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Forests moderate the effectiveness of water treatment at reducing childhood diarrhea

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Abstract

Environmental degradation has been associated with increased burden of diseases such as malaria, diarrhea, and malnutrition. As a result, some have argued that continuing ecosystem change could undermine successes in global health investments. Here we conduct an empirical study to investigate this concern. Child deaths due to diarrhea have more than halved since the year 2000, partly due to increased access to improved water, sanitation and hygiene (WASH). We examine how the effectiveness of a water quality treatment may vary as a function of upstream watershed condition. We use data on occurrence of diarrhea and point-of-use water treatment methods from the Demographic and Health Surveys for Haiti and Honduras. We integrate these data with a variable that reflects the influence of upstream tree cover on surface water quality. Point-of-use chlorination is significantly associated with 3.4 percentage points reduction in prevalence of diarrheal disease on average. However, we only detect a significant reduction in diarrheal prevalence when upstream watersheds are moderately forested. At low upstream tree coverage, point-of-use water chlorination does not have significant effects, suggesting that forest clearing could undermine its effectiveness at reducing childhood diarrhea. Our results suggest that forested watersheds may reduce water-borne sediments and contaminants, and thus improve raw water quality in ways that moderate the effectiveness of water quality treatment. Watershed protection should be considered in WASH investments, as deforested watersheds could undermine their effectiveness, particularly in parts of low-income countries where access to improved WASH services is challenging.

1. Introduction

In the last decade, the world has made significant progress fighting disease. The burden of disease per 1000 people has decreased due, in significant part, to declining death and disability in children under the age of five (Murray *et al* 2012). At the same time, the world's growing population, expected to reach 9.8 billion in 2050 (United Nations 2017), puts increasing pressure on the world's natural systems (e.g. forests, grasslands, watersheds, climate; Foley 2005). As these natural systems support a variety of services important to human health (e.g. nutrition, regulation of some infectious diseases, water and air filtration; Millennium Ecosystem Assessment 2005), their alteration has been associated with an increasing burden of disease (WHO 2016). This association has led to concerns that continuing alteration of natural systems could counter or even reverse some of the progress made in the fight against some diseases (Whitmee *et al* 2015). The empirical literature testing these ideas is scant but growing. We explore how natural systems may moderate the effectiveness of efforts to fight diarrheal disease.

Diarrheal disease killed roughly 526 000 children under the age of five in 2015 (UNICEF 2016). This figure amounts to more than 1400 children dying every day (United Nations International Children's Emergency Fund 2016). Inadequate access to water, sanitation and hygiene (WASH) are major risk factors for diarrheal disease across the world (Prüss-Ustün *et al* 2019). The rates of deaths due to diarrheal disease are highest in low and lower-middle-income countries (Liu *et al* 2016). In these countries, for example, consumption of unimproved drinking water, which is associated with high pathogen contamination, can affect over 20% of the population; in rural areas, this percentage is often much higher (WHO 2017). Child deaths due to diarrhea have more than halved between 2000 and 2015 (United Nations International Children's Emergency Fund 2016), partly, because of improvements in access to WASH (Prüss-Ustün *et al* 2019). For example, 2.6 billion people gained access to improved drinking water source between 1990 and 2015 (WHO and UNICEF 2015).

While progress has been made towards increasing grey infrastructure for improved drinking water, green infrastructure—natural systems that contribute to improved water quality—has been in decline in many regions of the world. For example, forests can improve water quality by reducing sediment load from soil erosion and filtering pathogens (e.g. fecal coliform bacteria), sediment and pollutants (Ensign and Mallin 2001, Brauman *et al* 2007). Despite these benefits, forests in developing countries have continued to shrink in recent decades (Kauppi *et al* 2018). Continued forest clearing and degradation could therefore negatively impact water quality and result in increased incidence of diarrheal disease. Recent studies indeed suggest that forests in upstream areas of watersheds are associated with lower prevalence of diarrheal disease downstream (Pattanayak and Wendland 2007, Herrera *et al* 2017).

