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Effects of functional latrine density on household drinking water contamination, soil-transmitted helminth infection, and diarrhea: a spatial analysis

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Global Environmental Health

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Abstract

Effects of functional latrine density on household drinking water contamination, soil-transmitted helminth infection, and diarrhea: a spatial analysis

By
Heather Amato

Background: India accounts for 60% of the 2.4 billion people practicing open defecation worldwide. The Government of India's Total Sanitation Campaign (TSC) aimed to increase sanitation coverage. A large cluster-randomized trial (CRT) in Orissa found that coverage across intervention villages varied greatly, and found no village-level health benefits. Latrine use remained low due to poor construction/sociocultural barriers. Given the transmission pathways of sanitation-related illnesses, transmission may often occur on a fine spatial scale. This spatial analysis assesses environmental health impacts of *functional* latrine coverage, as a proxy of latrine use, within various distances from a household.

Methods: This is a secondary analysis of geospatial data from households in 50 intervention villages in Clasen's CRT. The density of latrines and functional latrines within 25m, 50m, 100m, and 200m was calculated using a multiple ring buffer analysis in ArcGIS. The number and proportions of all latrines and functional latrines were assessed as predictors of household drinking water contamination (N=1,009), soil-transmitted helminthiasis (N=822), diarrhea among all ages (N=1,275) and among children <5 (N=1,017) in univariate and multivariate regressions adjusted for village-level clustering with Generalized Estimating Equations.

Results (of multivariate regressions, unless otherwise stated): Increased latrine coverage, regardless of functionality, was associated with decreased levels of thermotolerant coliform (TTC) in household drinking water at 200m. Increasing the number of functional latrines within 25m yielded the greatest reduction of TTC (28 cfu per 100 mL for each additional functional latrine), though the estimate was not statistically significant (p=0.165). For every additional 10 latrines within 25m, regardless of functionality, household longitudinal diarrhea prevalence (all ages) increased by 2.13 days per 1,000 person days (p=0.044). In univariate models, a 10% increase in the proportion of functional latrines within 200m was associated with about one fewer days of diarrhea per 1,000 person days (p=0.006). The presence of a functional latrine within the household was associated with up to 8 fewer days of childhood diarrhea per 1,000 person days (p<0.05).

Conclusion: Ensuring 100% sanitation coverage and functionality within the immediate surroundings of the home is critical for reducing exposure to pathogenic feces that cause diarrheal diseases.

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I. LITERATURE REVIEW

Global sanitation

The Millennium Development Goals designated sanitation as a priority, aiming to achieve 77% global coverage of improved sanitation facilities by 2015 (UNICEF & WHO, 2015). Global overage increased from 54% in 1990 to 68% in 2015, missing the target by 9%; 2.4 billion people still lack access to improved sanitation facilities (WHO, 2015). While 95 countries met the sanitation target, increases in coverage have occurred disproportionately in wealthier, urban populations, leaving poor, rural areas behind (WHO, 2001; UNICEF & WHO, 2015). This gap is largest in Southern Asia, and the majority of the global population still practicing open defecation lives in rural areas in Southern Asia (UNICEF & WHO, 2015).

India has seen little change in coverage over the last 20 years and has one of the largest urban-rural gaps in coverage: 49% of the urban population compared to only 6% of the rural population have access to improved sanitation (UNICEF & WHO, 2015). India decreased open defecation rates from 75% to 44% from 1990 to 2015, but this change is marginal considering India's role in global open defecation; India alone makes up 60% of the 2.4 billion people practicing open defecation worldwide (UNICEF & WHO, 2015).

The eastern coastal state of Orissa (also referred to as Odisha) ranks lowest in India in terms of coverage of household sanitation facilities (Census of India, 2011). Compared to the national average of 53.1%, 78% of households in Orissa did not have any type of latrine in 2011 (Census of India, 2011). The rural-urban discrepancy is apparent in Orissa, where only 32% (18.6% nationally) of urban households did not have any latrine versus 85.9% (69.3% nationally) of rural households (Census of India, 2011).

Disease burden

The World Health Organization (WHO) estimates that the global burden of disease attributed to water supply, sanitation, and hygiene (WASH) is 99 million disability-adjusted life years (DALYS) (WHO, 2016). This includes diarrhea and intestinal nematode (including soil-transmitted helminth) infections as well as malnutrition, schistosomiasis, trachoma, and lymphatic filariasis (WHO, 2016). Diarrhea and soil-transmitted helminth (STH) infections disproportionately affect low-income countries where latrine coverage is often lowest (WHO, 2008a; UNICEF & WHO, 2015). Globally, an estimated 280,000 diarrhea deaths were attributed to inadequate sanitation in 2012 alone (Prüss-Ustün et al., 2014).

In Southeast Asia, 32,594 thousand DALYs attributable to WASH based on WHO estimates; 53% of those DALYs are caused by diarrheal diseases (WHO, 2016). Southeast Asia is the highest ranking region for deaths attributable to both diarrheal diseases and intestinal nematode infections, with estimates of 600,000 and 3,000 deaths, respectively (WHO, 2016).

The WHO estimates that the combined burden of WASH-attributable diseases in India amounts to nearly 25 million DALYS (WHO, 2016). India suffers from 15 million DALYS caused by diarrhea alone, and 610,500 DALYS caused by intestinal nematode infections (WHO, 2016). The country's disease burden attributed to inadequate sanitation alone was 5.9 million DALYs as recently as 2012 (WHO, 2015). Over 30,000 deaths among children under five in India are attributable to inadequate sanitation (WHO, 2015).

Transmission pathways

Improving methods of excreta disposal by constructing improved sanitation facilities reduces the spread of feces in the environment (WHO, 2001). Improved sanitation should reduce contact between people and human feces and provide an alternative to practicing open defecation (UNICEF & WHO, 2015). Open defecation spreads enteric pathogens in feces throughout the environment, including drinking water sources; ingesting contaminated drinking water can cause diarrheal diseases via the fecal-oral route (WHO, 2001). Parasite eggs in feces may also be washed into drinking water and can persist and spread in soil, transmitting intestinal worms (primarily STH) through both the fecal-oral route and through direct skin contact with soil (WHO, 2001).

While hygiene habits, access to safe drinking water, and host characteristics affect transmission pathways, the use of effective sanitation blocks the pathway entirely by preventing the spread of feces in the environment (WHO, 2001). Improved sanitation could, therefore, have a substantial impact on the global burden of disease, especially among low-income, rural populations. Sanitation may be the most effective barrier of the transmission of fecal pathogens in India given the country’s high open defecation rates. In Orissa, open defecation often occurs at a water source away from the household. Regardless of access to sanitation, lack of access to water in the household drives individuals to defecate near ponds or streams in order to have ample water to perform necessary cleansing rituals (Routray et al., 2015). However, there are many cases in which open defecation occurs close to the home. Women defecate near the household at night because it isn’t necessary to walk far for privacy in the dark; the sick, elderly, and disabled are less restricted by social norms and often defecate in the backyard; infants and young children defecate inside the home and “their faeces are usually disposed either in the waste/garbage pit, or a vacant plot next to the house” (Routray et al., 2015).

While lack of access to a latrine is the most frequently reported reason to continue practicing open defecation, individuals defecate near the household regardless of access to sanitation. Individual household latrines (IHLs) are often constructed far from households in India to separate a behavior perceived as disgusting and shameful from the home; this distance might deter women, children, and the elderly or disabled from using the latrine (Routray et al., 2015). Nearly 44% of Indian households that have a working latrine have at least one household member who continues to practice open defecation (Coffey et al., 2014). Sociocultural barriers related to caste, gender, and purity rituals drive the strong preference for open defecation in India (Routray et al., 2015).

Details regarding defecation behaviors are critical for understanding transmission pathways. One household may have several household members practicing open defecation near the household, exposing neighbors to fecal contamination in the environment. Neighbors could, therefore, become ill from exposure to pathogens even if their own household has access to effective sanitation facilities. If a greater proportion of neighboring households have access to and utilize improved household latrines, individuals living nearby are more protected from fecal exposure in the environment.

Evidence for health benefits of interventions

Interventions that aim to improve inadequate water, sanitation and hygiene (WASH) reduce the severity and prevalence of adverse health outcomes such as diarrhea, STH infection, and malnutrition (Table 1) (Esrey, Feachem & Hughes, 1985; Esrey & Habicht, 1986; Esrey et al., 1991; Wolf et al., 2014; Clasen et al., 2010; Clasen et al., 2015).

However, much of the evidence of such health benefits from improvements in sanitation alone lacks rigor (Esrey et al., 1985; Esrey et al., 1986; Fewtrell et al., 2005; Cairncross et al., 2010; Strunz et al., 2014). Despite significant reductions in diarrhea and STH infections reported in sanitation intervention studies, most studies were of low epidemiologic quality. Many lacked a comparison group or adequate randomization, did not control for confounding variables, analyzed a small sample size, had limited external validity, and/or were observational in nature and could not imply causal relationships between the intervention and the outcome (Esrey et al., 1985; Esrey et al., 1986, Esrey et al., 1991; Fewtrell et al., 2005; Cairncross et al., 2010; Strunz et al., 2014). Sanitation interventions are almost always implemented at a group or community level. Studies often include an insufficient number of clusters or fail to adjust for clustering in the analysis, which may compromise the internal validity of results (Clasen et al., 2010). Rigorously designed evaluations of specific interventions, which we explore in the next section, often report that sanitation interventions were effective in increasing latrine coverage, but *ineffective* in reducing health outcomes.

Review	No. Studies (san.)	Type of Interv.	Health Outcome(s)	Pooled Estimates	Key Findings
Esrey 1985	67 (10)	Water quality, water supply, sanitation	Diarrhea, growth, mortality	16% reduction in diarrhea with improved water quality, 25% with increased water supply, and 22% with improved sanitation	Increased water supply and improved sanitation interventions yield greatest reduction in diarrhea.
Esrey 1986	54 (26)	Water quality, water supply, sanitation	Child morbidity, growth, mortality	No pooled estimates	Studies including sanitation consistently report that sanitation has a greater impact on child health than water.
Esrey 1991	144 (30)	Water quality, water supply, hygiene, sanitation	Diarrhea, parasite infections, trachoma	15% reduction in diarrhea with improved water quality, 20% with increased water quantity, 33% for improved hygiene, and 36% with improved sanitation among rigorous studies, only	Water supply interventions yield greatest reduction in parasite infections; sanitation facilities yield greatest reduction in diarrhea morbidity and mortality.
Fewtrell 2005	46 (2)	Water quality, water supply, hygiene, sanitation, combined interventions	Diarrhea (including cholera and dysentery)	31% reduction in diarrhea with improved water quality, 25% with increased water supply, 37% with improved hygiene, 32% with improved sanitation, 33% with multiple interventions	Point-of-use treatment of household drinking water significantly reduces diarrhea, whereas source treatment has no effect; rigorous studies of hygiene interventions yield the greatest reduction of diarrhea.

Cairncross 2010	56 (7)	Water quality, handwashing with soap, excreta disposal	Diarrhea, severe enteric infections, and diarrhea mortality	17% reduction in diarrhea with improved water quality, 48% with handwashing, 36% with improved excreta disposal	Blinded water quality interventions yield no impact on diarrhea; evidence for health impacts of sanitation is weakest.
Clasen 2010	13 (13)	Excreta disposal	Diarrhea	No pooled estimates (11/13 studies reported protective effect of intervention against diarrhea)	Improved sanitation is consistently reported to reduce diarrhea; methodology of sanitation intervention trials is highly variable without random allocation; high risk of bias for subjective outcome measure.
Wolf 2014	72 (11)	Drinking water, sanitation	Diarrhea	59% reduction in diarrhea with water filter and safe storage, 37% with chlorine and safe storage, 81% with high quality piped water, 23% with basic piped water, 16% with improved sanitation, 69% with sewer connection (compared to unimproved water or sanitation)	Water filters with safe with safe storage, high quality piped water, and sewer connections yield the greatest reduction in diarrhea; blinded drinking water interventions have a lesser impact.
Strunz 2014	95 (79)	Drinking water, hygiene, sanitation,	STH infection	7% reduction in odds of STH infection associated with piped water use, 54% with treated water use,	Sanitation access yields greatest reduction in *T. trichiura* and *A. lumbricoides* infection

Strunz 2014 (cont.)	combined interventions	70% with wearing shoes, 53% with handwashing after defecation, 34% with sanitation access	prevalence, but less of a reduction in hookworm infection prevalence; evidence for health impacts of sanitation is weak.

