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Where Does CLTS Work Best? Quantifying Predictors of CLTS Performance in Four Countries

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ABSTRACT: Improving the effectiveness of rural sanitation interventions is critical for meeting the United Nations' Sustainable Development Goals and improving public health. Community-led total sanitation (CLTS) is the most widely used rural sanitation intervention globally; however, evidence shows that CLTS does not work equally well everywhere. Contextual factors outside the control of implementers may partially determine CLTS outcomes, although the extent of these influences is poorly understood. In this study, we investigate the extent to which 18 contextual factors from readily available datasets can help predict the achievement and sustainability of open-defecation-free (ODF) status in Cambodia, Ghana, Liberia, and Zambia. Using multilevel logistic regressions, we found that the predictors of CLTS performance varied between countries, with the exception of small community size. Accessibility and literacy levels were correlated with CLTS outcomes, but the direction of correlation differed between countries. To translate findings into practical guidance for CLTS implementers, we used classification and regression trees to identify a "split point" for each contextual factor significantly associated with ODF achievement. We also identified the combinations of factors conducive to a minimum of 50% ODF achievement. This study demonstrates that publicly available, high-resolution datasets on accessibility, socioeconomic, and environmental factors can be leveraged to target CLTS activities to the most favorable contexts.

1. INTRODUCTION

As of 2017, an estimated 673 million people were practicing open defecation (OD), largely concentrated in poor, rural areas.[1] The United Nations' Sustainable Development Goal (SDG) 6.2 calls for ending OD globally by 2030. Although the proportion of the global population practicing OD has decreased from 21 to 9% from 2000 to 2017, 40 countries are not on track to achieve SDG 6.2 by 2030, and 11 reported an increase in OD.[1] Improving access to, and use of, sanitation facilities is critical for improving public health and enhancing the privacy, safety, dignity, and well-being of individuals, particularly women.[2,3] In 2016, it was estimated that inadequate sanitation caused approximately 432,000 deaths annually.[4]

Community-led total sanitation (CLTS) is the most widely employed approach to reduce OD in rural areas, implemented in some manner in nearly 60 countries.[5,6] The approach traditionally employs emotional triggers such as shame and disgust at OD to catalyze collective action to end the practice.[6] After a "triggering" event where a community is convened by a facilitator, households publicly commit to changing behavior and building their own latrines. Conventionally, no monetary or hardware subsidies are offered to aid construction. In most CLTS programs, facilitators return to communities to monitor progress or reinforce messaging. When a community reaches a nationally set latrine coverage threshold without visible signs of OD, they are awarded "open-defecation-free" (ODF) status from local authorities, sometimes with an official celebration. Although the evidence on CLTS effectiveness is mixed,[7−9] the approach has been credited with the achievement of ODF districts in sub-Saharan Africa and Asia.[5] CLTS is now increasingly applied in combination with other approaches such as market-based sanitation or targeted subsidies and remains a core strategy to achieve SDG 6.2.[10]

While the literature has documented how the quality of CLTS implementation can improve toilet coverage and use,[11−13] it also indicates that CLTS does not perform equally well across contexts,[9,14,15] irrespective of implementation quality. Early research pointed to a suite of contextual factors that could enhance the intervention's ability to achieve ODF status: low community population, remoteness, low water tables, high baseline OD rates, and access to construction

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materials.[6,16−18] However, few studies examined these associations quantitatively, and those that did were typically limited to a single geographic area and included just a few contextual characteristics.[19,20] To our knowledge, there has been no attempt to systematically quantify the relative association of various contextual factors with CLTS performance across geographies. With a better understanding of the predictors of performance, implementers could better identify suitable locations, prioritize resources, and consider other implementation approaches, such as market-based sanitation, where CLTS alone is unlikely to succeed.[10,21]

This study analyzed CLTS program datasets from four countries in combination with publicly available information derived from satellite imagery, surveys, and hydrogeological models to quantify associations between contextual factors and CLTS program outcomes and provide operational guidance for implementers to identify favorable locations.

2. METHODS

2.1. CLTS Program Data. In response to a public call for CLTS implementation data in 2018, we obtained datasets from six programs across Cambodia, Ghana, Liberia, and Zambia, covering a combined 40,482 communities before data cleaning. Data from Cambodia covered 2301 communities enrolled in the Cambodia Rural Sanitation and Hygiene Improvement Program (CRSHIP) coordinated by Plan International (Table 1). The data included information on household count, latrine coverage at baseline (i.e., before CLTS implementation), and one follow-up reporting period, and, for approximately half the records (53%), the date of CLTS triggering (Table S1). Three CLTS programs in Ghana provided data covering 5909 communities: the UNICEF/Government of Ghana program (4201 communities), the Water, Sanitation, and Hygiene (WASH) for Health program delivered by Global Communities (GC) (862 communities), and the Resiliency in Northern Ghana (RING) program also delivered by GC (846 communities). The resulting dataset included information on household count, ODF status, GPS coordinates (for 49% of communities), and triggering date (for 52% of communities) (Table S1). Data from Liberia covered 2095 communities enrolled in the Improved Water, Sanitation and Hygiene Program and Partnership for Advancing Community-Based Services Program coordinated by GC (Table 1). The Liberian dataset included information on household count, baseline latrine coverage, triggering date, ODF status, certification date, GPS coordinates, and 30-day diarrhea prevalence at baseline (Table S1). The GC projects in Ghana and Liberia were funded by USAID. For Zambia, we received data from the Government of Zambia/UNICEF Sanitation and Hygiene Program. The Zambian dataset included counts of latrines, households, and improved water sources collected at varying frequencies for 30,177 communities over the period 2013−2018 (Table 1). On average, communities had data reported for 51% of months over the record. GPS coordinates were available for 57% of communities and information on triggering dates for 65% of communities (Table 1). There were operational differences between programs with respect to community selection criteria (Text S1) and implementation strategies; notably, some programs were implemented in conjunction with other approaches (i.e., sanitation marketing, nutrition programs, or provision of subsidies) (Table 1).

