SSM - Population Health 19 (2022) 101159

Contents lists available at ScienceDirect

SSM - Population Health

journal homepage: www.elsevier.com/locate/ssmph

The importance of community during rapid development: The influence of social networks on acute gastrointestinal illness in rural Ecuador

Sonia T. Hegde [a,*], James A. Trostle [b], Bhramar Mukherjee [c], Joseph N.S. Eisenberg [a]

[a] Department of Epidemiology, University of Michigan, Ann Arbor, MI, USA
[b] Department of Anthropology, Trinity College, Hartford, CT, USA
[c] Department of Biostatistics, University of Michigan, Ann Arbor, MI, USA

ARTICLE INFO

Keywords:
Social network
Bayesian hierarchical model
Diarrhea
Ecuador

ABSTRACT

Social networks are often measured as conduits of infection. Our prior cross-sectional analyses found that denser social ties among individuals reduces transmission of acute gastrointestinal illness (AGI) in coastal Ecuador; social networks can describe both risk and protection. We extend findings to examine how social connectedness influences AGI longitudinally in Ecuador from 2007 to 2013, a time of rapid development, using a two-stage Bayesian hierarchical model to estimate multiple network effects. A larger community network of people to discuss important matters with was consistently protective against AGI over time, and a network defined by people passing time together became a stronger measure of risk, due to increasing population density and travel. These networks were interdependent: the joint effect of having a small passing time network and large important matters network reduced the odds of AGI over time (2007: OR 1.16 (95% CI: 0.94, 1.44), 2013: OR 0.56 (95% CI: 0.45, 0.71)); and synergistic: the people an individual passed time with became the people they discussed important matters with. Focus groups emphasized that with greater remoteness came greater community cohesion resulting in safer WASH practices. Social networks can enhance and reduce health differently as social infrastructure evolves, highlighting the importance of community-level factors in a period of rapid development.

1. Main text

The protective effects of social influences like connectivity play a significant role in public health (Aiello, 2017; Holt-Lunstad et al., 2017), and have been well studied in the field of social epidemiology (Holt-Lunstad et al., 2017). Social connectedness, referred to here as *sociality* and measured by characterizing the configuration of social networks, is a construct that represents the different ways an individual can interact with others (Holt-Lunstad et al., 2017). While human-to-human interactions are often viewed as transmission conduits in the context of infectious diseases (Bi et al., 2020; Zelner et al., 2012), such contacts can also contribute to disease reduction (Diez-Roux, 2000). The dynamics of such social interactions are influenced by environmental change (Eisenberg et al., 2006) and human mobility (Kraay et al., 2018b). In the last century particularly, many societies have shifted towards capitalistic economic growth and infrastructural development (Cooper, 2004), which has influenced socialization patterns and mechanisms of disease spread. Though infrastructure improvements like centralized water systems or access to healthcare facilities are important for controlling infectious diseases like cholera and Ebola, few studies have examined the moderating effect of environmental change on sociality and health. While infrastructure like new roads, power lines, or fiber optic cables are central for changing economies and health, linking regions of significant health disparity (MacPherson et al., 2009), it changes the social infrastructure of communities and therefore behaviors and attitudes that may be critical for preventing disease. For example, the development of new transportation mechanisms like roads has led to increased migration (e.g., for new employment and changing commuting patterns), reduced mean duration of residence, and reduced mean community network sizes over time (Bates et al., 2007b; Kraay et al., 2018a).

Social network research in public health has largely focused on analyzing one social network as an indicator of a single social process that is realistically more complex. Among the different types of egocentric networks, the "important matters" network (generated by asking the question "with whom did you discuss matters important to you?") has a strong historical base in social science research.

* Corresponding author. Department of Epidemiology, Johns Hopkins Bloomberg School of Public Health. 615 North Wolfe Street Rm E6038. Baltimore, MD, 21205, USA.

E-mail address: shegde@jhu.edu (S.T. Hegde).

https://doi.org/10.1016/j.ssmph.2022.101159
Received 4 November 2021; Received in revised form 10 May 2022; Accepted 26 June 2022
Available online 29 June 2022

Hypothesized to establish a network of social influence, this core discussion network (CDN) (Marsden, 1987) elicits important connections to an individual who one may not feel close to, but who is an intentionally chosen (Perry & Pescosolido, 2010), context-dependent social supporter (Small, 2013). CDNs map access to ideas or resources that an individual might activate in forming attitudes or in pursuing goals (Perry & Pescosolido, 2010). Conversely, the passing time network (PTN) (generated by asking the question “in the past week who have you spent time with?”) has been used to establish contact networks and therefore has proved useful in studying the transmission of infections like influenza and SARS (Bates et al., 2007a; Meyers et al., 2005).

Though social networks can be quite distinct and impact human health differentially, social network analyses seldom consider that social networks map social infrastructure or capture that social processes are multidimensional and evolve over time (Wesolowski et al., 2016). Acute gastrointestinal illness (AGI), a disease that is prevalent in resource poor settings and is environmentally mediated, is influenced by social connection (Forrest & Kearns, 2001) and social capital (Eisenberg et al., 2007). It therefore allows for the study of how a community’s social infrastructure may contribute to the occurrence of disease independent of the environmental infrastructure (Goldstick et al., 2014). Though our prior cross-sectional analysis suggested that a greater density of social ties between individuals in remote communities is associated with reduced AGI (Zelner et al., 2012), we examined only one network type from northern coastal Ecuador. To gain a more nuanced understanding of how the underlying social infrastructure influences an individual’s health behavior, we extend earlier findings to examine the effect of sociality, embodied through the joint effects of two social networks (a *PTN* often used to describe disease transmission and a *CDN* often used to describe the protective effect of social structures), on AGI over time, modified by significant environmental change due to road infrastructure development.

