identified and synthesized existing literature to assess the extent to which exposure to poorly managed animal feces could affect health outcomes in humans. We modified the traditional "F-diagram" to focus on animal feces exposure in households and small-scale animal operations, in households with pets, and in communities with synanthropic rodents; through this lens we propose research priorities to better understand human exposure to

poorly managed animal feces. We identified interventions that have been used to control human exposure to animal feces and summarized what is known about their effectiveness in reducing the presence of animal feces in the environment, preventing human exposure to animal feces, and/or limiting negative human health outcomes. Based on this review, we identified a set of priority research areas to improve our understanding of the human health burden associated with exposure to animal feces, with the ultimate goal of identifying potential control measures to reduce this burden in LMIC.

■ MATERIALS AND METHODS

Search Strategy. To assess the impacts of animal feces on human health, we searched for papers with terms for "animals, feces, exposure, and humans" (Supporting Information (SI) 1, p. 2). The search was limited to English- and Spanish-language studies and included papers published before October 3, 2016. We searched in the following databases: PubMed, Web of Science, Cochrane Library, EMBASE, and CAB Direct. We also included a partial search of the Environmental Sciences and Pollution Management (ESPM) database, but due to host database server challenges at the time of the search, 26% of full search results from this database could not be downloaded. We conducted a search of gray literature in International Food Policy Research Institute (IFPRI), Consultative Group on International Agricultural Research (CGIAR), International Livestock Research Institute (ILRI), Food and Agriculture Organization of the United Nations (FAO), U.S. Centers for Disease Control and Prevention (CDC), and the World Health Organization (WHO). We also included papers from personal libraries and literature collections, including a limited number of highly relevant studies that were published between October 2016 and September 2017. We included experimental and observational study designs. All study settings and populations were eligible for inclusion.

Selection of Studies. Search results were cataloged and organized in EndNote X7 (Clarivate Analytics, Boston, MA). Four researchers (GP, JS, LM, BW) examined every publication's title and abstract to assess if the publication met one or more of the following inclusion criteria: (a) human exposure to poorly managed animal feces; (b) negative human health outcomes from exposure to animal feces (e.g., diarrhea, gastroenteritis, EED, trachoma, STH infections, child growth (anthropometric) outcomes, and infection by zoonotic pathogens); and (c) animal feces contamination of the environment (e.g., water or fields). First, the four researchers all independently reviewed an initial 150 publications to ensure consistency among the study team when determining if papers met the above inclusion criteria. Afterward, the remaining search results were divided equally among the four researchers who independently reviewed the title and abstract of their designated search results. We define poorly managed feces as animal feces that are not contained or separated from human domestic and public environments. We define exposure to animal feces as behaviors related to handling animal feces (e.g., spreading manure on fields or removing domesticated cat feces from litter) and human activity conducted in close proximity to animals and their feces (e.g., children playing on the ground where chickens also roam). While identifying publications that met the inclusion criteria, we simultaneously identified papers that discussed animal husbandry practices and animal feces/manure management, and we identified papers that discussed control measures for reducing human exposure to animal waste. If researchers were unable to make a decision about including or excluding a publication during the title and abstract review process, the publication's features were discussed among the four researchers and a decision was made.

We excluded publications that discussed one or more of the following: no exposure to animals or animal feces, exposure to animal or animal feces in occupational or industrial settings (e.g., commercial farms), exposure to animal urine, animal health outcomes, human respiratory health outcomes, and diseases related to exposure to insect feces (e.g., Chagas Disease). We excluded papers from HIC because piped sanitation and piped water infrastructure are prevalent, and we wanted to explore how humans are exposed to animal feces in LMIC where sanitation and water infrastructure may be limited or nonexistent.

Two researchers (GP, JS) reviewed the full-text of publications that met the inclusion criteria to confirm the publication met the inclusion criteria as well as one of the following: (a) risk factors, such as exposure to or contact with animals or animal feces, associated with zoonotic infection; (b) animal husbandry practices/behaviors and information about animal feces management; or (c) control measures or interventions aimed at reducing human exposure to animal waste. Other areas of potential interest that were beyond the scope of this review include papers that focused on the epidemiology and etiology, antibiotic resistance, or animal shedding of zoonotic fecal pathogens. No publications from the gray literature met our inclusion criteria for this review.

Data Extraction and Synthesis. Data from papers deemed to meet the inclusion criteria were extracted into a prepiloted extraction form, which included research objectives, key findings, descriptions of study populations, descriptions of health outcomes, and descriptions of exposures to animals and/or their feces (SI Table S1). During synthesis, data were classified by health outcomes, pathogens of concern, exposures

to common domestic animals, and regions in which the studies were conducted. Health outcomes, such as diarrhea and trachoma, were assessed by individual studies in a variety of methods including recall, health professional diagnosis, and/or testing. Publications that discussed control measures to remove or reduce the presence of animal feces were identified and classified according to control approach. We did not conduct a meta-analysis or a risk of bias assessment because of the heterogeneity of methods, exposures, and outcomes used across the studies included in the review. We conducted the systematic review according the evidence-based minimum requirements identified by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) checklist (SI Table S2).[35]

RESULTS & DISCUSSION

Our search yielded 12 425 unique results, of which the full texts of 329 articles were reviewed. A total of 62 publications met the inclusion criteria (SI Figure S1). Characteristics of publications included in this review are summarized in Table 1 (regions, health outcomes, and animals) and Table 2 (pathogens).

Most of the studies we identified for this review were cross-sectional studies ($n = 42$); other study designs included case-control ($n = 3$), experimental and quasi-experimental ($n = 2$), longitudinal ($n = 2$), cohort ($n = 4$), and qualitative studies ($n = 1$). The remaining publications, reported on secondary data analyses ($n = 1$), a conceptual model ($n = 1$), or systematic review/meta-analysis ($n = 1$). Study populations included children, adults, animals, and environmental samples (e.g. stool, blood, water). Most of the studies were conducted in Asia ($n = 30$), but this review also includes studies conducted in Africa ($n = 20$), South America ($n = 12$), and Oceania ($n = 1$) as well; one literature review included papers from around the globe. Relevant characteristics of the publications included in this review are presented in SI Table S3.

IMPACT OF EXPOSURE TO ANIMALS AND/OR ANIMAL FECES ON HUMAN HEALTH

Most studies assessed exposure to animal feces based on contact with or presence of animals in the environment. Few ($n = 9$) measured direct human contact with animal feces per se. We illustrate the role of exposure to animal feces and/or contact with or presence of animals and its impact on WASH-related health outcomes in Figure 2. Below we synthesize findings for each of the health outcomes considered, including diarrhea, child growth, EED, pathogen isolation in human stool (bacterial, protozoan, microsporidian, viral), trachoma, and STH infections.

Diarrhea. Heterogeneous effects of exposure to animals and animal feces on human diarrheal illness were observed among the 18 studies examining diarrhea in this review. A systematic review and meta-analysis found consistent evidence of a positive association between domestic poultry and livestock exposure and diarrheal illness.[5] Animals housed in living quarters increased the risk of diarrhea and/or infection by enteric pathogens in several studies and increased the risk of longer durations of diarrhea.[36−41] Living with chickens infected by zoonotic enteric pathogens increased the risk of diarrhea among children in Lima, Peru.[39]

No associations were found between the presence of animals or animal feces and diarrhea or enteric infection in urban Accra, Ghana and rural Odisha, India.[42,43] An assessment of

Table 1. Summary of Characteristics of Studies (n = 62)[a] Included in Review of Potential Health Impacts from Exposure to Animal Feces

Region	n (%)
Africa	
North Africa	1 (2%)
Sub-Saharan Africa	19 (31%)
Asia	
Middle East	1 (2%)
South Asia	19 (31%)
Southeast Asia	9 (15%)
East Asia	1 (2%)
South America	12 (19%)
Oceania	1 (2%)
Global	1 (2%)
Health Outcomes	**n (%)**
Diarrhea	18 (29%)
Environmental Enteric Dysfunction	2 (3%)
Helminth Seropositivity	5 (8%)
Mortality	1 (2%)
Nutrition and Growth Outcomes	8 (13%)
Pathogens Found in Stool	17 (27%)
Trachoma	3 (5%)
Hookworm-Related Cutaneous Larva Migrans	1 (2%)
Other: human behaviors/practices	5 (8%)
No Health Outcomes Specified	14 (23%)
Animal	**n (%)**
Livestock	
Buffalo	5 (8%)
Cattle	25 (40%)
Goats	19 (30%)
Sheep	14 (22%)
Pigs	9 (14%)
Poultry (chickens, ducks, geese, quail)	29 (46%)
Synanthropic Rodents	3 (5%)
Pets/Free-Roaming	
Cats	11 (17%)
Dogs	14 (22%)
Other (horses, guinea pigs, rabbits)	2 (3%)
Not Specified	13 (21%)

[a]A total of 62 unique publications were reviewed. The total N for *Regions, Health, Outcomes,* and *Animals* is greater than 62 because publications that assessed multiple regions, health outcomes, or animals in their study were counted for each unique region, health outcome, or animal.

Table 2. Summary of Pathogen Characteristics of Studies (n = 62)[a] Included in Review of Potential Health Impacts from Exposure to Animal Feces

Pathogens	n (%)
Bacteria	
Aeromonas hydrophila	1 (2%)
Bacteriodales spp.	1 (2%)
Campylobacter spp.	9 (15%)
Chlamydia trachomatis	3 (5%)
Escherichia coli	11 (17%)
Klebsiella spp.	1 (2%)
Salmonella spp.	5 (8%)
Shigella spp.	5 (8%)
Vibrio spp.	4 (7%)
Yersinia spp.	2 (3%)
Helminths	
Ascaridia spp.	1 (2%)
Ascaris spp.	4 (7%)
Clonorchis spp.	1 (2%)
Echinococcus spp.	2 (3%)
Enterobius spp.	1 (2%)
Hookworm (*Ancylostoma* spp.)	7 (11%)
Hymenolepis spp.	1 (2%)
Schistosoma spp.	3 (5%)
Spirometra spp.	1 (2%)
Strongyloides spp.	3 (5%)
Taenia spp.	1 (2%)
Toxocara spp.	6 (10%)
Trichuris spp.	6 (10%)
Microsporidia	
Enterocytozoon bieneusi	1 (2%)
Protozoa	
Blastocystis hominis	1 (2%)
Cryptosporidium spp.	10 (16%)
Cyclospora cayetanensis	2 (3%)
Entamoeba spp.	6 (10%)
Giardia spp.	15 (24%)
Isospora belli	2 (3%)
Toxoplasma spp.	1 (2%)
Trichomonas hominis	1 (2%)
Viruses	
Adenovirus	2 (3%)
Astrovirus	1 (2%)
Hepatitis E virus	1 (2%)
Rotavirus	5 (8%)

[a]A total of 62 unique publications were reviewed. The total N for all pathogens is greater than 62 because publications that assessed multiple pathogens were counted for each unique pathogen.