2.2. Data Cleaning. For each country, we integrated CLTS program data from different sources into a single dataset. We

Table 1. Key Statistics of CLTS Program Datasets

	Cambodia	Ghana	Liberia	Zambia
# communities before data cleaning	2301	5909	2095	30,177
# communities after data cleaning	2234	2038	2011	9017
% ODF achievement in cleaned datasets[a]	32%	49%	57%	35%
% ODF sustainability in cleaned datasets (among achieving communities)[b]	NA	NA	NA	27%
geographic representation of the datasets	50 communes out of 1431 nationally	77 districts (72 after cleaning) out of 216 nationally	151 clans out of 815 nationally	803 wards (434 after cleaning) out of 1287 nationally
# CLTS programs covered	1 program (2 phases)	3 programs	1 program	1 program
period covered by the dataset	2012−2018	2014−2019	2015−2018	2013−2018
administrative identifiers provided in datasets (from largest to smallest)	province, district, commune	region, district	county, district, clan	province, district, ward
programmatic additions/variations to traditional CLTS[c]	market-based sanitation (in a subset of communities)	RING program: nutrition programming W4H program: hardware subsidies	natural leader networks, local institution integration, localized WASH technologies	CLTS with a unique mobile-to-web service delivery and monitoring system

[a]In Ghana and Liberia, we determined ODF achievement based on ODF certification information provided in the program dataset. In Cambodia and Zambia, where this information was not available, we determined ODF achievement based on latrine coverage (using thresholds of 85 and 100%, respectively, according to national guidelines[22,23]). [b]Among communities that achieved ODF, a community was considered to have "sustained ODF" if latrine coverage equaled or exceeded 90% in all follow-up reports posterior to ODF achievement. Follow-up reports ranged from 1 to 57 months across communities. [c]Programmatic additions applied to all communities in a program unless otherwise specified.

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matched community identifiers provided in CLTS datasets (Table 1) with identifiers from administrative boundary shapefiles. Where possible, we utilized GPS coordinates to facilitate the match. We excluded 197 communities (<1%) that lacked recognizable identifying information. We also removed 1233 communities with <5 households (the household count data were likely to be a data entry error) (3%); 257 in which ODF status could not be determined due to missing latrine or household count information (<1%, all in Zambia); 1843 that were duplicate or unverified according to implementing partners (5%); and 57 that met ODF coverage requirements at baseline (<1%). In Zambia, we identified as potentially erroneous, and removed, any latrine coverage report differing by more than 25% from the preceding and the subsequent monthly reports, or that exceeded 110%. We removed 5591 communities that contained multiple of these potentially erroneous reports (14%). In the case of a single erroneous report, we removed only the report in question. We excluded 16,004 (40%) communities lacking GPS coordinates in Ghana (3007/5909), Liberia (11/2095), and Zambia (12,986/30,177) to allow for more granular analyses while conserving sufficiently large datasets. No GPS information was available in the Cambodian dataset, which constrained us to less granular analyses. We examined how granularity affected results in a subsequent section. Overall, across the six datasets, data cleaning reduced the number of communities by 62%, from 40,482 to 15,300; nearly all (99%) of the excluded records were from Zambia and Ghana (Table 1). These data cleaning steps may have biased the datasets toward communities with higher quality of program implementation.

All datasets included the number of households per community, referred to as "community size." Liberia only reported household counts at baseline. For Cambodia and Ghana, we used the arithmetic mean of baseline and follow-up household counts. In Zambia, we used the arithmetic mean of all values reported for a community record. Similarly, we averaged all positive counts of improved water sources in the Zambian dataset. In Liberia, GC reported the number of diarrhea cases (of any age) in the prior 30 days during baseline data collection. We defined as "diarrhea prevalence" the number of cases divided by the baseline household count. We excluded any data identified by implementing partners as outdated.

2.3. Definition of CLTS Performance Metrics (Outcome Variables).

We relied on a community-level CLTS performance metric, or outcome variable, indicating whether a community had achieved ODF status ("ODF achievement"). For Ghana and Liberia, we computed this variable using the ODF certification information contained in the CLTS program datasets. In both countries, latrine coverage is the primary criteria for ODF certification, with thresholds of 80% in Ghana and 100% in Liberia.[14,24] For Cambodia and Zambia, the datasets did not include ODF information, so we computed ODF achievement ourselves using the latrine coverage data; we defined a community as "ODF" if a follow-up report equaled or exceeded the 85% or 100% latrine coverage threshold required by Cambodian and Zambian guidelines, respectively (Table S2).[22,25] Although the Cambodian threshold was instituted during CRSHIP Phase 1, we have applied the threshold to all communities.

The Zambian dataset allowed for an additional CLTS performance metric: a binary outcome variable indicating whether an ODF community had sustained ODF status over the longitudinal data record ("ODF sustainability"). We defined a community as "sustaining ODF" if latrine coverage equaled or exceeded 90% in all follow-up reports posterior to ODF achievement.[20] For example, if a community achieved ODF status in month 3 of programming but follow-up reporting in month 15 showed <90% latrine coverage, then the community did not sustain ODF. We did not institute a minimum duration for sustaining ODF. Post-ODF follow-up ranged from 1 to 57 months with a median of 23 months.

2.4. Explanatory Variables and Their Computation.

We acquired publicly available, geospatial datasets on 14 demographic, socioeconomic, health, geographic, and environmental variables plausibly influencing CLTS program performance based on the literature (Table 2). To these variables, we added information contained in the CLTS program datasets: community size, baseline latrine coverage (Cambodia and Liberia), diarrhea prevalence (Liberia), and the number of improved water sources (Zambia). The rationale for considering each of these variables, their sources, definitions, and resolutions is specified in Table 2. A number of contextual variables with potential influence on CLTS were not available or too low resolution to be included in this analysis: hydrogeological characteristics, flood burden, decision-maker demographic characteristics (such as age, gender, and religion), and in some cases, poverty levels and baseline latrine coverage. Data on historical and qualitative factors such as prior WASH programs, quality of program implementation, and commitment of local authorities were also unavailable (Table 2, Figure 1), although a complementary qualitative study in Ghana and Cambodia was completed in parallel which specifically investigated these factors through primary data collection.[26] Furthermore, the waterbody datasets only included major rivers and lakes, which we included as a partial proxy for nearby environmental shelter for OD and likelihood of flooding.