Forest clearing could undermine advances made by other efforts to improve drinking water quality in a number of ways. For example, when upstream areas are cleared, downstream raw water can become more contaminated (e.g. by fecal coliform bacteria) or turbid (Ensign and Mallin 2001, Cunha *et al* 2016). The resulting poor raw water quality can limit the effectiveness or increase the costs of water quality improvement efforts (LeChevallier and Au 2004, Asami *et al* 2016, Price and Heberling 2018). Turbidity, for example, can shield pathogens from disinfectants (e.g. chlorine) used at source (e.g. in water treatment plants) or at point-of-use (Mohamed *et al* 2015, 2016, Cunha *et al* 2016). Improvement of raw water quality by forests could therefore make source or point-of-use efforts more effective at delivering clean and safe drinking water (Ernst *et al* 2004, Cunha *et al* 2016) that could reduce risk of diarrheal disease.

We examine the potential of forests to moderate the effectiveness of water quality treatment at reducing childhood diarrhea across Haiti and Honduras, the poorest countries in the Latin America and Caribbean region (World Bank 2020). Haiti is among the most deforested countries in the world with less than 1% of its original primary forest remaining (Hedges *et al* 2018). As for Honduras, it lost 35% of its primary forest from 2002 to 2020, one of the highest rates of forest loss in Central America (Hansen *et al* 2013, Sesnie *et al* 2017, Turubanova *et al* 2018). These two countries are among those with the highest percentages of deaths caused by diarrhea in children under 5 years of age in the Latin America and Caribbean region, 9% and 6% respectively (UNICEF 2018). Over 2.7 million people in Haiti and over 430 000 people in Honduras do not have access to improved source of drinking water (WHO and UNICEF 2017). Levels of practice of point-of-use chlorination of drinking water are high in both countries. Forty-one percent of households in Haiti and 23% of households in Honduras report practicing point-of-use chlorination (Cayemittes *et al* 2013, SS, INE, ICF 2013). We investigate how the effectiveness of point-of-use chlorination at reducing prevalence of diarrhea varies as a function of upstream tree cover. Our investigation sheds light into the roles that forests could play in the effectiveness of water improvement efforts designed to reduce the prevalence of diarrheal disease.

2. Materials and methods

2.1. Data

The Demographic and Health Surveys (DHS) program, administered by the United States Agency for International Development (USAID), has collected nationally representative data on demography, health, and nutrition across millions of households in over 90 developing countries. DHS surveys use a stratified two-stage sampling design. In the first stage, a sample of clusters (group of households) are selected and in the second stage, a sample of households are selected in each cluster (ICF International 2012). DHS data have been increasingly used in studies linking human health and the environment (Johnson *et al* 2013, Ickowitz *et al* 2014, Herrera *et al* 2017, Pienkowski *et al* 2017, Galway *et al* 2018, Rasolofoson *et al* 2018, 2020, Acharya *et al* 2020, Bauhoff and Busch 2020) thanks to the georeferenced DHS clusters, which make it possible to link the DHS observations to spatial environmental data. We use DHS for the year 2012 for Haiti that comprises 370 communities (or clusters in DHS documentation) scattered across the country (Cayemittes *et al* 2013) and DHS for the year 2011, with 923 communities, for Honduras (Secretaría de Salud—SS/Honduras, Instituto Nacional de Estadística—INE/Honduras, ICF International 2013). In the survey year (2012), the average annual temperature and precipitation in Haiti were 24.87 °C and 1749.09 mm, which are consistent with the average annual temperature and precipitation in the past several years (e.g. 25.13 °C and 1489.17 mm between 2000 and 2016, World Bank 2021). Similarly, the average annual temperature and precipitation (24.12 °C and 1968.38 mm) in Honduras in the survey year (2011) fit in with the average annual temperature and precipitation in the past several years (e.g. 24.12 °C and 1934.73 mm between 2000 and 2016, World Bank 2021).

2.2. Study design

2.2.1. Diarrheal disease

The DHS woman's questionnaire asks a woman whether her children under the age of five had diarrhea within the two weeks prior to the interview. Our outcome variable is thus whether the youngest child had diarrhea within the two-week period prior to the interview. We only select the most recent birth for each mother interviewed as our unit of analysis to avoid intra-household correlations in the selected outcomes.