Demographic Health Surveys (DHS) from 30 sub-Saharan African countries found an inconsistent relationship across contexts between childhood diarrhea and household livestock ownership; 13 countries indicated livestock ownership as a risk factor but 10 countries exhibited a protective association likely due to confounding with socio-economic status and varied access to improved water and sanitation infrastructure.[26] Cattle ownership in Madagascar was found to be protective against severe diarrhea.[44]

Child Growth. Exposure to fecal pathogens of animal origin may impair child growth, although these effects are not consistently found in the literature (n = 8). For most studies, child growth was measured using anthropometric measurements to calculate standardized age- and sex-specific height-for-age Z-scores (HAZ), weight-for-age Z-scores (WAZ), and weight-for-height Z-scores (WHZ) to classify levels of stunting,

being underweight, and wasting, respectfully. In a study in rural Ethiopia, poultry ownership was positively associated with child HAZ, but corralling poultry indoors at night was negatively associated with child HAZ; no association was found between corralling animals indoors at night and child HAZ for other animal species (cattle, goats, sheep, pack animals).[45,46] Several studies found no association between livestock ownership and child HAZ and WAZ, though livestock diseases might be related to lower child HAZ and WHZ in some groups in rural Kenya.[43,47] The presence of animal feces in household compounds was negatively associated with child HAZ in rural Bangladesh and Ethiopia.[40]
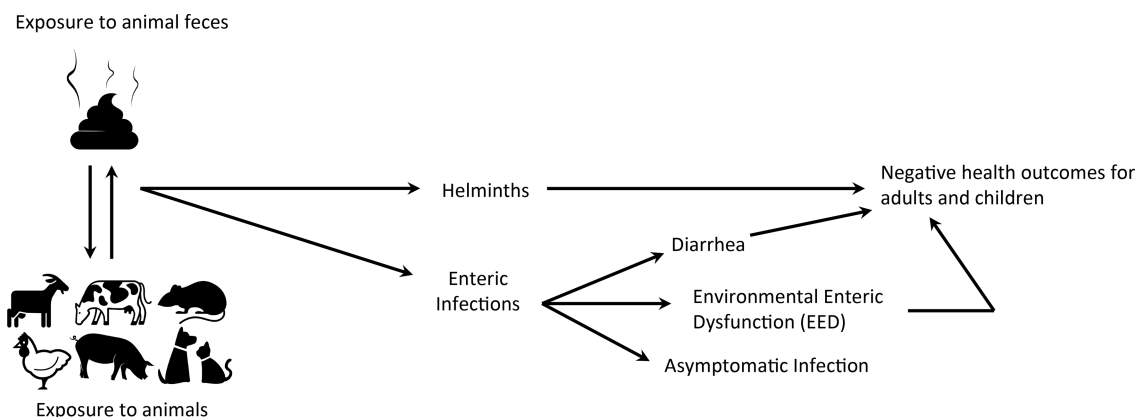
Figure 2. Impact of exposure to animal feces and/or contact with animals to human health.

A recent analysis of agricultural, nutritional, and interview data, along with anthropometric measurements from sub-Saharan Africa, revealed inconsistent evidence for the effects of animal ownership and consumption of animal-sourced foods on child growth. Children in households that consumed animal-sourced foods in Rwanda, Uganda, and Malawi had better anthropometric scores (WHZ and HAZ) than those that did not consume animal-sourced foods; however, children who consumed animal-sourced foods in Ghana and Senegal had lower relative anthropometric scores (WHZ (Ghana only) and HAZ).[46] The analysis of DHS from 30 sub-Saharan African countries similarly found inconsistent results, but data revealed a slight protective effect of the number of animals owned on child stunting.[26]

Child growth effects may be mediated by animal containment and housing practices. Children in households that kept poultry outside the home had significantly better HAZ compared to those in households that kept poultry inside the home in rural Ethiopia.[45] Similarly, in rural Bangladesh the odds of being stunted were higher among children in households with animals corralled in sleeping quarters versus households where animals were not corralled in sleeping quarters.[48]

Environmental Enteric Dysfunction (EED). Two studies in this review suggest that exposure to animals and animal feces might increase the risk of EED, also referred to as environmental enteropathy, an impairment of intestinal function evident in many young children in low-resource settings that leads to growth faltering and cognitive impairment.[49−54] Children sleeping in households with animal corrals in the sleeping quarters had significantly higher EED scores (calculated from fecal biomarker measurements) than those without animals in the sleeping quarters in rural Bangladesh.[48] Among rural Malawian children, animals sleeping in the same room as the children, combined with use of potentially contaminated water sources and the absence of household pit latrines, was positively associated with EED.[55]

Pathogen Isolation in Human Stool. Several studies examined associations between exposure to animals and/or their feces to subsequent isolation of pathogens in human stool.

Among bacteria, *Campylobacter* spp. infection was common among children living with domesticated animals, especially poultry, compared to children not living with animals, because children were likely to be in direct contact with chicken feces.[5,41,56,57] A study in peri-urban Peru noted that chickens, dogs, and cats were commonly infected with *C. jejuni*.[36] Genetic analysis of animal and child stool samples in semirural Ecuador found that *C. jejuni* sequence types were identical between children and chickens, dogs, guinea pigs, and rabbits; atypical enteropathogenic *Escherichia coli* (aEPEC) sequence types were identical between children and pigs, dogs, and chickens.[58]

Among protozoal pathogens, *Cryptosporidium* spp., *Giardia* spp., and *Entamoeba* spp. have been associated with exposure to animals. *Cryptosporidium* spp. identification in child stool was associated with the presence of chickens in the household in Cambodia.[59] In urban Kenya, a study among HIV/AIDS patients found that cryptosporidiosis was associated with contact with animals,[60] and in urban Democratic Republic of the Congo, exposure to farm pigs increased the odds of *Cryptosporidium* infection among HIV/AIDS patients.[61] Individuals with household pets were 2.6 times more likely to be infected with *G. duodenalis* assemblage A compared to those without pets in Malaysia.[62] A study of outpatient stool samples from an urban hospital in Yemen found that contact with animals increased the risk of any intestinal protozoan infection (*G. duodenalis*, *E. histolytica*, *E. dispar*) and single infection with *Entamoeba* spp.; single infection of *G. duodenalis* was not associated with contact with animals.[63] A study in rural China among individuals with pulmonary tuberculosis found that those raising chickens, ducks, or pigs, and working farmlands barefoot to be significantly associated with protozoan (*Blastocystis hominis*, *Entamoeba* spp., *Trichomonas hominis*) and helminthic infections (hookworm, *Trichuris trichiura*, *Ascaris lumbricoides*, *Clonorchis sinensis*), respectively.[64]

Immunocompromised populations are particularly susceptible to infection by microsporidia, specifically *Enterocytozoon bieneusi*. A study of microsporidiosis in HIV patients in hospitals in Lima, Peru found that contact with duck or chicken fecal droppings was a risk factor for infection with the *E. bieneusi* genotype, Peru-1, as were lack of running water, flush toilets, or garbage collection.[65] Among HIV/AIDS patients in Kinshasa, Democratic Republic of the Congo, exposure to farm pigs was associated with higher odds of infection with *E. bieneusi* or *Cryptosporidium* spp.[61] In urban India, a study among HIV-positive individuals found that contact with pets and other animals increased the odds of infection with enteric pathogens, including bacterial, protozoan, helminthic, and microsporidian species.[66]

Several studies reported no association between presence of or contact with domestic animals or rodents and their feces and pathogenic infection with certain species of bacteria,[42,67,68] protozoans,[59,63] and viruses.[69]

Livestock

Fluids

1

Fields

2

Animal Feces

3

Flies

4

5

Fingers

6

Domestic/Free-roaming animals

Synanthropic rodents

Fomites

Food

7

7

7

7

7

7

8

8

8

8

8

Future Victim

→ Primary pathways: direct exposure to animal feces   - - - → Secondary pathways: indirect exposure to animal feces

1. Compromised water sources: animal feces runoff into drinking water sources, animals and humans sharing same water sources
2. Application of manure to fields, animal feces disposed in fields, animals defecating in fields/public spaces
3. Slaughtering practices, management of animal products (e.g., eggs or milk)
4. Unsafe, uncontained disposal of animal feces
5. Direct contact with animal feces (e.g., handling manure for fuel), cohabitation with animals, children ingesting uncontained feces
6. Contaminated domestic objects (toys, cooking utensils) and household surfaces (tables, food preparation and storage areas)

7. Contamination of food sources from contact with flies and/or fingers; produce grown in contaminated soil; contaminated water used to wash, prepare, and/or grow produce; feet/shoes transporting contaminated soil into food preparation/cooking areas; contaminated fomites (cooking utensils, food storage containers) used to prepare food
8. Ingestion of contaminated water and/or food, transmission of pathogens from hands to mouth or from contaminated fomite (utensil, toy) to mouth
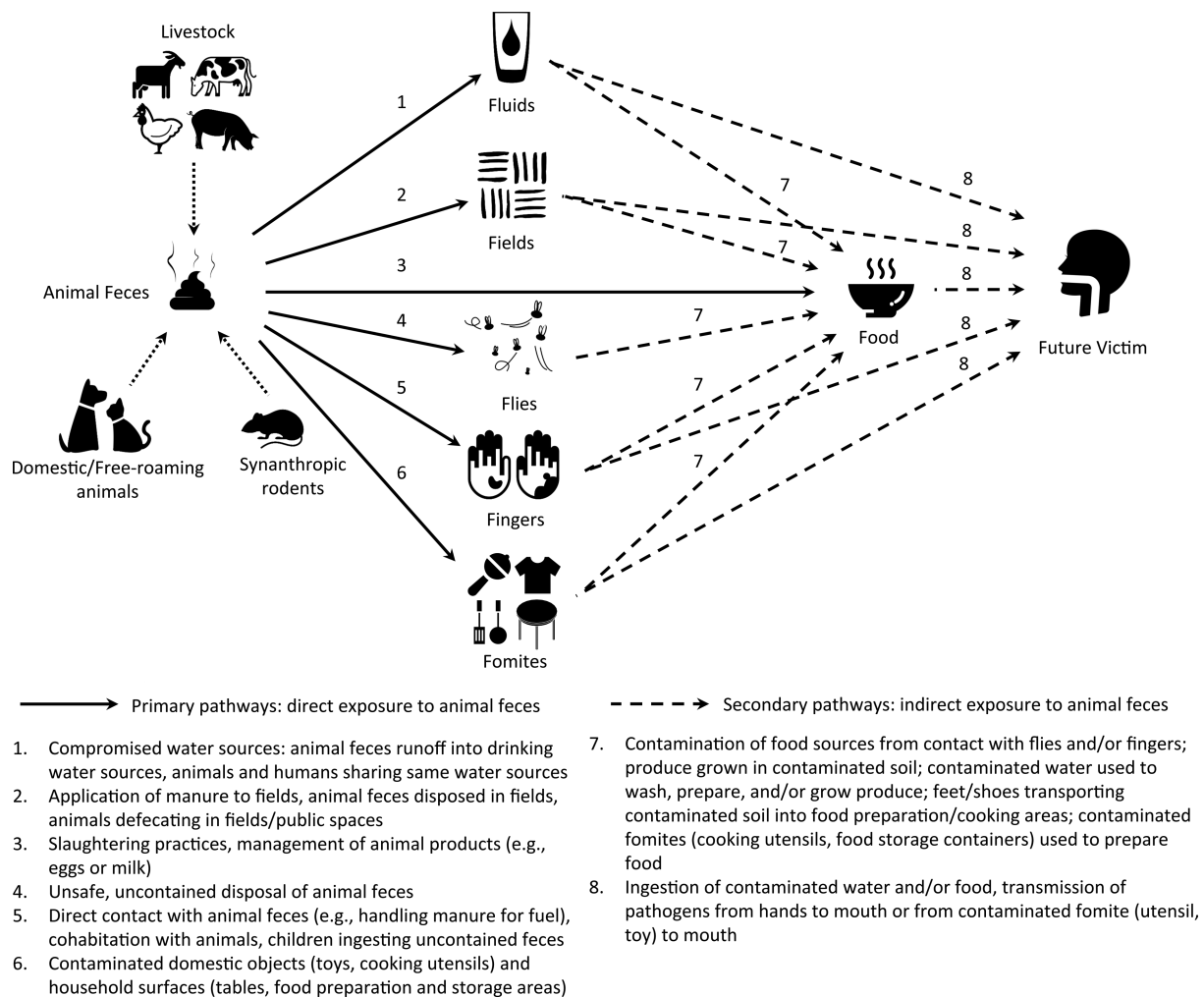
Figure 3. Modified F-diagram showing transmission routes of animal feces to humans. Adapted from Wagner, E.; Lanoix, J., Excreta disposal for rural areas and small communities. *Monograph Series World Health Organization.* **1958**, *39*, 182. Copyright 1958, World Health Organization.