The public datasets on water scarcity,[27] population density,[28] cholera risk,[29] time to cities,[30] forest coverage,[31] shrubland coverage,[32] literacy,[33] and access to drinking water[33] were gridded GIS datasets. For variables with resolutions >1 km (literacy, access to improved water, time to cities, cholera risk, and water scarcity), we assigned the grid cell value at the community's position. For variables with resolutions <1 km (population density, forest coverage, and shrubland coverage), we assigned the average of grid cells values within a 500 m radius of the community's position (Table 2). We used the raster package in R (v3.5.2)[34] for these computations. Additionally, we computed the average population density for each commune (Cambodia), district (Ghana), clan (Liberia), and ward (Zambia) captured in the CLTS program datasets. This "area-wide" population density variable was a proxy for the presence of market centers in the vicinity of communities. The roadways[35−38] and waterbody[39,40] variables were polyline datasets. For these, we calculated a community's straight-line distance to the nearest feature in ArcMap 10.6.[41] Cholera risk data were log-transformed prior to inclusion in models.

In the Cambodia dataset, which did not contain GPS coordinates, we linked communities to explanatory variables averaged at the commune level. For literacy and access to drinking water (expressed as percent of population), we weighed each grid cell by population density[28] prior to computing the average. Water scarcity was lower in resolution (60 km), thus we aggregated by district, and first weighted by

Table 2. List of Explanatory Variables Identified as Potentially Influential for CLTS Performance[a]

cat.	factor	available variables	possible link to CLTS performance	source(s)	original res.	model res.[b]
demographic	community size	number of households (#)	The number of households and their demographic characteristics can affect social cohesion and amenability to behavior change[16,18]	Zambia MOH/Akros, CRSHIP, Global Communities Ghana, Global Communities Liberia	comm.	comm.
	decision-maker demographics (income source, religion, age and gender of household head)	unavailable		NA	NA	NA
environmental	nearby environmental shelter for OD	average distance to inland waterways (km)	Forests, bushes, and waterbodies can provide shelter for OD and slow down its eradication.[13,43] Latrine pits may be more or less easy to dig and maintain depending on the local hydrogeology.[16,17] Flooding can damage latrines, and can be more common near waterways.[44]	RCMRD,[40] OCHA[39]	100 m	1 km
		forest coverage (%)		University of Maryland[31]	30 m	1 km
		Shrubland (bush) coverage (%)		Copernicus Climate Change Service[32]	300 m	1 km
	hydrogeology: water table depth, soil type, flood burden	unavailable		NA	NA	NA
accessibility	population density	average # of people per hectare (pp/km^2)	Accessibility may affect several factors linked to CLTS success: availability of materials, markets, local masons and information; and ease of triggering and follow-up for NGOs.[16]	WorldPop[28]	100 m	1 km[c]
	remoteness of community	time to cities (h)		Malaria Atlas Project[30]	1 km	1 km
		distance to major roads (km)[d]		Open Street Maps[35−38]	100 m	1 km
	access to construction materials	unavailable		NA	NA	NA
socioeconomic	literacy	men/women who can read all or part of a sentence (%)	Poverty and literacy are indicators of socioeconomic development, which can affect ability to pay for sanitation and health knowledge. Baseline OD reflects prevailing behaviors before CLTS and may affect a community's responsiveness to the approach.[16,45] Social cohesion and peer pressure can inspire collective action	Demographic and Household Survey[33]	5 km	5 km
	baseline OD	households with latrines at baseline (%)		CRSHIP, Global Communities Liberia	comm.	comm.
	poverty	population living below the national poverty line (%)		Ghana Statistical Service[46]	district	district
	social dynamics (social cohesion, peer pressure)	unavailable		NA	NA	NA
water availability	water supply	households having access to improved water (%)	Access to water supply eases latrine construction, repair, and cleaning.[47] Extreme water scarcity can affect behavior patterns within a community[48]	Demographic and Household Survey[33]	5 km	5 km
		number of improved water sources (#)		Zambia MOH/Akros	comm.	comm.
		rural population covered by a water supply system (%)		District League Table[49]	district	district
	water scarcity	the ratio of water use and water availability per area		Water Footprint Network[50]	60 km	60 km
health	waterborne disease burden	diarrhea prevalence at baseline (%)	Awareness of waterborne diseases may increase receptivity to health messaging[6]	Global Communities Liberia	comm.	comm.

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Table 2. continued

cat.	factor	available variables	possible link to CLTS performance	source(s)	original res.	model res.[b]
		predicted cholera incidence (cases/100,000 pp)		Infectious Disease Dynamics[29]	20 km	20 km
qualitative factors	commitment of local authorities	unavailable	Motivation of local government and traditional leaders such as chief and elders can affect program outcomes[8,51]	NA	NA	NA
	quality of program implementation	unavailable	Several aspects of implementation, including quality of facilitation, intensity of follow-up, and promotion of pro-poor support can affect outcomes[8,13,16,52]	NA	NA	NA
	prior WASH programs	unavailable	Can affect a community's expectation of subsidies, aspirations for specific latrine designs, or can result in implementation fatigue[13,16,18]	NA	NA	NA

[a]Variables investigated in this study are listed under "available variables". [b]All variable values were extracted at the community location; variables where data resolution was <1 km were aggregated within 1 km diameter of community location. [c]An additional variable, "area-wide population density" was defined at the smallest administrative boundary level for each country: commune (Cambodia), district (Ghana), clan (Liberia), and ward (Zambia). [d]"Major roadways" include trunk, primary, secondary, and tertiary road types as defined by Open Street Maps.

water availability (from a separate dataset, see Text S2).[42] To calculate a commune-level average distance to roadways and waterbodies, we computed straight-line distances between these features and the centroids of each 2 × 2 km cell within a commune in ArcMap 10.6[41] and then computed the arithmetic mean. To examine whether the different variable computation methodology used in Cambodia (due to the lack of GPS coordinates) may affect results, we reproduced this methodology to compute clan-averaged variables in Liberia, district-averaged variables in Ghana, and ward-averaged variables in Zambia and compared results with those of GPS-derived variables.

CLTS outcomes are likely influenced by the length of exposure to programming. To control for this influence, we computed a proxy variable ("time since triggering") for each community using the number of years (for Cambodia and Zambia) or months (for Ghana and Liberia) between the triggering event (Zambia and Liberia) or baseline data point (Cambodia and Ghana, where triggering dates were unavailable) and the last follow-up data point. Additionally, in Zambia, we recognized that we were more likely to identify both achievement of, and "slippage" from, ODF status in communities with a more complete longitudinal record (with each data point in the record corresponding to a monitoring visit from a volunteer field facilitator). To control for this bias, we computed the number of reports for each community. Bivariate analyses confirmed that these variables were associated with CLTS outcomes ($p < 0.05$). We did not control for change in community size because this information was only available for the Cambodian dataset where the vast majority of communities (97%) reported no change in size between baseline and endline data collection.