2. Methods

2.1. Study site

We collected sociometric and census data from 20 villages in the province of Esmeraldas in coastal Ecuador. Sociometric data was collected in-person by trained field staff during cross-sectional waves in 2007, 2010, and 2013 from all consenting community members ≥ 13 years of age, an age when more independent socialization tends to occur (Bates et al., 2007b). Information from younger participants, those <18 years, was obtained with parents and/or caretakers present.

Census data was collected from all communities within one month prior to each sociometric survey. Compared to this census denominator, the average sociometric response rate across communities and waves was 80%. The study population across communities consists of Afro-Ecuadorians, Mestizos, and Chachis, an indigenous group residing along the Cayapas river basin.

All study participants provided informed consent and consent from parental or legal guardians was obtained when participants were <18 years of age.

2.2. Outcome

Self-reported diarrhea and fever data was collected during the sociometric survey. Per the WHO standard definition (WHO & UNICEF, 2004), participants were asked if they had a fever in the last week and if they had three or more liquid stools in one day in the last week. We combined these two measures to assess an individual’s risk of having AGI, which captures more symptoms of enteric disease. Investigators have used different terms for gastrointestinal illness, including Intestinal Infectious Disease (Garthright et al., 1988; Roderick et al., 1995) and Highly Credible Gastrointestinal Illness (HCGI) (Payment et al., 1991). We define AGI as having diarrhea or fever, similar to other studies (Majowicz et al., 2008; Roy et al., 2006), and analyze AGI as a binary outcome.

2.3. Exposure

We measured our primary exposure, sociality, using household and community network measures. Social network data was collected using two different name generator questions on the sociometric survey to establish a passing time network (PTN) and a core discussion network (CDN). Study participants (*egos*) were asked to identify 1) members of their village outside their household with whom they had spent time within the previous week (PTN); and 2) members of their village outside their household with whom they could discuss important matters (CDN).

We measured sociality at the individual, household, and community-levels for each network type. At the individual-level we calculated the number of ties each person had to another individual in each network (*degree*). An ego’s household degree was defined as the highest degree in the ego’s household. We then measured household degree deviance from the village mean in standard deviation units from the mean village household degree. We aggregated individual degree to the community-level by taking the average degree across individuals in a village. We refer to this community-level network measure as a community’s network density. Standard measures of social capital like community trust and number of organizations an individual belongs to were also examined.

2.4. Covariates

The study villages exist along the Cayapas, Santiago, and Ónzole river basins. They vary by remoteness, which we defined as a function of the time and cost of travel to the nearest metropolitan center, Borbón (Eisenberg et al., 2006). Since 1996, paved roads have been built connecting this region to the coast and Andes. Smaller secondary roads continue to be built linking villages to the main road. Remoteness may affect both sociality and AGI and was therefore used as a continuous variable. Remoteness was normalized by rescaling each community’s remoteness value to be between zero and one, with the most remote community having a remoteness of one. For more details see Eisenberg et al., 2006 (Eisenberg et al., 2006) (Supplementary Methods 1).

2.5. Regression analysis

Since individuals entered and left the study continuously between 2007 and 2013, we chose not to limit our sample only to those included in all three surveys. To increase sample size and our ability to detect effects, we developed regression models using cross-sectional data and selected a model of best fit to estimate the odds of AGI adjusting for known confounders from prior analyses (Zelner et al., 2012) using the Akaike Information Criteria (AIC). We used a two-stage Bayesian analysis approach with a binomial distribution to account for: 1) separation (Heinze & Schemper, 2002) in the data when maximum likelihood estimates are not proven to exist and are not unique (Silvapulle, 1981), and 2) the nested structure of the data resulting in correlation. We applied this analytic strategy to two types of models where: 1) PTN and CDN measures are examined separately to avoid collinearity; and 2) PTN and CDN measures are examined together with an interaction effect to examine effect modification (Supplementary Methods 2).

2.6. Qualitative data & analysis

In 2016, two trained field staff conducted 15 focus groups with 6–8 community leaders and 15 key-informant (e.g., health promoter or community organization leader) in-depth interviews in 15 of the 20 study communities to help interpret our quantitative results. Focus groups were conducted within communities (i.e., community centers or the house of a community leader) and in-depth interviews were conducted within households of leaders. These 15 communities included 3 roadside communities, 5 at a medium distance from a road, and 7 only accessible by water. The discussions focused on community problem solving, social organization, kinship, and relationships with persons outside the community. Specific questions under each theme underwent an iterative process of change, whereby we continually updated our discussion guide to fully understand topics and no longer encounter unexpected responses. Focus group participants were purposively sampled. All focus groups and key informant interviews were audio-recorded and later transcribed by two individuals from the study region. Transcriptions were analyzed in Spanish for consistent themes across communities based on underlying codes identified from our quantitative analysis and social theories of Marsden and Small (Marsden, 1987; Small & Sukhu, 2016) and were iteratively compared to an emergent conceptual framework. The themes identified and analyzed for included forms of social organization, community problems, leadership, relationship to external resources, and access to water. These were chosen through prior experience in these communities as well as reviews of the most salient items in coded transcripts. For both the data collection and analysis the Consolidated Criteria for Reporting Qualitative Research (COREQ) checklist was largely used (Tong et al., 2007).

2.7. Social network structure

To note general differences in social connectedness in PTNs and CDNs by remoteness levels, we employed the Kamada-Kawai algorithm to visualize networks of ties between individuals in a remote community compared to a roadside community over time (Fruchterman & Reingold, 1991; Kamada & Kawai, 1989), and visualized network modularity (Newman, 2006) (Supplementary Methods 3).

2.8. Software

Analyses were conducted in R (v. 3.4.2) using the packages igraph, brms and rstan. Code is available on github (https://github.com/xxxxxxxx/two-stage-bayes).

3. Results

3.1. Regression analysis

At the household-level, the number of ties decreased over time in the passing time network (PTN) and core discussion network (CDN), as did the proportion of households with asset deprivation (68%–57%) and households with only a primary education (27%–20%) (Table 1). In a PTN, an increase in social ties within a household relative to the village mean was initially protective but over time became a risk; by 2013, a 1 unit increase in the household degree deviance from the village mean increased the odds of AGI by 1.20 (95% CI: 1.11, 1.30); whereas in a CDN there was no effect (Table 2).