Trachoma. Exposure to animals and animal feces might increase the risk of trachoma, an infection by the bacterium *Chlamydia trachomatis*, by potentially providing breeding sites for flies that propagate the infection. The studies in this review do not assess if flies carrying *C. trachomatis* actually bred on animal feces; the presence of human feces in or near study sites may be a confounding factor. In rural Nigerian households, the presence of animal feces in household compounds was a risk factor for trachomatous inflammation-follicular (TF), a precursor condition to blinding trachoma.[70] In rural Ethiopian households, active trachoma, measured by TF and trachomatous inflammation (TI), was more common in children in families who specifically housed their cattle in their sleeping quarters, though cattle ownership was not associated with trachoma risk.[71] Another study in rural Ethiopia also noted that the presence of animal feces near the house was associated with active trachoma in at least one child in the study households.[72]

Soil-Transmitted Helminth (STH) Infection. Evidence suggests that exposure to animals and animal feces, particularly those of cats and dogs, leads to an increased risk of STH infections. Individuals in urban, low-income households in Brazil were more likely to be diagnosed with hookworm-related cutaneous larva migrans (HrCLM), a parasitic skin disease caused by feline or canine hookworms, if animal feces were present in the compound.[73] Dog owners in Chile and Argentina

displayed positive human seropositivity to *Echinococcus granulosus* and *Toxocara canis*, respectively.[74,75] Similarly, the presence of dogs and their feces significantly contributed to children being seropositive for toxocariasis in Sri Lanka.[76] Pregnant women in Bali exposed to oocyst-positive cat feces in their environment were more likely to be serologically positive for *Toxoplasma gondii* than pregnant women who were not exposed to oocyst-positive cat feces.[77]

PATHWAYS OF EXPOSURE TO ANIMAL FECES

The means of characterizing exposure to animals and animal feces varied considerably in the literature we reviewed. Researchers assessed presence of or contact with animals, presence of or contact with animal feces, animal ownership, environmental contamination of public and domestic spaces, and risky husbandry practices (e.g., using cow dung as cooking fuel and slaughtering practices) through structured observations and semistructured interviews. Most publications assessed impacts of raising poultry (chickens, duck, geese, quail) and cattle; studies also assessed impacts of exposure to goats, dogs, sheep, cats, pigs, buffalo, synanthropic rodents (mice, rats), and less commonly, horses, guinea pigs, and rabbits.

We reviewed the literature to identify the extent of human-animal contact with attention to regional, cultural, and urban-rural contextual differences. The evidence of human-animal

contact between regional and cultural contexts revealed anecdotal study site-specific information, but did not provide a sufficiently generalizable set of behaviors. The comparative risk of exposure to animal feces in urban compared to rural areas is therefore difficult to determine.

Figure 3 illustrates the pathways for human exposure to zoonotic fecal pathogens using a modified F-diagram. We distinguished transmission pathways dependent on animal species and behaviors versus pathways dependent on human behaviors and practices; the pathways corresponding to human behaviors are independent of the animal species that is the source of the fecal exposure. Below we present the evidence around each of the exposure pathways highlighted in Figure 3; the numbers correspond to the pathways in Figure 3.

Pathway 1: Contamination of Water Sources. Contamination of both source and stored drinking waters is an important human exposure to animal feces. Several studies demonstrated that open ponds and surface waters are more susceptible to contamination by animal feces, though significant contamination has been observed in public and private tube wells also.[27,78,79] In rural India, higher sheep populations in villages increased the odds of detecting higher concentrations of *Cryptosporidium* spp. in public ponds.[80] Humans sharing water sources with livestock represents a particularly risky behavior in low-income settings.[78,81–83]

Pathway 2: Contamination of Soil. Many of the pathways for exposure to animal feces occur directly in and around the domestic environment. We found consistent evidence of animals contaminating fields and soil by indiscriminate defecation. Positive associations were found between seropositivity for helminths and soil contaminated by dog and cat feces in households and public settings (e.g., parks, playgrounds).[74,76] Stray, free-roaming cats and dogs contaminated domestic and public environments with *Toxoplasma* spp. and helminth eggs in rural and urban communities in LMIC.[29,30,84,85]

Ruminant fecal markers were observed in soil and hand rinse samples from households that did and did not own ruminant species in Bangladesh.[86,87] Widespread chicken feces contamination has been observed in household kitchens and backyards;[88] chickens might therefore be of particular concern in household environments, because children (up to five years old) have been observed to have contact with chicken feces an average of 2.9 times in a 12 hour span.[57]

Soil was contaminated during the use and disposal of manure on agricultural or residential areas as fertilizer.[83,89,90] Manure effluents may also be discharged from cattle storage, potentially contaminating surrounding land.[81]

Pathway 3: Contamination of Food. In the United States and other HIC, where human waste is arguably well-controlled, the burden of enteric disease is largely related to foodborne or animal-associated outbreaks. Most of the important bacterial pathogens of foodborne illness in the United States are transmitted by animals.[91] Even in the case of sophisticated human waste containment, pathogens from poorly managed animal feces can directly contaminate food during the food production process, particularly related to slaughter. As such, foodborne exposure to animal feces in LMIC is likely an important pathway that warrants further research.

Our search, however, uncovered few studies ($n = 2$) that reported on the contamination of food from animal feces. *Campylobacter* spp. contamination was found in 34.6% of samples of various types of goat meat collected in the

Democratic Republic of Congo.[92] Fresh produce collected from a suburban market in Vietnam was widely contaminated with parasite ova excreted by both humans and animals.[90]

Pathway 4: Contamination via Flies. Flies, potential vectors of fecal contamination, may be associated with negative health outcomes. Three studies specifically examined flies as vectors for trachoma infection[70,72] and diarrheal illness.[38] In rural Ethiopia and Nigeria, the presence of flies in the home (due to presence of cows, waste disposed near the home, and defecation near the home)[72] and on the face[70] was positively associated with trachoma. In rural India, higher fly densities were associated with longer durations of diarrhea.[38] Also, the absence of animals in or near the home was protective against high fly densities. An additional study in rural Indian households assessing the presence of cowsheds and the presence of flies noted that fly counts were higher in households owning cowsheds versus those without cowsheds.[43]

Pathway 5: Contamination of Human Hands. Cohabitation of animals and humans is a common practice in LMIC and is one of the primary risk factors we identified in this review. Though most studies did not explicitly observe human-to-animal contact, we used animal ownership and the presence of animals in and around households as a proxy for direct contact with animals, a pathway important for exposure to animal feces. In many domestic settings, livestock, including cattle and poultry, were housed in the family's sleeping quarters,[45,48,63,89] increasing the potential for contamination in the household environment. Households kept livestock in sleeping quarters at night to protect them from thieves or from being hunted by other animals.[89] Poultry were generally allowed to scavenge for food inside and outside living quarters in rural villages in Bangladesh.[89] Household members directly contacted animal feces when handling manure, sometimes handling cow manure from *E. coli*-positive and negative herds with bare hands.[81,83,93]

Multiple studies in rural and urban settings found positive associations between high levels of contact with animals and/or animal feces and negative health outcomes.[33,62,69,74,94,95] The presence of animal feces in household compounds has been associated with diarrhea, lower HAZ, and HrCLM.[37,40,73] Contact with manure has also been associated with the presence of antibodies to *C. jejuni* and pathogenic *E. coli*.[28]

Pathway 6: Contamination of Fomites. Other sources of direct or indirect contamination by animal feces include fomites, such as cooking and infant feeding utensils and toys. Two studies in South Asia evaluated environmental fecal contamination in rural households using toys which may be more likely to come into direct contact with animal feces as they are used for play. In rural India, the average fecal contamination of toys increased as the number of animal fecal piles observed in the household or within the compound increased.[96] The authors suggest that the fecal contamination detected on the toys is likely from both human and animal feces. In rural Bangladesh, fewer toys were contaminated with *E. coli* (used as a fecal indicator bacteria) in households in villages with more than 50% latrine coverage, no open defecation, handwashing facilities with soap, protected source water in dwellings, safe disposal of child feces, and no animals present in the household but used plaster floors with cow dung.[97] In this study, the households' substantial WASH infrastructure used to limit human fecal contamination likely played a role in minimizing fecal contamination in the household, but the absence of animals is also noteworthy.
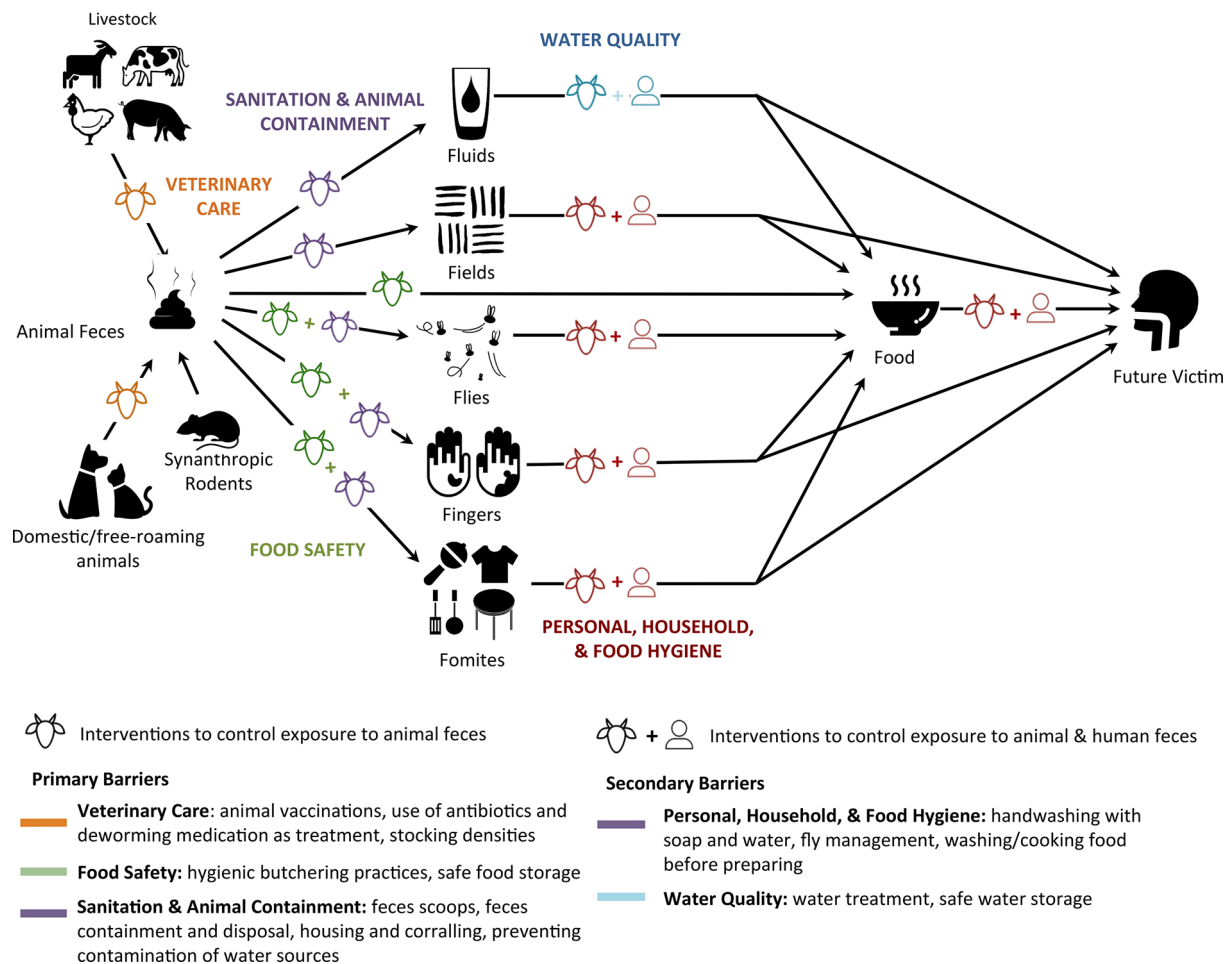
Figure 4. Modified F-diagram including interventions that can block human exposure to animal feces. Adapted from Wagner, E.; Lanoix, J., Excreta disposal for rural areas and small communities. *Monograph Series World Health Organization.* **1958**, *39*, 182. Copyright 1958, World Health Organization.