We verified that all explanatory variables had relative standard deviations >5% to ensure sufficient variability. All explanatory variables were continuous and normalized by country with a standard score.

2.5. Model Structure. We employed multilevel logistic regressions in R (v3.5.2).[34] We included administrative levels (province, district, and commune in Cambodia; region and district in Ghana; county and district in Liberia; and province and district in Zambia) as random effects to the model formulas to account for unmeasured influences of the enabling environment, such as political will and local government budget.[53] In Ghana and Cambodia, we included the CLTS program (or program phase) as an additional random effect to account for differences in program implementation strategies. Random effects allowed for observations within different administrative levels or programs to be treated independently. Additionally, we controlled for time since triggering and the number of longitudinal records in all models, as explained above.

We identified a specific set of confounders for each explanatory variable in each country using an approach inspired by Evans et al., 2012.[54] Briefly, our approach relied on: (i) a conceptual model, or directed acyclic graph (DAG), of plausible relationships between all variables (Figure 1); (ii) a stepwise process for identifying additional confounders not identified with the DAG. A model never included two variables reflecting the same factor (see Table 2); for example, we either included time to cities or distance to roads (both proxies for remoteness); similarly, we either included cholera risk or baseline diarrhea prevalence (both proxies for waterborne disease burden). Further details on the variable selection

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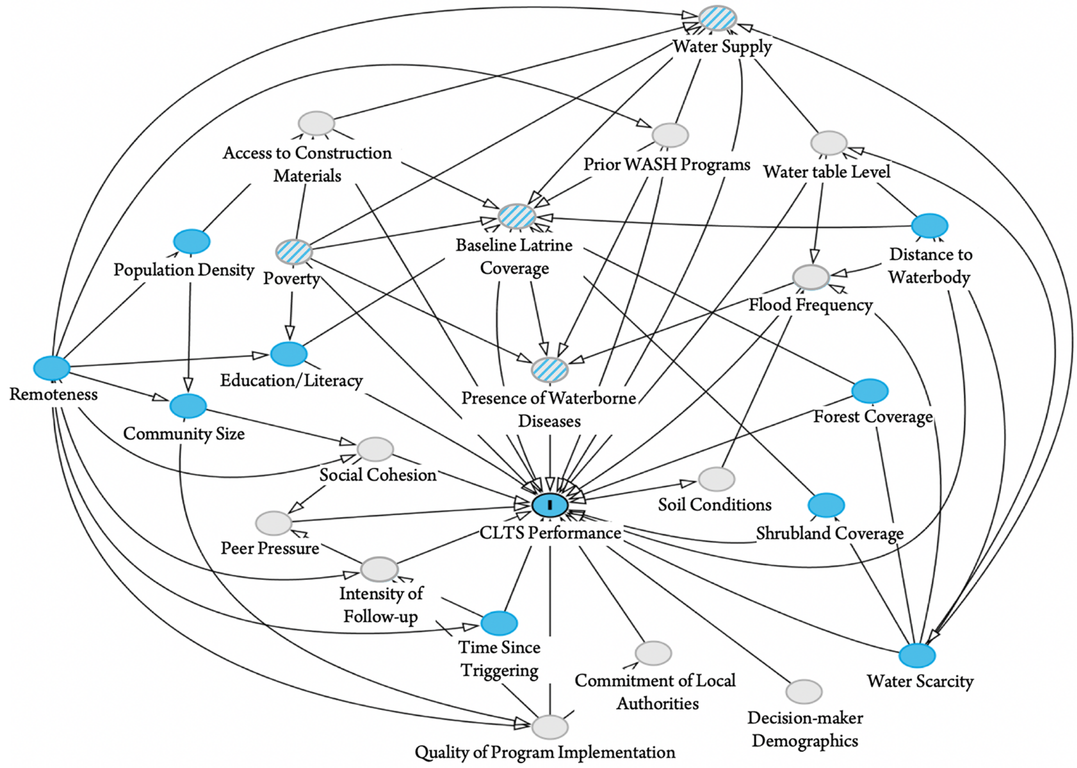

Figure 1. Directed acyclic graph mapping plausible relationships between explanatory variables and CLTS performance. CLTS performance = ODF achievement or ODF sustainability.

approach are available in Text S3 and Table S3. We confirmed that within each model, all confounders had variable inflation factors <3 (Table S4). We expressed model results as odd ratios (ORs) where values >1 indicate a positive association between explanatory and outcome variables. We also applied a post hoc Bonferroni correction to account for potential multiple-comparison bias. We discussed all results with implementing partners and solicited their input to interpret findings.

For explanatory variables significantly associated with ODF achievement, we further examined whether their influence differed depending on community size. We conducted a stratified analysis by computing the same models identified in Table S3 in two separate data subsets: below- and above-median-size communities.

2.6. Identifying Split Points. For statistically significant explanatory variables associated with ODF achievement ($p < 0.05$), we used a classification and regression tree (CART) approach to identify a "split point". The split point indicates the value of the variable that maximizes homogeneity of ODF achievement in one subgroup (i.e., on one side of the value) and of nonachievement in the other subgroup (i.e., on the other side of the value) (see Text S4).[34,55] We used the CART function in R and required a minimum of 10% of communities on either side of the split point. We then used Wilcoxon tests to confirm that the difference in ODF achievement among community subsets above and below a split point was statistically significant ($p < 0.05$). One (of 21) split point did not meet this criterion and was not reported.