At the community-level, having more PTN ties on average in one's community had no significant effect on AGI, whereas in a CDN, having a larger community network was protective against AGI over time. In 2013, for every 1 unit increase in the village average degree in a CDN, the odds of getting AGI decreased by 0.74 (95% CI: 0.63, 0.87) (Table 2). Both networks also shared numerous attributes: remoteness remained protective over time, trust and being male became significantly protective over time, and the number of organizations an individual belongs to had limited effects on AGI (Table 2).

When we examined the joint effects of the household-level PTN and CDN, not only the household PTN but also the community PTN degree trended toward becoming a risk from 2007 to 2013 (Table 3). In contrast, both the household degree deviance in a CDN and the average community degree in a CDN became more protective from 2007 to 2013. In these models, remoteness was no longer significantly protective by 2013.

Table 1
The means (ranges) and proportions reported for each measured variable by wave of data collection (2007, 2010, 2013). At the household-level, we report the highest household degree and degree deviance from the community average. Remoteness is a continuous measure that is a function of time and cost of travel from the community to the nearest township. A passing time network is referred to as PTN and a core discussion network as CDN.

	2007 N = 2204 Households = 1005	2010 N = 237 Households = 1121	2013 N = 232 Households = 1100
Outcome			
Acute gastrointestinal illness (AGI)[a]	10.6%	10.1%	12.5%
Covariates			
Household PTN Degree	6.3 (0–25)	3.6 (0–31)	5.0 (0–33)
Average Community PTN Degree	4.2 (2.2–6.6)	2.1 (0.8–3.0)	3.5 (1.8–6.2)
Household CDN Degree	3.8 (0–22)	3.0 (0–29)	3.4 (0–20)
Average Community CDN Degree	2.1 (0.8–3.3)	1.9 (0.5–3.0)	2.3 (1.1–4.1)
Age	36.9 (13.0–90.5)	37.7 (13.0–91.7)	37.9 (13.0–95)
Sex (Female)	48.8%	52.4%	52.7%
Remoteness	0.451 (0.06–1.00)	0.437 (0.06–1.00)	0.442 (0.06–1.00)
Trust (Yes)	51.0%	44.0%	32.8%
Number of organizations	1.8 (0–8)	1.58 (0–8)	1.00 (0–7)
Household size	2.9 (1–8)	2.8 (1–10)	2.7 (1–8)
Number infected in Household	0.28 (0–3)	0.27 (0–4)	0.32 (0–3)
Household asset deprivation	68.3%	62.8%	56.7%
Households highest education is primary (Yes)	26.9%	22.5%	19.5%

[a] Having diarrhea or fever.

The interaction term between household degree deviance in a PTN and CDN remained significant at all three time points; the joint effects of the co-network features were different from the marginal effects originally observed. Individuals with a low PTN and high CDN household degree experienced the lowest predicted probability of AGI by 2013 compared to the other subgroups (Supplementary Figure 1), and this was more pronounced in more remote communities (Supplementary Figure 2B). The joint effect of having a low PTN and high CDN resulted in reduced odds of AGI over time, which was protective by 2013, whereas having a high PTN and low CDN resulted in increased odds of AGI over time (Supplementary Table 1). Individuals with a high PTN and high CDN household degree had a synergistic effect resulting in an increased predicted probability of AGI over time.

The marginal effect of household degree deviance in a PTN on the odds of AGI decreased as an individual's household degree deviance in a CDN increased in 2007 and 2010. This effect direction changed in 2013, except for those that had an overlap in social ties between a PTN and CDN (i.e., the people individuals spend time with was not independent of the people they discussed important matters with) (Fig. 1; Supplementary Table 2). Further modification occurred when we stratified by whether one perceives their own community as trusting.

3.2. Qualitative analysis

Remoteness and the physical environment (e.g., water access and transportation) influenced a community's determination to solve problems and its self-perception of success and organizational leadership. All participants mentioned potable water, contaminated water due to mining activities, lack of jobs, and trash disposal as community problems. Roadside communities mentioned issues like disorganized youth, lack of community collaboration, and chronic illness (e.g. hypertension,

Table 2
Using a two-stage Bayesian hierarchical model to examine the effect of the passing time network (PTN) on acute gastrointestinal illness (AGI) and the effect of the core discussion network (CDN) on AGI separately (Model 1), we report the odds ratios (OR) and the 2.5% and 97.5% quantiles of the posterior distribution for the credible intervals (CI). Each wave of data was modeled separately.

	2007 OR (CI)	2010 OR (CI)	2013 OR (CI)
Passing time network (PTN)			
Household degree deviance	0.71 (0.66, 0.77)	0.91 (0.84, 0.97)	1.20 (1.11, 1.30)
Average community degree	1.04 (0.94, 1.15)	0.68 (0.59, 0.80)	1.06 (0.98, 1.15)
Trust	1.15 (0.98, 1.35)	1.26 (1.09, 1.45)	0.64 (0.54, 0.75)
Organizations	1.10 (1.04, 1.17)	1.03 (0.99, 1.07)	0.94 (0.88, 1.01)
Remoteness	0.28 (0.21, 0.38)	0.66 (0.53, 0.82)	0.53 (0.42, 0.67)
Age	1.01 (1.01,1.01)	1.00 (1.00, 1.00)	1.00 (1.00, 1.00)
Sex (Male)	1.09 (0.94, 1.27)	0.57 (0.50, 0.66)	0.74 (0.64, 0.85)
Core discussion network (CDN)			
Household degree deviance	1.09 (1.01, 1.19)	1.00 (0.93, 1.07)	1.04 (0.97, 1.12)
Average community degree	0.89 (0.74, 1.06)	0.61 (0.50, 0.73)	0.74 (0.63, 0.87)
Trust	1.03 (0.88, 1.21)	1.27 (1.09, 1.48)	0.61 (0.52, 0.71)
Organizations	1.07 (1.01,1.14)	1.04 (1.00, 1.08)	0.96 (0.91, 1.02)
Remoteness	0.40 (0.28, 0.57)	0.73 (0.58, 0.92)	0.78 (0.61, 1.00)
Age	1.01 (1.01, 1.01)	1.00 (1.00, 1.00)	1.00 (1.00, 1.00)
Sex (Male)	1.05 (0.91, 1.22)	0.57 (0.49, 0.65)	0.77 (0.68, 0.88)

drug addiction, and cancer); whereas remote communities mentioned lack of a pharmacy, medical personnel, teachers, and schools.

