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I get height with a little help from my friends: Herd protection from sanitation on child growth in rural Ecuador.

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Background-Infectious disease interventions, such as vaccines and bednets, have the potential to provide herd protection to non-recipients. Similarly, improved sanitation in one household may provide community-wide benefits if it reduces contamination in the shared environment. Sanitation at the household-level is an important predictor of child growth, but less is known about the effect of sanitation coverage in the community.

Methods-From 2008 to 2013, we took repeated anthropometric measurements on 1,314 children under five years of age in 24 rural Ecuadorian villages. Using mixed effects regression, we estimate the association between sanitation coverage in surrounding households and child growth.

Results-Sanitation coverage in the surrounding households was strongly associated with child height, as those with 100% coverage in their surroundings had a 67% lower prevalence of stunting (prevalence ratio [PR] 0.32, 95%CL 0.15-0.69) compared to those with 0% coverage. Children from households with improved sanitation had a lower prevalence of stunting (PR 0.86, 95%CL 0.64-1.15). When analyzing height as a continuous outcome, the protective effect of sanitation coverage is manifested primarily among girls during the second year of life, the time at which growth faltering is most likely to occur.

Conclusions-Our study highlights that a household's sanitation practices can provide herd protection to overall community. Studies which fail to account for the positive externalities that sanitation provides will underestimate the overall protective effect. Future studies could seek to identify a threshold of sanitation coverage, similar to a herd immunity threshold, to provide coverage and compliance targets.

Introduction

Childhood stunting (low height-for-age) affected 26% of children under 5 worldwide in 2011, contributing to over 1 million deaths (1). Childhood stunting is an important risk factor for mortality and outcomes later in life, including behavioral problems, underachievement in school, and chronic diseases such as diabetes (2-5). Child growth is influenced by many factors, including fetal exposures (5), food security (6), micronutrient deficiencies (7), and infections from inadequate access to water, sanitation, and hygiene (8, 9).

Increasing evidence suggests that a poor sanitation environment leads to not only diarrhea (10-12) and helminth infection (13) but also persistent exposure to pathogens responsible for environmental enteropathy (14-16), a chronic subclinical infection of the gut characterized by atrophy of the intestinal villi and decreased absorptive capacity (17). All three of these conditions reduce nutrient absorption and promote an immune response that increases energy expenditure, resulting in slower growth.

Most studies of sanitation and nutrition have focused on the sanitation environment of the household (8, 9, 18, 19), ignoring any effect of neighboring households. Increasing evidence suggests that sanitation can provide positive externalities, i.e. herd protection, whereby improved sanitation in one household prevents infection in nearby households by reducing contamination of the shared environment (20-26). We undertook a longitudinal study to estimate the effect of sanitation at the household and neighborhood level on child growth. We assessed the existence of general herd protection, defined as a partial reduction in risk due to reduced exposure levels in the surrounding population, and the existence of a herd protection threshold, defined as a particular level of exposure that results in the total elimination of risk (27).

Methods

Study Population

The study took place in 24 rural villages in the Esmeraldas province of northwestern Ecuador. These villages lie along several river systems near the town of Borbón, and many are still not accessible by road. The population is predominantly Afro-Ecuadorian, though some villages have high numbers of Chachis, an indigenous group. Between December 2008 and July 2013, each village was visited four times. The study design can be considered a repeated cross-section of all households and individuals, but longitudinal in the sense that individuals and households can be followed across study visits. More details of this population and the study design have been published previously (28).

Anthropometry

Anthropometric data was collected from all children under 5 years of age at each of the study visits. Age in days was calculated by the difference in date of measurement and the date of birth. At each study visit, standing height was measured by a trained nurse for all children that could walk (typically greater than

12 months of age) using a Seca mechanical measuring tape (model 206, Hamburg, Germany). For children that could not walk, length was measured using a Seca mobile measuring mat (model 210). Height-for-age z scores (HAZ) were calculated using World Health Organization Standards (29, 30). The z scores are standardized by age in days and sex. Observations were excluded if a z score was >6 or <-6. A binary indicator for moderate or severe stunting was created based on Z scores of less than -2. Chachi children were excluded from the analysis because their anthropometry was substantially different from that of other children.

Sanitation Variables

Concurrently with anthropometry, sanitation information was collected for each household during each of the 4 study visits. In this population we observed a full range of sanitation options, namely flush and pour-flush toilets, pit latrines with and without a washable slab, pit latrines with and without a seat (pit latrines without seats are typically open holes), and households that used no facilities. We classified each household's sanitation access as unimproved (no facility, pit latrine without a slab, pit latrines without a seat) or improved (pit latrines with a slab and seat, pour-flush and flush toilets). Though this classification is widely used in the sanitation sector, we also classified each household as either having any sanitation or no sanitation. However, too few households in this population practice open defecation, making it difficult to assess its impact (see Supplemental Materials). No data was available on compliance or the frequency of use. During each visit, the GPS location of the household was recorded or verified. For each household at each study visit, sanitation coverage was calculated as the proportion of households within a 500-meter radius that had improved sanitation. Other distances were considered (e.g., 250, 750, and 1000 meters, see Supplemental Materials), but had little impact on the results. We selected 500 meters based on the housing density and size of the villages.