Table 1. Selected systematic reviews that contribute to the understanding of WASH interventions and their effects on health outcomes. No. = number, san. = sanitation, Interv. = intervention.

Sanitation coverage

There are various approaches to ending open defecation, including Community-Led Total Sanitation (CLTS), social marketing, and subsidized sanitation. All of these approaches aim to end open defecation by increasing access to improved sanitation (e.g. constructing individual household latrines).

CLTS is a community-mobilizing sanitation intervention that involves education of the fecal-oral transmission pathway, transect walks through communities, "triggering" to shame individuals who practice open defecation, and promotion for latrine construction (Institute for Development Studies, 2011). CLTS has been implemented in at least 60 countries (Institute for Development Studies, 2011). Evaluations of CLTS in Madagascar, Cambodia, and Zambia report increased latrine construction after triggering (Azafady, 2011; Kunthy & Catilla, 2009; Bulaya et al., 2015). Pickering et al. conducted the first randomized control trial of CLTS in 2015. In this robust study across 122 villages in Mali, the intervention was effective in increasing latrine coverage from 33% to 65%, but ineffective in reducing diarrhea and most nutrition outcomes among children under five (Table 2) (Pickering et al., 2015).

Social marketing programs aim to decrease open defecation by generating large-scale demand for latrine construction and supporting local agencies with the supply-side. The Total Sanitation and Sanitation Marketing (TSSM) campaign combines the community education elements of CLTS with social marketing to both raise awareness of the health impacts of open defecation, and implement sustainable solutions that communities desire (Cameron, Shaw & Olivia, 2013). An evaluation of the TSSM in Indonesia reported slightly higher rates of latrine construction in intervention villages than in control villages (Cameron et al., 2013). The prevalence of childhood diarrhea and the intensity of STH infections decreased significantly more in TSSM villages. However, most health benefits were experienced by the "non-poor", who were more likely to construct improved sanitation facilities than the poor since they are less financially restricted (Cameron et al., 2013).

India's government addressed the nation's high open defecation rates and unequal access to improved sanitation facilities by launching the Total Sanitation Campaign (TSC), a subsidy-driven national program. The TSC was later expanded and renamed Nirmal Bharat Abhiyan, and more recently the Swachh Bharat Abhiyan. It encompasses components of CLTS such as changing cultural norms and behaviors through community participation and outreach, but is implemented by a variety of contracted non-governmental organizations instead of through community mobilization. A major component of the TSC is its reliance on subsidies for latrine construction, specifically for those living below the poverty line (Government of India, 2012).

In 2010, Arnold et al. conducted a non-randomized matched cohort study to evaluate the TSC in twelve rural villages in Tamil Nadu. Despite intervention villages increasing latrine coverage from 8% to nearly 60%, the study reported no differences in longitudinal prevalence of diarrhea or anthropometric indicators of nutrition (Table 2) (Arnold et al., 2010).

More recently, two rigorous cluster-randomized control trials evaluated the effectiveness of the TSC in rural villages in Madhya Pradesh and Orissa. Both intervention trials reported that despite a dramatic increase in the coverage of improved sanitation facilities, there were marginal or no reductions in fecal contamination in drinking water, and no improvements in village-level health outcomes (Table 2) (Patil et al., 2014; Clasen et al., 2014).

Across 80 villages in Madhya Pradesh, household drinking water quality (measured by *Escherichia coli* as a fecal indicator) was lower in intervention villages following TSC implementation, but this difference became insignificant when the analysis was adjusted for covariates (Patil et al., 2014). With adjustments, there was no difference between intervention and control villages in 7-day caregiver reported diarrhea prevalence, microbiologically-confirmed STH infections, or anemia and anthropometry (Patil, 2014).

Clasen et al.'s (2014) evaluation of the TSC in Orissa similarly found no significant impact on environmental exposure or adverse health outcomes in 50 intervention villages compared to 50 control villages. Household water contamination (measured by thermotolerant coliforms as a fecal indicator), hand contamination, sentinel toy contamination and synanthropic flies were measured to assess exposure to feces in the environment. There was no difference in exposure between intervention and control villages (Clasen et al., 2014). There was also no difference in 7-day caregiver reported diarrhea prevalence, most types of STH infections, or anthropometric outcomes (Clasen et al., 2014).

Among Clasen et al.'s (2014) study population in Orissa, the TSC did not reach universal or even goal level (70%) latrine coverage, with an average of 63% coverage across 50 intervention villages. Boisson et al.'s (2014) process evaluation of the TSC showed that one year after implementation began, less than half of intervention villages had reached 80% latrine coverage – some villages remained at less than 20% coverage. Patil's (2014) trial in Madhya Pradesh reported average latrine coverage of only 41% across 40 TSC villages. Arnold's (2010) matched cohort study in Tamil Nadu reported that average latrine coverage only reached 57% across 12 intervention villages. Moreover, latrine construction during the study period varied greatly between wealth quintiles. Over 60% of households in the highest wealth quintile built private latrines from 2003-2008, while less than 30% of households in the lowest wealth quintile built private latrines (Arnold, 2010).

Focus group discussions with community members in Orissa after TSC implementation confirmed that a "lack of cash income" was the main reason participants chose not to install a latrine, despite the subsidy because "participation in the TSC requires making a small contribution to toilet construction" (Routray et al., 2015). Despite increases in village-level coverage, the lack of access to a latrine was stated as a main reason for continuing to practice open defecation (Routray et al., 2015).

Study	**Location**	**Intervention**	**Average Latrine Coverage (%)**		**Child Health Outcomes**	**General Findings**
			(Baseline)	(Endline)		
Pickering 2015	Koulikoro, Mali	CLTS	33	65	diarrhea, malnutrition	reduced stunting
Arnold 2010	Tamil Nadu, India	TSC	8	57	diarrhea, malnutrition	no change
Patil 2014	Madhya Pradesh, India	TSC	14	41	diarrhea, anemia, malnutrition, STH infection	no change
Clasen 2014	Orissa, India	TSC	9	63	diarrhea, malnutrition, STH infection	no change

Table 2. Sanitation intervention trials and overall impacts on child health. CLTS = Community-Led Total Sanitation, TSC = Total Sanitation Campaign.

Latrine use & other routes of exposure

Not only does inadequate coverage allow for continued fecal contamination in the environment, but a lack of behavior change – even in areas with access to improved sanitation – negates the effects of constructing improved sanitation facilities (WHO, 2015; Clasen et al., 2014; Patil et al., 2014). In Madhya Pradesh, open defecation rates among men, women and children at follow-up were lower in intervention villages than control villages, but remained high at 75, 73, and 84%, respectively (Patil, 2014). A cross-sectional study three years after TSC implementation in Orissa revealed that despite achieving an average of 72% latrine coverage, 37% of those surveyed still reported always practicing open defecation (Barnard et al., 2013).

Exploratory qualitative analyses of in-depth-interviews and focus group discussion in Orissa revealed myriad barriers to latrine adoption; notably, the lack of structural integrity and completeness of government-subsidized latrines was an important reason for maintaining open defecation behaviors (Sahoo et al., 2015; Routray et al., 2015). Only 53% of latrines observed in the aforementioned cross-sectional study were functional (Barnard et al., 2013). Among TSC intervention villages in Clasen et al.'s (2014) study population, only 38% of households had functional latrines; an even smaller proportion of households had functional latrines with signs of use. Given the variability in latrine coverage, functionality, and use in multiple evaluations of India's TSC, it is no surprise that open defecation is still widely practiced in India. The lack of improvements in environmental contamination and health outcomes reported at the village level is, therefore, not to be unexpected.

Even when high levels of latrine coverage and compliance are achieved, this may not protect against other routes of exposure to feces containing pathogenic bacteria, viruses, protozoa, and helminthes. Poor hygiene behavior, child and animal fecal contamination, and poor fecal sludge management are additional sources of exposure (Cairncross et al., 2015; Routray et al., 2015; Schriewer et al., 2015; WHO 2008b; Wolf et al., 2014).

Handwashing with soap can reduce childhood diarrhea prevalence by an estimated 48% (Table 1) (Cairncross et al., 2015). In Orissa, lack of water availability near sanitation facilities prevents individuals from using the latrine because of cultural cleansing practices, which require large quantities of water (Routray et al., 2015). For those who do use the latrine, the lack of available water would likely prevent them from effectively washing their hands post-defecation to remove fecal contamination. Fecal contamination on the hands of mothers and children in Orissa is common; among a subgroup of households (N=137) within Clasen et al.'s (2014) study population, 37% had detectable levels of human fecal indicators from hand rinses (Schriewer et al., 2015).

Animal fecal contamination on hands (96%) and in stored drinking water (52%) is even more common than human fecal contamination in Orissa (Schriewer et al., 2015). Pathogens in both human and animal feces, including *Escherichia coli*, noroviruses, and *Cryptosporidium parvum*, cause diarrheal disease in humans if ingested via the fecal-oral route (WHO, 2008b). Interventions, such as the TSC, that focus on latrine coverage and use do not address animal fecal contamination in the environment. Child feces also remains in the domestic environment, despite increased coverage and use of latrines. As previously discussed, caretakers in Orissa often dispose child feces in the garbage pit or a neighboring yard rather than in the latrines (Routray et al., 2015).

Finally, ineffective or nonexistent fecal sludge management (i.e. service for emptying pits when full) may also contribute to environmental contamination (WHO, 2001). Sewer systems may be the most effective method of reducing diarrhea by containing feces from the point of defecation to waste treatment facilities, but these systems are not always viable in rural settings (Table 1) (Wolf et al., 2014). These additional routes of exposure that are not mitigated by improved coverage and use of household latrines might explain the ineffectiveness of sanitation interventions (Table 2) in reducing WASH-related morbidity.

Spatial analyses in WASH

Spatial analyses involve examining the locations and attributes of data to identify and explain relationships that are dependent of space. Some analytical tools include overlaying data layers to visually assess spatial relationships, testing for statistically significant hot spots of a disease, and creating buffers around data points to identify objects within a given radius from the data. In environmental health, spatial analyses are useful for mapping and identifying relationships between environmental determinants of health and disease.

Study	**Location**	**Method**	**Health Outcomes**	**Key Findings**
Rajeshwari 2008	Haryana, India	Mapping district-level sanitation and disease patterns	Infectious & parasitic diseases	80% of infectious and parasitic diseases correspond to lack of household toilet facility
Kaliappan 2013	Tamil Nadu, India	Poisson regression; spatial scan cluster analysis	STH infection	Using a designated OD area increases odds of hookworm infection; possible clustering of hookworm infections in one village
Tsiko 2015	Zimbabwe	Geoadditive Bayesian regression	Child diarrhea, cough, or fever	Presence of flush or pit latrine increased odds of illness

Table 3. Spatial analyses that incorporate sanitation as a risk factor for health outcomes.

Geographic information systems (GIS) have been used to map the geographic inequity of water access and sanitation coverage (Ntozini et al., 2015; Yu, Bain, Mansour & Wright, 2014). Spatial analyses are particularly useful for identifying clusters of WASH-related diseases, such as STH infections (Tsiko, 2015; Karagiannis-Voules et al., 2015; Chammartin et al., 2013; Ngui et al., 2014; Pullan et al., 2010; Davis et al., 2014; Kaliappan et al., 2013; Rajeshwari, 2008; Santos et al., 2014; Chammartin et al., 2014; Brooker et al., 2006a; Souza et al., 2006) and diarrhea (Santos et al., 2014; Tsiko, 2015;

Azage et al., 2015). An overwhelming majority of these studies – both of sanitation coverage and disease – aggregate the exposure or outcome of interest at the country, district or village level, obtaining a minimal understanding of patterns on a smaller spatial scale. A fundamental assumption of spatial analyses is that objects closer in space are more likely to be associated and more likely to come in contact with one another. Given the fecal-oral and skin contact transmission routes of sanitation-related diseases, proximity to fecal contamination is necessary for contact with a pathogen to occur. Therefore, spatial analyses are critical tools for identifying relationships between environmental factors that affect fecal contamination and associated health outcomes. However, few studies that conducted spatial analyses of health outcomes incorporate sanitation as a risk factor (Table 3) (Kaliappan et al., 2013; Tsiko, 2015; Rajeshwari, 2008).