Interestingly, the study noted that households with floors of soil or mud surfaces in the living and entrance areas had statistically lower amounts of bacteria on toys compared to households with cement floors, but there was no difference in contamination levels of the toys between households that plastered with cow dung versus households that did not plaster with cow dung.[97]

Two studies in this review examined fecal contamination on cooking and feeding utensils. In a peri-urban community in Lima, Peru, a study of environmental contamination of household objects, including infant bottle nipples, feeding bottles, spoons, and can openers, found that 35% of the objects (*n* = 80) were positive for *E. coli* cultures.[36] Another household-level study found that infants' cups and spoons yielded *E. coli* cultures in 23% of households (*n* = 5).[88] In these studies, indirect contamination of fomites likely occurred when the fomites dropped onto contaminated floors or were handled by contaminated fingers; direct exposures of fomites to animal feces were not addressed in these studies.[36,88]

■ **INTERVENTIONS LIMITING EXPOSURE TO ANIMAL FECES**

We adapted the traditional F-diagram to show pathways of human exposure to animal feces and assessed potential interventions along those pathways (Figure 4). While "secondary" barriers to block transmission of animal feces to

humans are capable of controlling both human and animal feces, "primary" barriers are specific to controlling exposure to animal feces. These primary barriers have largely not been considered in traditional WASH interventions designed to limit exposure to human feces, and few studies have evaluated their potential in reducing the burden of animal feces on human health. Our review uncovered only seven intervention studies specifically aimed at controlling this primary barrier of exposure to animal feces. The control measures that have been evaluated and/or suggested as potential interventions in the studies included in this review are described below; Table 3 summarizes these intervention studies.

Separating Chickens from Human Living Quarters. Cohabitation with animals has been associated with negative health outcomes. Animal containment practices can reduce human exposure to animal feces contamination in domestic environments. However, according to two studies that evaluated the effects of separating chickens from human living quarters in peri-urban areas of Lima, Peru, corralling chickens did *not* eliminate child exposure to poultry; it might actually increase the risk of campylobacteriosis potentially due to continued exposure to chickens and/or from increased concentrations of *Campylobacter* spp. in the corralling area.[41,98] Harvey et al. evaluated an intervention to contain poultry in wooden corrals with commercial fish netting walls and fiberglass roofs, in addition to separating poultry by age,

Table 3. Summary of Trials Evaluating Potential Interventions Limiting Exposure to Animal Feces

intervention	interrupted fecal-oral pathway	reference	description of intervention	study context	effectiveness of intervention
separating chickens from human living quarters	feces → fluids, food, fingers	Harvey et al. (2003)	provided wooden corrals with commercial fish netting walls and fiberglass roofs; separated poultry by age, sex, and/or species	peri-urban Peru	uptake was low among households that did not corral their poultry before the study; corralling did not eliminate child exposure to poultry
		Oberhelman et al. (2006)	provided corrals sized based on number of chickens in household and the size of available areas on the property outside living quarters	peri-urban Peru	chicken feces from corralled chickens was colonized with *Campylobacter* spp. more often than control group; corralling might have increased the risk of campylobacteriosis in children
providing animal feces scoops	feces → fluids, fields, fingers	Boehm et al. (2016)	provided metal scoops for removal of animal feces and safe disposal in a dual-pit latrine; provided concrete ring-based dual-pit latrines with slabs, water seals, and superstructures; provided "potties" for young children	rural Bangladesh	ruminant fecal markers detected more often in stored water of control vs sanitation compounds; impossible to disentangle effects of provision of metal scoop from other components
		Hussain (2013)	provided "sani-scoops" for disposal of child and animal feces; provide "potties" for young children	rural Bangladesh	reported use of the hardware was relatively high; minimal differences detected in the presence of human and animal feces in compounds between baseline and follow-up visits
creating safe child play spaces	feces → fingers; fields → human	SHINE Trial et al. (2015)	provided safe play areas among a package of other WASH interventions	rural Zimbabwe	ongoing trial; results not yet published
improving animal veterinary care	animal → feces	Hall et al. (2012)	increased veterinary care of dairy cattle; encouraged behavior change to reduce exposure to manure; improved agricultural production	rural Bangladesh	increased access to health services, human and veterinary, in most villages reduces exposure to emerging infectious disease hazards, as well as removing livestock from one in three households, improving manure management in all villages, and improving water and latrines in all villages

sex, and/or species.[98] Households that used corrals most of the time before the study consistently used the experimental corrals from the start; households who let their poultry roam before the study intervention housed their poultry in corrals less consistently. Despite efforts to separate children from poultry, some children were still exposed because they helped catch poultry and move them into the corral, climbed on corral walls and doors, poked fingers through the netting, entered corrals to play with the poultry, or helped with daily animal care. In another area of peri-urban Lima, researchers installed chicken corrals in intervention households.[41] They found that chicken feces from the control group were colonized with *Campylobacter* spp. more often than that from the corral group, but both groups were heavily colonized (63.9% and 58.1% of chicken stool samples, respectively). The rate of diarrhea in children was higher in the corral group (2.79 episodes per person per year [epy]) than the group without corrals (2.07 epy; $p = 0.017$), suggesting that chicken corralling may have increased the risk of *Campylobacter*-related diarrhea in children from children entering and handling the chickens in the corrals and/or encouraged the children to interact with the chickens due to close proximity of the corrals to the home. In addition, the corrals concentrated chicken feces in a single area that could have contributed to an increased concentration of *Campylobacter* spp. in the area.

Providing Animal Feces Scoops. Similar to animal containment practices, promotion of animal waste removal from the domestic environment and proper disposal could disrupt the contamination of environmental reservoirs by animal feces. Though sanitation interventions have primarily focused on containing human feces by providing improved latrines, some studies have added components to encourage the safe disposal of animal feces as well. The WASH Benefits trial provided a metal scoop to households for removal of animal feces from the environment and safe disposal in a dual-pit latrine as part of a sanitation intervention in rural Bangladesh.[99] The authors hypothesize that the use of the metal scoops might remove animal feces from sanitation compounds, but might ultimately contaminate the community's water source downstream of the disposed animal feces. While the intervention group had lower ruminant fecal markers, the scoop was coupled with provision of a household dual-pit latrine as well as potties for young children, so disaggregating the impact of animal feces disposal was not feasible.[86]

In rural Bangladesh, households were provided potties and "sani-scoops", hoe-like tools for disposal of child and animal feces. Although reported use of the hardware was relatively high, minimal differences were detected between the presence of human and animal feces in compounds at baseline and follow-up visits.[100] Interviews with study participants revealed that liquid feces was hard to remove from uneven or hard surfaces with the sani-scoop, and animal feces was not generally perceived as "disgusting". Additionally, household members were unlikely to change their habits of sweeping and cleaning courtyards of feces only at certain times during the day, potentially exposing them to fecal contamination at other times of day.[100] To reduce exposure to animal feces, education regarding safe animal feces disposal methods might be necessary as a complement to provision of sanitary scoops designed to remove animal feces.

Reducing Contamination of Environmental Sources by Controlling Animal Movement. Soil is oftentimes a reservoir for animal feces contamination in both public and domestic areas, and animal containment measures may reduce animal fecal contamination. In urban Brazil, fencing around public sandboxes was a significant protective factor against soil contamination of helminths from dog feces because the fences prevented stray dogs from accessing the area.[84]

Creating Safe Child Spaces. Rather than corralling animals, protective and hygienic barriers may prevent humans, specifically children, from coming into contact with animal feces. Since there are constant opportunities for young children to put contaminated fingers in their mouths or ingest feces-contaminated soil, creating spaces for children separate from livestock could reduce exposure to animal feces. The Sanitation, Hygiene, and Infant Nutrition Efficacy (SHINE) trial in Zimbabwe is testing this approach by providing households with safe play areas for children in addition to a package of other water and sanitation interventions.[101] The trial is ongoing, and results have not yet been published.

Improving Animal Veterinary Care. Veterinary care may reduce the spread of zoonotic fecal pathogens from livestock and domestic animals by reducing pathogen carriage in animals. In Bangladesh, exposure to emerging infectious disease hazards were significantly reduced by removing livestock from one in three households, improving manure management in all villages, improving water and latrines in all villages, and increasing access to health services—human and veterinary—in most villages.[102] The intervention also increased income from animal agriculture.

Promoting Handwashing and Domestic Environment Hygiene. Handwashing and domestic hygiene have been recommended by several studies finding positive associations between animal exposure, raw vegetable consumption, geophagy, or lack of handwashing before meals and zoonotic pathogenic infection.[36,56,62,74,103] Unlike the animal feces "sanitation" interventions, handwashing and domestic hygiene are designed to protect humans from exposure to both animal and human feces. Lack of handwashing might be a generalizable and important behavior to target; another study found that handwashing by mothers was infrequent and children placed their hands in their mouths 38 times in 130 h on average.[88] However, we did not find any studies that explicitly examined the effects of handwashing after contact with animals.

■ LIMITATIONS

We included all studies that meet the inclusion criteria regardless of methodological rigor. A majority of the publications are cross-sectional studies, making it difficult to assess the causal attribution of exposure to animal feces on human health. Due to the lack of in-home observations, most studies we reviewed used surveys and interviews assessing animal ownership or contact with animals as proxies for exposure to animal feces. Such exposure measures might be poor indicators of true exposure to animal feces, and in fact, could measure behaviors associated with potential health benefits to households. For example, a study in rural Ethiopia carefully looked at the benefits of poultry ownership on egg consumption versus the risks posed by corralling poultry inside the home,[45] but few studies empirically address these competing risks and benefits. There is also limited research on specific exposure pathways to animal feces and important confounding variables are not well understood or quantified. Due to the use of household interviews, studies were subject to recall bias when participants were asked to self-report past bouts of diarrhea. The use of convenience sampling methods,
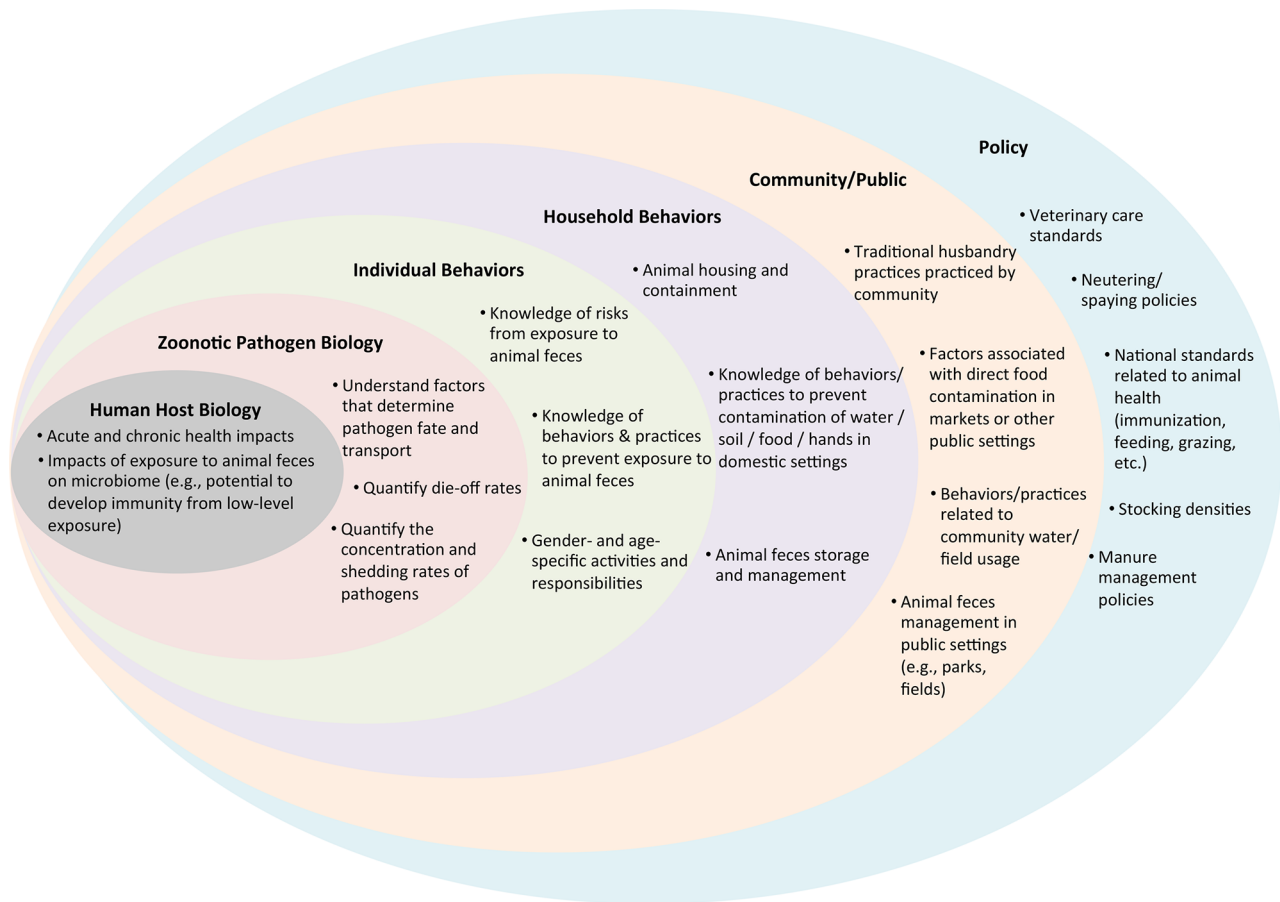
Figure 5. Priority research gaps in assessing human health impacts from exposure to poorly managed animal feces. This figure, an adaption from the socio-ecological model, represents how the "spheres of influence," from human host and zoonotic pathogen biology to national policies, influence the health of the human host. Example items for future research within each sphere are provided.

