A comparative cohort study of the effect of rainfall and temperature on diarrhoeal disease in faecal sludge and non-faecal sludge applying communities, Northern Ghana

Razak Seidu, Thor Axel Stenström and Owe Löfman

ABSTRACT

This study assesses the effect of temperature and rainfall on diarrhoea incidence in sludge and non-faecal sludge applying farming communities in Northern Ghana. Diarrhoea episode data were obtained through an open cohort survey involving 1,341 and 1,323 individuals from the sludge and non-faecal sludge communities, respectively. The effects of temperature and rainfall variables on diarrhoea incidence were assessed using autoregressive Poisson regression models. Maximum rainfall events in the same bi-week increased the risk of diarrhoea in the sludge (relative risk, RR: 1.034; confidence interval, CI: 1.02–1.05) and non-sludge (RR: 1.003; CI: 0.99–1.01) communities. However, this was not significant in the non-sludge communities ($p > 0.05$). Minimum rainfall occurring in the same bi-week decreased the risk of diarrhoea in both communities. Maximum temperature decreased the risk of diarrhoea in the sludge communities (RR: 0.50; CI: 0.38–0.65), but increased the risk in the non-sludge communities (RR: 1.19 CI: 1.02–1.40). Minimum temperature increased diarrhoea disease risk (RR: 3.50; CI: 2.10–5.80) in the sludge communities, but decreased the risk (RR: 0.70; CI: 0.54–0.84) in the non-sludge communities. The study stresses the need to account for weather variables when developing schemes for the land application of faecal sludge.

Key words | diarrhoea, rainfall, risk factors, seasonality, sludge application, temperature

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INTRODUCTION

Diarrhoea remains a major cause of morbidity worldwide accounting for the death of some 1.8 million people annually (WHO 2009). Diarrhoeal disease incidence exhibits seasonal patterns (Feachem *et al.* 1983) dictated by a myriad of complex factors within the public and domestic domains (Cairncross *et al.* 1996), of which the impact of public domain factors such as the application of faecal sludge in agriculture is significant (WHO 2006). The risk of diarrhoeal diseases associated with faecal sludge application depends on the occurrence of pathogens in farm soils and their decay rates – all of which are, to some extent, influenced by seasonal variations in temperature and precipitation (Gerba & Bitton 1984). The ultraviolet light from the sun inactivates viruses and bacteria (Feachem *et al.* 1983; Gerba & Bitton 1984). For instance, viruses and *Salmonella* occurring in faecal sludge can just survive for <70 days (usually <20) and <100 days (usually <20), respectively, in farmland soils at temperatures of 20–30 °C (WHO 2006). However, under constantly low temperatures, the survival of viruses and *Salmonella* can increase to one year, to cause infections in exposed farmers (Feachem *et al.* 1983). Increased precipitation is associated with the transport of pathogens on sludge-amended farms. The movement of *Cryptosporidium*, through tilled and untilled soils under different rainfall intensities has been demonstrated in a recent study (Ramirez *et al.* 2009). Depending on the precipitation intensity and hydro geological conditions this may lead to the contamination of surface and underground water resources. Hoorman & Shipitalo (2006) reported results from a survey they conducted that investigated

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98 incidents, over a 4-year period (2000–2003), where agricultural wastes in subsurface drainage waters contaminated streams in Ohio. The foregoing suggests that variations in these key weather variables can mediate in the transmission of diarrhoeal diseases, especially in settings where the land application of untreated faecal sludge is practised.

To our knowledge, no study has assessed the relationship between weather variables and diarrhoea incidence in communities applying faecal sludge or wastewater in agriculture. However, ample evidence exists about the impact of seasonal variations in temperature and rainfall on the occurrence of pathogens in the environment and of the incidence of diarrhoea diseases (Checkley *et al.* 2000; Rose *et al.* 2001; Hashizume *et al.* 2007; Hu *et al.* 2007). For instance, diarrhoea (particularly that caused by the bacteria and protozoan pathogens which predominate in developing regions) is highly sensitive to variations in both temperature and precipitation over daily, seasonal and inter annual time periods (Checkley *et al.* 2000; Curriero *et al.* 2001). In settings where untreated faecal sludge application is common, clarifying the potential role of weather variables in the transmission of diarrhoeal disease is important. From an applied perspective, interventions can be developed not only within the matrix of curtailing exposure to pathogens as presently prescribed by the World Health Organization guidelines (WHO 2006), but also related to temperature and rainfall variations.

In this study, a comparative assessment of the effect of rainfall and temperature on diarrhoeal disease incidence in faecal sludge and non-faecal sludge applying communities in Northern Ghana is made. Northern Ghana is the region most impacted by climate change in Ghana. Since the late 1990s, floods have been increasingly frequent and mean annual temperatures have increased greatly over the years in the region. This study differs in scope and methodology compared to other studies assessing the effect of temperature and rainfall on diarrhoea cases. It employs a prospective cohort framework in combination with the observation of weather variables from a local station. Thus, specific local heterogeneities are implicitly captured, to allow a better assessment of the effect of temperature and rainfall, at a very local scale that compares communities in relation to the application of faecal sludge. Furthermore, new insights into the interaction between risk factors may generate a potential for new interventions.

METHODS

The study population and data collection

The study was performed in the Tamale Metropolitan Area (9°18′–9°26′ N, 1°15′ E–1°23′ W) of the Northern Region of Ghana. It is situated in the Guinea Savanna Agro-Ecological Zone and characterized by one distinct wet (rainy) and one dry season. The uni-modal rainfall pattern gives a precipitation of about 1,000 mm per annum and the mean annual temperature is 29 °C (Tamale Metropolitan Assembly 2000). Tamale is an urban centre, but has fringe areas where people practise traditional subsistence agriculture. In these communities, the land application of faecal sludge follows a seasonal pattern. Sludge collected from pit latrines and septic tanks by trucks is mainly dewatered in the field adjacent to or on agricultural land in the dry season (November–April) when temperatures reach about 39 °C. Two traditional sludge dewatering methods, random spot spreading and pit containment, are used to process sludge into 'cakes' and subsequently incorporated into the soil, by tilling with hoes or tractor before the start of the rainy season that lasts from May to October. Of the two dewatering methods, the random spot spread method is widely used by farmers, as sludge is rapidly dewatered under this method. The dewatering time under the random spot spread method ranged from 7 to 60 days, producing dried sludge with *Escherichia coli* concentration in the range of 2.4 most probable number (MPN)/g of total solids (TS) to 1.6×10^4 MPN/g TS (Seidu *et al.* submitted).