Remote communities used social structures designed specifically to solve problems and visited community leaders such as the community president, elders, or leaders of organized collective labor groups called *mingas*. Their successes (e.g., building a community house, soccer field, church, tourist hotel, sidewalks, staircase from the riverbed, piped water, energy system, a night club, and pooling community money to care for the sick) were attributed to similar concepts: an ability to solve problems through organization and unity by considering themselves as a single unit or commune. One remote community leader took pride in her community's self-sufficiency, "We are incomparable and independent … when a child broke his arm we came together as a community to pool money so that the child could go to hospital."

Roadside communities claimed they had less success compared to remote communities due to lack of participation and poor relationships between community members. For example, roadside communities commented on the negative disruption that resulted from NGOs visiting their easily reachable households like the one-time distribution of water filters or bed nets without oversight or continuity. In contrast, remote communities cited more positive involvement from governmental ministries due to economic support for agriculture (cacao), goldmining and tourism. Communities at a medium level of remoteness stated they were neglected by external agents, too far for easy access and too close to look under-resourced. One leader from a medium-level remote community stated, "We have been fighting with the government for 30 years and they have ignored us … we don't have the resources to have a closer school. It is 4 h away by canoe. Many kids do not go to school."

Residents of one remote community talked about having greater kinship and connectedness, whereas roadside communities were more

Table 3
Using a two-stage Bayesian hierarchical model whereby the effect of the passing time network (PTN) and core discussion network (CDN) on acute gastrointestinal illness (AGI) were modeled jointly (Model 2) to examine effect modification, we report the odds ratios (OR) and the 2.5% and 97.5% quantiles of the posterior distribution for the credible intervals (CI). Each wave of data was modeled separately.

	2007 OR (CI)	2010 OR (CI)	2013 OR (CI)
Passing time network (PTN)			
Household degree deviance	0.64 (0.56, 0.71)	0.91 (0.85, 0.98)	1.13 (1.04, 1.22)
Average community degree	1.04 (0.93, 1.16)	0.79 (0.65, 0.95)	1.55 (1.38, 1.75)
Core discussion network (CDN)			
Household degree deviance	1.44 (1.31, 1.60)	1.08 (1.01, 1.16)	0.94 (0.87, 1.02)
Average community degree	0.87 (0.71, 1.06)	0.79 (0.63, 0.99)	0.34 (0.26, 0.45)
Interaction			
Household degree deviance passing time x Household degree deviance important matters	0.77 (0.71, 0.84)	0.94 (0.91, 0.98)	1.20 (1.13, 1.27)
Other covariates			
Trust	1.11 (0.94, 1.30)	1.26 (1.09, 1.45)	0.67 (0.57, 0.79)
Organizations	1.09 (1.03, 1.16)	1.03 (0.99, 1.07)	0.91 (0.86, 0.97)
Remoteness	0.36 (0.25, 0.53)	0.73 (0.58, 0.92)	0.95 (0.73, 1.23)
Age	1.01 (1.01, 1.01)	1.00 (1.00, 1.00)	1.00 (1.00, 1.00)
Sex (Male)	1.07 (0.92, 1.25)	0.57 (0.50, 0.66)	0.75 (0.66, 0.85)

impacted by migration (Supplementary Results 1).

3.3. *Social network structure*

Remote communities were visually cohesive and had more highly connected individuals in a PTN compared to a CDN (Fig. 2). The roadside community had more separated or disjointed sub-communities with no ties between them compared to the remote community, which had on average fewer sub-communities (Supplementary Figure 3). Modularity differences decreased over time; the remote community went from having 10 sub-communities in 2007 to 7 in 2013, and the roadside community went from having 17 sub-communities in 2007 to 9 in 2013.

4. Discussion

Sociality can both reduce and increase the risk of acute gastrointestinal illness (AGI). Though many studies have used social networks to describe protection (Aiello, 2017) or risk (Bates et al., 2007a; Meyers et al., 2005), we find that both phenomena can operate simultaneously and that mapping social networks allow us to more fully understand the complex social infrastructure of communities. This social infrastructure can modify the influence of material infrastructures (Harvey, 2014), and its effects can change over time. We summarize our findings in two key results: first, in the early years of our study, a passing time network (PTN) was more protective against AGI in households with an increased number of individuals visited for important matters (CDN), indicating the importance of community leaders. However, a PTN became a