3. RESULTS AND DISCUSSION

3.1. Variability in CLTS Performance. After data cleaning, we found that the CLTS programs had led to ODF achievement in 32% of communities in Cambodia, 49% in Ghana, 57% in Liberia, and 35% in Zambia (Table 1). Levels of ODF achievement however varied widely across administrative areas (min: 0%, max: 100%) within each country (Figure S1). In the Zambian dataset, 70% of ODF communities slipped below 90% latrine coverage at least once over the period of record and 25% did so without recovering to 100% coverage over the posterior record. On average, the first instance of slippage occurred 9 months after ODF achievement (interquartile range or IQR: 2−13). The occurrence of slippage increased from 53% one year after ODF achievement to 72% three years after. These numbers were rather consistent with other studies in Africa, which have reported post-ODF slippage ranging between 15 and 100% up to 5 years after ODF achievement.[20,56,57]

3.2. Wide Diversity of Implementation Contexts. The explanatory variables revealed a wide diversity of implementation contexts within and between the four countries (Table S5). Among study communities, the median number of households was 153 in Cambodia (IQR: 105−217) compared to only 25 in Ghana (IQR: 13−58), 20 in Liberia (IQR: 12−41), and 25 in Zambia (IQR: 14−46). Study areas were the most accessible in Cambodia, with a median distance to main roads of 1 km (IQR: 0−2) compared to 5 km (IQR: 1−9) in Ghana, 5 km (IQR: 1−11) in Liberia, and 9 km (IQR: 2−20) in Zambia. Time to cities was less contrasted, with a median ranging from 1 h (Cambodia, Ghana, and Zambia) to 1.4 h (Liberia). Area-level population density was the highest in Cambodia (median: 290 pp/km^2, IQR: 209−413), followed by Ghana (median: 77 pp/km^2, IQR: 41−135), Liberia (median: 39 pp/km^2, IQR: 29−65), and Zambia (median: 23 pp/km^2, IQR: 13−39), suggesting that study communities in Cambodia may have higher access to market centers and supply chains.

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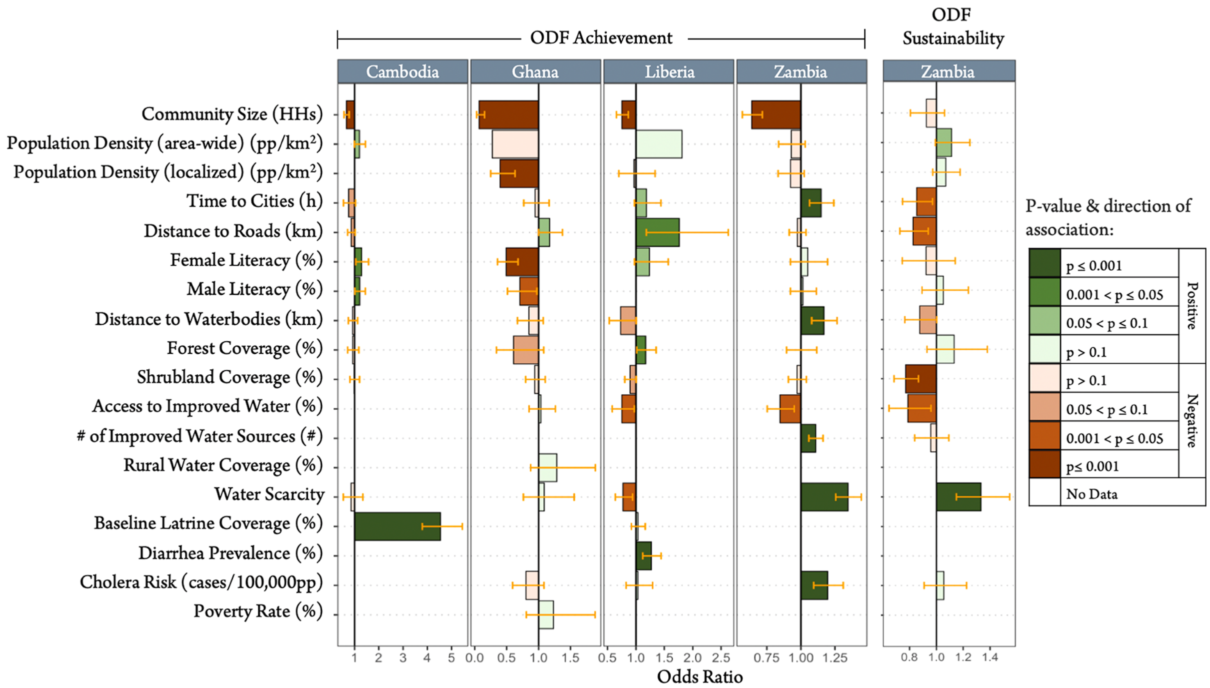

Figure 2. Outputs of logistic regression models in terms of ORs. Each bar represents the output of a specific multivariate model (Table S3), derived for the standardized explanatory variable of interest (rows) by country (columns). Results are displayed as ORs (length of the bar), *p*-values (shade, darker = more significant, lighter = less significant), direction of impact (color, green = positive, red = negative), and 95% confidence intervals (in gold). The confounders applied to each explanatory variable are listed in Table S3. Confidence intervals for area-wide population density were removed for clarity (Ghana: 0.03−2.93, Liberia: 0.61−5.34). See Table 2 for additional details on variables and their resolutions and Table S7 for numerical results. All results with $p < 0.001$ met the significance test when considering post hoc Bonferroni corrections.

Female literacy, a proxy for socioeconomic development, was the highest in Cambodia (median: 76%, IQR: 72−79), followed by Zambia (median: 59%, IQR: 50−70), Ghana (median: 31%, IQR: 21−53), and Liberia (median: 14%, IQR: 9−25). Male literacy, although generally higher than female literacy, indicated the same trend. Access to improved water was the highest among study areas in Ghana (median: 89%, IQR: 73−96), followed by Zambia (median: 74%, IQR: 45−89) and Liberia (median: 38%, IQR: 13−88) (not available for Cambodia, national rural average = 73%).[1] In Zambia, the two metrics for water supply, percent access to improved water (interpolated from DHS cluster survey data) and number of improved water sources per community (primary data collected during CLTS programming), were not correlated (correlation coefficient: 0.03). Environmental factors such as distance to major waterbodies, type of land cover, and water scarcity were also variable across the four countries.

Compared to national medians, study communities in Cambodia had higher literacy (+12%) and lower forest coverage (−39%) indicating that the program did not operate in the most rural areas, although population density was nearly half the national median (Table S6). In Ghana, study communities had lower literacy (−13%) than the national median yet were in more densely populated districts (+35%) (Table S6). In Liberia, study communities were generally representative of national medians (Table S6). In Zambia, study communities had higher access to improved water (+40%) than the national median, suggesting that the program likely operated in the proximity of small urban centers (Table S6). These comparisons indicate that implementers' criteria for community selection (Text S1) may have resulted in their program areas not being entirely representative of all areas with poor sanitation in their country.