Covariates

During each study visit, information was also gathered on educational attainment, asset ownership, and housing construction. For each household, the maximum number of years of completed education of any person was used. Principal components analysis was used to create a wealth index for each household for each visit based on the following variables: house tenancy, house construction, roof material, floor material, source of lighting, source of drinking water, and ownership of assets (television, stove, refrigerator, blender, stereo, DVD player, computer, washing machine, solar panel, generator, bicycle, motorcycle, car, canoe, cell phone, chainsaw, business, farm, cattle). From this index, we then created wealth quintiles (see the Supplemental Materials for more details on the construction of the wealth index). For each household, we also calculated the mean wealth index of other households within 500 meters. Based on the assumption that wealth and sanitation practices are relatively stable over time, missing data on sanitation and wealth were imputed using values from previous or later study visits. Anthropometric data was not imputed.

Ethnography

Throughout the study period, ethnographic observations were led by a full-time anthropologist who had resided in the study area for approximately 20 years. Focused observations and interviews related to sanitation, breastfeeding, and other health-related behaviors were conducted at each study visit and lasted for 2 to 7 days per village. Extended visits were also conducted with anthropologists spending 1 to 8 weeks in a village at a time. Field notes and digitally recorded interviews were subsequently transcribed and maintained in a Spanish textual database where they were coded and retrievable for analysis.

Ethical Approval

Informed assent was obtained from a guardian of each child before anthropometric measures were taken. Key informants in each household provided informed consent before providing household information. All study protocols were approved by institutional review board committees at the University of Michigan, Trinity College, and Universidad San Francisco de Quito.

Statistical Analysis

Bivariate relationships were examined separately for each study visit. Pearson's chi-square test was used to test the association of stunting prevalence across levels of categorical variables. Because enteric pathogens are often transmitted through the environment, we sought to control for spatial clustering. We assessed spatial correlation between households by running linear mixed models with HAZ as the dependent variable and constructing empirical semivariograms of the residuals. We then re-ran these models including an exponential spatial covariance function, where observations close in space will be more correlated than those far away. This approach accounts for clustering of children in the same household and similarities among children in neighboring households. These spatial models showed little evidence of spatial correlation, had a higher Akaike Information Criterion (AIC), and had similar regression coefficients compared to models without spatial covariance (see Supplemental Materials). As a result, we opted to use simpler models without spatial covariance.

A series of mixed effects Poisson regressions (Models 1-4) was used to model the association between sanitation and the prevalence of moderate or severe stunting (HAZ < -2) across all study visits. To account for multiple observations on the same children over time, these models include a random intercept for each child. The exponentiated coefficients of these models can be interpreted as a prevalence ratio (PR). Models 3 and 4 compare the prevalence of moderate stunting among children from areas with 100% coverage to areas with 0% coverage, and thus show the maximum potential impact of sanitation coverage. Because this amount of change in sanitation coverage is unrealistic, we also present the prevalence ratio associated with a two standard deviation (36.3 percentage points) change in coverage. This type of standardized regression coefficient can be directly compared with the prevalence ratio for the binary household sanitation variable to assess their relative importance (31).

In additional analyses, we examined the association between sanitation and linear growth using height as a continuous outcome. Growth curves were estimated using mixed effects linear regression with height in centimeters as the dependent variable. Age was included in the model as a restricted cubic spline with knots at 0.5, 1, 1.5, 2.5, and 4 years. These models account for repeat observations over time by including a random intercept for each child and a random slope for the linear age term for each child. Because environmental conditions may affect the growth of boys and girls differently, the growth curve models include a 3-way interaction between the age terms, sanitation coverage and sex. This allows boys and girls to have distinct growth curves, and for the effect of sanitation coverage to vary by age.

Our final analysis involves predicting the prevalence of moderate or severe stunting with sanitation coverage included as a categorical variable, based on 10 percent increments. This allows for the detection of non-linearity in the association between sanitation and height, which may suggest a threshold effect. An upper threshold would exist if sufficient coverage can interrupt transmission of enteric pathogens. This is analogous to the concept of a herd immunity threshold of vaccination coverage, above which additional vaccination provides little community benefit. A lower threshold would exist if a critical mass were required before any community effect is observed. This model includes all covariates in the previous analyses and a random intercept for each child. All statistical analysis was conducted using the lme4 (32) and nlme (33) packages in R version 3.0.2.

Results

Summary Statistics

The study population contained of 1,618 children for a total of 2,692 observations. 39 (1.4%) of these observations were missing data on either height, the child's age, or the child's sex, making it impossible to calculate the HAZ. Of those with a calculated HAZ, 64 (2.4%) observations had extreme values (HAZ >6 or < -6). An additional 366 (14.1%) observations were missing data on either a household or neighborhood covariate, resulting in a final sample of 1,314 children for a total of 2,223 observations. 672 children were observed during only 1 study visit, 409 children were observed twice, 200 children were observed three times, and 33 children were observed during all 4 study visits.

Approximately 75% children were from households with an improved sanitation facility. Sanitation coverage within 500 meters of households varied from 0% to 100%, though only 8% of children were from households with < 50% coverage (Figure 1).

(Figure 1 here)

Table 1 shows the bivariate associations between moderate stunting (height-for-age Z score < -2) and each covariate of the study. Overall, the prevalence of moderate stunting was ranged from 12.1% in the 3rd study visit to 14.3% in the 1st visit In all 4 study visits, stunting was more common among children from households with unimproved sanitation than those from households with improved sanitation. The prevalence of stunting tended to be inversely associated with sanitation coverage in surrounding households, with the lower quintiles of coverage having the highest prevalence of stunting, with the exception of the 1st study visit. Stunting was also more common among males than females, though the difference narrowed in the 4th study visit.