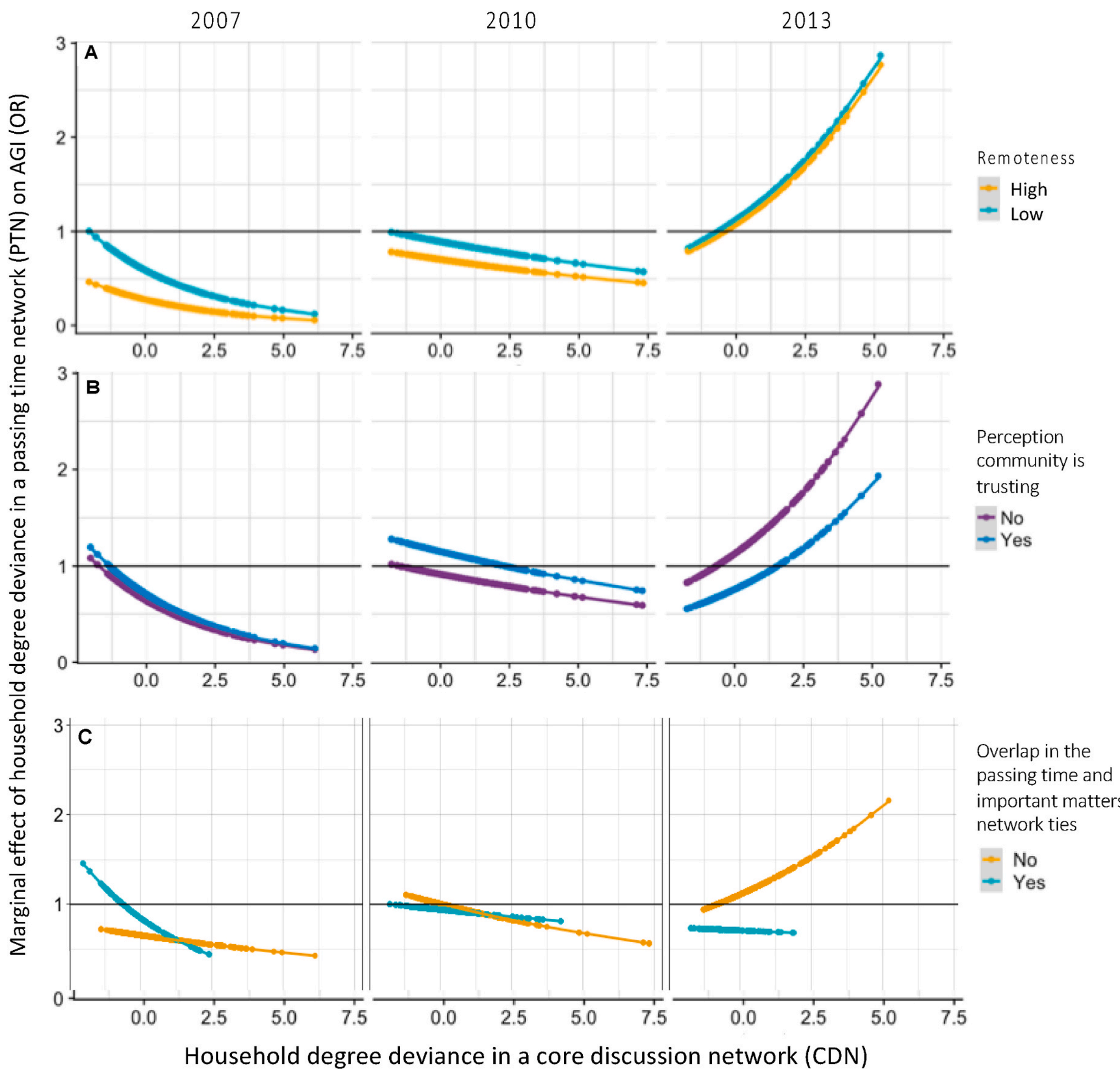

Fig. 1. Using the results from Model 2 (the joint effects model), we show the marginal effect of a passing time network (PTN) by a core discussion network (CDN) at the household-level. On the y-axis we show the odds ratio (OR) of having acute gastrointestinal illness (AGI) for every one unit increase in household degree deviance in a PTN as household degree deviance in a CDN increases (x-axis). This is shown by remoteness levels (A), defined by the midpoint of the continuous remoteness score, by whether individuals have trust in their community (B), and by whether individuals have overlap in social ties between their PTN and CDN (C) from 2007 to 2013.

stronger measure of risk as infrastructure changed and wage earnings increased. Second, having a larger community-level CDN consistently led to protection against AGI, likely mediated through the increased spread of intervention awareness and safe WASH practices as noted in our qualitative findings (Fig. 3).

4.1. The effect of sociality on AGI

Our findings suggest the increasing importance of *passing time* as an indicator of household risk. By 2013, the PTN switched from being protective to being associated with increased risk. The people individuals go to for important matters became the people they pass time with and vice versa, reaching 40% overlap by 2013 (i.e., social people are more likely to pass time with persons in their CDN). Additionally, increased travel, for both non-remote and remote communities (Kraay et al., 2018b) as infrastructure changed and the economy shifted toward wage-earning, can explain why the PTN became a conduit of transmission.

Conversely, having a large network of individuals at the community-level who can discuss *important matters* is critical for AGI reduction. When we control for multidimensional effects at the household-level, we observe stronger protective effects of the community-level CDN over time. As mobility increases, communities can become dislocated and exposure to disease risk increases. Study communities with a stronger CDN can overcome this, however, by addressing issues of water contamination and supporting community members to access health-care. Thus, community-level sociality better indexes cohesion leading to disease reducing behaviors.

In the early years of our study, CDNs are more stable and stronger in more remote communities, where mobility and transience are lower, but likely due to increased access to roads over time and the change to a wage economy the protective effect of remoteness against AGI attenuated. Despite this, CDNs became increasingly protective, suggesting that community-level cohesion is not just an attribute of remoteness, but an important social resource in preventing disease.

Other measures of social influence at the individual level, like trust and participation in organizations, similarly showed increased protection over time against AGI, but at smaller magnitudes than the CDN.