instead of random sampling methods, may have led to selection bias. Many of the studies included in this review had small sample sizes, thus preventing them from achieving sufficient power to detect many of the health outcomes examined in this review.

FUTURE RESEARCH

Our review highlights the scarcity of information available on the human health impacts of exposure to poorly managed animal feces transmitted via WASH-related pathways. To accurately capture human exposure to animal feces, future research could prioritize longitudinal studies with in-home observation methodologies. In addition, data to inform a rigorous assessment of the contribution of poorly managed animal feces to the global burden of disease is not available. Yet many associations between some measure of animal or animal feces exposure and health effects have been explored, and interventions designed to control human fecal waste will likely lead to suboptimal health gains in the absence of efforts to control animal feces in the same environment. Understanding the true burden of disease from poorly managed animal feces given the current infrastructure and behavioral contexts would provide important guidance for policy and programs.

It would be of considerable value to categorize and measure exposure to animal feces and to develop and evaluate interventions to mitigate that risk. Using direct observations and interviews/discussion with domestic animal owners,

household members including women and children, veterinarians, and community leaders, more data are needed to

- understand the key behaviors and contexts associated with exposure to animal feces;
- identify key points ("hot spots") of human contact with animals and/or their feces in different contexts (e.g., domestic, community);
- understand the factors associated with direct contamination of food from poorly managed animal feces, particularly in food markets and noncommercial agricultural/meat production facilities; and
- identify cultural behaviors that influence animal husbandry and animal feces management practices.

Understanding the various pathways and behaviors that expose humans to animal feces could allow researchers develop innovative interventions limiting such exposures in LMIC. Behavioral approaches to WASH should be evaluated further to understand their potential for controlling human exposure to animal feces. Our review demonstrates that many people did not feel disgust toward animal feces[100] and exposure to poorly managed animal feces might occur at the community-level rather than just the household-level. An evaluation of a community-led total sanitation (CLTS) program in rural Mali found that households that participated in the CLTS program were less likely to have observable animal feces in their compound courtyard;[20] CLTS programs integrating animal feces management could therefore be considered as potential

control measures. Interventions executed in HIC, such as building bridges across streams to reduce point source contamination of waterways by livestock, could be also adapted for LMIC.[104]

Once the various pathways of human exposure to animal feces are explored and understood, it would be possible to calculate specific health risks associated with exposure to animal feces, including both acute infectious diseases and chronic sequelae, such as EED and growth faltering, by conducting intervention trials. These intervention trials can measure before-and-after health outcomes among study populations who are provided interventions to limit or eliminate exposure to animal feces across multiple pathways compared to health outcomes in similar study populations who are not provided interventions to limit or eliminate exposure to animal feces. In addition to understanding the human behaviors and possible health outcomes associated with exposure to animal feces, future laboratory and field-based research must also consider pathogen biology by

- quantifying the concentration and shedding rates of pathogens in the feces of animal hosts and understanding the factors that determine variability in these parameters;
- quantifying die-off rates of pathogens outside of animal hosts and the factors that determine them;
- understanding the factors controlling the fate and transport processes of pathogens outside of the animal host, under varying environmental conditions; and
- understanding how antibiotic usage in humans and animals may be contributing to antibiotic resistance of zoonotic pathogens.

These types of data will be critical for parametrizing quantitative microbial risk assessment models and transmission models that can provide important insights on zoonotic transmission of pathogens from animal feces to humans. Studies could also take advantage of new molecular techniques that provide insights into transmission processes, such as microbial source tracking,[105] strain typing, multiplex enteropathogen assays,[106,107] and metagenomics.[108]

In addition, work is needed to understand the role of exposure to animal feces on negative human health outcomes in various rural, urban, and peri-urban contexts, from human host and pathogen biology to overarching public policy. This is illustrated in Figure 5, a diagram showing priority research gaps in assessing the role of contact with animal feces on human health, which we adapted from the socio-ecological model.[109] The potential for acute and chronic human health impacts to manifest from exposure to animal feces is dependent on biology within the human host (i.e., intestinal microbiome), including age- and sex-dependent susceptibilities to different zoonotic fecal pathogens and potential immunities developed from low-level exposures to animals and their feces. To understand the health risks associated with exposure to animal feces, it is crucial to understand the microbiology of pathogens found in animal feces, including their shedding and die-off rates and their transport processes. Human behaviors and practices are additional vital elements to assessing human health outcomes from exposure to animal feces. At the individual level, it is important to understand knowledge around risks and preventions of exposure to animal feces. In LMIC, gender and age divisions in responsibility for care, decisions, and the control of livestock production are common.[93,110] Gender and age divisions in labor should be explored further to understand how these variables influence risk of exposure to animal feces. Future research could characterize human behaviors in the household that result in exposure to animal feces, such as animal housing and containment practices or animal feces management. Our review points to the probable importance of community-level animal feces contamination on the human health burden, particularly in regards to food contamination in markets, soil contamination in the public environment from free-roaming animals, and contamination of community water sources; as such future research should investigate traditional husbandry practices in different regions and contexts. At the policy level, it would be valuable to monitor and evaluate the effect of national policies and regulations aimed at promoting animal health (e.g., immunization, feed standards), veterinary care (e.g., neutering/spaying policies), and safe management of animal manure and feces.

One particularly interesting line of inquiry would be to evaluate the trade-off between the nutritional benefits of livestock ownership with the health risks associated with exposure to animals. Many development projects promote animal husbandry as a way to improve nutrition and livelihoods, yet this review highlights the ways that contact between animal feces and humans may potentially be deleterious to health, especially in children. This trade-off was highlighted by several of the articles in this review.[26,44] Once more information is available on the magnitude of the health risk posed by animal feces exposure, knowledge around animal feces management, and key points of contact between humans and animals, culturally appropriate intervention strategies can be developed and rigorously evaluated.

■ CONCLUSIONS

As envisioned by the Sustainable Development Goals, the world will achieve universal access to safe water, coverage of safely managed sanitation, and handwashing with soap by 2030.[111] However, even if these ambitious targets are met, effectively eliminating direct and indirect exposure to human feces, risks associated with exposure to animal feces will remain. The literature in this review suggests that exposure to animals and animal feces has mixed effects on diarrhea and child growth, potentially increases risks of EED, STH infection, and trachoma, and has mixed effects on isolation of zoonotic pathogens in human stool. There is some evidence for the WASH-related pathways by which humans are exposed to animals and animal feces, but more research on pathogen transmission parameters, animal husbandry practices, and cultural/social influences is warranted. Furthermore, few studies have tested interventions that control the transmission of pathogens in animal feces and limit human exposure to animal feces. As we increasingly understand the contribution of poorly managed animal feces to the overall global burden of disease, it is important to gain insights into the routes by which humans are exposed to animal feces to design efforts to interrupt these pathways and reduce subsequent human health impacts.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.7b02811.

Further details about methods including full search string and databases used, global PRISMA chart, data extraction

form, PRISMA checklist, and table of study characteristics (PDF)

■ AUTHOR INFORMATION

Corresponding Author

*Phone: (404) 712-8767; e-mail: matthew.freeman@emory.edu.

ORCID ⊙

Gauthami Penakalapati: 0000-0003-2119-7431

Matthew C. Freeman: 0000-0002-1517-2572

Notes

The authors declare no competing financial interest.

■ REFERENCES

(1) Jones, K. E.; Patel, N. G.; Levy, M. A.; Storeygard, A.; Balk, D.; Gittleman, J. L.; Daszak, P. Global trends in emerging infectious diseases. *Nature* **2008**, *451* (7181), 990−993.

(2) World Health Organization. *The Control of Neglected Zoonotic Diseases: A Route to Poverty Alleviation: Report of a Joint WHO/DFID-AHP Meeting*; WHO: Geneva, Switzerland, 2006.

(3) Wagner, E.; Lanoix, J. Excreta disposal for rural areas and small communities. *Monogr Ser. World Health Org.* **1958**, *39*, 182.

(4) Food and Agricultural Organization FAOSTAT. http://www.fao.org/faostat/en/#home (accessed 7 February 2017).

(5) 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.* **2014**, *108* (6), 313−325.

(6) Batz, M. B.; Henke, E.; Kowalcyk, B. Long-term consequences of foodborne infections. *Infectious disease clinics of North America.* **2013**, *27* (3), 599−616.

(7) Moore, S. R.; Lima, N. L.; Soares, A. M.; Oriá, R. B.; Pinkerton, R. C.; Barrett, L. J.; Guerrant, R. L.; Lima, A. A. Prolonged episodes of acute diarrhea reduce growth and increase risk of persistent diarrhea in children. *Gastroenterology* **2010**, *139* (4), 1156−1164.

(8) Lorntz, B.; Soares, A. M.; Moore, S. R.; Pinkerton, R.; Gansneder, B.; Bovbjerg, V. E.; Guyatt, H.; Lima, A. M.; Guerrant, R. L. Early childhood diarrhea predicts impaired school performance. *Pediatric infectious disease journal* **2006**, *25* (6), 513−520.

(9) Robert-Gangneux, F.; Dardé, M.-L. Epidemiology of and diagnostic strategies for toxoplasmosis. *Clin. Microbiol. Rev.* **2012**, *25* (2), 264−296.

(10) Wang, H.; Naghavi, M.; Allen, C.; Barber, R. M.; Bhutta, Z. A.; Carter, A.; Casey, D. C.; Charlson, F. J.; Chen, A. Z.; Coates, M. M.; al, e. Global, regional, and national life expectancy, all-cause mortality, and cause-specific mortality for 249 causes of death: a systematic analysis for the Global Burden of Disease Study. *Lancet.* **2015**, *388* (10053), 1459−1544.