(Table 1 here)

Stunting

Children from households with improved sanitation had a 26% lower prevalence (PR 0.74, 95%CL 0.57-0.98) of being moderately or severely stunted compared to those from households without improved sanitation (Table 2, Model 1). After adjusting for household and child characteristics, this protective association was unchanged (Table 2, Model 2). There was a clear non-linear association between age and stunting, where the prevalence of stunting was lowest in the first year of life, highest in the second year, and remained high but gradually decreased for the remaining years. We also observed that the prevalence of stunting was 40% higher (PR 1.40, 95%CL 1.09-1.81) among male children compared to females. Household wealth quintile and education were not associated with stunting.

(Table 2 here)

Sanitation coverage within 500 meters of the household was a much stronger predictor of stunting than the household's own sanitation status. The prevalence of stunting was 63% lower (PR 0.37, 95%CL 0.20-0.69) among children from areas with 100% coverage compared to children from areas with 0% coverage (Table 2, Model 3). Adjusting for characteristics of the child, household, and neighborhood increased the point estimate (PR = 0.32, 95%CL 0.15-0.69) (Table 2, Model 4). After accounting for sanitation coverage, however, the association between household sanitation and stunting was attenuated (PR 0.86, 95%CL 0.64-1.15). A two standard deviation change in sanitation coverage (36.3 percentage points) was associated with a 34% reduction in moderate stunting (PR 0.66, 95%CL 0.50-0.87). Stunting was still associated with both the age and the sex of the child.

Growth Curves

During the first year of life, children in this cohort were on average equal to the WHO standard population (Figure 1). During the second year of life, however, growth stalled, leading to 3.0 and 3.9 cm deficits by age 24 months among girls and boys, respectively. These deficits mostly persisted up to 5 years of age.

(Figure 2 here)

Girls with 100% sanitation coverage in their vicinity were taller than those with 0% coverage. At 2 years of age, girls in areas with 100% coverage were 4.9 cm ($p<0.01$) taller than girls from areas with 0% coverage. Among boys, however, there appeared to be no association between sanitation coverage and growth.

Threshold Analysis

In order to detect a possible threshold, we also ran a model with sanitation coverage included as a categorical variable based on 10 percent increments. The prevalence of stunting was highest (42%) among children from areas with 0 to 10% sanitation coverage and decreased with higher levels of coverage (Figure 3). Beyond

31 to 40% coverage, however, there seemed to be no additional benefit from living in an area with greater sanitation coverage (upper threshold). Our study, however, included relatively few children in areas with low sanitation coverage, resulting in a large degree of statistical uncertainty.

(Figure 3 here)

Discussion

This is the first longitudinal study showing an association between sanitation coverage in the community and child growth. The association between stunting and improved sanitation at the household was modest, but it was eclipsed by the much stronger association of sanitation coverage in the surrounding households. Had we only accounted for household sanitation as many studies do, we would have drastically underestimated the overall benefit of sanitation. Cluster randomized trials capture both the household and the community effects of sanitation, and thus will not result in an underestimate. Such studies, however, typically do not separate the effects of household access from the effects of community coverage. Our results show that the benefits of sanitation are shared across the community suggesting that the households that are difficult to reach may be protected by sanitation in neighboring households.

We also sought to identify whether the association with sanitation coverage exhibited a threshold. We saw a slight indication of an upper threshold of sanitation coverage, but our inference was seriously hindered by a small sample at lower levels of coverage. Thus our data could not assess definitively whether a threshold exists or whether incremental increases in coverage lead to incremental increases in nutritional status across all levels of coverage.

Two recent cluster randomized trials (34, 35) in India's Total Sanitation Campaign showed no health gains from improved sanitation. Coverage and/or compliance for each trial was low, and may be at least partially the reason for the null result. The Clasen et al (34) trial achieved 63% coverage in intervention villages compared to 12% in controls, but compliance was remarkably low (39% of latrines were not used by anyone in the household (36)). In the Patil et al (35) study, open defecation among adults was still very high at 73% in intervention villages compared to 84% in control villages. These trials may, therefore, indicate the existence of a critical threshold of coverage and use, below which sanitation interventions have little effect. Our study, conducted in a natural setting as opposed to a sanitation campaign, did not disentangle the concepts of coverage and compliance.

The herd protective effect of sanitation manifested during the second year of life, when a child's growth is most likely to falter (37), suggesting that sanitation can play an important role in prevention. While sanitation showed a strong protective effect, children with the optimal sanitation scenario were still stunted, suggesting the importance of other pathways such as breastfeeding and micronutrients. We also observed important sex differences. First, boys were more likely to be stunted than girls. Based on ethnography that we conducted in our study villages, the duration of breastfeeding in this population is shorter for boys than for girls, possibly leading to better anthropometric outcomes in girls. This finding of female nutritional advantage is consistent with studies conducted in Guatemala (38) and Sub-Saharan Africa (39), though studies in South Asia (40) typically report male nutritional advantages. Second, sanitation coverage in the vicinity was protective for girls but not for boys. One possible explanation is that boys, due to earlier weaning, have a higher pathogen burden from food and water. At high levels of exposure from these other pathways, the cleanliness of the community environment may not be as important.