II. CURRENT STUDY

Rationale

The current study addresses the gaps in sanitation spatial analyses by analyzing the relationships between sanitation, fecal contamination in the environment, and health outcomes on a fine spatial scale. This research also addresses the underlying mechanism in the causal pathway between latrine construction and health outcomes: latrine use.

Clasen et al. (2014) defined a functional latrine as one that has a roof, is not used for storage, has an unbroken and unblocked pan that is not full of leaves or dust, and is completely constructed. Owning a functional latrine in Orissa has been correlated with increased likelihood of latrine use (Barnard et al., 2013). If owning a functional latrine increases latrine use, it should effectively reduce open defecation and prevent the spread of feces in the environment. Since they promote use, functional latrines may protect individuals in a given area from exposure to human feces.

However, a high number of functional latrines may not protect individuals from fecal exposure if there are also many households without functional latrines, or any latrine at all. Therefore, as the *proportion* of households with functional latrines within a given distance of a household approaches 100%, we hypothesize that members of that household are less likely to be exposed to fecal pathogens in the environment. This decrease in exposure should correspond with lower odds of STH infections and lower prevalence of diarrhea among household members.

Research questions

Is the density of latrines or functional latrines within varying distances of a household associated with:

1. fecal contamination of household drinking water?
2. the prevalence of soil-transmitted helminth (STH) infections among all household members?
3. the longitudinal prevalence of diarrhea among all household members and among children under five?

III. METHODS

The current study investigates the effects of the density of functional latrines at the household level, building on the primary analyses of village-level effects from Clasen et al.'s (2014) cluster-randomized control trial. Detailed methods of data collection during the initial trial have been previously described (Clasen et al., 2014; Clasen et al., 2012).

Study population

This analysis includes only households among the 50 intervention villages. Control households were excluded because the average proportion of households in control villages with any latrine remained very low (12%) at follow-up (Clasen et al., 2014). Baseline characteristics of the study population were collected in 2010 (Clasen et al., 2012).

Of households in the intervention group, 27% of the head of household had received no formal education, and 17% of caregivers had no education. 42% of intervention households had a below poverty line (BPL) card. While 79% of intervention households had electricity, only 3% had piped water and only 10% had access to any type of latrine. Most households collected water from shallow (41%) and deep (38%) tube wells. Most household drinking water sources were located outside the household compound (70%) (Clasen et al., 2012).

For the purpose of this study, we also excluded households that did not have GPS coordinates or data for the outcome variable of interest, or whose functional latrine ownership status was unknown. The deletion method for missing data is justified since missing values for each variable accounted for less than 5% of observations. Given the large sample size even after deleting observations with missing data, we can assume the subset of the study population included in this analysis is comparable to study households surveyed at baseline.

Latrine functionality

Latrine functionality may serve as a proxy of use. Clasen et al. (2014) defined a functional latrine as having the following elements: "existence of a roof; latrine not used for storage; pan not broken, not blocked, and not full of leaves or dust; and pit completed". Barnard et al. (2013) found that functional latrines – similarly defined as those with walls over 1.5 meters, with a pan that is not broken or blocked, with a closure over the entry and a functional pan-pipe-pit connection – had 25 times the odds of being used than non-functional latrine. Participants are more likely to use their latrine if it is functional and, therefore, less likely to practice open defecation. To address our hypothesis that functional latrines are more beneficial, we compare the effects of the density of functional latrines to the effects of the density of all latrines surrounding households.

Latrine density

Health outcomes and drinking water contamination for each household with available data were mapped using ArcMap 10.3.1 projected in UTM WGS 1984 45N. To understand the impact of the density of latrines, we calculated the number of latrines within various distances from each household. We used a multiple ring buffer analysis to create 25 m, 50m, 100 m, and 200 m buffers around households surveyed for each outcome variable. We created variables for the raw number of latrines and functional latrines surrounding each household within the four buffers using the spatial join tool. We then calculated the proportion of households with any latrine (functional and non-functional) and the proportion of households with functional latrines in each buffer.

We selected an example village to demonstrate the multiple ring buffer analysis (Figure 1). In this example, soil-transmitted helminth (STH) infection is the outcome variable of interest. Three households in this village provided stool samples at endline data collection. Household 2 had at least one household member test positive for an STH infection, while Households 1 and 3 had no STH infections at endline. Households 1 and 2 had latrines that did not meet the qualifications to be considered functional. Household 3 had a functional latrine.

Using multiple variables to predict latrine density allows for useful comparisons in the analysis. By comparing functional latrines to any latrines, we can assess the exposure and health of households more or less likely to use their latrines, respectively. By comparing the proportion of households with latrines to the number of households with latrines, we can assess the impact of the number of households *without* functional latrines on exposure and health in areas despite the raw count of functional latrines.

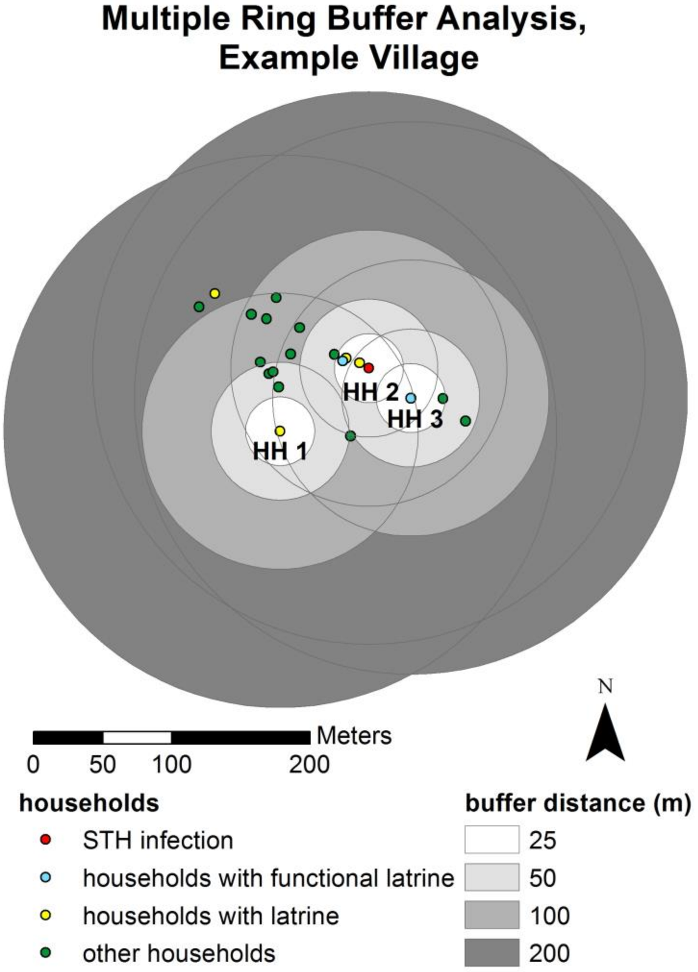

Figure 1. Multiple ring buffer analysis in an example village of the study site.

Fecal contamination in drinking water

To explore the effect of the intervention on one possible source of exposure, we first assessed the effects of functional latrine density on fecal contamination of household drinking water. At every 3-month surveillance visit, household drinking water quality was tested for fecal contamination among a random selection of 20% of all households included in the study (Clasen et al., 2012). Fecal contamination was indicated by thermotolerant coliforms (TTC) per 100 mL of water (Clasen et al., 2014). To estimate a representative contamination level for each household, we averaged TTC per 100 mL for each household across all surveillance visits.

Health outcomes

We hypothesized that the proportion of functional latrines surrounding a household would predict household prevalence of STH infections and diarrhea among members in the household. These health outcomes were chosen for analysis based on the burden of disease in India and their association to sanitation (see above).

The Orissa trial assessed the prevalence of STH infections of all eligible intervention households at follow-up. Stool samples were collected from August-October 2013, about 2.5 years after the start of the intervention, and 1.5 years after intervention villages reached the initial target for latrine coverage (Clasen et al., 2012). Because STH infections were rare among the study population, we aggregated infections across helminth species (hookworm, *Ascaris lumbricoides*, and *Trichuris trichuria*) for all individuals in a household for this analysis. We analyzed STH infection prevalence as a binary outcome variable: households were classified as either having at least one individual with any STH infection (1) or not (0).

Diarrhea was measured by 7-day self- or caregiver-report (Clasen et al., 2014). During the initial trial, surveillance visits were conducted up to nine times per household, though not every household member was available for data collection at each visit (Clasen et al., 2012). In order to estimate the overall disease burden from diarrhea for each household, we assessed diarrhea based on average household longitudinal prevalence (total diarrhea days / total observation days). Diarrhea days were calculated by multiplying the number of total number of diarrhea-positive visits across household members by seven (for 7-day recall period). Total observation days were calculated by totaling the number of visits for each household member and multiplying by seven. Average household longitudinal prevalence was transformed by multiplying by 1,000 to reflect the number of diarrhea days per 1,000 person days. The same methods were used to create household longitudinal diarrhea prevalence among children under five.

Statistical analysis

Statistical analyses were conducted in SAS 9.4. We explored the distribution of all latrine density predictor variables for households surveyed for each outcome variable of interest. Descriptive analyses were conducted to assess the distribution of outcome variables. All analyses were stratified by distance.

The effect of latrine density predictors on household-level STH infection prevalence was determined via logistic regression models. We assessed both unadjusted log odds of infection, and adjusted log odds of infection. The adjusted model included household population and functional latrine ownership as potential confounders. Whether or not a household owns a functional latrine could impact fecal contamination of drinking water and STH infection prevalence; owning a functional latrine may increase the use of the latrine by household members, decreasing open defecation that contributes to fecal contamination in the household environment, thus reducing exposure to STH (Barnard et al., 2013). Generalized estimating equations (GEE) were implemented for the final logistic regression models to adjust for village-level clustering and determine population-based estimates.

We conducted an initial analyses of bivariate correlations between latrine density predictors, potential confounding variables, and continuous outcome variables (household drinking water contamination and household longitudinal diarrhea prevalence). For diarrhea, household population or the number of children under five per household (the latter for childhood diarrhea, the former for diarrhea among all ages), as well as functional latrine ownership, were assessed for potential confounding. More people (or children) in the household increases the opportunity for the transmission of pathogens within the household compound. Indicators of household population and functional latrine ownership were significantly correlated with household longitudinal diarrhea prevalence, and were included in the final model.

In addition to household population and functional latrine ownership, the location of the household's water source was included as a confounder for household drinking water contamination based on the assumption that drinking water quality in the home would reflect the quality of the water source. None of these confounders were significantly correlated with household drinking water contamination in bivariate correlations. However, to generate conservative estimates we included all three potential confounders in the final models for drinking water contamination. To account for village-level clustering, these regressions were also adjusted by implementing GEE models for the final linear regressions. For all adjusted models, we applied an exchangeable working correlation (EWC) structure for robust standard errors.

IV. RESULTS

Observations included in analysis

After aggregating individual and longitudinal data to the household level, and after removing control households and households with missing data, there were 1,009 observations for drinking water contamination, 822 observations for soil-transmitted helminth infection (STH) prevalence, 1,275 observations for household diarrhea prevalence of household members of all ages, and 1,017 observations for household diarrhea prevalence of children under five. For all households with latrine GPS data included in the buffer analysis for the creation of latrine density predictor variables, a total of 2,602 observations remained.

Regression coefficients presented in tables represent the change in the outcome variable given a single unit increase in the latrine density predictor. While a single unit in the number of latrines is a realistic expectation, the proportion of households with latrines is more likely to increase by larger than 1% at a time. Therefore, estimates are often multiplied by 10 in the explanation of results to provide a more realistic interpretation.

Potential confounding factors

The distribution of functional latrines was similar across all subgroups (households surveyed for drinking water, STH infection, and diarrhea) of the study population analyzed for each outcome variable. Among households analyzed for drinking water contamination, STH infection, and diarrhea among all ages and among children under five (N=1,009, N=822, N=1,275, N=1,017, respectively), 43% owned functional latrines. For all subgroups analyzed the median household population size was 6, ranging from 1 to 30 household members. Among households assessed for fecal contamination, household drinking water was collected from 49 unique locations. The most frequently used source was shared by 128 households; 8 water source locations were only used by one household each. EWCs for all adjusted regression models remained low, indicating minimal effects due to village-level clustering (Tables 12, 13, 17, 18, 21, 22, 25 and 26).

Latrine functionality and density

There was also little variation in the distribution of latrine density (any type of latrine) and functional latrine density among intervention households across the subgroups (Tables 4 through 9). On average, less than 2 functional latrines were present within 25 meters (m) of intervention households. There were up to 54 latrines within 200 m of households surveyed for drinking water contamination, STH prevalence, and diarrhea prevalence, but only 24 functional latrines within 200 m (Tables 4, 6 and 8).