A prospective bi-weekly cohort survey was conducted from March 2008 to February 2009. Participants of the study were drawn from peri-urban farming communities in the Tamale Metropolitan Area. A total of 2,664 individuals were involved in the study, of which 1,341 were drawn from two communities applying untreated faecal sludge in the fields and 1,323 from two non-faecal sludge communities. Prior to the study, a written purpose was read in the local language to all the household heads of the participants and informed consent was obtained from them. The study instruments and methods were reviewed and approved by the

University for Development Studies ethics committee. Standard pre-coded disease incidence questionnaires were developed and revised after conducting a pilot survey in two communities with similar socio-demographic characteristics as the study communities. All questionnaires were administered by trained fieldworkers and supervised by a lead investigator. The disease incidence questionnaires were used to collect information on individuals at bi-weekly intervals over a full year cycle. In this study, an episode of diarrhoea was defined as three or more loose (or watery) stools within 24 hours, regardless of other gastrointestinal symptoms (Baqui *et al.* 1991), and without the influence of a purgative (or medication). Diarrhoea episode information for infants and children was obtained from their mothers. In addition to the disease incidence survey, a comprehensive farm observation survey was conducted to document the timing of faecal sludge application in the sludge communities and related practices. Rainfall and temperature data over the study period for both community groups were collected from the Ghana Meteorological local station in Tamale. It was assumed to be the same for all peri-urban communities of the Tamale Metropolitan Area. Daily records of rainfall and maximum and minimum temperatures were collected. From the daily records, the bi-weekly means, minimum and maximum of the rainfall and temperature data were calculated.

Statistical analysis

All statistical analyses were carried out using STATA 10 (Stata Corporation, College Station, TX, USA). The calculations were based on the bi-weekly incidence of diarrhoea cases, aggregated from the reported episodes for the individuals in each of the study communities. A descriptive analysis of the diarrhoea cases was made with time plots to identify any potential peaks and observable trends. A simple stratified analysis was also undertaken to identify whether there was any difference in the incidence of diarrhoea, in the period during and after sludge application. A similar analysis was made to ascertain any difference in diarrhoea cases between the wet and dry seasons. Following this, integrated time-plots that captured diarrhoea incidence in relation to temperature and rainfall were made, to identify any first-hand relationship between weather variables and the incidence of diarrhoea cases. By assuming that the counts of diarrhoea cases were Poisson distributed, an autoregressive Poisson regression model was constructed to assess the relationship between diarrhoea cases, weather variables and the period of sludge application. The period of sludge application was introduced into the model as a dummy, with 1 and 0 representing the periods during and after the application of faecal sludge respectively. The seasonal component of the model was accounted for by introducing sinusoidal trigonometric terms into the autoregressive model. In our model specifications for the faecal sludge and non-faecal sludge communities, all variables were entered and eliminated manually from the model in a stepwise manner, with the criterion for elimination being a p-value >0.05. Autocorrelation function (ACF) and partial autocorrelation function (PACF) were used to detect autocorrelation of diarrhoea cases and weather variables. Time series data are always not independently distributed but demonstrate autocorrelation with adjacent observations that need to be controlled. Verification of the data for autocorrelation was undertaken with plots of PACF and ACF. For the faecal sludge communities' model, maximum temperature, minimum temperature, minimum rainfall and maximum rainfall, with relevant lagged terms were significantly correlated with the reported diarrhoea cases. Two bi-week lagged effects of maximum and minimum temperature on cases of diarrhoea were detected while one lagged effect was detected for minimum rainfall. Lagged effect of maximum rainfall at one bi-week and three bi-weeks were also significantly correlated with diarrhoea cases. Additionally, a three order autocorrelation of the number of diarrhoea cases was detected by the PACF. Accordingly, a third order autocorrelation in combination with the lags for the weather variables was chosen in building the autoregressive Poisson model for the faecal sludge communities. In the case of the non-sludge communities, no autocorrelation was observed in the number of diarrhoea cases. However, maximum temperature, minimum temperature and maximum rainfall at a lag of one bi-week were found to be significantly associated with diarrhoea cases and were therefore included in the model of the non-sludge communities. The Akaike's Information Criterion (AIC) was used to examine the best model fit. The model with the smaller AIC fits the data better. $\mathrm{AIC} = -2 \ln (L) + 2k$, where L is the likelihood function and k is the number of free parameters. Further goodness of fit test was undertaken by graphically examining the ACF and PACF plots of the residuals that minimized the residuals' autocorrelation. To compensate for over-dispersion, standard errors were scaled using the square root of the Pearson χ^2 dispersion.

The final model adjusted for autocorrelation and seasonality took the general form:

$$\begin{aligned}\ln(E[Y_t]) = {} & \beta_0 + \beta_1 Y_{t-n} + \beta_2 \mathrm{Temp}_t + \beta_3 \mathrm{Temp}_{t-n} \\ & + \beta_4 \mathrm{Rain}_t + \beta_5 \mathrm{Rain}_{t-n} + \beta_6 \sin\left[\frac{2\pi t}{T}\right] \\ & + \beta_T \cos\left[\frac{2\pi t}{T}\right] + \beta_8 X_t \qquad (1)\end{aligned}$$

where Y_t is the diarrhoea cases for each bi-week; T is the number of time periods described by each sinusoidal function (e.g., $T = 24$ bi-weeks); t is the time period (e.g., $t = 1$ for first bi-week; $t = 2$ for second bi-week, etc.); Y_{t-n} autoregressive terms for diarrhoea cases; Temp_t is maximum or minimum temperature; Temp_{t-n} autoregressive terms for maximum or minimum temperature; Rain_t is maximum or minimum amount of rainfall; Rain_{t-n} autoregressive terms for maximum or minimum rainfall; β_0 is the intercept; and X_t ($X_t = 1$ identifies the period during sludge application; $X_t = 0$ identifies the period after sludge application).