Other studies have shown some evidence of herd protection from sanitation. Barreto et al (22) showed that after a decade-long city-wide sanitation campaign, reductions in the prevalence of diarrhea were explained by increases in sanitation coverage and not by the sanitation of the household. Buttenheim (23) followed 153 children in Bangladesh slums for 1 year for changes in weight-for-height, a short-term indictor of nutritional status. Improved sanitation at the household level did not have an impact on weight-for-height, but there was a 0.1 z score increase for each 10 percentage point increase in neighborhood sanitation coverage. Using data from a cross-sectional household survey in Peru, Alderman et al (20) compared the HAZ for 2,084 children. They also saw no effect of household sanitation, but children from sample clusters with 100% sanitation coverage had 0.47 greater HAZ than children from clusters with 0% coverage. Corsi et al (25) used data from the Demographic and Health Survey in Bangladesh, and compared both HAZ and weight-for-age among 5,731 children. They did not, however, disentangle the effects of water and sanitation, and the protective community effect of water and sanitation disappeared after adjusting for other community-level covariates. Using a much larger survey in rural India, Andres et al (21) observed an effect of both household sanitation and community sanitation on the prevalence of diarrhea.

Our study makes several key contributions to the literature. First, we employ a longitudinal study on a large sample of children. With the exception of Barreto et al (22) and Buttenheim (23), all other studies on this topic have been cross-sectional (20, 21, 25) or ecological in nature (24, 41). Even those studies that were longitudinal, had short follow-up periods (≤ 1 year). Our longitudinal design, covering 5 years, allowed for a robust construction of growth curves; it is not an intervention study, hence causal inference related to changes in sanitation coverage are limited. Second, we sampled all households in the villages along with the GPS location of each household. National household surveys use a multiple stage sampling design, where neighborhood sanitation coverage is calculated by the non-self mean of sanitation in the survey cluster. Because all households in a survey cluster are not sampled, the estimate of sanitation coverage is susceptible to random sampling error, which will bias the results toward the null. Also, survey clusters may vary in size geographically, a problem that we addressed by defining employing a 500 meter radius.

Because this is an observational study, it is susceptible to confounding. Just as households with improved sanitation are typically different in many ways than households with unimproved sanitation, communities with high sanitation coverage are different than those with low coverage. Many of these differences may also be risk factors for stunting. We have attempted to capture these differences by controlling for education, household wealth, and community wealth. Information on breastfeeding, nutritional intake, handwashing, and food security was unavailable, limiting our ability to draw inferences from our study. Other studies have adjusted for these factors, but none have adjusted for all simultaneously.

Based on data from our study site in northern coastal Ecuador, we provide evidence that sanitation coverage has a stronger impact on child height than sanitation at the household level. As with other diseases and interventions, these externalities suggest that community context should not be ignored, for failure to do so will lead to an underestimate of the overall protective effect of sanitation. Also, these findings raise the possibility that a sanitation campaign can protect everyone in a community, even those that are most vulnerable and difficult to reach. Future studies should investigate the link between sanitation coverage and child growth by incorporating causal intermediates such as symptomatic diarrhea, helminth infection, environmental enteropathy, as well as accounting for other pathways such as breastfeeding and nutritional intake.

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Authors' Contributions

JA Fuller contributed to the literature search, data analysis, data interpretation, and writing of the manuscript. E Villamor contributed to the data analysis and data interpretation. W Cevallos contributed to the study design and data collection. J Trostle contributed to the study design, data collection, and data interpretation. JNS Eisenberg contributed to the study design, data collection, data analysis, and data interpretation. The authors have no conflicts of interest to declare.

References

References

1. Black RE, Victora CG, Walker SP, Bhutta ZA, Christian P, de Onis M, et al. Maternal and child undernutrition and overweight in low-income and middle-income countries. Lancet. 2013 Aug 3;382(9890):427-51.

2. Berkman DS, Lescano AG, Gilman RH, Lopez SL, Black MM. Effects of stunting, diarrhoeal disease, and parasitic infection during infancy on cognition in late childhood: a follow-up study. Lancet. 2002 Feb 16;359(9306):564-71.

3. Chang SM, Walker SP, Grantham-McGregor S, Powell CA. Early childhood stunting and later behaviour and school achievement. J Child Psychol Psychiatry. 2002 Sep;43(6):775-83.

4. Victora CG, Adair L, Fall C, Hallal PC, Martorell R, Richter L, et al. Maternal and child undernutrition: consequences for adult health and human capital. Lancet. 2008 Jan 26;371(9609):340-57.

5. Black RE, Allen LH, Bhutta ZA, Caulfield LE, de Onis M, Ezzati M, et al. Maternal and child undernutrition: global and regional exposures and health consequences. Lancet. 2008 Jan 19;371(9608):243-60.

6. Hackett M, Melgar-Quinonez H, Alvarez MC. Household food insecurity associated with stunting and underweight among preschool children in Antioquia, Colombia. Rev Panam Salud Publica. 2009 Jun;25(6):506-10.

7. Rivera JA, Hotz C, Gonzalez-Cossio T, Neufeld L, Garcia-Guerra A. The effect of micronutrient deficiencies on child growth: a review of results from community-based supplementation trials. J Nutr. 2003 Nov;133(11 Suppl 2):4010S-20S.