Latrine coverage within 200 m ranged from 2%-100%, and functional latrine coverage ranged from 0% to 50% (Tables 5, 7 and 9). It is likely that households with 100% latrine coverage were the only household within 200 m, and that households with 50% functional latrine coverage were one of two households within 200 m. This was visually confirmed in ArcMap for some households, though it was not always the case.

The distribution of latrines within various distances among households surveyed for childhood diarrhea is not presented in a separate table. The 1,017 households with at least one child under the age of five are represented within the 1,275 households surveyed for 7-day diarrhea prevalence (Tables 8 and 9). The distribution of latrine density did not differ among only households with children.

Distance (m)

count	25		50		100		200	
	Latrine	FL	Latrine	FL	Latrine	FL	Latrine	FL
mean # (SD)	4.8 (3.4)	1.9 (1.9)	8.4 (5.8)	3.4 (3.0)	14.0 (9.0)	5.7 (4.4)	20.9 (11.2)	8.5 (5.4)
median	4	1	8	3	12	5	19	8
min	1	0	1	0	1	0	1	0
max	19	8	31	16	46	18	54	24

Table 4. Distribution of c*ounts* of households with any latrine and functional latrines surrounding households surveyed for household drinking water contamination (N=1.009). FL = functional latrine, SD = standard deviation.

Distance (m)

proportions	25		50		100		200	
	Latrine	FL	Latrine	FL	Latrine	FL	Latrine	FL
mean % (SD)	39.5 (21.7)	17.4 (20.9)	34.0 (15.5)	14.8 (15.1)	31.2 (11.7)	13.6 (11.1)	29.8 (8.8)	12.9 (8.7)
median	33	13	32	12	31	12	29	12
min	4	0	5	0	3	0	2	0
max	100	100	100	100	100	50	100	50

Table 5. Distribution of the *proportion* of households with any latrine and functional latrines surrounding households surveyed for household drinking water contamination (N=1.009). FL = functional latrine, SD = standard deviation.

Distance (m)

count	25		50		100		200	
	Latrine	FL	Latrine	FL	Latrine	FL	Latrine	FL
mean # (SD)	4.8 (3.4)	1.9 (1.9)	8.4 (5.7)	3.4 (3.0)	14.0 (9.0)	5.7 (4.4)	20.6 (11.1)	8.4 (5.4)
median	4	1	8	3	12	5	19	8
min	1	0	1	0	1	0	1	0
max	19	8	29	13	46	18	54	24

Table 6. Distribution of c*ounts* of households with any latrine and functional latrines surrounding households surveyed for soil-transmitted helminth (STH) infection (N=822). FL = functional latrine, SD = standard deviation.

Distance (m)

proportions	25		50		100		200	
	Latrine	FL	Latrine	FL	Latrine	FL	Latrine	FL
mean # (SD)	39.3 (21.4)	17.5 (20.8)	34.1 (15.6)	14.9 (14.9)	31.3 (11.6)	13.8 (11.1)	29.7 (8.9)	12.8 (8.9)
median	33	13	31	12	30.5	12	29	12
min	4	0	5	0	3	0	2	0
max	100	100	100	100	100	50	100	40

Table 7. Distribution of the *proportions* of households with any latrine and functional latrines surrounding households surveyed for soil-transmitted helminth (STH) infection (N=822). FL = functional latrine, SD = standard deviation.

Distance (m)

count	25		50		100		200	
	Latrine	FL	Latrine	FL	Latrine	FL	Latrine	FL
mean # (SD)	4.6 (3.3)	1.9 (1.9)	8.1 (5.7)	3.3 (3.0)	13.7 (8.9)	5.6 (4.4)	20.6 (11.3)	8.5 (5.4)
median	4	1	7	3	12	5	18	8
min	1	0	1	0	1	0	1	0
max	19	8	31	16	46	18	54	24

Table 8. Distribution of the *counts* of households with any latrine and functional latrines surrounding households surveyed for 7-day diarrhea prevalence (all ages, N=1,275). FL = functional latrine, SD = standard deviation.

Distance (m)

proportions	25		50		100		200	
	Latrine	FL	Latrine	FL	Latrine	FL	Latrine	FL
mean % (SD)	39.7 (21.6)	17.7 (21.1)	34.1 (15.6)	15.0 (14.9)	31.4 (12.0)	13.8 (11.0)	29.9 (9.4)	13.0 (8.8)
median	33	13	32	12	31	12	29	12
min	4	0	5	0	3	0	2	0
max	100	100	100	100	100	50	100	50

Table 9. Distribution of the *proportions* of households with any latrine and functional latrines surrounding households surveyed for 7-day diarrhea prevalence (all ages, N=1,275). FL = functional latrine, SD = standard deviation.

Fecal contamination in drinking water

Of 1,009 intervention households, only 13% had no fecal contamination in their household drinking water while 60% had high levels of contamination, indicated by >100 coliform forming units (cfu) of thermotolerant coliforms (TTC) per 100 milliliters (mL). The average level of fecal contamination was nearly 700 cfu TTC per 100 mL of drinking water (Table 10).

HH drinking water contamination		
Frequency	**cfu TTC / 100 mL**	**n (%)**
	0	135 (13.4)
	1-10	26 (2.6)
	10-100	243 (24.1)
	>100	605 (60.0)
Distribution		
	mean (SD)	696.39 (902.87)
	min	0 (ND)
	max	3000 (TNTC)

Table 10. Descriptive statistics of household drinking water contamination among intervention households (N=1.009). HH = household, cfu = coliform forming units, TTC = thermotolerant coliforms, SD = standard deviation, ND = not detectable, TNTC = too numerous to count.

Bivariate correlations revealed that as the number of functional latrines within 25 m, 50 m, 100 m, and 200 m increased, household drinking water contamination significantly decreased ($p<0.05$) (Table 11). Higher proportions of households with functional latrines were also significantly correlated with lower drinking water contamination, but only at 50 m and 100 m ($p<0.05$). Among potential confounders, only the location of the source of drinking water was significantly correlated with household drinking water contamination at a 90% significance level.

After adjusting for village-level clustering using GEE regressions, an increase in the number of functional latrines within 50 m was still significantly correlated with decreased household drinking water contamination (*p*<0.05) (Table 12). For every additional latrine within 50 m of a household, TTC decreased by an estimated 21.4 cfu per 100 mL. The negative association between the proportion of functional latrines and household drinking water remained significant (*p*<0.05) at 50 m and 100 m in the adjusted univariate regression. Contamination reduced by 40.8 cfu per 100 mL for every 10% increase in functional latrine coverage within 50 m, and 58.2 cfu per 100 mL for an equivalent increase within 100 m.

Although potential confounders were not significantly correlated with the outcome variable at a 95% significance level in bivariate correlations, we included them in multivariate GEE regressions for conservative estimates of the effect of latrine density predictors (Table 13). The location of the water source was a significant covariate in all adjusted models (i.e. for each latrine density predictor), but household population and functional latrine ownership were not. In the adjusted multivariate regressions, only the number of latrines within 200 m was significantly associated with a decrease in household drinking water contamination (*p*<0.05). Although, the number of latrines and the proportion of functional latrines within 50 m were negatively associated with fecal contamination at a 90% significance level. Despite the wide confidence intervals, increasing the number of functional latrines within smaller buffers (25 m and 50 m) yielded the highest estimated decrease in TTC levels (Figure 2). TTC in household drinking water decreased by 28.9 cfu per 100 mL (p=0.165) with each additional functional latrine within 25 m, and by 18.6 cfu per 100 mL (p=0.109) with each additional functional latrine within 100 m (Table 13).

Distance (m)	**Latrine Density Predictor**	**Pearson Correlation Coefficients**	***Pr* > |*r*|**
25	# latrines	-0.023	*0.3654*
	# FL	-0.066	*0.0373†*
	Proportion of HHs with latrines	-0.018	*0.5630*
	Proportion of HHs with FL	-0.035	*0.2686*
50	# latrines	-0.052	*0.1019*
	# FL	-0.076	*0.0162†*
	Proportion of HHs with latrines	-0.012	*0.7078*
	Proportion of HHs with FL	-0.067	*0.0322†*
100	# latrines	-0.042	*0.1838*
	# FL	-0.072	*0.0224†*
	Proportion of HHs with latrines	0.022	*0.4869*
	Proportion of HHs with FL	-0.069	*0.0288†*
200	# latrines	-0.050	*0.1133*
	# FL	-0.063	*0.0453†*
	Proportion of HHs with latrines	-0.018	*0.5729*
	Proportion of HHs with FL	-0.054	*0.0852*
Covariates	HH population	-0.020	*0.5335*
	Location of drinking water source	-0.056	*0.0778‡*
	Functional latrine ownership	-0.050	*0.1140*

Table 11. Unadjusted bivariate linear correlations between mean household drinking water contamination and latrine density predictors at varying distances.
† = Pr > |*r*| is significant at a 95% confidence level (p<0.05), ‡ = Pr > |*r*| is significant at a 90% confidence level (p<0.10), HH = household, FL = functional latrine.

Distance (m)	Latrine Density Predictor	EWC	GEE Beta Estimate (95% CI)	*Pr* > |Z|
25	# latrines	0.0134	-5.69 (-24.70, 13.33)	*0.5577*
	# FL	0.0109	-28.93 (-57.90, 0.04)	*0.0503*‡
	Proportion of HHs with latrines	0.0158	-0.96 (-3.12, 1.2041)	*0.3854*
	Proportion of HHs with FL	0.0141	-1.41 (-3.84, 1.02)	*0.2553*
50	# latrines	0.0116	-7.33 (-16.75, 2.09)	*0.1271*
	# FL	0.0099	-21.42 (-42.76, -0.09)	*0.0490*†
	Proportion of HHs with latrines	0.0152	-0.85 (-3.58, 1.87)	*0.5399*
	Proportion of HHs with FL	0.0144	-4.08 (-7.35, -0.81)	*0.0145*†
100	# latrines	0.0122	-3.69 (-9.13, 1.74)	*0.1831*
	# FL	0.0102	-13.93 (-29.08, 1.23)	*0.0717*‡
	Proportion of HHs with latrines	0.0148	1.66 (-2.52, 5.84)	*0.4362*
	Proportion of HHs with FL	0.0143	-5.82 (-11.06, -0.58)	*0.0295*†
200	# latrines	0.0156	-4.53 (-9.40, -0.35)	*0.0689*‡
	# FL	0.0129	-10.51 (-21.65, 0.62)	*0.0643*‡
	Proportion of HHs with latrines	0.0157	-2.39 (-8.57, 3.79)	*0.4481*
	Proportion of HHs with FL	0.0139	-5.75 (-12.54, 1.05)	*0.0975*‡

Table 12. Univariate linear regressions adjusted for village-level clustering with Generalized Estimating Equations (GEE) for mean household drinking water contamination and latrine density predictors at varying distances. † = Pr > |*r*| is significant at a 95% confidence level (p<0.05), ‡ = Pr > |*r*| is significant at a 90% confidence level (p<0.10), EWC = exchangeable working correlation, HH = household, FL = functional latrine, CI = confidence interval.

Distance (m)	Latrine Density Predictor	EWC	GEE Beta Estimate (95% CI)	*Pr* > |Z|
25	# latrines	0.0130	-8.40 (-27.80, 11.00)	*0.3963*
	# FL	0.0126	-28.85 (-57.49, 9.79)	*0.1646*
	Proportion of HHs with latrines	0.0165	-0.65 (-2.77, 1.48)	*0.5527*
	Proportion of HHs with FL	0.0158	-0.15 (-2.77, 2.48)	*0.9118*
50	# latrines	0.0107	-8.82 (-18.60, 0.95)	*0.0769*‡
	# FL	0.0114	-18.58 (-42.23, 5.07)	*0.1236*
	Proportion of HHs with latrines	0.0160	-0.42 (-3.15, 2.32)	*0.7655*
	Proportion of HHs with FL	0.0160	-3.15 (-6.64, 0.33)	*0.0760*‡
100	# latrines	0.0114	-4.44 (-9.89, 0.99)	*0.1087*
	# FL	0.0117	-11.64 (-27.55, 4.28)	*0.1517*
	Proportion of HHs with latrines	0.0155	2.38 (-1.68, 6.44)	*0.2499*
	Proportion of HHs with FL	0.0161	-4.49 (-9.97, 0.98)	*0.1078*
200	# latrines	0.0149	-5.05 (-9.81, -0.29)	*0.0378*†
	# FL	0.0139	-8.60 (-19.85, 2.65)	*0.1341*
	Proportion of HHs with latrines	0.0164	-1.51 (-7.49, 4.46)	*0.4481*
	Proportion of HHs with FL	0.0157	-3.39 (-10.82, 4.03)	*0.3704*

Table 13. Multivariate linear regressions adjusted for village-level clustering with Generalized Estimating Equations (GEE) for mean household drinking water contamination and latrine density predictors at varying distances. This model controlled for three covariates: household population, location of drinking water source, and functional latrine ownership. † = Pr > |*r*| is significant at a 95% confidence level (p<0.05), ‡ = Pr > |*r*| is significant at a 90% confidence level (p<0.10), EWC = exchangeable working correlation, HH = household, FL = functional latrine.