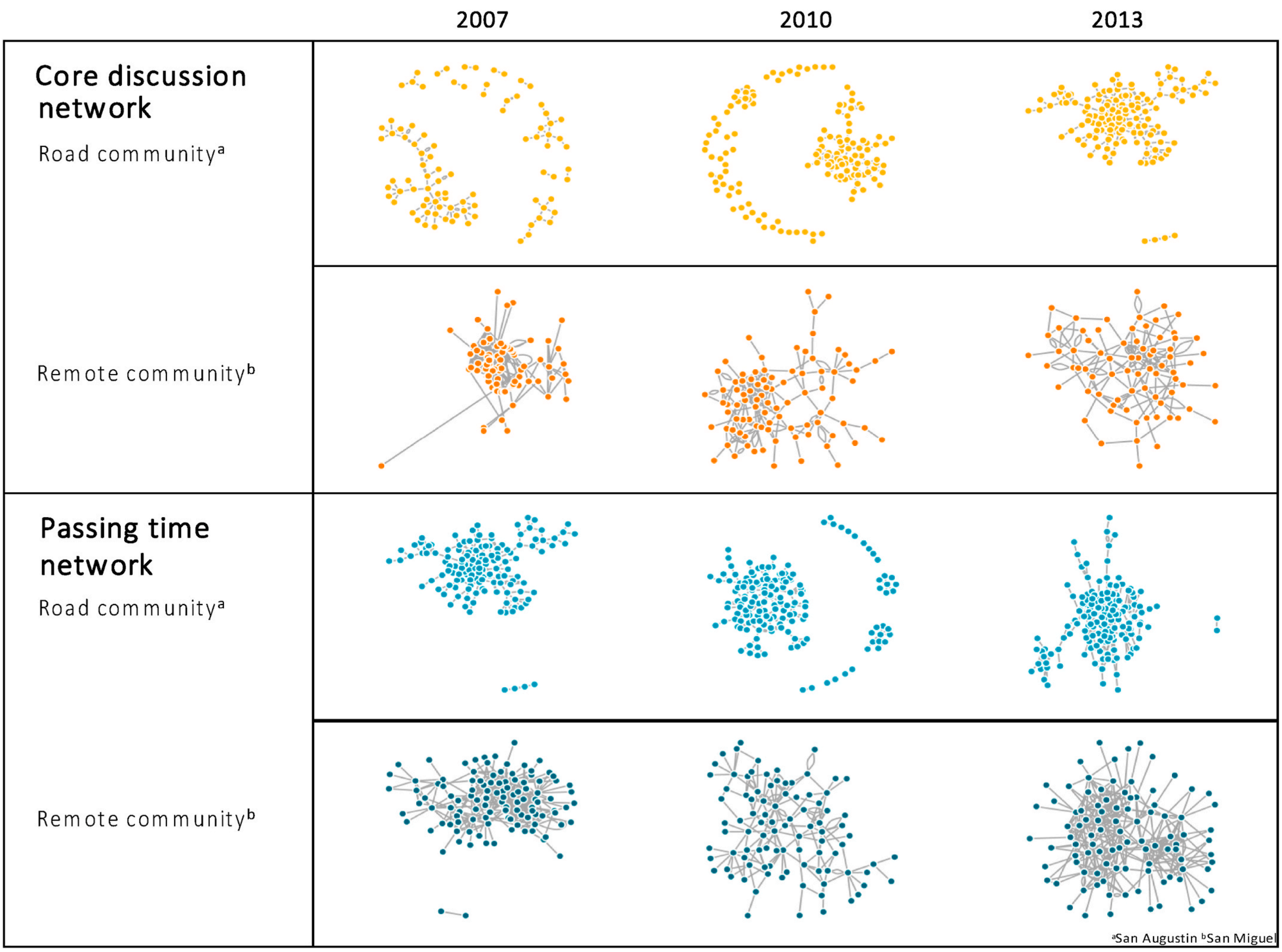

Fig. 2. Community network visualizations by remoteness using the Kamada-Kawai network layout of both a core discussion network (CDN) and passing time network (PTN) in a roadside (San Augustin) and remote community (San Miguel) from 2007 to 2013.

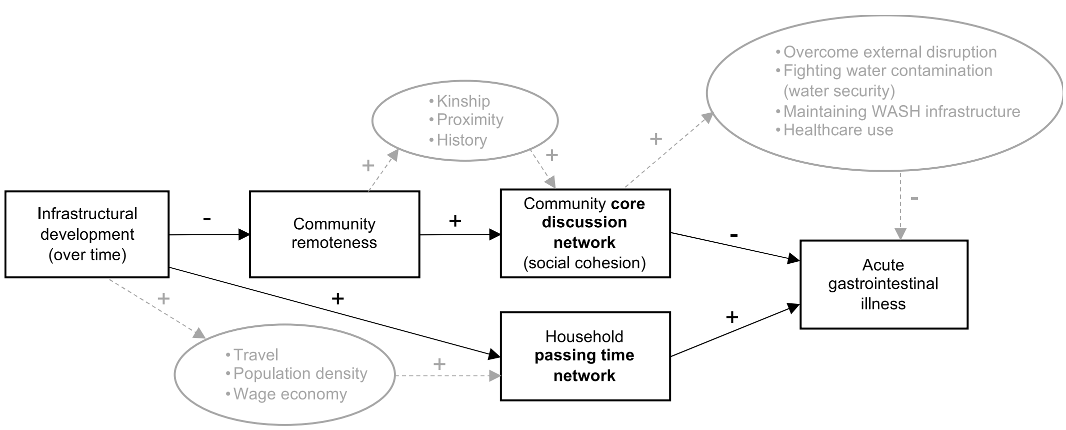

Fig. 3. A conceptual framework for the quantitative and qualitative results of this study, 2007–2013. Quantitative associations are noted in black text and squares. Qualitative derived associations are noted in grey text and ovals. Community-level core discussion network (CDN) density is a measure of social cohesion. This leads to an ability to overcome external disruptions like water insecurity, maintaining WASH infrastructure, and promoting healthcare use, and results in reduced acute gastrointestinal illness (AGI). Community social cohesion is not just an attribute of remoteness as historical kinship and proximity still strengthen the collective. Household-level passing time network (PTN) degree deviance increases over time as infrastructure develops and travel, population density, and a wage economy increase, resulting in increased risk exposure and AGI. Sociality can both reduce and increase the risk of acute gastrointestinal illness (AGI).

Network density is a stronger measure of social cohesion.