8. Fink G, Gunther I, Hill K. The effect of water and sanitation on child health: evidence from the Demographic and Health Surveys 1986-2007. Int J Epidemiol. 2011 Oct;40(5):1196-204.

9. Merchant AT, Jones C, Kiure A, Kupka R, Fitzmaurice G, Herrera MG, et al. Water and sanitation associated with improved child growth. Eur J Clin Nutr. 2003 Dec;57(12):1562-8.

10. Checkley W, Epstein LD, Gilman RH, Cabrera L, Black RE. Effects of acute diarrhea on linear growth in Peruvian children. Am J Epidemiol. 2003 Jan 15;157(2):166-75.

11. Checkley W, Buckley G, Gilman RH, Assis AM, Guerrant RL, Morris SS, et al. Multi-country analysis of the effects of diarrhoea on childhood stunting. Int J Epidemiol. 2008 Aug;37(4):816-30.

12. Assis AM, Barreto ML, Santos LM, Fiaccone R, da Silva Gomes GS. Growth faltering in childhood related to diarrhea: a longitudinal community based study. Eur J Clin Nutr. 2005 Nov;59(11):1317-23.

13. Stephenson LS, Latham MC, Ottesen E. Malnutrition and parasitic helminth infections. Parasitology. 2000;121(S1):S23-38.

14. Schmidt CW. Beyond malnutrition: the role of sanitation in stunted growth. Environ Health Perspect. 2014 Nov;122(11):A298-303.

15. Korpe PS, Petri WA,Jr. Environmental enteropathy: critical implications of a poorly understood condition. Trends Mol Med. 2012 Jun;18(6):328-36.

16. Humphrey JH. Child undernutrition, tropical enteropathy, toilets, and handwashing. Lancet. 2009 Sep 19;374(9694):1032-5.

17. Fagundes-Neto U, Viaro T, Wehba J, Patricio FR, Machado NL. Tropical enteropathy (environmental enteropathy) in early childhood: a syndrome caused by contaminated environment. J Trop Pediatr. 1984 Aug;30(4):204-9.

18. Checkley W, Gilman RH, Black RE, Epstein LD, Cabrera L, Sterling CR, et al. Effect of water and sanitation on childhood health in a poor Peruvian peri-urban community. Lancet. 2004 Jan 10;363(9403):112-8.

19. Lin A, Arnold BF, Afreen S, Goto R, Huda TM, Haque R, et al. Household environmental conditions are associated with enteropathy and impaired growth in rural Bangladesh. Am J Trop Med Hyg. 2013 Jul;89(1):130-7.

20. Alderman H, Hentschel J, Sabates R. With the help of one's neighbors: externalities in the production of nutrition in Peru. Soc Sci Med. 2003;56(10):2019-31.

21. Andres LA, Briceño B, Chase C, Echenique JA. Sanitation and Externalities: Evidence from Early Childhood Health in Rural India. World Bank Policy Research Working Paper No. 6737. Washington, DC: World Bank; 2014.

22. Barreto ML, Genser B, Strina A, Assis AMO, Rego RF, Teles CA, et al. Effect of city-wide sanitation programme on reduction in rate of childhood diarrhoea in northeast Brazil: assessment by two cohort studies. The Lancet. 2007;370(9599):1622-8.

23. Buttenheim AM. The Sanitation Environment in Urban Slums: Implications for Child Health. Popul Environ. 2008;30(1):26-47.

24. Spears D, Ghosh A, Cumming O. Open defecation and childhood stunting in India: an ecological analysis of new data from 112 districts. PloS one. 2013;8(9):e73784.

25. Corsi DJ, Chow CK, Lear SA, Rahman MO, Subramanian SV, Teo KK. Shared environments: a multilevel analysis of community context and child nutritional status in Bangladesh. Public Health Nutr. 2011 Jun;14(6):951-9.

26. Geruso M, Spears D. Neighborhood sanitation and infant mortality. Nat Bur Econ Res. 2015;Working paper 21184.

27. Fine PE. Herd immunity: history, theory, practice. Epidemiol Rev. 1993;15(2):265-302.

28. Eisenberg JN, Cevallos W, Ponce K, Levy K, Bates SJ, Scott JC, et al. Environmental change and infectious disease: how new roads affect the transmission of diarrheal pathogens in rural Ecuador. Proc Natl Acad Sci U S A. 2006 Dec 19;103(51):19460-5.

29. World Health Organization. WHO Anthro. 2011;3.2.2.

30. WHO Multicentre Growth Reference Study Group. WHO Child Growth Standards based on length/height, weight and age. Acta Paediatr Suppl. 2006 Apr;450:76-85.

31. Gelman A. Scaling regression inputs by dividing by two standard deviations. Stat Med. 2008;27(15):2865-73.

32. Bates D, Maechler M, Bolker B, Walker S. lme4: Linear mixed-effects models using Eigen and S4. R package version 1.0-4. Accessed online: December. 2013.

33. Pinheiro J, Bates D, DebRoy S, Sarkar D. R Development Core Team. 2010. nlme: linear and nonlinear mixed effects models. R package version 3.1-97. R Foundation for Statistical Computing, Vienna. 2011.

34. Clasen T, Boisson S, Routray P, Torondel B, Bell M, Cumming O, et al. Effectiveness of a rural sanitation programme on diarrhoea, soil-transmitted helminth infection, and child malnutrition in Odisha, India: a cluster-randomised trial. The Lancet Global Health. 2014;2(11):e645-53.