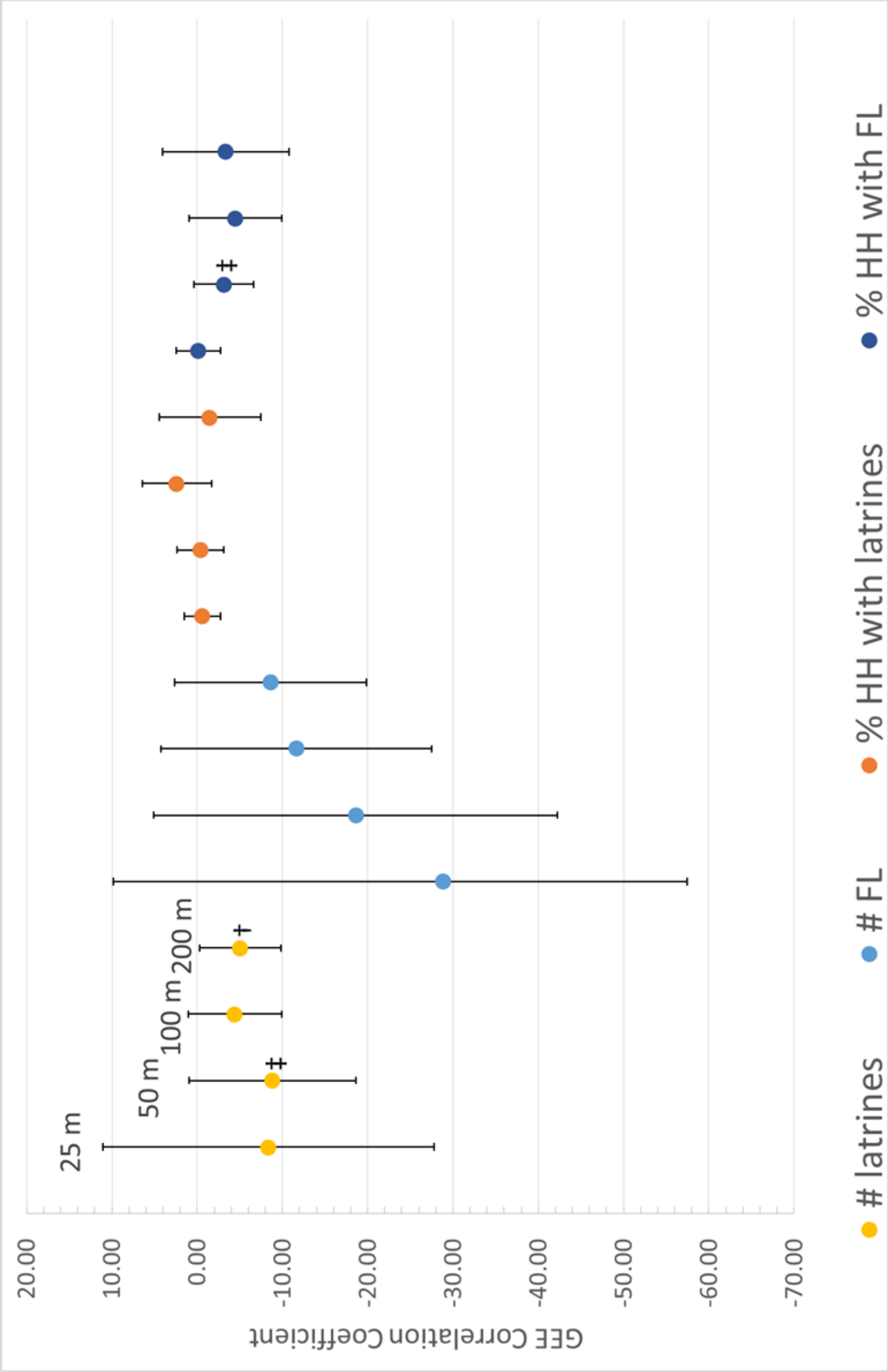

Figure 2. Adjusted estimates from multivariate linear regression for mean household drinking water contamination (Table 13). Error bars are 95% confidence intervals. † = Pr > |*r*| is significant at a 95% confidence level (p<0.05), HH = household, FL = functional latrine.

Soil-transmitted helminthiasis

STH infections among the intervention population were rare, occurring in less than 6% of households (Table 14). In the unadjusted univariate logistic regressions, an increase in the number of latrines within 25 m, 100 m, and 200 m were associated with significantly lower odds of STH infection within the household ($p<0.05$) (Table 15). However, an increase in the *proportion* of latrines within 100 m was associated with higher odds of STH infection ($p<0.05$). Estimated odds ratios did not change by more than 20% in the unadjusted multivariate logistic regressions (Table 16). This suggests that the covariates included in the model (household population and functional latrine ownership) did not confound the relationship between latrine density predictors and STH infection.

STH infection prevalence

Prevalent	Frequency	Percent
Yes	44	5.35%
No	778	94.65%

Table 14. Frequency of soil-transmitted helminth (STH) infection prevalence among intervention households (N=822).

In the adjusted univariate GEE models, the number of latrines within 25 m ($p<0.05$) and 100 m ($p<0.10$) were the only predictor associated with reduced odds of STH infection (Table 17). The GEE logistic regressions were run again, controlling for household population and functional latrine ownership to obtain conservative estimates (Figure 3). For every additional latrine within 25 m, regardless of functionality, the odds of any household member having an STH infection reduced by 10% ($p=0.038$) (Table 18). Estimates produced by the adjusted multivariate models did not differ from the adjusted univariate models by more than 20%, and the two covariates were not significant predictors in any of the multivariate models (Table 18). This confirmed our preliminary assessment indicating that household population and functional latrine ownership were not confounders.

Distance (m)	Latrine Density Predictor	Odds Ratio (95% CI)	Pr > ChiSq
25	# latrines	0.869 (0.765, 0.972)	*0.0220*†
	# FL	0.927 (0.774, 1.088)	*0.3779*
	Proportion of HHs with latrines	1.013 (1.000, 1.025)	*0.0389*†
	Proportion of HHs with FL	1.010 (0.997, 1.022)	*0.1084*
50	# latrines	0.949 (0.888, 1.006)	*0.1008*
	# FL	0.973 (0.873, 1.075)	*0.6002*
	Proportion of HHs with latrines	1.004 (0.984, 1.022)	*0.6443*
	Proportion of HHs with FL	1.001 (0.980, 1.020)	*0.8919*
100	# latrines	0.958 (0.917, 0.996)	*0.0395*†
	# FL	0.974 (0.905, 1.044)	*0.4705*
	Proportion of HHs with latrines	1.001 (0.974, 1.025)	*0.9378*
	Proportion of HHs with FL	1.01 (0.982, 1.035)	*0.4774*
200	# latrines	0.964 (0.932, 0.994)	*0.0270*†
	# FL	0.995 (0.939, 1.053)	*0.8656*
	Proportion of HHs with latrines	1.005 (0.970, 1.036)	*0.7651*
	Proportion of HHs with FL	1.017 (0.984, 1.049)	*0.2888*

Table 15. Unadjusted univariate logistic regressions for soil-transmitted helminth (STH) infection prevalence and latrine density predictors at varying distances. † = Pr > |*r*| is significant at a 95% confidence level ($p<0.05$), HH = household, FL = functional latrine, CI = confidence interval.

Distance (m)	Latrine Density Predictor	Odds Ratio (95% CI)	Pr > ChiSq
25	# latrines	0.872 (0.767, 0.974)	*0.0240*†
	# FL	0.875 (0.703, 1.057)	*0.1980*
	Proportion of HHs with latrines	1.013 (1.000, 1.025)	*0.0379*†
	Proportion of HHs with FL	1.012 (0.996, 1.026)	*0.1303*
50	# latrines	0.951 (0.889, 1.008)	*0.1118*
	# FL	0.952 (0.844, 1.065)	*0.4205*
	Proportion of HHs with latrines	1.005 (0.985, 1.023)	*0.6046*
	Proportion of HHs with FL	0.998 (0.972, 1.020)	*0.8815*
100	# latrines	0.958 (0.917, 0.996)	*0.0436*†
	# FL	0.962 (0.888, 1.037)	*0.3271*
	Proportion of HHs with latrines	1.001 (0.974, 1.026)	*0.9154*
	Proportion of HHs with FL	1.008 (0.977, 1.037)	*0.6156*
200	# latrines	0.965 (0.932, 0.995)	*0.0298*†
	# FL	0.998 (0.928, 1.049)	*0.6979*
	Proportion of HHs with latrines	1.005 (0.970, 1.036)	*0.7649*
	Proportion of HHs with FL	1.016 (0.979, 1.052)	*0.3783*

Table 16. Unadjusted multivariate logistic regressions for soil-transmitted helminth (STH) infection prevalence and latrine density predictors at varying distances. This model controlled for two covariates: household population and functional latrine ownership. † = Pr > |*r*| is significant at a 95% confidence level ($p<0.05$), HH = household, FL = functional latrine, CI = confidence interval.

Distance (m)	Latrine Density Predictor	Odds Ratio (95% CI)	*Pr* > |Z|
25	# latrines	0.904 (0.820, 0.996)	*0.0416*†
	# FL	0.947 (0.812, 1.092)	*0.4258*
	Proportion of HHs with latrines	1.011 (0.996, 1.026)	*0.1588*
	Proportion of HHs with FL	1.007 (0.992, 1.022)	*0.3889*
50	# latrines	0.977 (0.930, 1.026)	*0.3499*
	# FL	0.989 (0.904, 1.081)	*0.8014*
	Proportion of HHs with latrines	1.002 (0.980, 1.025)	*0.8477*
	Proportion of HHs with FL	0.995 (0.972, 1.019)	*0.6714*
100	# latrines	0.975 (0.947, 1.004)	*0.0849*‡
	# FL	0.988 (0.933, 1.046)	*0.6751*
	Proportion of HHs with latrines	1.0002 (0.978, 1.022)	*0.9961*
	Proportion of HHs with FL	1.0002 (0.974, 1.028)	*0.9909*
200	# latrines	0.979 (0.953, 1.006)	*0.1195*
	# FL	1.014 (0.958, 1.074)	*0.6249*
	Proportion of HHs with latrines	1.008 (0.986, 1.032)	*0.4662*
	Proportion of HHs with FL	1.009 (0.978, 1.041)	*0.5665*

Table 17. Univariate logistic regressions adjusted for village-level clustering with Generalized Estimating Equations (GEE) for soil-transmitted helminth (STH) infection prevalence and latrine density predictors at varying distances. † = Pr > |*r*| is significant at a 95% confidence level (p<0.05), ‡ = Pr > |*r*| is significant at a 90% confidence level (p<0.10), HH = household, FL = functional latrine, CI = confidence interval.