4.2. Mechanisms of sociality and collectivism

Our data support prior work that concludes social processes differ between individuals with whom we pass time and individuals with whom we seek to discuss important matters. As our qualitative data illustrate, a strong CDN manifests as resolve to overcome disruption from outside and internal forces and thus represents more critical relationships than a PTN. Communities resistant to disruption and determined to resolve important matters engage in community-led processes to address shared household and community problems. For example, communities in this area engage in *mingas*, a type of collective labor to accomplish needed tasks like tending local farms and picking cacao.

We found the community average CDN degree reduces AGI among individuals consistently over time in both the marginal and joint effects models. Life in these study communities involves collective gatherings like political meetings, feasts, sport, musical, or religious events (Collender et al., 2019). Participation in such collective events often enhances social identity (Neville & Reicher, 2011), ethnic identification (Gasparre et al., 2010), identity fusion with others (Swann et al., 2012), social cohesion (Kanyangara et al., 2007; Rimé et al., 2011), perceived social support (Páez et al., 2007), and solidarity (Hawdon & Ryan, 2012), and presents opportunities for community members to emotionally invest in and adopt learned behaviors like safe WASH practices and improved access for the betterment of the collective.

With increased infrastructure development, however, more remote communities have become increasingly accessible by bus and/or water taxi, changing the salience of the collective action. *Mingas* have been supplanted by a wage economy, and labor relations increasingly dominated by wage laborers commuting to nearby towns or plantations. As external employment opportunities increase, community-level social connection can become more important. Employers, government, and incomplete NGO development projects can act as negative external influences, rendering the CDN and community cohesion more relevant for village sustainability and disease reduction. For example, leadership and cohesion were cited as significant contributors to fixing broken systems and encouraging use of community problem solving and internally derived resources like pooling money to send ill community members to hospital.

In contrast to CDNs, PTNs represent a cruder measure of social interaction. More commonly used in the study of respiratory diseases like SARS and influenza (Meyers et al., 2005), PTNs often represent casual spatial contact that allows person-to-person transmission of airborne pathogens. For enteric diseases, however, fecal-oral transmission of the pathogen requires more intentional behavior like preparing food, collecting and storing water, or disposing feces. Thus, for enteric diseases, a PTN has different implications: disease risk and increased contact are not always linear.

4.3. Limitations

As in any network study based on self-report, our data collection methods may have biased our inference. First, since we collected data on “ego perceived friends” we do not know whether relationships were reciprocated. This matters less for a CDN as one discusses important matters with someone that is not necessarily close, but someone of influence (Small, 2013). Second, we elicit names from respondents with the same instrument to generate two distinct network types. There might be a significant overlap in individuals listed in the two networks because of “satisficing” (when respondents list more, not necessarily true, ties for the second question to please the interviewer) (Pustejovsky & Spillane, 2009). Third, our villages were small, and their remoteness limited the extent to which random encounters to discuss important matters can be measured. Yet, this small size allowed us to use the more powerful sociometric rather than egocentric approach to network measurement and have more complete data on the population. Fourth, we did not collect data on connections within the household, kinship among network ties, or ties with members of other communities. Because these factors likely play key roles in social connectedness, we aimed to address these through the qualitative data analysis.

Fifth, some social theorists argue that the complexity of a CDN is not adequately captured by a simple question like “who can you speak with about important matters” (Shakya et al., 2017; Small & Sukhu, 2016). Important matters differ among individuals, and people mobilize alters with distinct characteristics for different kinds of discussion topics or functions [34]. Generating a single list of names captures neither this nor the opportune moments when one might discuss important matters with relative strangers.

5. Conclusion

Longitudinal social network data allows us to examine how social connections evolve during a period of rapid infrastructure development when changes in these connections are both more probable and visible. Building roads and bus routes, and shifting from canoes to motorboats, all change social relationships and health risks. Our results highlight the utility of employing more complex measures of social infrastructure in social network studies, results of which can be useful in implementing and sustaining interventions. Future efforts should focus on unpacking the household and community-level effects of multidimensional social processes elicited by different network types. Targeting interventions among socially relevant groups (Shakya et al., 2014) and achieving sustainable behavior change (Shelton et al., 2019) depend upon identifying how core members of community networks influence which health interventions will be adopted (Valente, 2017).

Recent studies that have investigated the effect of social networks on reducing respiratory infection risk have underscored the important role that ‘friends’ and thought leaders play in the adoption of prevention behaviors (Steijvers et al., 2021), such as increasing vaccine uptake to reduce SARS-CoV-2 infection (Xu et al., 2021). As a global health community, however, we should simultaneously emphasize the importance of intervention monitoring and funding follow-through to ensure efforts are sustainable within vulnerable communities.

Ethics approval

All study participants provided informed consent and all data collection protocols were approved by institutional review boards at the University of Michigan, Trinity College, Hartford, and the Universidad San Francisco de Quito.

Funding

This work was funded by the National Institutes of Health (grant R01- AI050038) and the University of Michigan.

Author contributions

All authors contributed significantly to the manuscript. STH developed the research question and led the study design, analysis, interpretation of data, drafted the manuscript and revised the manuscript for intellectual content. JAT led the data collection, helped guide the qualitative methodological approaches, and reviewed the manuscript for intellectual content. BM helped guide the statistical methodological approaches and reviewed the manuscript for intellectual content. JNE led the data collection, helped develop the research question and interpretation of data, and revised the manuscript critically for intellectual content.

Data availability

The data underlying this article cannot be shared publicly for the privacy of individuals that participated in the study and until other analyses that are part of the primary objectives of the study are complete. The data will be shared on reasonable request to the corresponding author. Code is available on github (https://github.com/hegdesonia/two-stage-bayes).

Declaration of competing interest

We report no conflicts of interest.

Acknowledgements

We would like to thank the study participants, without whom this work would not be possible. We would also like to thank the field staff, particularly Mauricio Ayovi and Denys David Tenorio Castillo, for their valuable contribution collecting the data used in this work, and Karla Vasco Aguas and Maritza Cordova Lima for their indelible efforts transcribing the qualitative data.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ssmph.2022.101159.