2.2.2. Point-of-use water disinfection by chlorination

Point-of-use chlorination is a widely disseminated and tested method to improve the microbiologic quality of drinking water, particularly for households who lack access to safe water (Arnold and Colford 2007). DHS collect information about different methods households report practicing for water treatment, including chlorination. We construct a variable indicating whether a household reported treating water with chlorine or not treating water. We remove children of households that reported other water treatment methods (e.g. boiling, solar disinfection) as they may mask the effects of chlorination. Our data count 2867 children whose households reported treating drinking water with chlorine and 3491 children whose households reported not treating drinking water.

2.2.3. The moderating variable

Turbidity and higher pH values limit the effectiveness of chlorine to disinfect water (Spahl 2012, Mohamed *et al* 2015). Turbidity can shield pathogens from chlorine (Mohamed *et al* 2015). Higher water pH values limit the amount of highly effective free chlorine (hypochlorous acid) available for disinfection (Spahl 2012). Forests are known to reduce water turbidity by filtering sediment and other solid particles (Brauman *et al* 2007, Cunha *et al* 2016). Evidence suggests that forests can also lower water pH values in a number of ways, including the ability of forest canopies to capture atmospheric sulphur and nitrogen pollutants, particularly, in old, tall, and closed canopy forests (Nisbet and Evans 2014). Therefore, forests could improve the effectiveness of chlorination to disinfect water and thus reduce diarrheal disease incidence. Conversely, forest clearing or degradation may decrease the effectiveness of chlorination.

We investigate how the association of point-of-use water chlorination with diarrheal disease is moderated by upstream tree cover. Our moderating variable reflects the influence of upstream tree cover on surface water (Herrera *et al* 2017). It comes from a spatial layer where the value associated with a pixel estimates, out of the total quantity of water draining into that pixel, the percentage that fell as rain on, or passed through, a tree-covered upstream area. A value of 0 means that no water passing the pixel has interacted with forests since falling as rain, and a value of 100 means that 100% of the water has interacted with forests (Mulligan 2012, Herrera *et al* 2017). In sum, this variable represents the proportion of raw water draining into a community that, essentially, interacted with upstream forest cover when the water fell as rain or was on its way to the community location. The variable takes into account factors such as rainfall, evapotranspiration, and water routes (Mulligan 2012, Herrera *et al* 2017). It is a better approximation of effects of forests on surface water quality than the percentage of upstream forest cover in a watershed.

We integrate the spatial layer of the moderating variable with the DHS data through the georeferenced DHS clusters (hereafter communities). However, the DHS program randomly displaces the geographic coordinates of the communities up to 5 km to protect anonymity of survey respondents. To address the uncertainty caused by this displacement, we set the spatial layer of the moderating variable at 10 km resolution.

2.2.4. Confounding characteristics

Confounding characteristics affect the use (or non-use) of point-of-use chlorination and the prevalence of diarrheal disease. Cost, for example, affects access to chlorine and therefore use of it (Cairncross and Valdmanis 2006, Hulland *et al* 2015). We include confounding factors that affect both the cost of chlorine and the prevalence of diarrheal disease (population size, access to market, location: urban vs. rural). Household and community level wealth and the choice of residency can also influence the practice of water chlorination (Cairncross and Valdmanis 2006, Hulland *et al* 2015). We thus control for variables that affect both economic means or choice of residency and the prevalence of diarrheal disease (per capita gridded gross domestic product or GDP, household asset wealth, sex of heads of households, education level of heads of households, household size, number of children under the age of five, age of a child). We also control for variables that reflect the influences of upstream tree cover and upstream people and livestock on downstream raw water quality (Mulligan 2012, Herrera *et al* 2017) because raw water quality can influence choices of water technologies (Cunha *et al* 2016) and it also affects the prevalence of diarrheal disease (Herrera *et al* 2017). These variables represent the proportions of raw water draining into a community that interacted with upstream tree cover or upstream populated areas and livestock farms when the water fell as rain or was on its way to the community location (Mulligan 2012, Herrera *et al* 2017). Detailed description and data sources of the confounding variables are in supplementary table S1 (available online at stacks.iop.org/ERL/16/064035/mmedia).