(11) Kotloff, K. L.; Nataro, J. P.; Blackwelder, W. C.; Nasrin, D.; Farag, T. H.; Panchalingam, S.; Wu, Y.; Sow, S. O.; Sur, D.; Breiman, R. F.; Faruque, A. S. G.; Zaidi, A. K. M.; Saha, D.; Alonso, P. L.; Tamboura, B.; Sanogo, D.; Onwuchekwa, U.; Manna, B.; Ramamurthy, T.; Kanungo, S.; Ochieng, J. B.; Omore, R.; Oundo, J. O.; Hossain, A.; Das, S. K.; Ahmed, S.; Qureshi, S.; Quadri, F.; Adegbola, R. A.; Antonio, M.; Hossain, M. J.; Akinsola, A.; Mandomando, I.; Nhampossa, T.; Acácio, S.; Biswas, K.; O'Reilly, C. E.; Mintz, E. D.; Berkeley, L. Y.; Muhsen, K.; Sommerfelt, H.; Robins-Browne, R. M.; Levine, M. M. Burden and aetiology of diarrhoeal disease in infants

and young children in developing countries (the Global Enteric Multicenter Study, GEMS): a prospective, case-control study. *Lancet* **2013**, *382* (9888), 209−222.

(12) Dufour, A.; Bartram, J.; Bos, R.; Gannon, V. *Animal Waste, Water Quality and Human Health*; IWA Publishing: London, UK, 2012, 6−130.

(13) Clasen, T. F.; Bostoen, K.; Schmidt, W.-P.; Boisson, S.; Fung, I. C. H.; Jenkins, M. W.; Scott, B.; Sugden, S.; Cairncross, S., Interventions to improve disposal of human excreta for preventing diarrhoea. *Cochrane Database of Systematic Reviews* **2010**, (6). doi: 10.1002/14651858.CD007180.pub2.

(14) Stocks, M. E.; Ogden, S.; Haddad, D.; Addiss, D. G.; McGuire, C.; Freeman, M. C. Effect of Water, Sanitation, and Hygiene on the Prevention of Trachoma: A Systematic Review and Meta-Analysis. *PLoS Medicine.* **2014**, *11* (2), e1001605.

(15) Strunz, E. C.; Addiss, D. G.; Stocks, M. E.; Ogden, S.; Utzinger, J.; Freeman, M. C. Water, Sanitation, Hygiene, and Soil-Transmitted Helminth Infection: A Systematic Review and Meta-Analysis. *PLoS Medicine.* **2014**, *11* (3), e1001620.

(16) Barreto, M. L.; Genser, B.; Strina, A.; Assis, A. M. O.; Rego, R. F.; Teles, C. A.; Prado, M. S.; Matos, S. M. A.; Santos, D. N.; dos Santos, L. A.; Cairncross, S.; Teixeira, M. G. Effect of city-wide sanitation programme on reduction in rate of childhood diarrhoea in northeast Brazil: assessment by two cohort studies. *Lancet* **2007**, *370* (9599), 1622−1628.

(17) Clasen, T.; Boisson, S.; Routray, P.; Torondel, B.; Bell, M.; Cumming, O.; Ensink, J.; Freeman, M.; Jenkins, M.; Odagiri, M.; Ray, S.; Sinha, A.; Suar, M.; Schmidt, W.-P. Effectiveness of a rural sanitation programme on diarrhoea, soil-transmitted helminth infection, and child malnutrition in Odisha, India: a cluster-randomised trial. *Lancet Global Health* **2014**, *2* (11), e645−e653.

(18) Emerson, P. M.; Lindsay, S. W.; Alexander, N.; Bah, M.; Dibba, S.-M.; Faal, H. B.; Lowe, K.; McAdam, K. P. W. J.; Ratcliffe, A. A.; Walraven, G. E. L.; Bailey, R. L. Role of flies and provision of latrines in trachoma control: cluster-randomised controlled trial. *Lancet* **2004**, *363* (9415), 1093−1098.

(19) Patil, S. R.; Arnold, B. F.; Salvatore, A. L.; Briceno, B.; Ganguly, S.; Colford, J. M., Jr.; Gertler, P. J. The Effect of India's Total Sanitation Campaign on Defecation Behaviors and Child Health in Rural Madhya Pradesh: A Cluster Randomized Controlled Trial. *PLOS Medicine.* **2014**, *11* (8), e1001709.

(20) Pickering, A. J.; Djebbari, H.; Lopez, C.; Coulibaly, M.; Alzua, M. L. Effect of a community-led sanitation intervention on child diarrhoea and child growth in rural Mali: a cluster-randomised controlled trial. *Lancet Global Health* **2015**, *3* (11), e701−e711.

(21) Gyorkos, T. W.; Maheu-Giroux, M.; Blouin, B.; Casapia, M. Impact of Health Education on Soil-Transmitted Helminth Infections in Schoolchildren of the Peruvian Amazon: A Cluster-Randomized Controlled Trial. *PLoS Neglected Trop. Dis.* **2013**, *7* (9), e2397.

(22) West, S.; Muñoz, B.; Lynch, M.; Kayongoya, A.; Chilangwa, Z.; Mmbaga, B. B. O.; Taylor, H. R. Impact of face-washing on trachoma in Kongwa, Tanzania. *Lancet* **1995**, *345* (8943), 155−158.

(23) Freeman, M. C.; Clasen, T.; Brooker, S. J.; Akoko, D. O.; Rheingans, R. The Impact of a School-Based Hygiene, Water Quality and Sanitation Intervention on Soil-Transmitted Helminth Reinfection: A Cluster-Randomized Trial. *Am. J. Trop. Med. Hyg.* **2013**, *89* (5), 875−883.

(24) Colford, J. M. J.; Luby, S. P.; Null, C.; Stewart, C. P. In *The WASH Benefits Study: Cluster-Randomized Trials in Bangladesh and Kenya to Measure the Effects of Individual and Combined Water Quality, Sanitation, Handwashing and Nutrition Interventions on Child Growth and Diarrhea* ASTHM, Atlanta, GA, 2016; Atlanta, GA, 2016.

(25) Garn, J. V.; Sclar, G. D.; Freeman, M. C.; Penakalapati, G.; Alexander, K. T.; Brooks, P.; Rehfuess, E. A.; Boisson, S.; Medlicott, K. O.; Clasen, T. F. The impact of sanitation interventions on latrine coverage and latrine use: A systematic review and meta-analysis. *Int. J. Hyg. Environ. Health* **2017**, *220* (2, Part B), 329−340.

(26) Kaur, M.; Graham, J.; 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.* **2017**, *96* (3), 741−748.

(27) Odagiri, M.; Schriewer, A.; Daniels, M. E.; Wuertz, S.; Smith, W. A.; Clasen, T.; Schmidt, W.-P.; Jin, Y.; Torondel, B.; Misra, P. R.; Panigrahi, P.; Jenkins, M. W. Human fecal and pathogen exposure pathways in rural Indian villages and the effect of increased latrine coverage. *Water Res.* **2016**, *100*, 232−244.

(28) Belongia, E. A.; Chyou, P. H.; Greenlee, R. T.; Perez-Perez, G.; Bibb, W. F.; DeVries, E. O. Diarrhea Incidence and Farm-Related Risk Factors for Escherichia coli O157:H7 and Campylobacter jejuni Antibodies among Rural Children. *J. Infect. Dis.* **2003**, *187* (9), 1460−1468.

(29) Cinquepalmi, V.; Monno, R.; Fumarola, L.; Ventrella, G.; Calia, C.; Greco, M. F.; de Vito, D.; Soleo, L. Environmental Contamination by Dog's Faeces: A Public Health Problem? *Int. J. Environ. Res. Public Health* **2013**, *10* (1), 72.

(30) Jung, B. K.; Lee, S. E.; Lim, H.; Cho, J.; Kim, D. G.; Song, H.; Kim, M. J.; Shin, E. H.; Chai, J. Y. Toxoplasma gondii B1 gene detection in feces of stray cats around Seoul, Korea and genotype analysis of two laboratory-passaged isolates. *Korean J. Parasitol.* **2015**, *53* (3), 259−263.

(31) Tobin, M. R.; Goldshear, J. L.; Price, L. B.; Graham, J. P.; Leibler, J. H. A Framework to Reduce Infectious Disease Risk from Urban Poultry in the United States. *Public Health Rep.* **2015**, *130* (4), 380−391.

(32) Williams, S.; Patel, M.; Markey, P.; Muller, R.; Benedict, S.; Ross, I.; Heuzenroeder, M.; Davos, D.; Cameron, S.; Krause, V. Salmonella in the tropical household environment - Everyday, everywhere. *J. Infect.* **2015**, *71* (6), 642−648.

(33) Williams, S.; Markey, P.; Harlock, M.; Binns, P.; Gaggin, J.; Patel, M. Individual and household-level risk factors for sporadic salmonellosis in children. *J. Infect.* **2016**, *72* (1), 36−44.

(34) Headey, D. *Newsflash: Chickens don't use toilets - Why global WASH efforst should start focusing on animal feces*. http://www.ifpri.org/blog/newsflash-chickens-dont-use-toilets (accessed 7 February 2017).

(35) Moher, D.; Liberati, A.; Tetzlaff, J.; Altman, D. G. The, P. G., Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *PLOS Medicine.* **2009**, *6* (7), e1000097.

(36) Black, R. E.; Lopez de Romaña, G.; Brown, K. H.; Bravo, N.; Bazalar, O. G.; Kanashiro, H. C. Incidence and etiology of infantile diarrhea and major routes of transmission in Huascar, Peru. *Am. J. Epidemiol.* **1989**, *129* (4), 785−799.

(37) Bukenya, G. B.; Nwokolo, N. Compound hygiene, presence of standpipe and the risk of childhood diarrhoea in an urban settlement of Papua New Guinea. *International Journal of Epidemiology* **1991**, *20* (2), 534−539.

(38) Collinet-Adler, S.; Babji, S.; Sarkar, R.; Kattula, D.; Mohan, V.; Ward, H.; Kang, G.; Balraj, V.; Naumova, E. Environmental indicators of diarrhea in Vellore, India. *Am. J. Trop. Med. Hyg.* **2011**, *85* (6), 175.

(39) Grados, O.; Bravo, N.; Black, R. E.; Butzler, J. P. Paediatric campylobacter diarrhoea from household exposure to live chickens in Lima, Peru. *Bull. World Health Org.* **1988**, *66* (3), 369−374.

(40) Headey, D.; Nguyen, P.; Kim, S.; Rawat, R.; Ruel, M.; Menon, P. Is Exposure to Animal Feces Harmful to Child Nutrition and Health Outcomes? A Multicountry Observational Analysis. *Am. J. Trop. Med. Hyg.* **2017**, *96* (4), 961−969.

(41) Oberhelman, R. A.; Gilman, R. H.; Sheen, P.; Cordova, J.; Zimic, M.; Cabrera, L.; Meza, R.; Perez, J. An Intervention-Control Study of Corraling of Free-Ranging Chickens to Control *Campylobacter* Infections Among Children in a Peruvian Periurban Shanty-town. *Am. J. Trop. Med. Hyg.* **2006**, *74* (6), 6.

(42) Adjei, A. A.; Armah, H.; Rodrigues, O.; Renner, L.; Borketey, P.; Ayeh-Kumi, P.; Adiku, T.; Sifah, E.; Lartey, M. *Cryptosporidium* spp., a frequent cause of diarrhea among children at the Korle-Bu Teaching Hospital, Accra, Ghana. *Jpn. J. Infect. Dis.* **2004**, *57* (5), 216−219.

(43) Schmidt, W.-P.; Boisson, S.; Routray, P.; Bell, M.; Cameron, M.; Torondel, B.; Clasen, T. Exposure to cows is not associated with diarrhoea or impaired child growth in rural Odisha, India: a cohort study. *Epidemiol. Infect.* **2016**, *144* (1), 53−63.