3.3. Favorable Conditions for CLTS Varied across Countries. The contextual factors associated with CLTS performance differed between countries (Figure 2, Table S7). In Cambodia, ODF achievement was more likely in smaller communities (OR: 0.66, $p < 0.001$) with higher latrine coverage at baseline (OR: 4.55, $p < 0.001$), as well as in communes with higher male literacy (OR: 1.21, $p = 0.04$) and female literacy (OR: 1.28, $p = 0.02$) (Figure 2). In Ghana, ODF achievement was more likely in smaller communities (OR: 0.07, $p < 0.001$), with low population density (OR: 0.40, $p < 0.001$), low female literacy (OR: 0.49, $p < 0.001$), and low male literacy (OR: 0.71, $p = 0.03$) (Figure 2). In Liberia, ODF achievement was more likely in smaller communities (OR: 0.75, $p < 0.001$), further from roads (OR: 1.76, $p = 0.01$) [and cities, although less significant (OR: 1.18, $p = 0.09$)], higher forest coverage in the immediate vicinity (OR: 1.17, $p = 0.03$), lower access to improved water sources (OR: 0.75, $p = 0.03$), lower water scarcity (OR: 0.77, $p = 0.010$), and higher diarrhea prevalence at baseline (OR: 1.27, $p < 0.001$) (Figure 2).

In Zambia, ODF achievement was more likely in smaller communities (OR: 0.64, $p < 0.001$), with higher travel time to cities (OR: 1.15, $p < 0.001$), higher distance from major waterbodies (OR: 1.17, $p < 0.001$), higher water scarcity (OR: 1.35, $p < 0.001$), and higher cholera risk (OR: 1.20, $p < 0.001$) (Figure 2). The results on water access were seemingly contradictory: communities with a higher number of improved water sources (as of 2018) were more likely to have achieved ODF (OR: 1.11, $p < 0.001$); yet, communities located in areas with lower percent access to improved water (as of 2013) were also more likely to achieve (OR: 0.85, $p = 0.01$) and sustain

ODF (OR: 0.77, $p = 0.004$). This result possibly reflects that CLTS programs are closely intertwined with water supply programs in Zambia, as WASH implementers often require sanitation improvements as a condition for communities to receive water supply projects.[58] In this context, communities with a low initial water access may be more motivated to achieve ODF status, which is subsequently rewarded with the construction of an improved water source, consistent with our results. ODF communities were also more likely to sustain ODF if they had a shorter time to cities (OR: 0.85, $p = 0.02$), lower distance to roads (OR: 0.88, $p = 0.03$), and lower shrubland coverage (OR: 0.79, $p < 0.001$) (Figure 2).

While existing CLTS guidance documents promote generalized characteristics of favorable environments for implementation,[6,59] our results show that, with the exception of community size, contextual predictors differ from one country to another. Therefore, attempts to provide universal guidance can be misleading. For example, the CLTS Handbook proposes that the lack of cover in the surrounding area, unprotected water supplies, and high incidence of waterborne diseases constitute a favorable environment for CLTS.[6] However, we found that forest cover had a positive association with ODF achievement in Liberia; a weak, negative association in Ghana; and no association in Cambodia or Zambia. Distance to major waterbodies was only significant in Zambia, and lower access to improved water was associated with higher ODF achievement in Zambia and Liberia but not in Ghana. CLTS was indeed more successful in areas with high diarrhea prevalence in Liberia and high cholera risk in Zambia, but no other association for cholera risk was detected. Additionally, we found that water scarcity was positively associated with both ODF achievement and sustainability in Zambia, negatively associated in Liberia, and had no association in Cambodia and Ghana. Given this variability, implementers should first understand the contextual predictors of performance in their specific geographies.

Our analysis found that a number of contextual factors were statistically significant predictors of CLTS performance. This does not mean these factors cause CLTS performance but rather that they are good indicators of where the approach may succeed. The mechanisms through which a specific contextual factor is correlated with CLTS performance can be complex and may involve influences that are difficult to capture quantitatively. The next two sections provide our interpretation of these mechanisms for the key predictors that we identified.

3.4. Community Size: The Most Generalizable Predictor. Small community size was a strong predictor of ODF achievement ($p < 0.001$) in all countries, which is consistent with the CLTS Handbook and other literature.[16,18,20] Smaller communities may be more favorable for a number of reasons. Engagement during triggering events and follow-up visits may be easier in communities with fewer households.[24,58,60,61] Additionally, smaller communities may have higher social cohesion, particularly as households are more likely to be related to neighbors, as well as stronger local leadership and higher socioeconomic homogeneity. This may manifest in peer pressure, a stronger impetus for collective action, and easier information sharing between households.[8,62−64] Small communities may also have more space and less land ownership challenges for building latrines.[61,65] In Ghana, communities with low population density were more likely to become ODF, suggesting that the availability of space may have been an important factor. Finally, smaller communities require less construction to reach ODF requirements. However, community size was not correlated with ODF sustainability in Zambia ($p = 0.26$) (Figure 2), which indicates that the abovementioned benefits of small communities may not translate to sustained behavior change.

A stratified follow-up analysis of prior models indicated that predictors of ODF achievement differed according to community size. Low access to improved water in Liberia and Zambia, low men's literacy and population density in Ghana, and large time to cities in Zambia revealed to be key predictors of CLTS performance in above-median-size communities but not in below-median-size communities (Table S8). Conversely, small community size in Cambodia, high diarrhea prevalence in Liberia, and high cholera risk in Zambia were only key predictors of CLTS performance in below-median-size communities (Table S8). Finally, high forest coverage in Liberia was no longer a significant predictor when considering the two subsets of community sizes separately (Table S8). These additional results indicate that community size can modulate the influence of other contextual factors, which can simplify implications for implementers. For example, in Zambia, smaller communities are favorable settings for CLTS independent of their remoteness or access to improved water, while larger communities are less favorable independent of their cholera risk.