35. Patil SR, Arnold BF, Salvatore AL, Briceno B, Ganguly S, Colford Jr JM, et al. 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.

36. Barnard S, Routray P, Majorin F, Peletz R, Boisson S, Sinha A, et al. Impact of Indian Total Sanitation Campaign on latrine coverage and use: a cross-sectional study in Orissa three years following programme implementation. PloS one. 2013;8(8):e71438.

37. Victora CG, de Onis M, Hallal PC, Blossner M, Shrimpton R. Worldwide timing of growth faltering: revisiting implications for interventions. Pediatrics. 2010 Mar;125(3):e473-80.

38. Tumilowicz A, Habicht JP, Pelto G, Pelletier DL. Gender perceptions predict sex differences in growth patterns of indigenous Guatemalan infants and young children. Am J Clin Nutr. 2015 Sep 30.

39. Wamani H, Astrom AN, Peterson S, Tumwine JK, Tylleskar T. Boys are more stunted than girls in sub-Saharan Africa: a meta-analysis of 16 Demographic and Health Surveys. BMC Pediatr. 2007 Apr 10;7:17.

40. Pande RP. Selective gender differences in childhood nutrition and immunization in rural India: the role of siblings. Demography. 2003;40(3):395-418.

41. Spears D. How much international variation in child height can sanitation explain? World Bank Policy Research Working Paper No. 6351. Washington, DC: World Bank; 2013.

Table 1. Prevalence of stunting across different levels of covariates among children < 5 years of age in rural northern Ecuador, 2008-2011.

	Number Stunted (%)			
	Visit 1 (n=489)	**Visit 2 (n=510)**	**Visit 3 (n=605)**	**Visit 4 (n=619)**
Overall	70 (14.3)	62 (12.2)	73 (10.3)	85 (13.8)
Household Sanitation[1]				
Unimproved	29 (16.2)	19 (16.5)	21 (15.8)	20 (17.5)
Improved	41 (13.2)	43 (10.9)	52 (11)	65 (12.9)
Sanitation Coverage[2] (Quintiles)				
1 - (0-63%)	30 (15.4)	20 (25.6)†	18 (18.4)†	9 (15.3)
2 - (63-76%)	18 (14.5)	9 (9.8)	7 (6)	21 (18.6)
3 - (76-85%)	15 (12.3)	12 (10.3)	13 (10.4)	16 (16.3)
4 - (85-90%)	1 (9.1)	11 (8.3)	13 (9.8)	19 (12.6)
5 - (90-100%)	6 (16.2)	10 (11.1)	22 (16.3)	20 (10.2)
Household Wealth (Quintiles)				
1 - Poorest	9 (10.8)	4 (10.8)	7 (26.9)	4 (19)
2	18 (15.7)	24 (18.5)	18 (12.6)	18 (14.6)
3	16 (14.7)	14 (11.8)	17 (10.8)	27 (16.7)
4	19 (18.4)	12 (10.3)	20 (13.8)	11 (6.8)
5 - Wealthiest	8 (10.1)	8 (7.5)	11 (8.1)	25 (16.7)
Neighborhood Wealth[3] (Quintiles)				
1 - Poorest	17 (14.8)	15 (12.9)	18 (11.9)	6 (9.5)†
2	10 (13.5)	12 (14.1)	16 (12.2)	29 (17.8)
3	17 (12.6)	10 (11.2)	4 (6.5)	10 (6.6)
4	19 (15.7)	6 (12.5)	15 (10.3)	34 (18)
5 - Wealthiest	7 (15.9)	19 (11.1)	20 (16.9)	6 (11.8)
Years of Education (Maximum of the Household)				
0-5	16 (11.2)	15 (14.6)	11 (10.6)	18 (17)
6-7	20 (13.5)	23 (13.9)	22 (11.1)	21 (11.4)
8-9	15 (20)	8 (8.9)	16 (13.9)	13 (12.1)
10 or more	19 (15.4)	16 (10.7)	24 (12.6)	33 (14.9)
Child's Sex				
Female	26 (10.4)†	24 (9.1)†	30 (9.8)	41 (13.3)
Male	44 (18.3)	38 (15.5)	43 (14.2)	44 (14.2)
Child's Age (Years Completed)				
0	7 (8.3)†	10 (9.9)	6 (5.5)†	8 (9.2)
1	23 (20.7)	16 (16.8)	22 (17.5)	22 (16.3)
2	26 (22.8)	13 (11.5)	26 (20.3)	21 (16.7)
3	5 (5.4)	15 (14.6)	14 (10.2)	19 (12.8)
4	9 (10.3)	8 (8.2)	5 (4.7)	15 (12.4)

[1]Defined as JMP Improved, but ignoring sharing.

[2]Defined as the proportion of households within a 500-meter radius that have improved sanitation.

[3]Defined as the mean wealth index of households within a 500-meter radius.

†$p<0.05$, Chi-square test of the association between moderate stunting and the covariate during a given study visit.

Figure 1. Distribution of coverage of improved sanitation within 500 meters of the household in rural northern Ecuador, 2008-2011.