2.3. Statistical approaches

2.3.1. Matching

To control for the confounding characteristics, we use statistical matching. Matching selects children not using chlorine that are similar to children using chlorine in terms of observed confounding characteristics. Effectiveness is measured by the difference in prevalence of diarrhea between the matched children.

We execute one-to-one matching with replacement using the multivariate Mahalanobis distance measure to calculate the similarity between the matched units. We perform exact matching on country and location (urban or rural). We apply the bias-adjustment regression procedure of Abadie and Imbens (2006) to correct remaining post-matching imbalance. The reduced characteristic imbalance between children using chlorine and the matched children not using chlorine renders the post-matching regression less sensitive to the common support assumption invoked in regression analysis (i.e. for each child using chlorine there is a compatible child not using chlorine, Ferraro and Hanauer 2014). We perform matching with the R 'matching' package (Sekhon 2011). We cluster the standard errors at the community level using the R 'clusterSEs' package (Esarey 2017).

2.3.2. Moderating effect of upstream tree cover

Effectiveness is measured by the difference in prevalence of diarrhea between children using chlorine and the matched children not using chlorine. We graphically examine how this difference is moderated by upstream tree cover. We isolate the moderating effect of upstream tree cover, independent of the effects of other variables. To do so, we use a two-stage semi-parametric partial linear differencing model (PLM, Ferraro and Hanauer 2011). The first stage consists of linearly controlling for other variables that co-vary with upstream tree cover. The second stage uses a nonparametric locally weighted scatter plot smoothing to graphically estimate the variation of the effectiveness of point-of-use chlorination as a function of upstream tree cover. In other words, PLM estimates how the effectiveness of chlorination at reducing diarrhea varies as a function of upstream tree cover, while holding constant the other confounding variables. Confidence intervals are based on standard errors clustered at the community level. We use the R functions developed by Hanauer and Canavire-Bacarreza (2015) to perfom the PLM with clustered standard errors.

3. Results

3.1. Characteristic differences in children using and not using chlorine

In Haiti and Honduras, children whose households treat drinking water with chlorine are, on average, located in areas less populated, further from a market, more rural, and with higher per capita gross domestic product (GDP) than those whose households do not treat drinking water. More of the children using chlorine have piped water source than children not using chlorine (table 1).

3.2. Effectiveness of point-of-use water chlorination

Because of the systematic differences between children using and not using water chlorination (table 1), a direct comparison of the prevalence of diarrhea between these groups may yield biased estimates of effectiveness. Overall, our matching approach reduces the characteristic differences between children with and without access to chlorination (supplementary table S2).

We find that, on average, point-of-use chlorination is associated with lower prevalence of diarrhea. Children consuming water treated with chlorine show a 3.4 percentage points (95% CI: 1.8%–5.0%) lower prevalence of diarrhea (21.2%, SD: 40.9%) than the matched children consuming untreated drinking water (24.5%, SD: 10.0%).

3.3. Moderating effect of upstream tree cover

While point-of-use water chlorination is associated with a 3.4% reduction in prevalence of diarrheal disease on average, this reduction is not statistically significant when the percentage of raw water interacting with upstream forests is lower than 20% or higher than 55%. The reduction of the prevalence of diarrhea is only statistically significant between these percentages (with a maximum reduction of prevalence of nearly 5% at 35% of raw water interacting with upstream forests) (figure 1). Of note, below 5% and above 55% of raw water interacting with upstream forests, we do have enough data for a precise estimation as seen from the wide 95% confidence

Table 1. Means and SDs (in parentheses) of characteristics of children living in households that treat water with chlorine and children living in households that do not treat water in Haiti and Honduras.