RESULTS

Temperature and rainfall variables

Descriptive statistics of the rainfall and temperature data used in the study are presented in Table 1. The mean bi-weekly maximum and minimum temperatures for the sludge and non-sludge application periods were 31.6 and 23.2 °C, respectively, and the corresponding bi-weekly rainfalls were 3.4 and 26.4 mm, respectively. For both periods, there was a significant difference ($p < 0.05$) in maximum temperature and maximum and minimum rainfall. However, no significant difference in minimum temperature ($p > 0.05$) was observed.

Diarrhoea cases and sludge application

The total number of diarrhoea cases recorded for the faecal sludge and non-faecal sludge communities over the study period were 1,352 and 888 respectively. In the sludge and non-sludge communities, the mean bi-weekly diarrhoea incidence was 56 and 37, respectively. This resulted in bi-weekly incidences of 0.042 per person for the sludge communities and 0.028 per person for the non-sludge communities. There was a decreasing trend in the bi-weekly diarrhoea incidence per person from the period of sludge application to the period of non-sludge application in the sludge and non-sludge communities. For the sludge communities, the bi-weekly diarrhoea incidence per person decreased from 0.03 in the sludge application period to 0.015 per person in the non-sludge period. In the case of the non-sludge communities, the bi-weekly diarrhoea incidence per person was 0.012 in the period of sludge application compared to 0.011 for the non-sludge application period. However, the effect of the sludge and non-sludge application periods as risk factors was not significant in both the sludge and non-sludge communities' models, and thus was not included in the final models.

Table 1 | Descriptive statistics of aggregated bi-weekly rainfall and temperature in the Tamale Metropolis

	Sludge application period (November–April)			Period after sludge application (May–October)		
Climatic variables	**Range**	**Mean**	**SD**	**Range**	**Mean**	**SD**
Temperature						
Maximum (°C)	36.3–39.0	36.8	1.5	29.7–35.3	31.5	1.7
Minimum (°C)	18.6–27.2	23.1	3.1	22.5–25.4	23.2	0.7
Rainfall						
Maximum (mm)	0–44	6.8	13.6	4.4–92.6	37.5	26.4
Minimum (mm)	0–6	0.7	1.7	0.4–13.6	6.1	3.4

SD = standard deviation.

Figures 1(a) and 1(b) show the predicted bi-weekly cases of diarrhoea against the observed cases in the sludge and non-sludge communities as derived from the Poisson autoregressive model after controlling for autocorrelation, seasonality and the effects of rainfall and temperature. The accompanying ACF and PACF plots of the models' residuals are shown in Figures 2 and 3 respectively. Examining the functions indicates random distribution and no significant spike in the PACF; thus the final model was properly adjusted. A further scatter plot of the predicted and observed

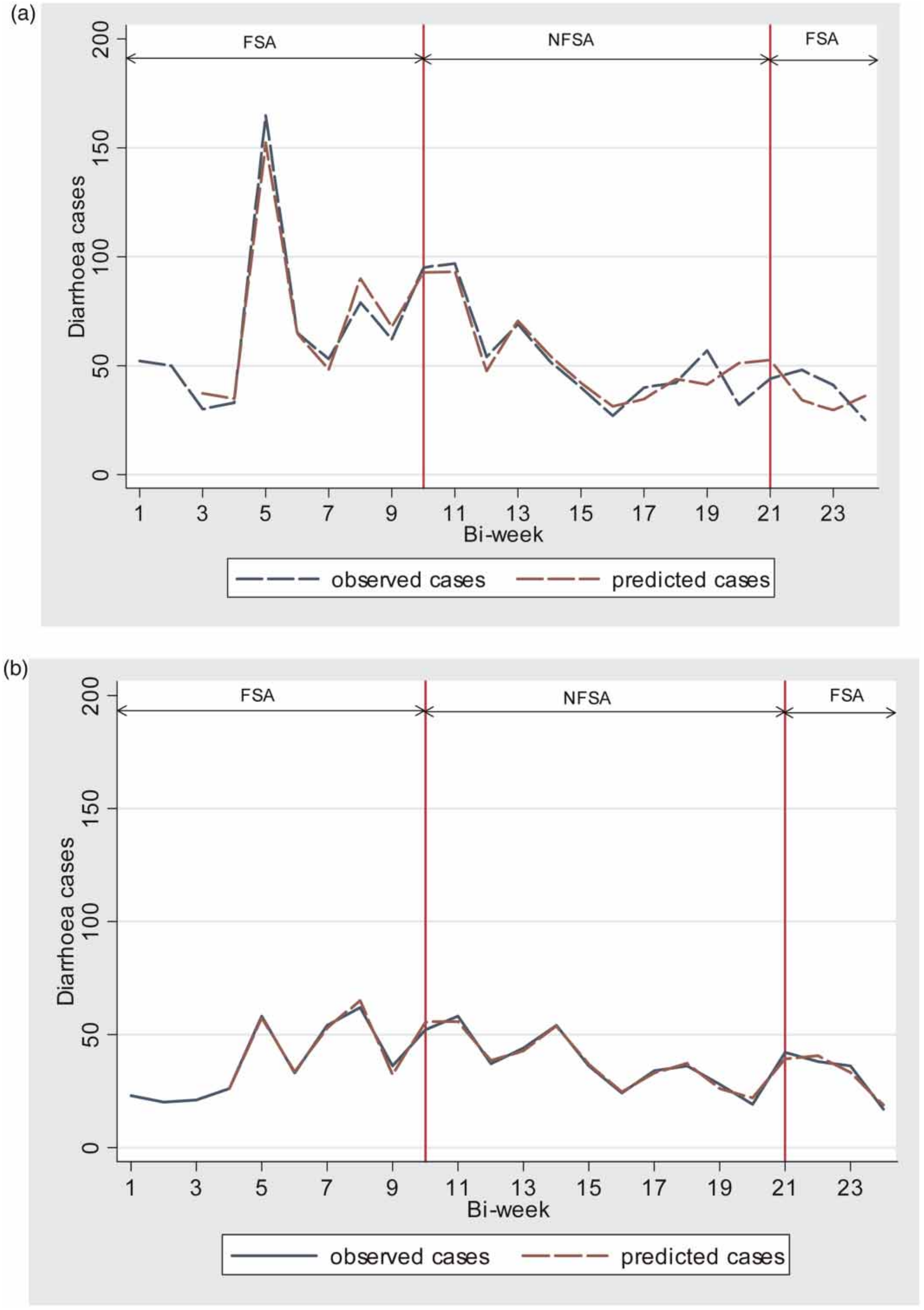

Figure 1 | Observed and predicted diarrhoea cases for (a) faecal sludge and (b) non-faecal sludge communities (FSA, faecal sludge application period; NFSA, non-faecal sludge application period).