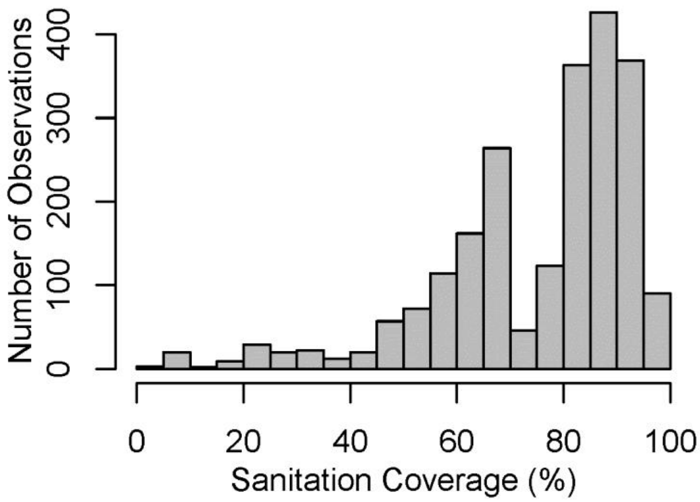


Table 2. Prevalence ratios (and 95% confidence limits) for moderate or severe stunting (height-for-age z score < -2) among children < 5 years of age in rural northern Ecuador, 2008-2011. All models include a random intercept for each child.

Variable[1]	Model 1	Model 2	Model 3	Model 4
Household Sanitation (Improved[2] vs Unimproved)	0.74 (0.57-0.97)	0.74 (0.57-0.97)		0.86 (0.64-1.15)
Sanitation Coverage[3] (100% vs 0%)			0.37 (0.20-0.69)	0.32 (0.15-0.69)
Child's Sex (Male vs Female)		1.40 (1.09-1.81)		1.42 (1.10-1.82)
Child's Age (Years completed)				
1 vs 0		2.26 (1.48-3.45)		2.22 (1.46-3.38)
2 vs 0		2.23 (1.46-3.39)		2.22 (1.46-3.37)
3 vs 0		1.37 (0.87-2.16)		1.37 (0.87-2.16)
4 vs 0		1.15 (0.70-1.87)		1.16 (0.71-1.89)
Years of Education (Maximum of the Household)		1.01 (0.97-1.05)		1.02 (0.98-1.06)
Household Wealth Quintile (1=poorest)				
2 vs 1		1.03 (0.64-1.67)		0.98 (0.60-1.60)
3 vs 1		0.88 (0.54-1.43)		0.83 (0.50-1.36)
4 vs 1		0.78 (0.47-1.30)		0.72 (0.43-1.22)
5 vs 1		0.77 (0.45-1.29)		0.68 (0.39-1.19)
Neighborhood Wealth Index[4]				1.19 (1.01-1.40)
Observations	2,223	2,223	2,223	2,223
Number of Children	1,314	1,314	1,314	1,314
AIC[5]	1,168.3	1,147.8	1,163.5	1,142.7

95% Confidence Intervals in parentheses
[1]All variables, except child's sex, are time-varying and were measured concurrently with the child's height
[2] Defined as JMP Improved, but ignoring sharing.
[3]Defined as the proportion of households within a 500-meter radius that have improved sanitation.
[4]Defined as the mean wealth index of households within a 500-meter radius.
[5]Akaike Information Criterion.

Figure 2. Predicted height in CM among females and males by coverage of sanitation in the 500 meters surrounding the household, northern Ecuador, 2008-2011. Multilevel model includes a 3-way interaction between child's age, child's sex, and sanitation coverage, and is adjusted for the following time-varying covariates: household sanitation, household education, household wealth, and wealth in the surrounding households. Age was included as a continuous variable using a restricted cubic spline with knots at 0.5, 1, 1.5, 2.5, and 4 years. Model also includes random intercept and random age slope for each child. Asterisks indicate the range over which the effect of sanitation coverage is significant at the $p<0.05$ level.