Variable	Children in households with chlorine-treated drinking water[a]	Children in households without chlorine-treated drinking water[a]
Prevalence of diarrhea (%)	21.17 (40.86)	22.75 (41.93)
Age (month)	24.29 (16.36)	23.60 (16.35)
DHS household wealth index factor score	−0.40 (0.76)	−0.13 (0.97)
Use of piped water source (%)	51.22 (49.99)	41.76 (49.32)
Mother's education (years)	5.14 (3.72)	5.66 (4.13)
Male household head (%)	72.50 (44.66)	68.86 (46.31)
Household size (individual)	5.97 (2.52)	5.74 (2.48)
Children under 5 in a household (individual)	1.50 (0.76)	1.46 (0.76)
GDP per capita (US$ PPP)	4623.89 (3543.82)	4380.50 (2976.29)
Population (individual)	88129 (226 473)	147 765 (289 776)
Distance to a market (km)	22.69 (28.38)	17.26 (24.51)
Rural dwellers (%)	74.25 (43.73)	62.67 (48.38)
Annual precipitation (mm)	1394.03 (1520.62)	1299.61 (1592.78)
Water interacting with upstream populated area and livestock farm (%)	43.55 (49.59)	40.09 (48.98)
Water interacting with upstream forests (%)	28.93 (12.89)	27.55 (14.07)

[a] Means and SDs weighted by each country's sample size. Sources: see supplementary table S1.

intervals in figure 1. In our sample, there are 93 households with less than 5% of their raw water interacting with upstream forests, 1512 households between 5% and 20%, 4521 households between 20% and 55%, and 232 households with more than 55% of their raw water interacting with upstream forests.

4. Discussion

Our results suggest that upstream forests moderate the effectiveness of point-of-use chlorination at reducing diarrheal disease. Our result that, on average, point-of-use chlorination is associated with a reduction in prevalence of diarrhea is in line with a large body of evidence (Arnold and Colford 2007). The effectiveness of chlorination at reducing diarrhea depends on many factors, including water storage safety, chlorine concentration and contact time with water, water temperature, pH, pathogen load and turbidity. The moderating effect of forests we found indicates that forests may influence some of these factors. Forests, particularly old, tall and closed canopy, have been associated with lower stream water pH in the United Kindom and Nigeria (Nisbet and Evans 2014, Ogbozige and Alfa 2019). Lower raw water pH increases the availability of free chlorine (hypochlorous acid), which is highly effective for disinfection (Spahl 2012). Forests have also been associated with lower stream water loads of *Escherichia coli* when compared to other types of land uses in many countries (e.g. Ensign and Mallin 2001, Miller *et al* 2011, Knee and Encalada 2014, Larned *et al* 2016). Stream water turbidity has also been lower when watersheds are forested (Knee and Encalada 2014, Larned *et al* 2016). For example, mean turbidity of stream water in forested watersheds in Sao Paulo State in Brazil is 10 NTU, while the values for other types of land uses range from 48 to 56 NTU (Cunha *et al* 2016). Less turbid raw water has fewer solid particles that can shield pathogens from chlorine (Mohamed *et al* 2015).

Our finding that the effectiveness point-of-use water chlorination is not statistically significant at low upstream tree coverage (less than 20% of raw water interacting with upstream forests) supports the concern that forest clearing could undermine the progress achieved in the fight against childhood diarrhea (Whitmee *et al* 2015). When upstream areas of watersheds are cleared, downstream raw water can have higher pH, become more contaminated or more turbid. Such water conditions can render point-of-use chlorination less effective. While technologies can still treat poor-quality raw water, they may cost more (Price and Heberling 2018) and therefore be less accessible, particularly for poor communities or households in low-income countries who cannot afford expensive water treatment (Amrose *et al* 2015).

At moderate levels of upstream forest coverage (i.e. between 20% and 55% of raw water interacting with upstream forests), the effectiveness of point-of-use chlorination is statistically significant. Moderate upstream forest coverage may filter raw water to an extent where the concentrations of sediments and contaminants still need reduction to avoid diarrhea, but are not high enough to undermine the effectiveness of point-of-use chlorination. Moderate upstream tree coverage may also increase water pH