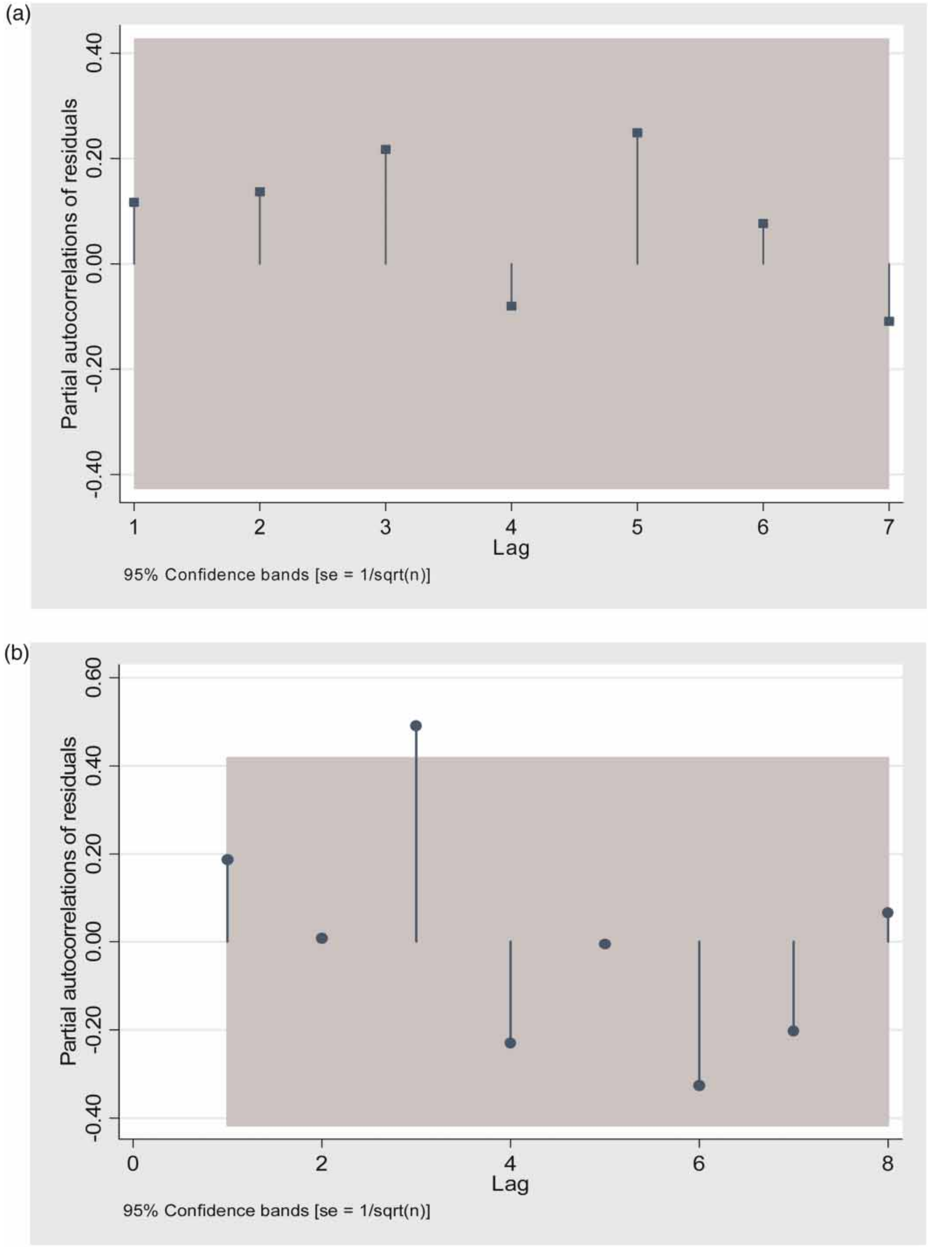

Figure 2 | PACF plots of residuals for (a) faecal sludge and (b) non-faecal sludge communities.

diarrhoea cases of the models revealed a goodness of fit with a correlation coefficient of 0.99 ($p < 0.001$).

Effect of rainfall on diarrhoea incidence

Figures 4(a) and 4(b) show the bi-weekly incidence of maximum and minimum rainfall in relation to the bi-weekly diarrhoeal incidence in the faecal sludge and non-faecal sludge communities, respectively. In the sludge and non-sludge communities an increase in diarrhoea cases was seen with maximum rainfall in bi-weeks 5, 8 and 11. For the sludge communities, the largest bi-weekly diarrhoea incidence coincided with the onset of the first maximum rainfall in April (bi-week 5) which followed a long dry period. In the non-faecal sludge communities, the peak diarrhoea incidence occurred in