Distance (m)	**Latrine Density Predictor**	**Odds Ratio (95% CI)**	***Pr* > |Z|**
25	# latrines	0.903 (0.819, 0.994)	*0.0380*†
	# FL	0.904 (0.738, 1.106)	*0.3258*
	Proportion of HHs with latrines	1.011 (0.996, 1.026)	*0.1410*
	Proportion of HHs with FL	1.008 (0.991, 1.025)	*0.3449*
50	# latrines	0.976 (0.929, 1.026)	*0.3427*
	# FL	0.978 (0.870, 1.099)	*0.7060*
	Proportion of HHs with latrines	1.003 (0.981, 1.026)	*0.7832*
	Proportion of HHs with FL	0.992 (0.962, 1.023)	*0.6019*
100	# latrines	0.975 (0.946, 1.004)	*0.0910*‡
	# FL	0.981 (0.911, 1.056)	*0.6068*
	Proportion of HHs with latrines	1.001 (0.980, 1.023)	*0.9382*
	Proportion of HHs with FL	0.999 (0.967, 1.031)	*0.9351*
200	# latrines	0.978 (0.952, 1.006)	*0.1216*
	# FL	1.012 (0.947, 1.081)	*0.7318*
	Proportion of HHs with latrines	1.009 (0.987, 1.031)	*0.4467*
	Proportion of HHs with FL	1.009 (0.975, 1.044)	*0.3212*

Table 18. Multivariate logistic regressions adjusted for village-level clustering with Generalized Estimating Equations (GEE) for soil-transmitted helminth (STH) infection prevalence and latrine density predictors at varying distances. This model controlled for two covariates: household population and functional latrine ownership. † = Pr > |*r*| is significant at a 95% confidence level (p<0.05), ‡ = Pr > |*r*| is significant at a 90% confidence level (p<0.10), HH = household, FL = functional latrine, CI = confidence interval.

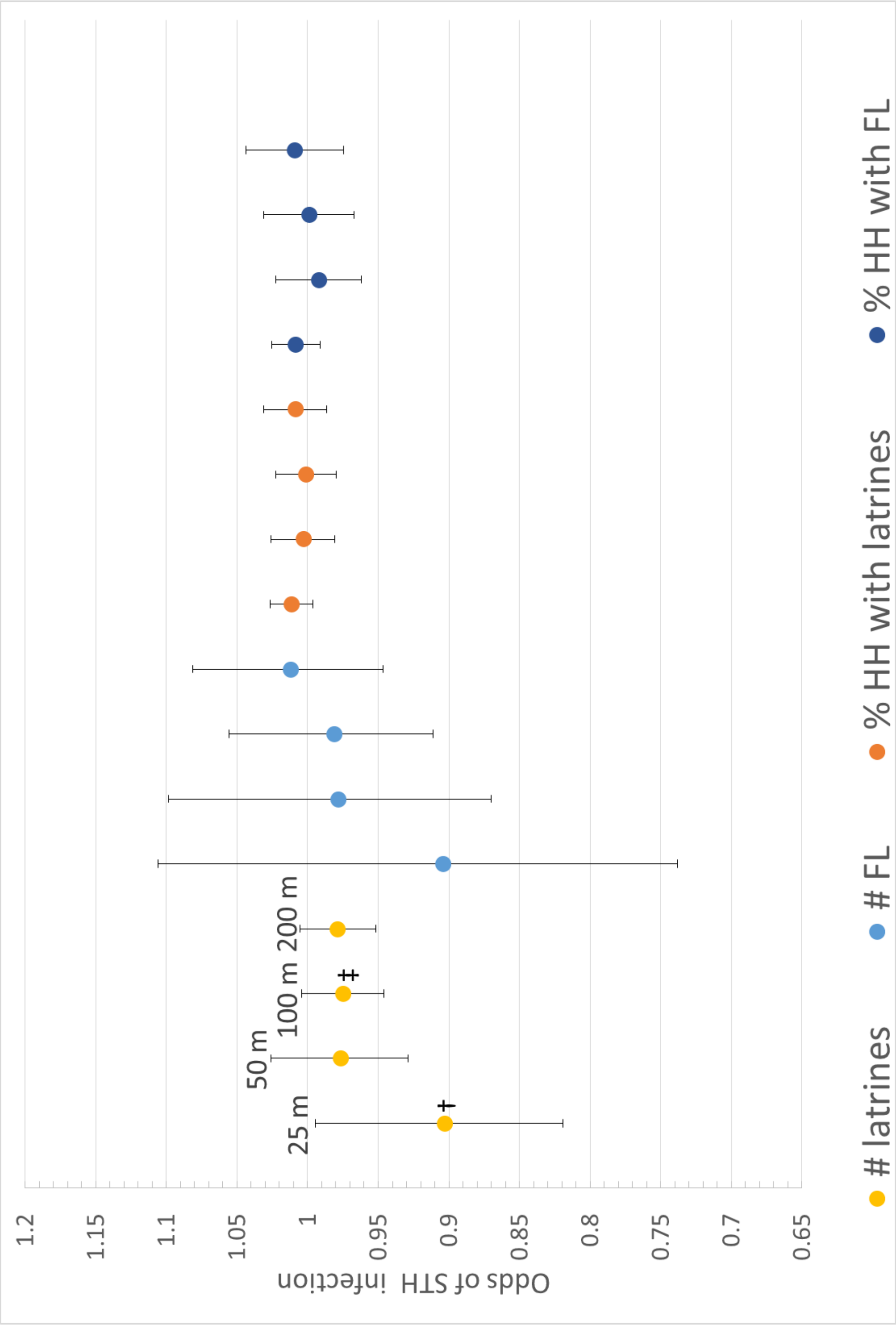

Figure 3. Adjusted estimates from multivariate logistic regression soil-transmitted helminth (STH) infection prevalence (Table 18). Error bars are 95% confidence intervals. † = Pr > |*r*| is significant at a 95% confidence level ($p<0.05$), ‡ = Pr > |*r*| is significant at a 90% confidence level ($p<0.10$), HH = household, FL = functional latrine.

Diarrhea among all household members

Of households surveyed for diarrhea prevalence (N=1,275), 27% reported no days of diarrhea among any household members during the 7-days prior to any surveillance visit. Of those households with no reported diarrhea, 55% owned functional latrines (odds ratio of diarrhea given functional latrine ownership was insignificant in OpenEpi.com). Average longitudinal diarrhea prevalence was 8.34 days of diarrhea among all household members per 1,000 person days (Table 19).

HH longitudinal diarrhea prevalence per 1,000 person days

mean (SD)	min	max
8.34 (11.06)	0	87.72

Table 19. Average household longitudinal diarrhea prevalence (N=1,275 households). HH = household, SD = standard deviation.

Bivariate correlations show significant negative associations between the proportion of households with functional latrines within 25 m, 50 m, 100 m, and 200 m and household longitudinal diarrhea prevalence ($p<0.05$), with the strongest effect occurring within 25 m (Table 20). The number of all latrines, whether functional or not, was positively associated with diarrhea prevalence at 25 m ($p<0.05$) and 50 m ($p<0.10$). The proportion of households with any latrine, however, was associated with decreased diarrhea prevalence ($p<0.05$).

Results were similar after adjustment for village-level clustering with GEE univariate models. The proportion of households with functional latrines within all distances was still negatively associated with diarrhea prevalence ($p<0.05$), but the strongest effect was now seen within 200 m (Table 21). For every 10% increase in the proportion of functional latrines within 200 m, household longitudinal diarrhea prevalence decreased by 0.91 (p=0.006) days of diarrhea per 1,000 person days.

Bivariate correlations suggested that household population and functional latrine ownership were significantly correlated with lower diarrhea prevalence (p<0.0001) (Table 20). Household population was always a significant predictor in multivariate models, but was negatively correlated with diarrhea prevalence. We might expect the contrary, since more people in a household should increase the opportunity for person-to-person transmission. Functional latrine ownership, however, was almost never a significant predictor of diarrhea prevalence when included in adjusted multivariate models with household population and individual latrine density predictors. Owning a functional latrine was only significantly associated with about one fewer day of diarrhea per 1,000 person days when included in the model for the number of functional latrines within 25 m (p<0.05). For every additional 10 latrines, regardless of functionality, within 25 m, there was a notable increase of 2.13 diarrhea days per 1,000 person days (p=0.044) (Table 22) (Figure 4).

Distance (m)	**Latrine Density Predictor**	**Pearson Correlation Coefficient**	***Pr* > |*r*|**
25	# latrines	0.086	*0.0020*†
	# FL	0.013	*0.6333*
	Proportion of HHs with latrines	-0.092	*0.0010*†
	Proportion of HHs with FL	-0.089	*0.0016*†
50	# latrines	0.053	*0.0606*‡
	# FL	-0.007	*0.8098*
	Proportion of HHs with latrines	-0.080	*0.0044*†
	Proportion of HHs with FL	-0.087	*0.0019*†
100	# latrines	0.026	*0.3565*
	# FL	-0.011	*0.6952*
	Proportion of HHs with latrines	-0.043	*0.1211*
	Proportion of HHs with FL	-0.065	*0.0203*†
200	# latrines	0.012	*0.6665*
	# FL	-0.029	*0.3004*
	Proportion of HHs with latrines	-0.037	*0.1826*
	Proportion of HHs with FL	-0.078	*0.0051*†
Potential Confounding Covariates	HH population	-0.298	<*.0001*†
	Functional latrine ownership	-0.066	<*.0001*†

Table 20. Unadjusted bivariate linear correlations between household longitudinal diarrhea prevalence and latrine density predictors at varying distances. † = Pr > |*r*| is significant at a 95% confidence level ($p<0.05$), ‡ = Pr > |*r*| is significant at a 90% confidence level ($p<0.10$), HH = household, FL = functional latrine.

Distance (m)	Latrine Density Predictor	EWC	GEE Beta Estimate (95% CI)	*Pr* > |Z|
25	# latrines	0.028	0.279 (0.063, 0.494)	*0.0112*†
	# FL	0.031	0.071 (-0.368, 0.510)	*0.7519*
	Proportion of HHs with latrines	0.028	-0.044 (-0.068, -0.020)	*0.0003*†
	Proportion of HHs with FL	0.029	-0.042 (-0.069, -0.016)	*0.0016*†
50	# latrines	0.030	0.101 (-0.033, 0.234)	*0.1400*
	# FL	0.032	-0.029 (-0.286, 0.229)	*0.8283*
	Proportion of HHs with latrines	0.030	-0.053 (-0.090, -0.016)	*0.0047*†
	Proportion of HHs with FL	0.029	-0.059 (-0.093, -0.025)	*0.0006*†
100	# latrines	0.032	0.042 (-0.034, 0.118)	*0.2752*
	# FL	0.031	-0.011 (-0.174, 0.151)	*0.8923*
	Proportion of HHs with latrines	0.030	-0.031 (-0.086, 0.025)	*0.2772*
	Proportion of HHs with FL	0.028	-0.053 (-0.102, -0.004)	*0.0357*†
200	# latrines	0.033	0.026 (-0.030, 0.082)	*0.3571*
	# FL	0.031	-0.052 (-0.181, 0.078)	*0.4318*
	Proportion of HHs with latrines	0.030	-0.034 (-0.108, 0.041)	*0.3752*
	Proportion of HHs with FL	0.028	-0.091 (-0.155, -0.026)	*0.0059*†

Table 21. Univariate linear regressions adjusted for village-level clustering with Generalized Estimating Equations (GEE) for household longitudinal diarrhea prevalence and latrine density predictors at varying distances. † = Pr > |*r*| is significant at a 95% confidence level ($p<0.05$), EWC = exchangeable working correlation, HH = household, FL = functional latrine, CI = confidence interval.

Distance (m)	Latrine Density Predictor	EWC	GEE Beta Estimate (95% CI)	*Pr* > |Z|
25	# latrines	0.030	0.213 (0.006, 0.420)	*0.044*†
	# FL	0.031	0.242 (-0.199, 0.682)	*0.2823*
	Proportion of HHs with latrines	0.030	-0.034 (-0.057, -0.012)	*0.0032*†
	Proportion of HHs with FL	0.031	-0.014 (-0.055, -0.001)	*0.0404*†
50	# latrines	0.032	0.090 (-0.037, 0.216)	*0.1655*
	# FL	0.032	0.087 (-0.168, 0.343)	*0.5043*
	Proportion of HHs with latrines	0.031	-0.038 (-0.073, -0.003)	*0.0349*†
	Proportion of HHs with FL	0.031	-0.033 (-0.069, 0.002)	*0.0643*‡
100	# latrines	0.033	0.042 (-0.030, 0.113)	*0.2497*
	# FL	0.032	0.064 (-0.092, 0.220)	*0.4223*
	Proportion of HHs with latrines	0.031	-0.016 (-0.066, 0.034)	*0.529*
	Proportion of HHs with FL	0.032	-0.014 (-0.063, 0.036)	*0.5938*
200	# latrines	0.036	0.035 (-0.015, 0.084)	*0.1711*
	# FL	0.032	0.005 (-0.108, 0.118)	*0.9350*
	Proportion of HHs with latrines	0.031	-0.029 (-0.097, 0.038)	*0.3931*
	Proportion of HHs with FL	0.031	-0.056 (-0.114, 0.003)	*0.0649*‡

Table 22. Multivariate linear regressions adjusted for village-level clustering with Generalized Estimating Equations (GEE) for household longitudinal diarrhea prevalence and latrine density predictors at varying distances. This model controlled for two covariates: household population and functional latrine ownership. † = Pr > |*r*| is significant at a 95% confidence level (p<0.05), ‡ = Pr > |*r*| is significant at a 90% confidence level (p<0.10), EWC = exchangeable working correlation, HH = household, FL = functional latrine.