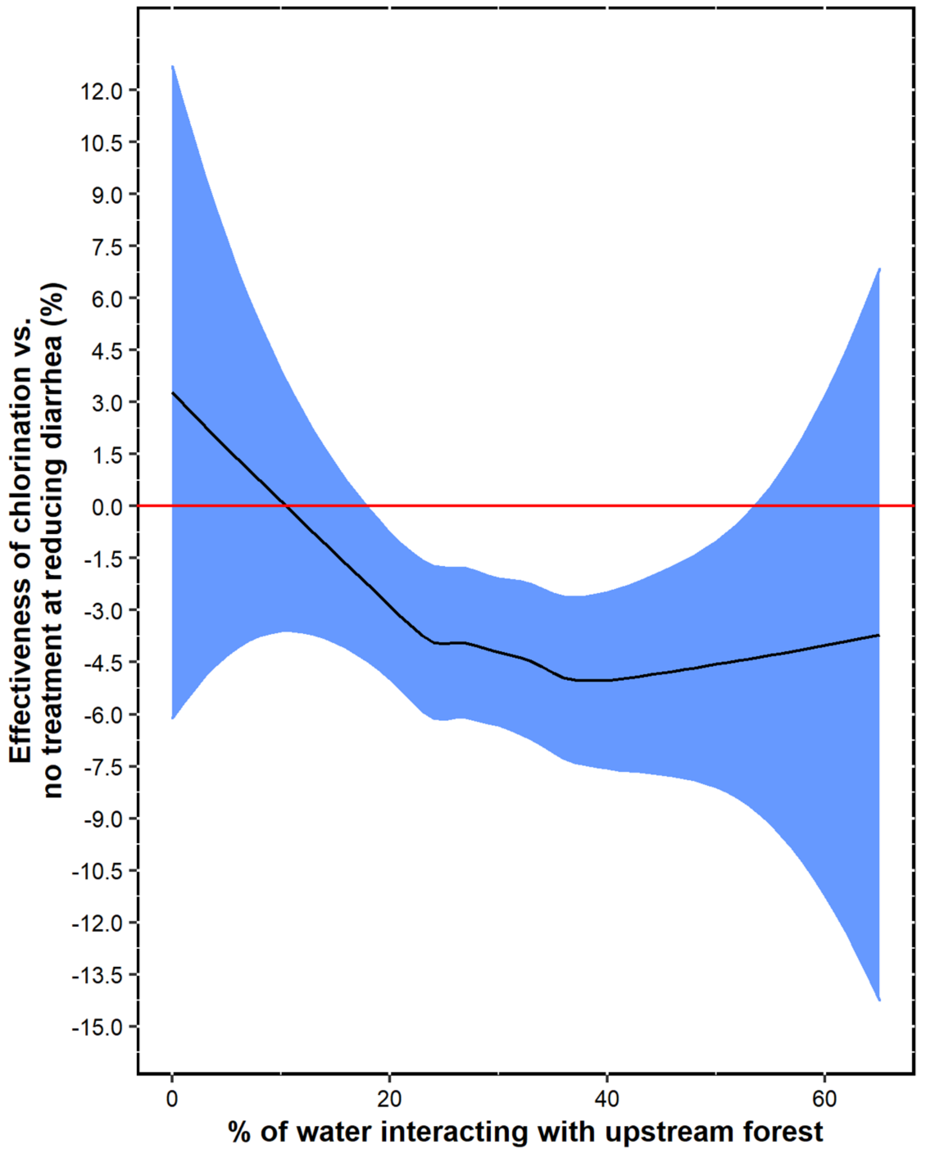

Figure 1. Upstream forests moderate the effectiveness of point-of use chlorination at reducing the prevalence of diarrheal disease. *Y*-axis: difference in prevalence (in percentage points) of diarrhea between children using chlorine and the matched children not using chlorine; blue bands: 95% confidence intervals.

(compared to low upstream tree coverage). In brief, moderate upstream forest coverage may render raw water conditions more favorable to disinfection by chlorine. At high upstream tree coverage (more than 55% of raw water interacting with upstream forests), we do not make any conclusion because we do not have enough data for a precise estimation of the association between point-of-use chlorination and diarrheal prevalence. Nevertheless, evidence suggests that water filtration service by abundant upstream forests can contribute to raw water attaining high quality, which in turn may reduce additional benefits of water treatment (Cunha *et al* 2016).