3.5. Context-Specific Influence of Accessibility and Socioeconomic Development. Accessibility is often cited as a possible determinant of CLTS performance: while the CLTS Handbook and a number of studies have suggested that remote areas may be more receptive to the CLTS approach,[16,18,20,59] other authors have pointed out that proximity to supply chains of construction materials may promote toilet construction.[13,66] In this study, we used two indicators of accessibility, distance to roads and time to cities, complemented by a third indicator, area-wide population density, a proxy for the presence of supply chains. In the three African countries, while we found no associations with area-wide population density, we did observe that remoteness, as measured by distance to roads (Ghana and Liberia) or time to cities (Liberia and Zambia) was correlated with ODF achievement (Figure 2). In Ghana, achievement was also higher in communities with low population density (Figure 2), consistent with small, remote locations. This is potentially because remote communities have stronger social cohesion, higher socioeconomic homogeneity, and have been exposed to fewer subsidy-driven sanitation programs in the past.[6,13,16] Our implementing partners have also observed that urbanized communities are more difficult to trigger because households have less time to attend mobilization events and also have less space for building latrines.[24,61]

In contrast, Cambodian communities were more likely to achieve ODF in densely populated communes with proximity to cities and roads (although these associations were less statistically significant, $p < 0.1$) (Figure 2). Such communities may have easier access to market centers and materials, facilitating the construction of high-quality pour-flush latrines and durable superstructures, which Cambodian households tend to prefer.[60] High population density may also promote latrine construction as there are fewer suitable locations for OD,[67] although we were unable to investigate this variable at the community level. Additionally, remoteness (short distance to roads and short travel time to cities) was positively

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Table 3. Split Points for Variables Significantly Associated with ODF Achievement[a,b]

explanatory variable	split point	% ODF achievement[c] (proportion of communities on each side of the split point): below split point	above split point	percentage point difference in ODF achievement across split point
		Cambodia		
baseline latrine coverage	≥34%	16 (50)	49 (50)	33
community size	<110 HH	40 (28)	29 (72)	11
female literacy	≥68%	20 (12)	34 (88)	14
male literacy	≥85%	29 (89)	57 (11)	28
		Ghana		
community size	<40 HH	61 (70)	20 (30)	41
female literacy	<57%	56 (81)	18 (19)	38
male literacy	<35%	62 (28)	43 (72)	19
population density	<280 pp/km^2	57 (78)	22 (22)	35
		Liberia		
community size	<61 HH	60 (82)	40 (18)	20
diarrhea prevalence	≥25%	55 (89)	73 (11)	18
distance to roads	≥16 km	48 (12)	58 (88)	10
forest coverage	≥51%	50 (22)	59 (78)	9
water scarcity	<1.4	65 (42)	52 (58)	13
		Zambia		
access to improved water	<95%	36 (90)	26(10)	10
cholera risk	≥0.83	27 (30)	38 (70)	11
community size	<74 HH	37 (90)	19 (10)	18
distance to major waterbodies	≥12 km	27 (20)	37 (80)	10
number of improved water sources	≥1.4	33 (28)	36 (72)	3
time to cities	≥0.6 h	23 (23)	38 (77)	15
water scarcity	≥0.053	33 (78)	43 (22)	10

[a]One split point (access to improved water in Liberia) had a Wilcoxon p-value > 0.05 and is not listed. Split points were derived using bivariate analyses. [b]We identified split points using a CART approach. The split point is the value of the variable defining the greatest homogeneity in ODF achievement on one side of the value and the greatest homogeneity in nonachievement on the other side. [c]Wilcoxon tests confirmed that the difference in ODF achievement below and above split points was statistically significant ($p < 0.05$).

correlated with ODF sustainability in Zambia ($p < 0.05$) (Figure 2). This suggests that proximity to market centers may allow for the construction of more durable latrines or for quicker recovery when latrines are damaged or pits filled, benefiting sustainability.

Our results indicate that socioeconomic development is a predictor of CLTS performance independent of accessibility. Controlling for remoteness, we found that ODF achievement had a stronger statistical association with literacy than accessibility in two of the four countries (Cambodia and Ghana) (Figure 2), indicating that socioeconomic development can be a more robust predictor of CLTS performance than accessibility. The direction of this correlation was also context-specific. In Cambodia, ODF achievement was more likely in areas with higher literacy, while in Ghana, we observed the opposite trend. These differences are likely due to cultural preferences and the historical context. In Cambodia, a parallel study identified strong cultural preferences for pour-flush toilets with cemented superstructures, while rudimentary latrines made of local materials were stigmatized, likely a result of prior subsidy and market-based sanitation programs.[26] In this context, wealthier (i.e., more educated) communities are more likely to make progress. In contrast, rudimentary latrines are generally acceptable in rural Ghana. Thus, remote communities with easy access to traditional construction materials (mud, thatch, sand, and wood) are more likely to progress, while wealthier, urbanized areas tend to be slower. This interpretation is consistent with prior research in Ghana that showed better CLTS performance in remote, poorer areas.[19] Implementers also noted that urbanized areas, although generally wealthier (and more educated), were more challenging because social cohesion was weaker, people had less time for community activities, expected assistance from NGOs, or faced space and land tenure constraints.[61,65]

While existing guidance for practitioners focuses on accessibility as a singular indicator to inform decisions,[59] our results suggest that CLTS programs should consider both accessibility and socioeconomic development in their planning phase. The quantitative results presented here apply only to the four study countries, but practitioners elsewhere should conduct similar analyses of their data to identify contextual predictors applicable to their programs. High-resolution literacy maps extrapolated from surveys are increasingly available[28,33] and provide opportunities to refine the existing guidance.

3.6. Impact of Explanatory Variable Resolution. In the three African countries, models using low-resolution explanatory variables (defined at the district, clan, or ward level) yielded different results than models using high-resolution explanatory variables (defined at the community level) (Figure S2, Table S9). High-resolution models identified a number of factors significantly correlated ($p < 0.05$) with ODF achievement that low-resolution models did not detect: distance to roads in Ghana; distance to major waterbodies and access to improved water in Zambia; and time to cities, distance to roads, female literacy, distance to major waterbodies, and forest and shrubland coverage in Liberia. Additionally, low-resolution models identified several significant associations that were not

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verified in the high-resolution models: access to improved water in Liberia; population density, time to cities, distance to roads, female and male literacy, and shrubland coverage in Zambia. While low-resolution models are the only option without GPS coordinates (as in the Cambodian dataset), the abovementioned comparison shows that they may overlook or misinterpret significant influences, particularly when there is high heterogeneity within administrative units. Therefore, we recommend implementers to collect GPS coordinates of program communities if they wish to examine contextual predictors of CLTS performance.