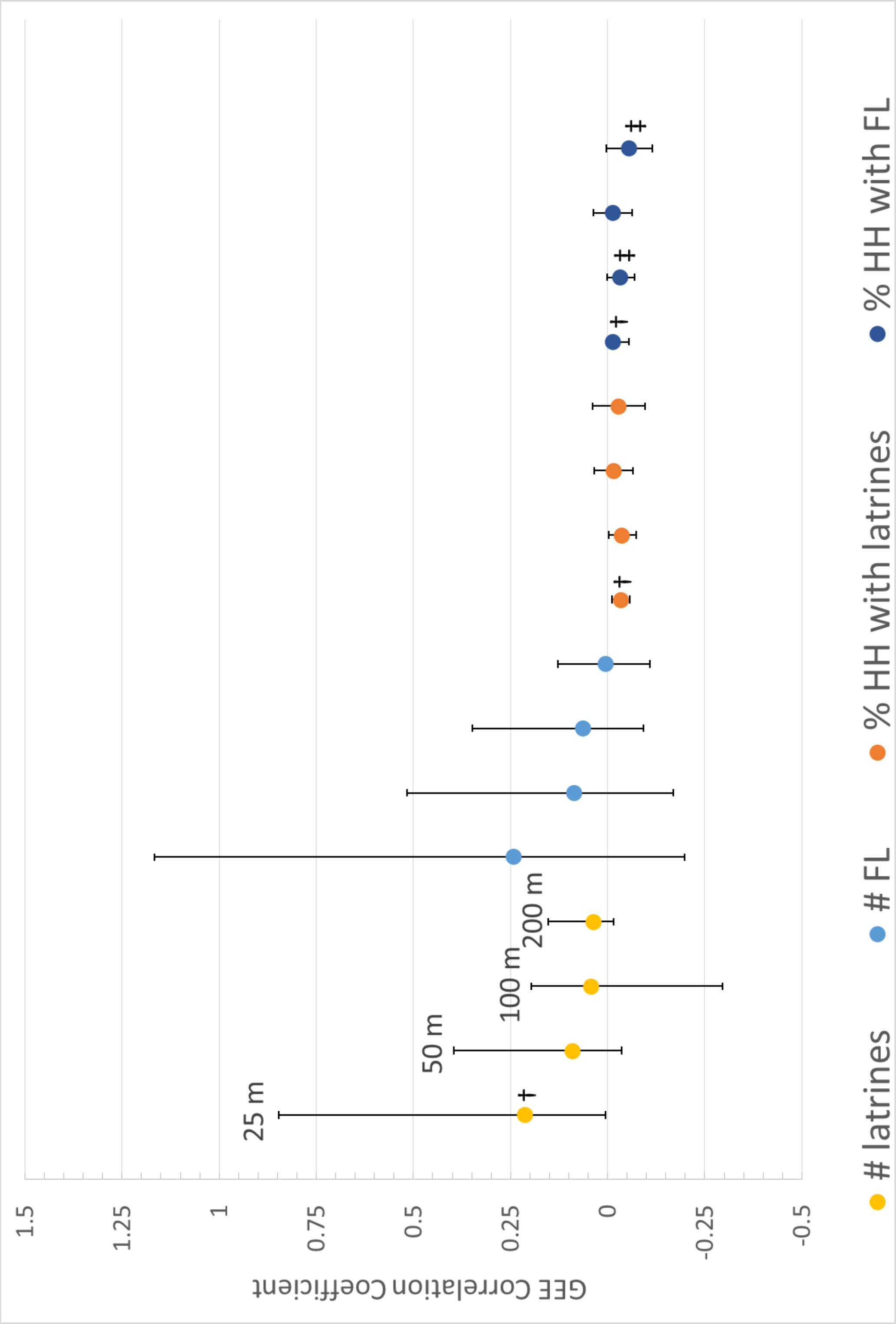

Figure 4. Adjusted estimates from multivariate linear regression for mean household longitudinal diarrhea prevalence (Table 22). Error bars are 95% confidence intervals. † = Pr > |*r*| is significant at a 95% confidence level (p<0.05), ‡ = Pr > |*r*| is significant at a 90% confidence level (p<0.10), HH = household, FL = functional latrine.

Diarrhea among children under five

Among all households with children under the age of 5 (N=1,017), 26% of households had zero days of caregiver-reported child diarrhea. Among households without any child diarrhea days, 53% owned functional latrines (odds ratio of child diarrhea given functional latrine ownership was insignificant in OpenEpi.com). Household longitudinal diarrhea prevalence was much higher among children under five, with an average of 47.3 diarrhea days per 1,000 person days (Table 23).

HH longitudinal diarrhea prevalence per 1,000 person days (children >5)

mean (SD)	min	max
47.3 (5.37)	0	415.3

Table 23. Average household longitudinal diarrhea prevalence among children under five (N=1,017 households). HH = household, SD = standard deviation.

The proportion of households with functional latrines within 25 m ($p<0.05$), 50 m ($p<0.05$), and 200 m ($p<0.10$) were the only latrine density predictors significantly associated with a decrease in child diarrhea prevalence in bivariate correlations (Table 24). After adjustment for village-level clustering with GEE univariate regressions, the proportion of households with functional latrines was still a significant predictor of child diarrhea prevalence, but only within 25 m and 50 m ($p<0.05$) (Table 25). For every 10% increase in the proportion of functional latrines within 50 m, household longitudinal diarrhea prevalence among children under five decreased by 23.5 diarrhea days per 1,000 person days ($p=0.014$) prior to controlling for covariates.

The number of children in a household and functional latrine ownership were significantly correlated with lower child diarrhea prevalence at a 90% confidence level in bivariate correlations (Table 24). We included these in multivariate adjusted models, excluding household population because it was not associated with child diarrhea, and was correlated with household population. Including multiple covariates that capture household population would be redundant. In multivariate adjusted regressions, owning a functional latrine was associated with having from 3 to 6 fewer diarrhea days (per 1,000 person days, $p<0.10$) despite the number or proportion of all latrines (regardless of functionality) within any distance. Owning a functional latrine was associated with having from 6 to 8 fewer diarrhea days (per 1,000 person days, $p<0.05$) despite the number of functional latrines at 25 m, 100 m, or 200 m. This was the only outcome variable for which functional latrine ownership was a significant predictor. The number of children per household was consistently a significant predictor in multivariate regressions, associated with increased longitudinal prevalence of childhood diarrhea.

After controlling for functional latrine ownership and the number of children per household, the proportion of functional latrines within 50 meters was only significant at a 90% confidence level (Figure 5). A 10% increase in functional latrine coverage within 50 meters was still estimated to reduce child diarrhea days by over 17 diarrhea days per 1,000 person days ($p=0.093$) (Table 26). The proportion of households with any latrine became a significant predictor in the adjusted model, with an estimated reduction in childhood diarrhea of 12 diarrhea days per 1,000 person days given a 10% increase in coverage ($p=0.098$).

Distance (m)	**Latrine Density Predictor**	**Pearson Correlation Coefficient**	***Pr* > |*r*|**
25	# latrines	0.048	*0.1256*
	# FL	-0.001	*0.9759*
	Proportion of HHs with latrines	-0.051	*0.1073*
	Proportion of HHs with FL	-0.065	*0.0395*†
50	# latrines	0.023	*0.4678*
	# FL	-0.019	*0.5374*
	Proportion of HHs with latrines	-0.043	*0.1734*
	Proportion of HHs with FL	-0.071	*0.0230*†
100	# latrines	0.016	*0.6164*
	# FL	-0.015	*0.6233*
	Proportion of HHs with latrines	-0.019	*0.5447*
	Proportion of HHs with FL	-0.048	*0.1230*
200	# latrines	0.037	*0.2382*
	# FL	-0.001	*0.7595*
	Proportion of HHs with latrines	-0.038	*0.2234*
	Proportion of HHs with FL	-0.060	*0.0539*‡
Potential Confounding Covariates	HH population	-0.043	*0.1750*
	No. children in HH	0.059	*0.0595*‡
	Functional latrine ownership	-0.059	*0.0612*‡

Table 24. Unadjusted bivariate linear correlations between household longitudinal diarrhea prevalence and latrine density predictors at varying distances. † = Pr > |*r*| is significant at a 95% confidence level ($p<0.05$), ‡ = Pr > |*r*| is significant at a 90% confidence level ($p<0.10$), HH = household, FL = functional latrine.

Distance (m)	Latrine Density Predictor	EWC	GEE Beta Estimate (95% CI)	*Pr* > |Z|
25	# latrines	0.019	0.666 (-0.420, 1.752)	*0.2296*
	# FL	0.022	0.0483 (-2.15, 2.24)	*0.9656*
	Proportion of HHs with latrines	0.021	-0.120 (-0.264, 0.024)	*0.1012*
	Proportion of HHs with FL	0.019	-0.150 (-0.295, -0.005)	*0.0432*†
50	# latrines	0.021	0.141 (-0.504, 0.786)	*0.6676*
	# FL	0.022	-0.296 (-1.552, 0.960)	*0.6443*
	Proportion of HHs with latrines	0.021	-0.133 (-0.318, -0.053)	*0.1601*
	Proportion of HHs with FL	0.018	-0.235 (-0.421, -0.048)	*0.0135*†
100	# latrines	0.022	0.067 (-0.327, 0.462)	*0.7381*
	# FL	0.022	-0.144 (-1.027, 0.739)	*0.7486*
	Proportion of HHs with latrines	0.021	-0.047 (-0.316, 0.222)	*0.7314*
	Proportion of HHs with FL	0.019	-0.179 (-0.476, 0.117)	*0.2349*
200	# latrines	0.021	0.185 (-0.101, 0.472)	*0.2050*
	# FL	0.022	-0.083 (-0.723, 0.558)	*0.8000*
	Proportion of HHs with latrines	0.020	-0.174 (-0.476, 0.128)	*0.2593*
	Proportion of HHs with FL	0.017	-0.308 (-0.678, 0.061)	*0.1018*

Table 25. Univariate linear regressions adjusted for village-level clustering with Generalized Estimating Equations (GEE) for household longitudinal diarrhea prevalence (children under five) per 1,000 person days and latrine density predictors at varying distances. † = Pr > |*r*| is significant at a 95% confidence level (p<0.05), EWC = exchangeable working correlation, HH = household, FL = functional latrine, CI = confidence interval.

Distance (m)	Latrine Density Predictor	EWC	GEE Beta Estimate (95% CI)	*Pr* > |Z|
25	# latrines	0.017	0.631 (-0.478, 1.741)	*0.2647*
	# FL	0.019	1.041 (-1.353, 3.434)	*0.3940*
	Proportion of HHs with latrines	0.018	-0.120 (-0.262, 0.022)	*0.0980*‡
	Proportion of HHs with FL	0.018	-0.097 (-0.252, 0.059)	*0.2221*
50	# latrines	0.018	0.141 (-0.516, 0.798)	*0.6735*
	# FL	0.019	0.165 (-1.205, 1.535)	*0.8134*
	Proportion of HHs with latrines	0.018	-0.130 (-0.313, -0.053)	*0.1634*
	Proportion of HHs with FL	0.017	-0.171 (-0.371, 0.029)	*0.0934*‡
100	# latrines	0.019	0.077 (-0.312, 0.465)	*0.6987*
	# FL	0.019	0.152 (-0.765, 1.070)	*0.7447*
	Proportion of HHs with latrines	0.019	-0.052 (-0.321, 0.217)	*0.7039*
	Proportion of HHs with FL	0.018	-0.065 (-0.159, 0.246)	*0.6806*
200	# latrines	0.019	0.179 (-0.101, 0.459)	*0.2096*
	# FL	0.019	0.153 (-0.482, 0.789)	*0.6363*
	Proportion of HHs with latrines	0.017	-0.172 (-0.474, 0.130)	*0.2648*
	Proportion of HHs with FL	0.017	-0.171 (-0.571, 0.229)	*0.4015*

Table 26. Multivariate linear regressions adjusted for village-level clustering with Generalized Estimating Equations (GEE) for household longitudinal diarrhea prevalence (children under five) per 1,000 person days and latrine density predictors at varying distances. This model controlled for two covariates: number of children per household and functional latrine ownership. ‡ = Pr > |*r*| is significant at a 90% confidence level (p<0.10), EWC = exchangeable working correlation, HH = household, FL = functional latrine.