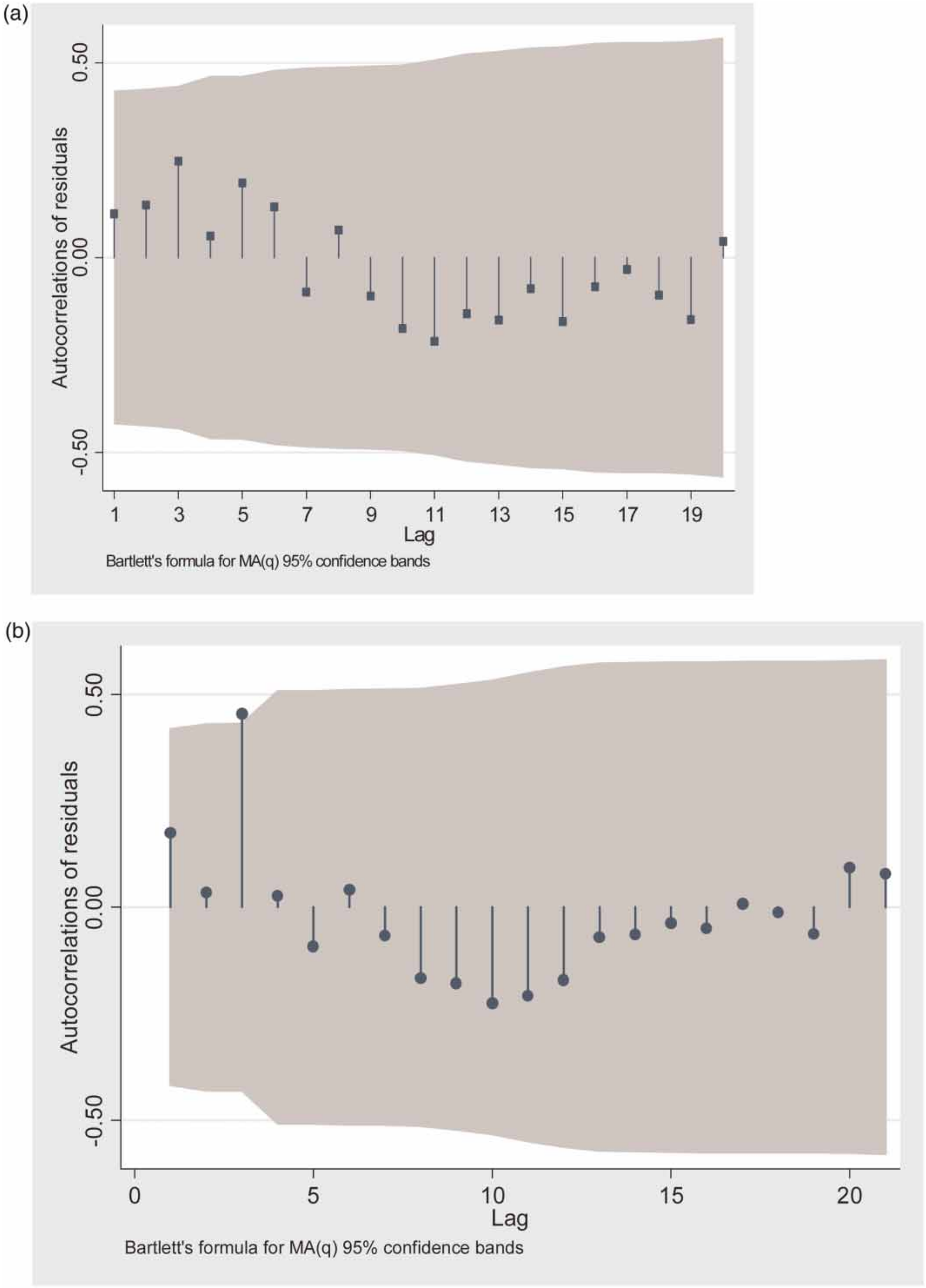

Figure 3 | ACF plots of residuals for (a) faecal sludge and (b) non-faecal sludge communities.

bi-week 8 after the long dry period. Subsequent maximum rainfall in bi-week 13 was associated with increased diarrhoea cases from bi-week 12 in the faecal sludge communities (from 54 cases in bi-week 12–69 cases in bi-week 13) and non-faecal sludge communities (from 37 cases in bi-week 12–44 cases in bi-week 13). There was no increase in diarrhoea cases associated with the highest rainfall of the entire study period recorded in bi-week 16 which occurred towards the end of the rainy season. From Figure 4, no clear associations could be drawn between minimum rainfall and the bi-weekly incidence of diarrhoea cases.