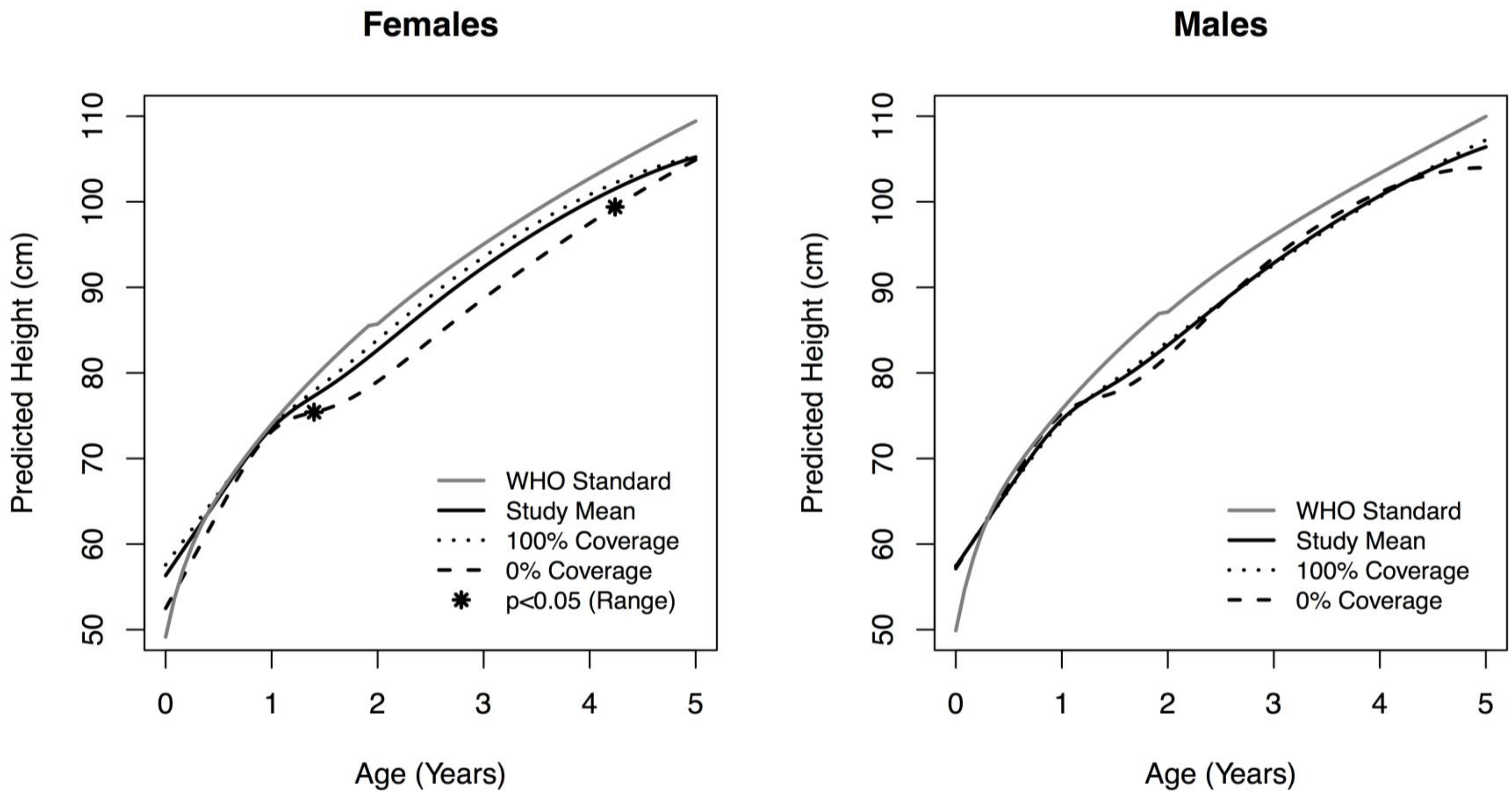
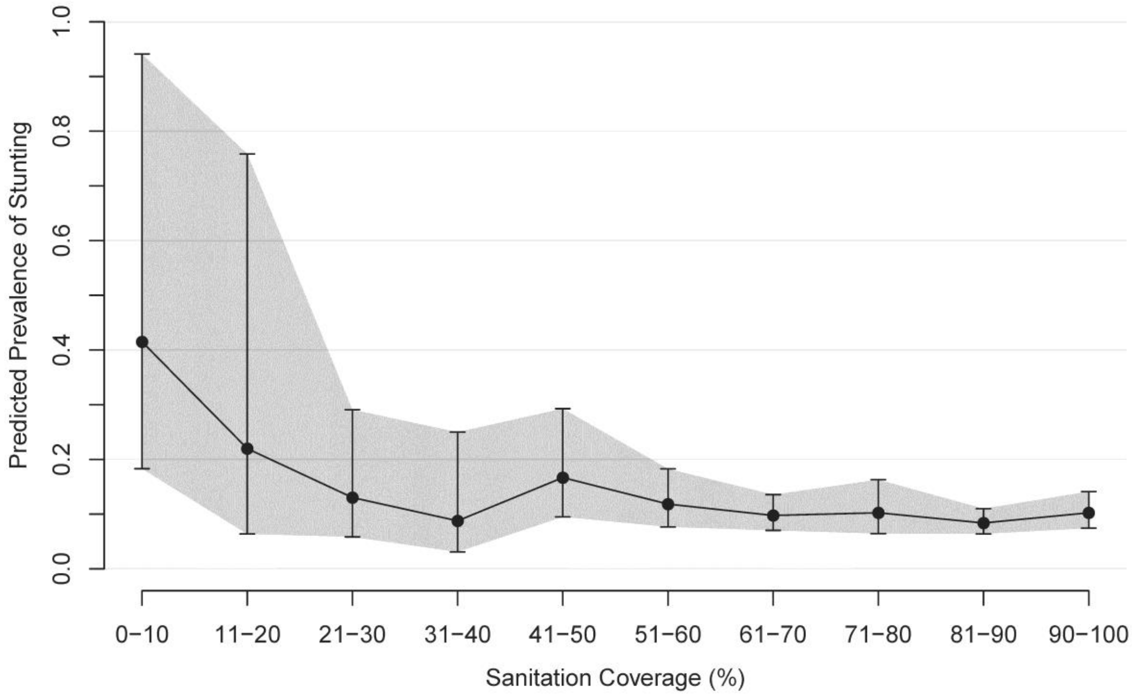


Figure 3. Predicted prevalence of moderate or severe stunting (and 95% confidence limits) by level of sanitation coverage within 500 meters of the household, rural northern Ecuador, 2008-2011. Predictions are adjusted for age, household sanitation, household education, household wealth, and neighborhood wealth. Model also includes random intercept for each child.



Box 1 - Key Messages

- Higher levels of sanitation coverage in surrounding households were associated with increased child growth
- A household's own sanitation access was less important
- This is conceptually related to herd immunity, where vaccination coverage provides an indirect benefit to the entire population
- Future studies must account for neighborhood sanitation or they will likely underestimate the total protective effect of sanitation