(44) Randremanana, R. V.; Razafindratsimandresy, R.; Andriatahina, T.; Randriamanantena, A.; Ravelomanana, L.; Randrianirina, F.; Richard, V. Etiologies, Risk Factors and Impact of Severe Diarrhea in the Under-Fives in Moramanga and Antananarivo, Madagascar. *PLoS One* **2016**, *11* (7), e0158862.

(45) Headey, D.; Hirvonen, K. Is Exposure to Poultry Harmful to Child Nutrition? An Observational Analysis for Rural Ethiopia. *PLoS One* **2016**, *11* (8), e0160590.

(46) Hetherington, J. B.; Wiethoelter, A. K.; Negin, J.; Mor, S. M. Livestock ownership, animal source foods and child nutritional outcomes in seven rural village clusters in Sub-Saharan Africa. *Agriculture and Food Security* **2017**, *6* (1), 9.

(47) Mosites, E.; Thumbi, S. M.; Otiang, E.; McElwain, T. F.; Njenga, M. K.; Rabinowitz, P. M.; Rowhani-Rahbar, A.; Neuhouser, M. L.; May, S.; Palmer, G. H.; Walson, J. L. Relations between Household Livestock Ownership, Livestock Disease, and Young Child Growth. *J. Nutr.* **2016**, *146* (5), 1118−1124.

(48) George, C. M.; Oldja, L.; Biswas, S. K.; Perin, J.; Lee, G. O.; Ahmed, S.; Haque, R.; Sack, R. B.; Parvin, T.; Azmi, I. J.; Bhuyian, S. I.; Talukder, K. A.; Faruque, A. G. Fecal Markers of Environmental Enteropathy are Associated with Animal Exposure and Caregiver Hygiene in Bangladesh. *Am. J. Trop. Med. Hyg.* **2015**, *93* (2), 269−275.

(49) Campbell, D.; Elia, M.; Lunn, P. Growth faltering in rural Gambian infants is associated with impaired small intestinal barrier function, leading to endotoxemia and systematic inflammation. *J. Nutr.* **2003**, *133* (5), 1332−1338.

(50) Goto, R.; Mascie-Taylor, C. G. N.; Lunn, P. G. Impact of intestinal permeability, inflammation status and parasitic infections on infant growth faltering in rural Bangladesh. *Br. J. Nutr.* **2009**, *101* (10), 1509−1516.

(51) Guerrant, R. L.; Oriá, R. B.; Moore, S. R.; Oriá, M. O. B.; Lima, A. A. M. Malnutrition as an enteric infectious disease with long-term effects on child development. *Nutr. Rev.* **2008**, *66* (9), 487−505.

(52) Humphrey, J. H. Child undernutrition, tropical enteropathy, toilets, and handwashing. *Lancet* **2009**, *374* (9694), 1032−1035.

(53) Lunn, P. G.; Northrop-Clewes, C. A.; Downes, R. M. Intestinal permeability, mucosal injury, and growth faltering in Gambian infants. *Lancet* **1991**, *338* (8772), 907−910.

(54) Lunn, P. G. Growth retardation and stunting of children in developing countries. *Br. J. Nutr.* **2002**, *88* (2), 109−110.

(55) Ordiz, M. I.; Shaikh, N.; Trehan, I.; Maleta, K.; Stauber, J.; Shulman, R.; Devaraj, S.; Tarr, P. I.; Manary, M. J. Environmental Enteric Dysfunction is Associated with Poor Linear Growth and Can be Identified by Host Fecal mRNAs. *J. Pediatr. Gastroenterol. Nutr.* **2016**, *63* (5), 453.

(56) El-Tras, W. F.; Holt, H. R.; Tayel, A. A.; El-Kady, N. N. Campylobacter infections in children exposed to infected backyard poultry in Egypt. *Epidemiol. Infect.* **2015**, *143* (2), 308−315.

(57) Marquis, G. S.; Ventura, G.; Gilman, R. H.; Porras, E.; Miranda, E.; Carbajal, L.; Pentafiel, M. *Am. J. Public Health* **1990**, *80* (2), 146−149.

(58) Vasco, K.; Graham, J. P.; Trueba, G. Detection of Zoonotic Enteropathogens in Children and Domestic Animals in a Semirural Community in Ecuador. *Appl. Environ. Microbiol.* **2016**, *82* (14), 4218−4224.

(59) Moore, C. E.; Elwin, K.; Phot, N.; Seng, C.; Mao, S.; Suy, K.; Kumar, V.; Nader, J.; Bousfield, R.; Perera, S.; Bailey, J. W.; Beeching, N. J.; Day, N. P. J.; Parry, C. M.; Chalmers, R. M. Molecular Characterization of Cryptosporidium Species and Giardia duodenalis from Symptomatic Cambodian Children. *PLoS Neglected Trop. Dis.* **2016**, *10* (7), e0004822.

(60) Wanyiri, J. W.; Kanyi, H.; Maina, S.; Wang, D. E.; Steen, A.; Ngugi, P.; Kamau, T.; Waithera, T.; O'Connor, R.; Gachuhi, K.; Wamae, C. N.; Mwamburi, M.; Ward, H. D. Cryptosporidiosis in HIV/AIDS Patients in Kenya: Clinical Features, Epidemiology, Molecular Characterization and Antibody Responses. *Am. J. Trop. Med. Hyg.* **2014**, *91* (2), 319−328.

(61) Wumba, R.; Longo-Mbenza, B.; Menotti, J.; Mandina, M.; Kintoki, F.; Situakibanza, N. H.; Kakicha, M. K.; Zanga, J.; Mbanzulu-Makola, K.; Nseka, T.; Mukendi, J. P.; Kendjo, E.; Sala, J.; Thellier, M. Epidemiology, clinical, immune, and molecular profiles of micro-sporidiosis and cryptosporidiosis among HIV/AIDS patients. *Int. J. Gen. Med.* **2012**, *5*, 603−611.

(62) Anuar, T. S.; Azreen, S. N.; Salleh, F. M.; Moktar, N. Molecular epidemiology of giardiasis among Orang Asli in Malaysia: application of the triosephosphate isomerase gene. *BMC Infect. Dis.* **2014**, *14* (1), 78.

(63) Alyousefi, N. A.; Mahdy, M. A.; Mahmud, R.; Lim, Y. A. Factors associated with high prevalence of intestinal protozoan infections among patients in Sana'a City, Yemen. *PLoS One* **2011**, *6* (7), e22044.

(64) Li, X.-X.; Chen, J.-X.; Wang, L.-X.; Tian, L.-G.; Zhang, Y.-P.; Dong, S.-P.; Hu, X.-G.; Liu, J.; Wang, F.-F.; Wang, Y.; Yin, X.-M.; He, L.-J.; Yan, Q.-Y.; Zhang, H.-W.; Xu, B.-L.; Zhou, X.-N. Prevalence and risk factors of intestinal protozoan and helminth infections among pulmonary tuberculosis patients without HIV infection in a rural county in P. R. China. *Acta Trop.* **2015**, *149*, 19−26.

(65) Bern, C.; Kawai, V.; Vargas, D.; Rabke-Verani, J.; Williamson, J.; Chavez-Valdez, R.; Xiao, L.; Sulaiman, I.; Vivar, A.; Ticona, E.; Ñavincopa, M.; Cama, V.; Moura, H.; Secor, W.; Visvesvara, G.; Gilman, R. H. The Epidemiology of Intestinal Microsporidiosis in Patients with HIV/AIDS in Lima, Peru. *J. Infect. Dis.* **2005**, *191* (10), 1658−1664.

(66) Dwivedi, K. K.; Prasad, G.; Saini, S.; Mahajan, S.; Lal, S.; Baveja, U. K. Enteric Opportunistic Parasites among HIV Infected Individuals: Associated Risk Factors and Immune Status. *Jpn. J. Infect. Dis.* **2007**, *60*, 76−81.

(67) Bublitz, D. C.; Wright, P. C.; Bodager, J. R.; Rasambainarivo, F. T.; Bliska, J. B.; Gillespie, T. R. Epidemiology of Pathogenic Enterobacteria in Humans, Livestock, and Peridomestic Rodents in Rural Madagascar. *PLoS One* **2014**, *9* (7), e101456.

(68) Leung, D.; Das, S.; Malek, M.; Ahmed, D.; Khanam, F.; Qadri, F.; Faruque, A.; Ryan, E. Non-typhoidal Salmonella gastroenteritis at a diarrheal hospital in Dhaka, Bangladesh, 1996−2011. *Am. J. Trop. Med. Hyg.* **2013**, *88* (4), 661−669.

(69) Labrique, A. B.; Zaman, K.; Hossain, Z.; Saha, P.; Yunus, M.; Hossain, A.; Ticehurst, J.; Kmush, B.; Nelson, K. E. An Exploratory Case Control Study of Risk Factors for Hepatitis E in Rural Bangladesh. *PLoS One* **2013**, *8* (5), e61351.

(70) Mpyet, C.; Lass, B. D.; Yahaya, H. B.; Solomon, A. W. Prevalence of and Risk Factors for Trachoma in Kano State, Nigeria. *PLoS One* **2012**, *7* (7), e40421.

(71) Nigusie, A.; Berhe, R.; Gedefaw, M. Prevalence and associated factors of active trachoma among childeren aged 1−9 years in rural communities of Gonji Kolella district, West Gojjam zone, North West Ethiopia. *BMC Res. Notes* **2015**, *8* (1), 641.

(72) Cumberland, P.; Hailu, G.; Todd, J. Active trachoma in children aged three to nine years in rural communities in Ethiopia: prevalence, indicators and risk factors. *Trans. R. Soc. Trop. Med. Hyg.* **2005**, *99* (2), 120−127.

(73) Reichert, F.; Pilger, D.; Schuster, A.; Lesshafft, H.; Guedes de Oliveira, S.; Ignatius, R.; Feldmeier, H. Prevalence and Risk Factors of Hookworm-Related Cutaneous Larva Migrans (HrCLM) in a Resource-Poor Community in Manaus, Brazil. *PLoS Neglected Trop. Dis.* **2016**, *10* (3), e0004514.

(74) Acosta-Jamett, G.; Weitzel, T.; Boufana, B.; Adones, C.; Bahamonde, A.; Abarca, K.; Craig, P. S.; Reiter-Owona, I. Prevalence and risk factors for echinococcal infection in a rural area of northern Chile: A household-based cross-sectional study. *PLoS Neglected Trop. Dis.* **2014**, *8* (8), 1−9.

(75) Chiodo, P.; Basualdo, J.; Ciarmela, L.; Pezzani, B.; Apezteguía, M.; Minvielle, M. Related factors to human toxocariasis in a rural community of Argentina. *Memorias do Instituto Oswaldo Cruz.* **2006**, *101* (4), 397−400.

(76) Fernando, S.; Wickramasinghe, V.; Kapilananda, G.; Devasurendra, R.; Amarasooriya, J.; Dayaratne, H. Epidemiological aspects and risk factors of Toxocariasis in pediatric population in Sri

Lanka. *Southeast Asian J. Trop. Med. Public Health* **2007**, *38* (6), 983−990.

(77) Subrata, I. M.; Suryadhi, N. T.; Mantik-Astawa, N.; Damriyasa, I. M. Epidemiological and molecular analysis of Taxoplasa gondii in faecal samples of house cats obtained from house of maternal in Bali. *Bali Medical Journal* **2015**, *4* (2), 68−75.

(78) Daniels, M. E.; Shrivastava, A.; Smith, W. A.; Sahu, P.; Odagiri, M.; Misra, P. R.; Panigrahi, P.; Suar, M.; Clasen, T.; Jenkins, M. W. Cryptosporidium and giardia in humans, domestic animals, and village water sources in rural India. *Am. J. Trop. Med. Hyg.* **2015**, *93* (3), 596−600.