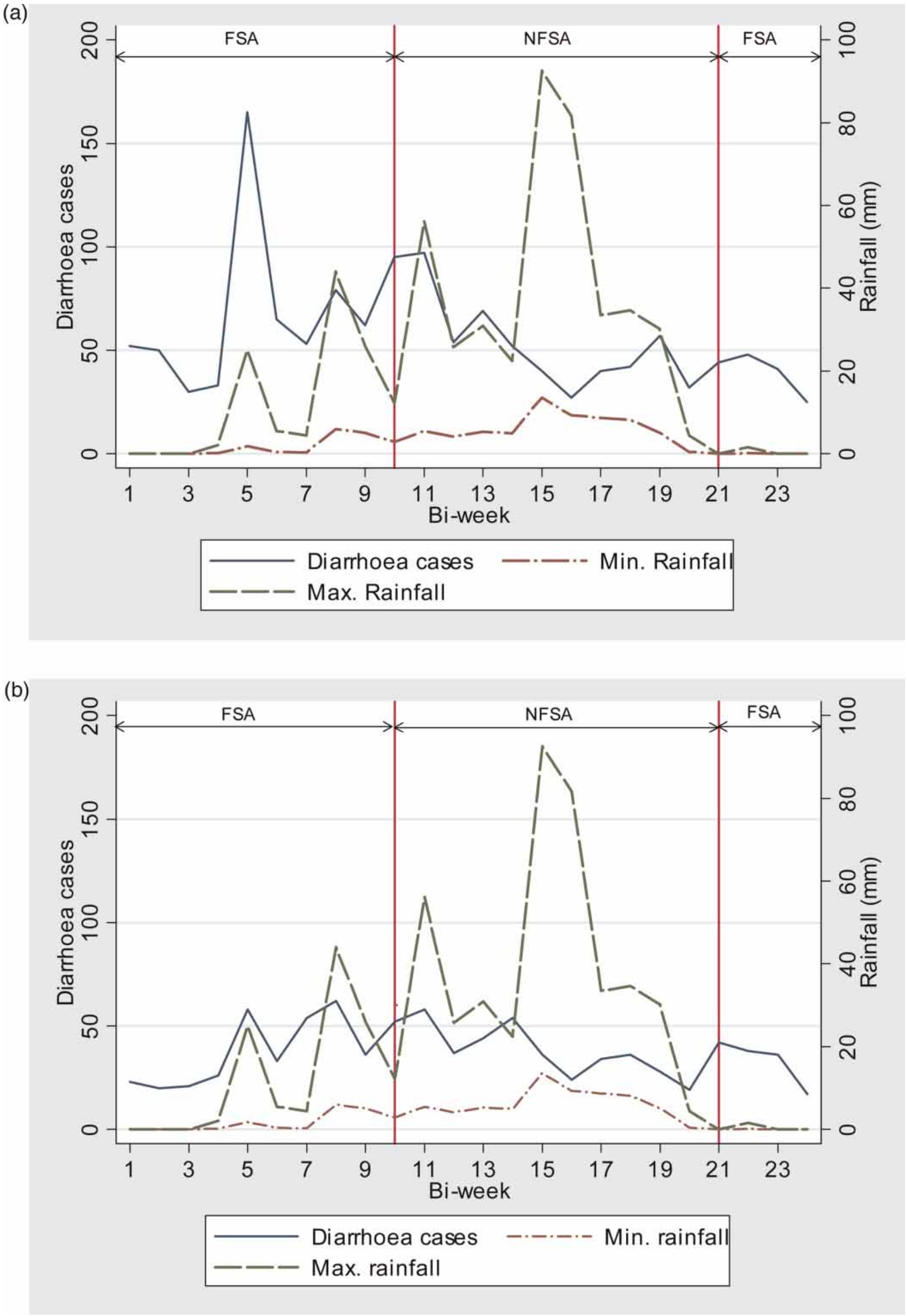

Figure 4 | Bi-weekly diarrhoea cases and rainfall in (a) faecal sludge and (b) non-faecal sludge communities (FSA, faecal sludge application period; NFSA, non-faecal sludge application period).

The effects of maximum and minimum rainfall on the bi-weekly incidence of diarrhoea as predicted by the adjusted Poisson autoregressive models for the sludge and non-sludge communities are presented in Tables 2 and 3 respectively. The model parameters indicate that maximum rainfall increased the risk of diarrhoea cases in both the sludge and non-sludge communities. The model also shows positive and negative lag effects of

Table 2 | Parameters estimated by autoregressive adjusted Poisson regression for the faecal sludge communities (RR: relative risk; *Z*: *z*-score; *P*: *p*-value; CI: confidence interval)

	RR	Z	P >|Z|	95% CI
Lag1 cases[a]	0.950	−4.77	0.000	(0.929–0.969)
Lag2 cases	0.988	−5.53	0.000	(0.983–0.992)
Lag3 cases	0.989	−4.01	0.000	(0.984–0.994)
Minimum rainfall	0.695	−4.63	0.000	(0.595–0.810)
Rainmin lag1	0.533	−4.22	0.000	(0.397–0.713)
Maximum rainfall	1.034	4.17	0.000	(1.018–1.050)
Rainmax lag1	1.048	3.47	0.001	(1.020–1.075)
Rainmax lag3	1.038	4.21	0.000	(1.020–1.057)
Maximum temp	0.504	−5.14	0.000	(0.388–0.654)
Tempmax lag2	2.337	3.45	0.001	(1.444–3.783)
Minimum temp	3.479	4.80	0.000	(2.090–5.791)
Tempmin lag2	0.629	−2.84	0.005	(0.456–0.866)
Tempmin lag3	1.633	4.17	0.000	(1.297–2.056)
Cos 24	1.163	0.37	0.711	(0.523–2.581)
Sin 24	0.082	−2.85	0.004	(0.014–0.457)
Cos12	1.490	2.75	0.006	(1.122–1.987)
Sin 12	1.822	2.85	0.004	(1.206– 2.754)
Constant		−3.19	0.001	–

[a]Cases: Diarrhoea cases.

Rainmin: average bi-weekly minimum rainfall; Rainmax: average bi-weekly maximum rainfall; Tempmax: average bi-weekly maximum temperature; Tempmin: average bi-weekly minimum temperature.

Lag: Lag effects of parameters on bi-weekly diarrhoea incidence (e.g., tempmax lag1 indicate the effect of maximum temperature in a particular bi-week on the incidence of diarrhoea in the next bi-week).

Table 3 | Parameters estimated by autoregressive adjusted Poisson regression for the non-sludge communities

	RR	Z	P >|Z|	95% CI
Minimum rainfall	0.880	−2.88	0.004	(0.807–0.960)
Maximum rainfall	1.003	0.77	0.440	(0.994–1.012)
Rainmaxlag1	0.988	−4.32	0.000	(0.983–0.993)
Maximum temp	1.186	2.25	0.024	(1.022–1.376)
Tempmax lag1	1.331	3.39	0.001	(1.128–1.571)
Tempmax lag2	0.959	−0.71	0.480	(0.854–1.076)
Minimum temp	0.678	−3.47	0.001	(0.544–0.844)
Tempmin lag1	0.692	−4.26	0.000	(0.584–0.819)
Cos 24	0.067	−5.41	0.000	(0.025–0.179)
Sin 24	0.545	−1.23	0.217	(0.208–1.427)
Cos12	0.373	−4.59	0.000	(0.245–0.568)
Sin 12	1.139	1.32	0.187	(0.938–1.382)
Constant		1.54	0.124	–

Rainmin: average bi-weekly minimum rainfall; Rainmax: average bi-weekly maximum rainfall; Tempmax: average bi-weekly maximum temperature; Tempmin: average bi-weekly minimum temperature.

Lag: Lag effects of parameters on bi-weekly diarrhoea incidence (e.g., tempmax lag2 indicate the effect of maximum temperature in a particular bi-week on the incidence of diarrhoea in the two bi-weeks after).

maximum rainfall events on the bi-weekly diarrhoea cases in both the sludge and non-sludge communities. In the sludge communities, maximum rainfall in a particular bi-week increased the risk of diarrhoea in the subsequent bi-week and three bi-weeks after. However, in the non-sludge communities, maximum rainfall event in a particular bi-week decreased the risk of diarrhoea in the subsequent bi-week. Unlike the maximum rainfall events, all the minimum bi-weekly rainfall events decreased the risk of diarrhoea cases in both the sludge and non-sludge communities. There was also no observable lag effect of minimum rainfall in the non-sludge communities. However, in the sludge communities, minimum rainfall in a particular bi-week was significantly associated with the risk of diarrhoea cases reported in the subsequent bi-week.

Effect of temperature on diarrhoea incidence

Figures 5(a) and 5(b) show the bi-weekly maximum and minimum temperature in relation to the bi-weekly incidence of diarrhoea in the faecal sludge and non-faecal sludge communities respectively.