Our results confirm the important role of forested watersheds in the multiple-barrier approach to drinking water provision. This approach stipulates that a number of consecutive barriers to sediments, pollutants and contaminants—from source watersheds to treatment and distribution—are needed to ensure safe finished drinking water (Ernst *et al* 2004, LeChevallier and Au 2004). Forested watersheds can act as early barriers that improve raw water quality and thus increase the effectiveness of subsequent barriers, which can be simple and inexpensive facilities or technologies if raw water attains a high-quality level (Cunha *et al* 2016).

Watershed protection could be a cost-effective approach to fighting diarrhea if the costs of protecting the watershed do not outweigh the value of its benefits. Recent studies suggest that the costs of watershed protection often exceed its benefits from avoided water treatment expenditures (Heberling *et al* 2015, Vincent *et al* 2016, Price and Heberling 2018). Watershed protection might still be justified if other forest benefits are accounted for (Vincent *et al* 2016, Price and Heberling 2018) (e.g. climate change mitigation, local livelihoods, nutrition and other health benefits, biodiversity conservation (Maes et al 2016)). In addition, cost-effectiveness studies to date have focused on higher-income countries, so their applicability to lower-income countries, like those in our study, is unclear. On one hand, some water facilities and treatment technologies may be more expensive in lower-income countries, with additional costs incurred for social marketing, mobilization, education, and community or household unpaid labor (Amrose et al 2015). On the other hand, watershed protection is likely to be less expensive in lower-income countries than in richer countries (Balmford et al 2003, Waldron et al 2013). As evidence for the effectiveness of 'green infrastructure' accumulates, understanding their cost effectiveness is an increasingly important research and policy question.

We used a set of confounding variables to control for potential sources of bias in our estimates; however, the causal interpretation of our results should be done with care. We examined the links between the status of children in terms of use of point-of use water chlorination and the prevalence of diarrheal disease. However, we lack baseline data that should have been collected before chlorination. There also may be other confounding variables that we were unable to account for. Further, we may have underestimated the effectiveness of point-of-use chlorination because in data on reported household water treatment practices, people who report treating their water may fail to do so consistently or correctly (e.g. poor-quality chlorine supplies, inadequate or inconsistent dosing or contact time, recontamination when water lacks a sufficient chlorine residual level and is not accompanied by safe storage, Sobsey et al 2008, Rosa and Clasen 2010, Harshfield et al 2012).

Nevertheless, our results indicate that conducting field experiments or rigorously designed observational studies on the moderating effects of natural systems (e.g. forests, climate) on the effectiveness of public health interventions might prove fruitful. For example, with a large enough sample where data are collected seasonally on the same children, it may be possible to examine how the moderating effects of upstream forests on the effectiveness of point-of-use chlorination vary with season. Such undertaking will provide important information given the evidence suggesting that season or extreme weather, through temperature and precipitation, interact with land use types to affect raw water quality (Miller et al 2011, Badgley et al 2019).

5. Conclusions

Forest destruction could weaken some of the advances in human health outcomes brought about by improved drinking water quality. Forested watersheds may increase the effectiveness, and reduce the costs, of water improvement efforts at reducing the prevalence of diarrheal disease (Ernst et al 2004, Abildtrup et al 2013, Cunha et al 2016). Watershed protection could therefore be factored into WASH investments designed to fight diarrheal disease, particularly in the world's most vulnerable communities. Given that forests also deliver other multiple benefits such as climate change mitigation, biodiversity conservation, and local livelihood provision, watershed protection could be an important and strategic element in development policies.

Data availability

The primary data on diarrhea, household, and individual socio-economic characteristics analyzed in this study were obtained from the Demographic and Health Surveys (DHS) Program of the United States Agency for International Development. Each DHS survey used in the analysis is identified in the Materials and Methods. Requests to access these datasets should be directly submitted at https://dhsprogram.com/Data/. The spatial data (watershed condition, market, population, GDP, precipitation) are available from the corresponding author upon request.

Software packages and functions used for the analyses are cited in the Materials and Methods. The specific code that uses these packages and functions to generate the results of this study is available from the corresponding author upon request.

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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