(79) Schriewer, A.; Odagiri, M.; Wuertz, S.; Misra, P. R.; Panigrahi, P.; Clasen, T.; Jenkins, M. W. Human and animal fecal contamination of community water sources, stored drinking water and hands in rural India measured with validated microbial source tracking assays. *Am. J. Trop. Med. Hyg.* **2015**, *93* (3), 509−516.

(80) Daniels, M. E.; Smith, W. A.; Schmidt, W. P.; Clasen, T.; Jenkins, M. W. Modeling Cryptosporidium and Giardia in Ground and Surface Water Sources in Rural India: Associations with Latrines, Livestock, Damaged Wells, and Rainfall Patterns. *Environ. Sci. Technol.* **2016**, *50* (14), 7498−7507.

(81) Lupindu, A. M.; Olsen, J. E.; Ngowi, H. A.; Msoffe, P. L. M.; Mtambo, M. M.; Scheutz, F.; Dalsgaard, A. Occurrence and characterization of Shiga toxin-producing Escherichia coli O157:H7 and other non-sorbitol-fermenting E. coli in cattle and humans in urban areas of Morogoro, Tanzania. *Vector-Borne and Zoonotic Diseases.* **2014**, *14* (7), 503−510.

(82) Nyariki, D. M.; Mwang'ombe, A. W.; Thompson, D. M. Land-use change and livestock production challenges in an integrated system: the Masai-Mara ecosystem, Kenya. *J. Hum. Ecol.* **2009**, *26* (3), 11.

(83) Wolking, D. J.; Clifford, D. L.; Kelly, T. R.; Kamani, E.; Smith, W. A.; Kazwala, R. R.; Mazet, J. A. K. Boma to banda - a disease sentinel concept for reduction of diarrhoea. *Pastoralism: Research, Policy and Practice* **2016**, *6* (1), 13.

(84) Sprenger, L. K.; Green, K. T.; Molento, M. B. Geohelminth contamination of public areas and epidemiological risk factors in Curitiba, Brazil. *Rev. Bras. Parasitol. Vet.* **2014**, *23* (1), 69−73.

(85) Tun, S.; Ithoi, I.; Mahmud, R.; Samsudin, N. I.; Heng, C. K.; Ling, L. Y. Detection of Helminth Eggs and Identification of Hookworm Species in Stray Cats, Dogs and Soil from Klang Valley, Malaysia. *PLoS One* **2015**, *10* (12), e0142231.

(86) Boehm, A. B.; Wang, D.; Ercumen, A.; Shea, M.; Harris, A. R.; Shanks, O. C.; Kelty, C.; Ahmed, A.; Mahmud, Z. H.; Arnold, B. F.; Chase, C.; Kullmann, C.; Colford, J. M.; Luby, S. P.; Pickering, A. J. Occurrence of Host-Associated Fecal Markers on Child Hands, Household Soil, and Drinking Water in Rural Bangladeshi House-holds. *Environ. Sci. Technol. Lett.* **2016**, *3* (11), 393−398.

(87) Harris, A. R.; Pickering, A. J.; Harris, M.; Doza, S.; Islam, M. S.; Unicomb, L.; Luby, S.; Davis, J.; Boehm, A. B. Ruminants Contribute Fecal Contamination to the Urban Household Environment in Dhaka, Bangladesh. *Environ. Sci. Technol.* **2016**, *50* (9), 4642.

(88) Ngure, F. M.; Humphrey, J. H.; Mbuya, M. N. N.; Majo, F.; Mutasa, K.; Govha, M.; Mazarura, E.; Chasekwa, B.; Prendergast, A. J.; Curtis, V.; Boor, K. J.; Stoltzfus, R. J. Formative Research on Hygiene Behaviors and Geophagy among Infants and Young Children and Implications of Exposure to Fecal Bacteria. *Am. J. Trop. Med. Hyg.* **2013**, *89* (4), 709−716.

(89) Sultana, R.; Nahar, N.; Rimi, N. A.; Azad, S.; Islam, M. S.; Gurley, E. S.; Luby, S. P. Backyard poultry raising in Bangladesh: a valued resource for the villagers and a setting for zoonotic transmission of avian influenza. A qualitative study. *Rural and Remote Health* **2012**, *12* (1927), 1−14.

(90) Uga, S.; Hoa, N. T.; Noda, S.; Moji, K.; Cong, L.; Aoki, Y.; Rai, S. K.; Fujimaki, Y. Parasite egg contamination of vegetables from a suburban market in Hanoi, Vietnam. *Nepal Med. College J.* **2009**, *11* (2), 75−78.

(91) Scallan, E.; Hoekstra, R. M.; Angulo, F. J.; Tauxe, R. V.; Widdowson, M.-A.; Roy, S. L.; Jones, J. L.; Griffin, P. M. Foodborne

Illness Acquired in the United States—Major Pathogens. *Emerging Infect. Dis.* **2011**, *17* (1), 7–15.

(92) a Mpalang, R. K.; Boreux, R.; Melin, P.; Akir Ni Bitiang, K.; Daube, G.; De Mol, P. Prevalence of Campylobacter among goats and retail goat meat in Congo. *J. Infect. Dev. Countries* **2014**, *8* (2), 168–175.

(93) Osbjer, K.; Boqvist, S.; Sokerya, S.; Kannarath, C.; San, S.; Davun, H.; Magnusson, U. Household practices related to disease transmission between animals and humans in rural Cambodia. *BMC Public Health* **2015**, *15* (1), 476.

(94) Anuar, T. S.; Sarhan Al-Mekhlafi, H. M.; Abdul Ghani, M. K.; Moktar, N. Prevalence and risk factors associated with Entamoeba histolytica/Entamoeba dispar/Entamoeba moshkovskii complex infection among different tribes of Malaysian aborigines. *Int. J. Infect. Dis.* **2012**, *16*, e175–e176.

(95) Suwannarong, K.; Chapman, R. S. Characteristics associated with contact with rodents in, around, and outside homes in Khon Kaen Province, Thailand. *Am. J. Trop. Med. Hyg.* **2015**, *92* (4), 784–790.

(96) Vujcic, J.; Ram, P. K.; Hussain, F.; Unicomb, L.; Gope, P. S.; Abedin, J.; Mahmud, Z. H.; Sirajul Islam, M.; Luby, S. P. Toys and toilets: cross-sectional study using children's toys to evaluate environmental faecal contamination in rural Bangladeshi households with different sanitation facilities and practices. *Trop. Med. Int. Health* **2014**, *19* (5), 528–536.

(97) Torondel, B.; Gyekye-Aboagye, Y.; Routray, P.; Boisson, S.; Schimdt, W.; Clasen, T. Laboratory development and field testing of sentinel toys to assess environmental faecal exposure of young children in rural India. *Trans. R. Soc. Trop. Med. Hyg.* **2015**, *109* (6), 386–392.

(98) Harvey, S. A.; Winch, P. J.; Leontsini, E.; Torres Gayoso, C.; López Romero, S.; Gilman, R. H.; Oberhelman, R. A. Domestic poultry-raising practices in a Peruvian shantytown: implications for control of Campylobacter jejuni-associated diarrhea. *Acta Trop.* **2003**, *86* (1), 41–54.

(99) Arnold, B. F.; Null, C.; Luby, S. P.; Unicomb, L.; Stewart, C. P.; Dewey, K. G.; Ahmed, T.; Ashraf, S.; Christensen, G.; Clasen, T.; Dentz, H. N.; Fernald, L. C. H.; Haque, R.; Hubbard, A. E.; Kariger, P.; Leontsini, E.; Lin, A.; Njenga, S. M.; Pickering, A. J.; Ram, P. K.; Tofail, F.; Winch, P. J.; Colford, J. M. Cluster-randomised controlled trials of individual and combined water, sanitation, hygiene and nutritional interventions in rural Bangladesh and Kenya: the WASH Benefits study design and rationale. *BMJ. Open* **2013**, *3* (8), e003476.

(100) Hussain, F. Continued household faecal contamination following a sanitation intervention in rural Bangladesh. *Health Sci. Bull.* **2013**, *11* (1), 9–14 (En), 9–14 (Bengali).

(101) Sanitation Hygiene Infant Nutrition Efficacy Trial, T.; Humphrey, J. H.; Jones, A. D.; Manges, A.; Mangwadu, G.; Maluccio, J. A.; Mbuya, M. N.; Moulton, L. H.; Ntozini, R.; Prendergast, A. J.; Stoltzfus, R. J.; Tielsch, J. M. The Sanitation Hygiene Infant Nutrition Efficacy (SHINE) Trial: Rationale, Design, and Methods. *Clin. Infect. Dis.* **2015**, *61* (Suppl 7), S685–702.

(102) Hall, D.; Alam, M. G. S.; Raha, S. K. Reducing risk of emerging infectious diseases in Bangladesh through ecohealth. *Int. J. Infect. Dis.* **2012**, *16*, e38.

(103) Cassenote, A. J. F.; de Abreu Lima, A. R.; Pinto Neto, J. M.; Rubinsky-Elefant, G. Seroprevalence and Modifiable Risk Factors for Toxocara spp. in Brazilian Schoolchildren. *PLoS Neglected Trop. Dis.* **2014**, *8* (5), e2830.

(104) Smolders, A.; Rolls, R. J.; Ryder, D.; Watkinson, A.; Mackenzie, M. Cattle-derived microbial input to source water catchments: An experimental assessment of stream crossing modification. *J. Environ. Manage.* **2015**, *156*, 143–149.

(105) Harwood, V. J.; Staley, C.; Badgley, B. D.; Borges, K.; Korajkic, A. Microbial source tracking markers for detection of fecal contamination in environmental waters: relationships between pathogens and human health outcomes. *FEMS Microbiology Reviews.* **2014**, *38* (1), 1–40.

(106) Liu, J.; Gratz, J.; Amour, C.; Kibiki, G.; Becker, S.; Janaki, L.; Verweij, J. J.; Taniuchi, M.; Sobuz, S. U.; Haque, R.; Haverstick, D. M.; Houpt, E. R. A Laboratory-Developed TaqMan Array Card for Simultaneous Detection of 19 Enteropathogens. *Journal of Clinical Microbiology* **2013**, *51* (2), 472–480.

(107) Platts-Mills, J. A.; Babji, S.; Bodhidatta, L.; Gratz, J.; Haque, R.; Havt, A.; McCormick, B. J. J.; McGrath, M.; Olortegui, M. P.; Samie, A.; Shakoor, S.; Mondal, D.; Lima, I. F. N.; Hariraju, D.; Rayamajhi, B. B.; Qureshi, S.; Kabir, F.; Yori, P. P.; Mufamadi, B.; Amour, C.; Carreon, J. D.; Richard, S. A.; Lang, D.; Bessong, P.; Mduma, E.; Ahmed, T.; Lima, A. A. M.; Mason, C. J.; Zaidi, A. K. M.; Bhutta, Z. A.; Kosek, M.; Guerrant, R. L.; Gottlieb, M.; Miller, M.; Kang, G.; Houpt, E. R. Pathogen-specific burdens of community diarrhoea in developing countries: a multisite birth cohort study (MAL-ED). *Lancet Global Health* **2015**, *3* (9), e564–e575.

(108) McLellan, S. L.; Eren, A. M. Discovering new indicators of fecal pollution. *Trends Microbiol.* **2014**, *22* (12), 697–706.

(109) McLeroy, K. R.; Bibeau, D.; Steckler, A.; Glanz, K. An Ecological Perspective on Health Promotion Programs. *Health Education Quarterly.* **1988**, *15* (4), 351–377.

(110) Mupawaenda, A. C.; Chawatama, S.; Muvavarirwa, P. Gender issues in livestock production: a case study of Zimbabwe. *Trop. Anim. Health Prod.* **2009**, *41* (7), 1017.

(111) WHO, UNICEF. WASH Post-2015: Proposed indicators for drinking water, sanitation, and hygiene. WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation, Geneca. 2015.