The relationship between maximum and minimum temperatures and the bi-weekly incidence of diarrhoea cases in the sludge and non-sludge communities as estimated by the models are shown in Tables 2 and 3. The models show that maximum temperature occurring in a given bi-week decreased the risk of diarrhoea incidence in that bi-week in the sludge communities, but increased the risk in the non-sludge communities. Lag effects of maximum temperature on the bi-weekly incidence of diarrhoea were also observed in both study communities. In this case, maximum temperatures recorded in a particular bi-week increased the risk of diarrhoea incidence in the subsequent bi-week in the sludge communities and in the subsequent two bi-weeks in the non-sludge communities. In terms of minimum temperature, different effects on diarrhoea were observed in the sludge and non-sludge communities.

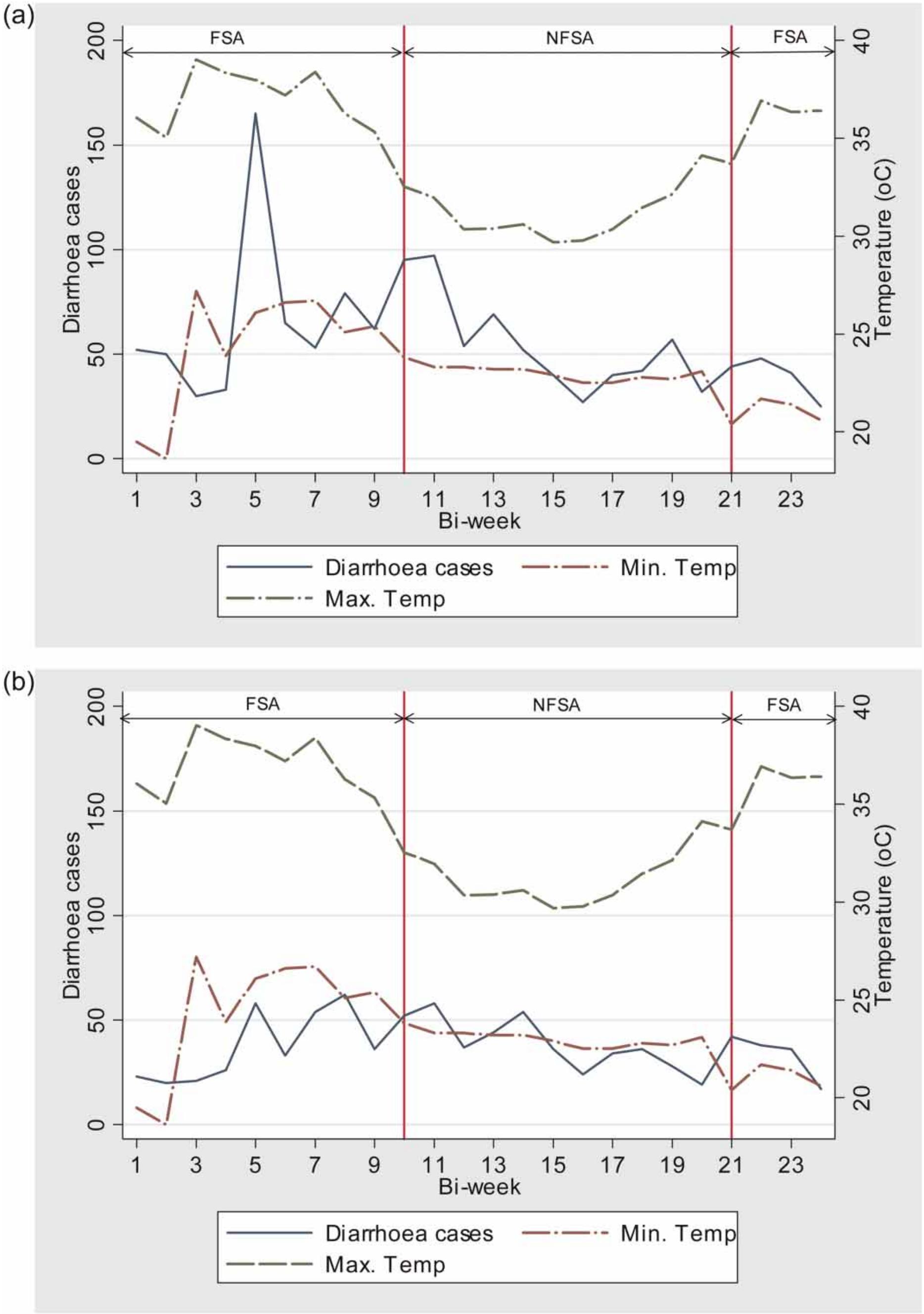

Figure 5 | Bi-weekly diarrhoea cases and temperature in (a) faecal sludge and (b) non-faecal sludge communities (FSA, faecal sludge application period; NFSA, non-faecal sludge application period).

Minimum temperature in a particular bi-week increased diarrhoea risk in the sludge communities but decreased it in the non-sludge communities. Lag effects of minimum temperature on diarrhoea cases were also observed in the sludge and non-sludge communities. In the sludge communities, minimum temperature in a particular bi-week decreased the risk of diarrhoea cases in the subsequent two bi-weeks but increased the risk three bi-weeks after. In the non-sludge communities, minimum temperature in a particular bi-week decreased the diarrhoea risk in the next bi-week.

DISCUSSION

The study revealed a similar seasonal pattern of reported diarrhoea cases in the sludge and non-sludge communities, with more cases reported during the period of sludge application compared to the non-sludge application period. The incidence was however lower in the non-sludge communities. Diarrhoeal incidence was negatively associated with the sludge application period but this relationship after accounting for the weather variables was not statistically significant. Therefore, other factors within the public and domestic domain, affected by rainfall and temperature may have mediated the diarrhoea disease incidence pattern in the sludge communities. This is more so, as the overall pattern of the diarrhoea disease incidence in both the sludge and non-sludge communities followed the well-known seasonal pattern in similar regions, where increased cases are recorded in warmer, wet months.