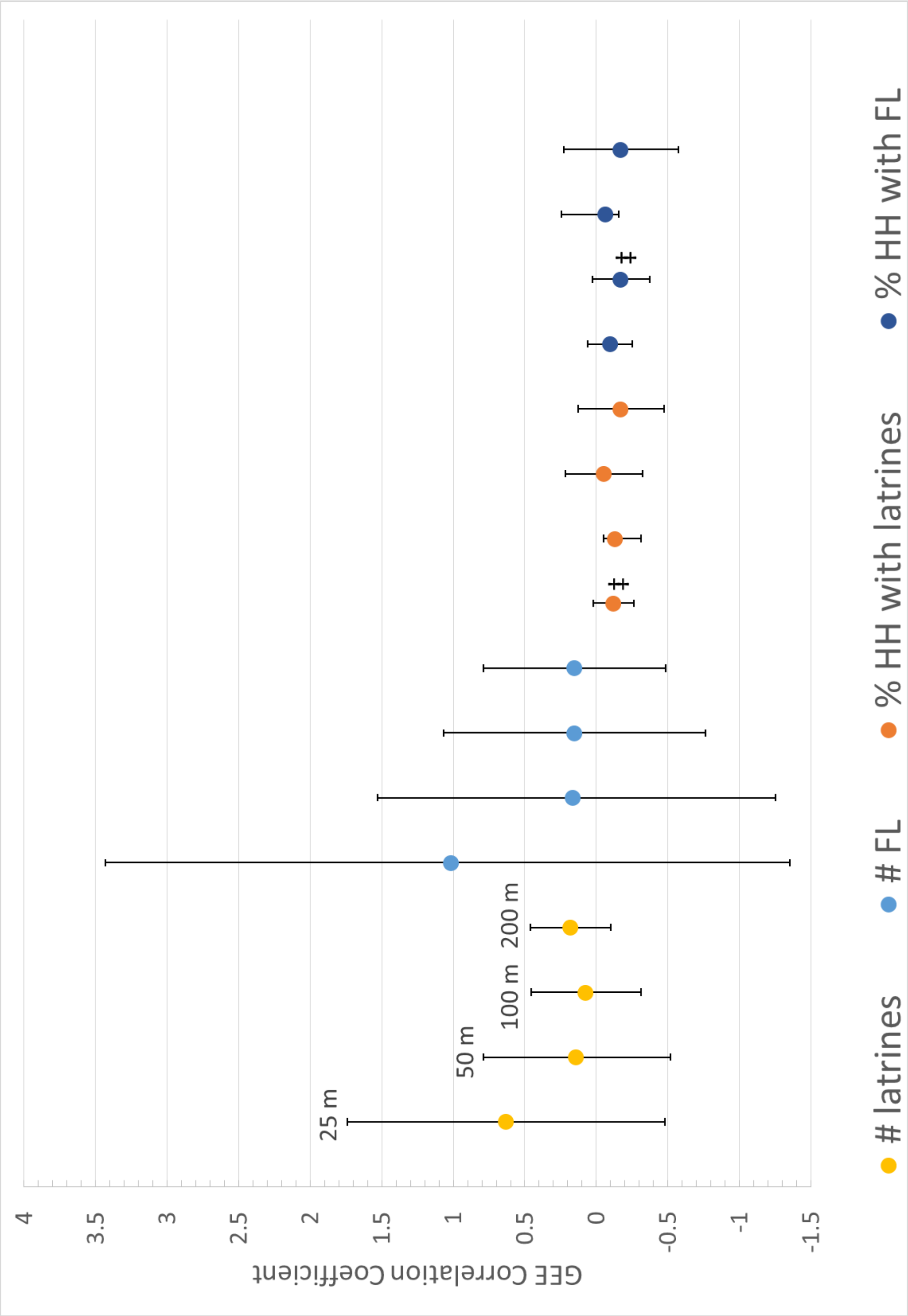

Figure 5. Adjusted estimates from multivariate linear regression for mean household longitudinal diarrhea prevalence among children >5 (Table 26). Error bars are 95% confidence intervals. ‡ = Pr > |*r*| is significant at a 90% confidence level ($p<0.10$), HH = household, FL = functional latrine.

V. DISCUSSION

The purpose of this study was to identify environmental health impacts of different measures of latrine density within a fine spatial scale. Despite the fecal-oral and skin contact exposure routes, which require close contact between humans and fecal contamination in the environment, latrine coverage and its associated outcomes have predominantly been assessed at village, district, or national levels (Tables 2 and 3). This is the first study to apply a multiple ring buffer analysis to assess latrine coverage within various distances from households. This research sheds light on the localized health impacts of latrine coverage following the TSC in India, which were not apparent when coverage and health data among the same study population were analyzed at the village level (Clasen et al., 2014).

This is also the first study in India to evaluate environmental health impacts of *functional* latrine coverage. The MDGs set the international standard for measuring sanitation coverage as “improved” or “unimproved” (UNICEF & WHO, 2015). Many sanitation facilities that are consider “improved” do not effectively separate human feces from the environment, were poorly constructed or are in disrepair and unlikely to be used (Rheingans, Dreibelbis, & Freeman, 2006; Routray et al., 2015). From a public health perspective, whether or not a latrine meets the Joint Monitoring Program definition of “improved” is arguably less important than if a latrine is considered to be in good enough condition to be used (Rheingans, Dreibelbis, & Freeman, 2006). Because functionality was associated with increased use in a survey of the target population, functional latrine coverage is a more accurate indicator of decreased open defecation than simply coverage of any improved latrine (Barnard et al., 2013).

Less than 2 functional latrines were present within 25 meters of intervention households on average. Low coverage of functional latrines may explain imprecise estimates. Based on the association between functionality and use, and considering the large household populations, it is likely that some household members still practiced open defecation due to the lack of functional facilities nearby (Barnard et al., 2013).

Following the TSC, increased latrine coverage within a fine spatial scale contributed to lower fecal contamination of drinking water. We observed statistically significant negative associations between average thermotolerant coliform (TTC) concentrations and latrine coverage within 200 m or less, regardless of functionality. Despite large confidence intervals surrounding some estimates, more functional latrines within 25 m of the household was associated with the largest decrease in fecal contamination of household drinking water. Based on the estimated reduction in TTC per single unit increase of latrine density predictors (Table 13), we could infer that adding 5 functional latrines within a 25 m radius of a household could potentially reduce household drinking water contamination by 144 cfu per 100 mL.

Soil-transmitted helminth (STH) infections were very rare among the study population, even when aggregating across helminth species and across household members. This limits our ability to detect any changes in prevalence associated with latrine density predictors. Hookworm larvae and *A. lumbricoides* and *T. trichiura* eggs can persist in soil for months (Brooker et al., 2006b). Decreasing open defecation may reduce some STH transmission, but it may not have a detectable effect unless 100% of the local population refrains from practicing open defecation over a prolonged period of time. STH infections are often clustered in space (Tsiko, 2015; Karagiannis-Voules et al., 2015; Chammartin et al., 2013; Ngui et al., 2014; Pullan et al., 2010; Davis et al., 2014; Kaliappan et al., 2013; Rajeshwari, 2008; Santos et al., 2014; Chammartin et al., 2014; Brooker et al., 2006a; Souza et al., 2006). A hot-spot analysis of STH infections given the density of functional latrines may be a better method to assess this association.

A higher number of latrines, regardless of functionality, within 25 m from the home was associated with higher diarrhea prevalence for household members of all ages. Our hypothesis was that functional latrines are more likely to effectively separate feces from the environment because they are cleaner and encourage use. Therefore, it is not unforeseen that an increase in latrines that do *not* effectively and prevent human contact with fecal matter or reduce open defecation would increase the transmission of pathogens. Many non-functioning latrines in a small area may concentrate the amount of fecal matter, increasing the potential for exposure. It is important to note that this same positive association between the number of latrines within 25 m and diarrhea among children was not significant. We suspect that children simply aren't old enough to use a latrine, and thus are not directly exposed to fecal matter in and around the latrine.

The large confidence intervals around the number of functional latrines, particularly within 25 m, were consistent across multivariate models. As previously mentioned, if a household owns a functional latrine, it may be the only functional latrine within 25 m. The overlap between these two predictor variables within 25 m may explain the significance of functional latrine ownership at this distance, alone, as well as imprecise estimates in the multivariate models.

Whether or not individual households owned a functional latrine was not a consistently significant predictor of any outcome variable *except* diarrhea among children under five. This may reflect the fact that young children, particularly infants and toddlers, do not leave the household compound often. Infants and toddlers do, however, crawl around the household; eating soil or putting their hands in their mouths after crawling on the ground increases their exposure to fecal matter in and around the home (Ngure et al., 2013). If members living in that household do not own a functional latrine, perhaps they are more likely to practice open defecation near the home (especially if one or more household members is elderly and/or disabled) (Routray et al., 2015). This would increase the level of fecal contamination of the soil in the immediate household environment, where children may spend the most time, leading to an increased risk of exposure. For these reasons, it is not surprising that owning a functional latrine significantly decreased diarrhea among children, in particular.

The TSC aimed to decrease open defecation and increase latrine coverage, but decreasing open defecation does not address all sanitation-related disease transmission pathways. There was no programmatic focus on removing animal or child feces from the community or household environment. It is likely that these alternative transmission pathways are contributing to fecal contamination and disease in the study population. Other interventions that improve water supply and availability, increase accessibility to handwashing materials, and promote hygiene behavior change address additional transmission pathways to reduce adverse health impacts (Table 1). Sanitation-focused interventions like the TSC may not be sufficient to dramatically reduce diarrhea and STH prevalence.

We assumed that functionality is a proxy for latrine use, which, in turn, equates to reduced open defecation. Based on this logic, increased functional latrine coverage should decrease fecal matter in the environmental and reduce human exposure to pathogens. Latrine functionality has been previously associated with improved health outcomes, such as reduced trachoma and childhood diarrhea in Ethiopia (Ejigu et al., 2013; Anteneh & Kumie, 2010). Latrine functionality may not, however, be the best predictor of use. This is especially true in this population given the cultural context; the lack of adequate water supply necessary for post-defecation cleansing rituals is a pervasive barrier to latrine uptake (Routray et al., 2015). Water availability near latrines was, in fact, associated with lower odds of childhood diarrhea among a culturally similar population in Malaysia, while latrine functionality itself was not associated with improved child health (Knight et al., 1992).

Finally, our method of calculating the proportion of latrines or functional latrines may be flawed in that it does not reflect the density of all households in a given distance. In other words, 50% of households owning functional latrines could mean one of two households, or ten of twenty households. We would expect that if at least one member per household were practicing open defecation, one household within 25 m would contaminate the environment much less than twenty households within 25 m. In realizing this limitation after the analysis, multivariate models were ran again, this time including the total number of households within each buffer as a covariate (data not presented). Household density was not a significant predictor for any outcome variables.

VI. CONCLUSIONS & RECOMMENDATIONS

Future evaluations of sanitation programs should consider assessing localized impacts rather than village-level impacts given the transmission pathways of sanitation-related diseases. While we were unable to determine a distance threshold in which functional latrine coverage is always protective of adverse health outcomes, it is clear that increasing functional latrine coverage could improve environmental health in rural India. Protective effects were associated with increased coverage among neighbors within less than 200 m from the home. Perhaps more critical is ensuring that all latrines are functional. This is especially important due to the potential increase in diarrhea prevalence associated with high latrine density in a 25 m radius. One or two homes without a functional latrine can adversely impact the health of their immediate neighbors. Consequently, it is imperative that sanitation programs achieve and maintain 100% coverage.

Moving forward with the Sustainable Development Goals, the United Nations and World Health Organization are shifting their sanitation target from merely increasing coverage to "[achieving] access to adequate and equitable sanitation and hygiene for all and [ending] open defecation" by 2030 (UN, 2015). This research supports the theory that universal coverage of functional, properly maintained sanitation coverage is necessary to improve environmental health.

VII. REFERENCES

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