3.7. Split Points Can Guide Implementation. Our analysis identified four variables significantly associated with ODF achievement in Cambodia and Ghana, six in Liberia, and seven in Zambia (Figure 2). To translate these findings into practical information for implementers, we identified a split point for each of these variables using a CART approach (Table 3). Simply, the split point is the value of an explanatory variable that maximizes the difference in ODF achievement above and below.[34,55] For example, in Ghana, the community size split point was 40 households (Table 3); 61% of communities below this size achieved ODF compared to only 20% of communities above this size, and no other community size yielded more distinct probabilities of ODF achievement. Where implementers subdivide large communities into subsets to facilitate triggering and monitoring,[63,65] they may use the split points identified here as guidance. However, as noted above, there may be multiple underlying causes for a large community to have poor CLTS performance (i.e., lower social cohesion, more difficult implementation, etc.). Subdividing communities may make implementation easier but may not affect the other underlying causes. Thus, split points should primarily be used to identify existing favorable areas and not to drive mitigation actions in unfavorable contexts. We also note that these split points should not be interpreted as strict thresholds; communities in a ±10% range around split points are expected to react similarly.

The difference in ODF achievement below and above split points ranged from 3 percentage points (pp) to 41 pp and was generally the largest in Ghana (33 pp on average), followed by Cambodia (22 pp), Liberia (14 pp), and Zambia (11 pp) (Table 3). The highest difference in ODF achievement across split points was with community size in Ghana (+41 pp in communities <40 households), baseline latrine coverage in Cambodia (+33 pp in communities >34% coverage at baseline), community size in Liberia (+20 pp in communities <61 households), and community size in Zambia (+18 pp in communities <74 households) (Table 3). Implementers can use these split points to target activities and resources to areas with the highest probability of success[68] and/or change their approach in areas anticipated to be less favorable. They may find the split points with the highest pp difference in ODF achievement most helpful for prioritizing program locations.

The CART approach can also be applied to multiple variables simultaneously, for example, to identify sets of conditions favorable to achieve target levels of ODF achievement. In Ghana, communities with over 70% probability of ODF achievement could be characterized with three variables (community size, female literacy, and population density) (Table S10). This was also the case in Liberia, although the three variables differed (community size, water scarcity, and forest coverage) (Table S10). In contrast, no combination of factors led to a 70% probability of ODF achievement in Cambodia or Zambia. However, identifying communities with a 50% probability of ODF achievement could be accomplished with consideration of three variables in Cambodia (baseline latrine coverage, male literacy, and community size) and four variables in Zambia (access to improved water, community size, distance to major waterbodies, and time to cities) (Table S10).

3.8. Limitations. This study had a number of limitations stemming from constraints with the CLTS and explanatory variable datasets. First, we aggregated CLTS data from multiple implementing partners that differed in quality (Table S1). Data limitations led us to use different definitions of ODF achievement across countries: in Cambodia and Zambia, we relied solely on latrine coverage, while in Ghana and Liberia, we used official ODF status, which primarily reflects latrine coverage but may also capture other factors such as acceptable disposal of excreta and lack of visible OD. In practice, ODF status may not be equitable to elimination of OD, as the latter is difficult to document reliably. Furthermore, it is important to note that latrine coverage thresholds required for ODF status differ between countries: 80% in Ghana, 85% in Cambodia, and 100% in Liberia and Zambia.[14,16,24] These differences may partly explain the different associations observed between countries. Second, our analysis captured communities for which monitoring data were available and that passed our data cleaning steps. This likely biased the data toward communities with higher quality of program implementation. A comparison of our study communities with national averages (Table S6) suggests that they likely did not capture the most remote or impoverished settings. Therefore, our findings may not generalize to the "last mile" communities. Third, the Cambodian dataset lacked sufficient information to geolocate communities below the commune level. We thus aggregated explanatory variables, and the resulting lack of granularity may have affected regression results, although we confirmed with implementing partners that communes were small enough to derive localized contextual variables. Fourth, we were unable to oversee data collection or validate any community-specific information provided in program datasets and relied on partners to identify outdated parts of the datasets. Fifth, for some models, we did not control for all potential confounders (Figure 1, Table S3), as some datasets were unavailable or too low resolution to be included. Specifically, models for remoteness, water supply, and presence of waterborne disease variables lacked one or more variables in their minimum sets of confounders (Table S3). Some of these confounders may have influenced model results, and we do not claim causality from any of our explanatory variables. Finally, explanatory variable datasets often differed temporarily with program data, which may have obscured some correlations. However, we argue that despite their limitations, available datasets can help implementers identify contextual predictors of CLTS performance and better target their programs.

3.9. Implications. Although CLTS is the most widely used approach to eradicate OD in rural Africa and Asia and is part of the national sanitation strategy in dozens of countries, it does not perform well everywhere. CLTS is often applied country- or district-wide, but a substantial proportion of the communities targeted (e.g., 63% across the six programs examined here) does not achieve ODF objectives. Of the countries studied, only Cambodia is on track to eliminate OD by 2030,[1] with the slowest progress observed in rural areas,

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further highlighting the need for efficient and sustainable rural sanitation programs. This study demonstrates that the large amounts of monitoring data that organizations collect along with publicly available, high-resolution datasets on accessibility, socioeconomic, and environmental factors can be leveraged to gain insights on favorability of the CLTS approach. Factors correlated with CLTS performance differed between countries and between performance metrics (ODF achievement vs ODF sustainability) within the same country. Thus, our findings do not support the hypothesis of a universal CLTS performance envelope. Although our analysis could not examine the relative influence of contextual factors and qualitative aspects such as commitment of local authorities and quality of program implementation, it demonstrated that a number of contextual factors available to implementers are good predictors of CLTS performance. This has practical implications for implementers, who could primarily target their CLTS programs to areas most suitable for the approach, and test alternative program approaches in less favorable areas. Such data-informed decisions could help improve the cost-effectiveness of CLTS interventions.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.0c05733.

Community selection criteria of implementing partners and detailed data analysis steps (for data treatment, confounder selection and split point determination); national CLTS guidelines, CLTS program dataset details, list of confounders for models, variable inflation factors, summary statistics of explanatory variables, comparison of study communities with national averages, results for all models, stratified analyses by community size, comparison of model results with high-resolution and low-resolution variables, and sets of conditions meeting ODF achievement levels; and ODF achievement among program regions and comparison of model results with high-resolution and low-resolution variables (PDF)

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Notes

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