To our knowledge, this is the first study reporting the effect of temperature and rainfall on diarrhoea incidence in faecal sludge communities. In both the sludge and non-sludge communities, maximum rainfall events occurring in the same bi-week increased the risk of diarrhoea incidence. This is consistent with findings made in other studies elsewhere. In Fiji, high rainfall was associated with significant increases in diarrhoea incidence among infants after adjusting for the effect of long-term trends and seasonal pattern (Singh *et al.* 2001). In our study, the impact of maximum rainfall on diarrhoea incidence was higher in the sludge communities compared to the non-sludge communities, suggesting a greater mediation of rainfall in the exposure to pathogens in the sludge communities. During the sludge application period, two maximum rainfall peak events occurred (in bi-weeks 5 and 9), and were both associated with increased incidence of diarrhoea cases. Blumenthal *et al.* (2001) associated high diarrhoea prevalence in the wet season with increased rainfall in communities using untreated wastewater for irrigation. However, that study did not quantify the effect of rainfall as an explanatory or risk factor of diarrhoea. In this study, initial maximum rainfall peaks coincided with increased diarrhoea incidence in both the sludge and non-sludge communities. However, prolonged peaks up to the 16th bi-week led to a significant reduction in diarrhoea disease incidence in both communities. A similar finding was made in a study in Fiji where a reduction in diarrhoea cases was observed in months with prolonged high rainfall events (Singh *et al.* 2001). A possible explanation for this is that, initially, high rainfall flushes faecal contaminants from fields and dwellings into different environmental routes for disease transmission, but continued rainfall leads to a subsequent reduction in the levels of contaminants along these routes due to washout and dilution effects. This study together with one study in Dhaka, Bangladesh (Hashizume *et al.* 2007), showed a decreased risk of diarrhoea disease incidence under minimum rainfall events. In contrast, a study in Fiji associated increased diarrhoea cases occurring in the same month and subsequent months with low rainfall (Singh *et al.* 2001).

A major observation was the disparate effect of maximum temperature on diarrhoea disease incidence in the sludge and non-sludge communities. A positive relationship was found between maximum temperature and diarrhoea incidence occurring in the same bi-week in the non-sludge communities. In Lima, increased diarrhoea cases were associated with maximum temperature following El-Nino events (Checkley *et al.* 2000). Also, in Bangladesh a positive linear relationship was found between non-cholera diarrhoea and temperature (Hashizume *et al.* 2007). In a Vietnamese study involving farmers using wastewater and excreta on crops, a higher incidence of diarrhoea was observed in the hottest months compared to the coldest months (Trang *et al.* 2007). However, this was not statistically significant, and it was not clear whether increased temperature had any direct role in the diarrhoea occurrence. Generally, temperature is known to influence the transmission of diarrhoeal disease in several ways. The survival of diarrhoeal pathogenic organisms of viral, bacterial, parasitic and protozoan origins is correlated with temperature variations. For instance, in the sludge communities, the negative relationship found between maximum temperature and diarrhoea disease incidence occurring in the same bi-week may be attributed to the potential die-off of pathogens in the sludge-amended fields. Seidu & Stenström (submitted) found low counts of *E. coli*/g TS in dewatered cake sludge handled by farmers in the sludge communities during the period of maximum temperatures.

This study has some limitations that need to be stressed. Time-aggregation of the data may produce biased estimates as it reduces sample size and introduces measurement errors that are negatively correlated with the duration (Peterson & Koput 1992). Therefore, our bi-weekly aggregation may be too coarse to fully establish the predictability of our autoregressive models. However, it is the best measure we could use in this study, and the fact that our model predicts reported incidence shows our approach in reducing the model error was successful. Also recall and reporting bias, may affect the overall incidence of diarrhoea cases reported here given the open-cohort design employed in the study. Furthermore, the aetiological agents of the diarrhoea cases were not assessed. Most aetiological agents implicated for the occurrence of diarrhoea exhibit a seasonal pattern. For instance, studies have shown that rotavirus-related diarrhoea among children in Northern Ghana exhibits a seasonal pattern with higher cases in the dry season compared to the wet season (Binka *et al.* 2003). Other studies elsewhere have reported seasonal variations in diarrhoea cases implicating *Salmonella* (Zhang *et al.* 2008), *Cryptosporidium* (Hu *et al.* 2007) and *Vibrio cholerae* (Fernandez *et al.* 2009). Further research on the seasonal variations of diarrhoea aetiology in the faecal sludge communities is thus warranted. Furthermore, this study did not account for other population risk factors, such as access to water and sanitation facilities as well as the socio-demographic variables of the communities. It has been shown that the relative importance of pathogens, which thrive at lower temperatures appears to be greater in populations of regions with higher standards, specifically access to clean water and sanitation (for which there is no clear and consistent evidence for peaks in all-cause diarrhoea in warmer months), compared to less well-off populations (where diarrhoea is usually more common in warmer, wetter months). For instance, Hashizume *et al.* (2007) found a relatively high effect of temperature on non-cholera diarrhoea for people with lower educational attainment and with poor socio-economic indicators. In a study in South Africa, clear summer peaks of diarrhoea in black, but not white infants was observed in Johannesburg (Robins-Browne 1984). Building on the findings made in this study, a more comprehensive hierarchical effect decomposition assessment of risk factors associated with diarrhoea disease in the sludge communities has been undertaken (Seidu *et al.* 2013). The study accounts for different risk factors (i.e., exposure pathways) of diarrhoeal disease transmission in the public and domestic domains of the faecal sludge communities, including risk behaviours and person-to-person transmission within the household by accounting for clustering.

CONCLUSIONS

Sludge application can significantly improve soil quality by providing a cheap source of organic fertilizer to farmers. However, it can also pose significant health risks if not undertaken in a safe manner. In areas where the application of faecal sludge is seasonal and limited treatment of sludge is undertaken prior to application, it is important for the effect of rainfall and temperature to be taken into account when designing schemes for sludge application. This is to ensure that the risks posed by the practice do not exceed the benefits.

The study revealed that rainfall and temperature can significantly affect diarrhoeal disease transmission in faecal sludge applying communities. It is recommended that weather variables should be accounted for in the design of faecal sludge reuse schemes. More importantly, WHO guidelines on faecal sludge application should clearly enunciate risk models that adequately encapsulate the effects of key weather variables. The model used in this paper can be extended to predict diarrhoea disease incidence in relation to untreated faecal sludge application given local climatic data. It may also be extended to include other socio-demographic risk factors.

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