References

Aiello, A. E. (2017). Invited commentary: Evolution of social networks, health, and the role of epidemiology. *American Journal of Epidemiology, 185*(11). https://doi.org/10.1093/aje/kwx076

Bates, S. J., Trostle, J., Cevallos, W. T., Hubbard, A., & Eisenberg, J. N. S. (2007a). Relating diarrheal disease to social networks and the geographic configuration of communities in rural Ecuador. *American Journal of Epidemiology, 166*(9), 1088–1095. https://doi.org/10.1093/aje/kwm184

Bates, S. J., Trostle, J., Cevallos, W. T., Hubbard, A., & Eisenberg, J. N. S. (2007b). Relating diarrheal disease to social networks and the geographic configuration of communities in rural Ecuador. *American Journal of Epidemiology, 166*(9), 1088–1095. https://doi.org/10.1093/aje/kwm184

Bi, Q., Wu, Y., Mei, S., Ye, C., Zou, X., Zhang, Z., Liu, X., Wei, L., Truelove, S. A., Zhang, T., Gao, W., Cheng, C., Tang, X., Wu, X., Wu, Y., Sun, B., Huang, S., Sun, Y., Zhang, J., … Feng, T. (2020). Epidemiology and transmission of COVID-19 in 391 cases and 1286 of their close contacts in Shenzhen, China: A retrospective cohort study. *The Lancet Infectious Diseases*. https://doi.org/10.1016/S1473-3099(20)30287-5

Collender, P. A., Morris, C., Glenn-Finer, R., Acevedo, A., Chang, H. H., Trostle, J. A., Eisenberg, J. N. S., & Remais, J. V. (2019). Mass gatherings and diarrheal disease transmission among rural communities in coastal Ecuador. *American Journal of Epidemiology, 188*(8), 1475. https://doi.org/10.1093/AJE/KWZ102

Cooper, R. N. (2004). A half century of development. https://doi.org/10.5874/jfsr.18.151, 1.

Diez-Roux, A. (2000). Multilevel analysis in public health research. *Annual Review of Public Health, 21*, 171–192.

Eisenberg, J. N. S., Cevallos, W., Ponce, K., Levy, K., Bates, S. J., Scott, J. C., Hubbard, A., Vieira, N., Endara, P., Espinel, M., Trueba, G., Riley, L. W., & Trostle, J. (2006). Environmental change and infectious disease: How new roads affect the transmission of diarrheal pathogens in rural Ecuador. *Proceedings of the National Academy of Sciences of the United States of America, 103*(51), 19460–19465. https://doi.org/10.1073/pnas.0609431104

Eisenberg, J. N. S., Scott, J. C., & Porco, T. (2007). Integrating disease control strategies: Balancing water sanitation and hygiene interventions to reduce diarrheal disease burden. *American Journal of Public Health, 97*(5), 846–852. https://doi.org/10.2105/ajph.2006.086207

Forrest, R., & Kearns, A. (2001). Social cohesion, social capital and the neighbourhood. *Urban Studies, 38*(12), 2125–2143. https://doi.org/10.1080/00420980120087081

Fruchterman, T. M. J., & Reingold, E. M. (1991). Graph drawing by force-directed placement. *Software: Practice and Experience, 21*(11), 1129–1164. https://doi.org/10.1002/spe.4380211102

Garthright, W. E., Archer, D. L., & Kvenberg, J. E. (1988). Estimates of incidence and costs of intestinal infectious diseases in the United States. *Public Health Reports, 103*(2), 107–115. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=1477958&tool=pmcentrez&rendertype=abstract.

Gasparre, A., Bosco, S., & Bellelli, G. (2010). Cognitive and social consequences of participation in social rites: Collective coping, social support, and post-traumatic growth in the victims of Guatemala genocide. *Revista de Psicología Social, 25*(1), 35–46. https://doi.org/10.1174/021347410790193513

Goldstick, J. E., Trostle, J., & Eisenberg, J. N. S. (2014). Ask when - not just whether - it's a risk: How regional context influences local causes of diarrheal disease. *American Journal of Epidemiology, 179*(10). https://doi.org/10.1093/aje/kwu034

Harvey, P. (2014). Infrastructures of the frontier in Latin America. *Journal of Latin American and Caribbean Anthropology, 19*(2), 280–283. https://doi.org/10.1111/JLCA.12096

Hawdon, J., & Ryan, J. (2012). Well-being after the Virginia tech mass murder. *Traumatology, 18*(4), 3–12. https://doi.org/10.1177/1534765612441096

Heinze, G., & Schemper, M. (2002). A solution to the problem of separation in logistic regression. *Statistics in Medicine, 21*(16), 2409–2419. https://doi.org/10.1002/sim.1047

Holt-Lunstad, J., Robles, T. F., & Sbarra, D. A. (2017). Advancing social connection as a public health priority in the United States. *American Psychologist, 72*(6), 517–530. https://doi.org/10.1037/amp0000103

Kamada, T., & Kawai, S. (1989). An algorithm for drawing general undirected graphs. *Information Processing Letters, 31*(1), 7–15. https://doi.org/10.1016/0020-0190(89)90102-6

Kanyangara, P., Rimé, B., Philippot, P., & Yzerbyt, V. (2007). Collective rituals, emotional climate and intergroup perception: Participation in "gacaca"tribunals and assimilation of the Rwandan genocide. *Journal of Social Issues, 63*(2), 387–403. https://doi.org/10.1111/j.1540-4560.2007.00515.x

Kraay, A. N. M., Trostle, J., Brouwer, A. F., Cevallos, W., & Eisenberg, J. N. S. (2018a). Determinants of short-term movement in a developing region and implications for disease transmission. *Epidemiology, 29*(1), 117–125. https://doi.org/10.1097/EDE.0000000000000751

Kraay, A. N. M., Trostle, J., Brouwer, A. F., Cevallos, W., & Eisenberg, J. N. S. (2018b). Determinants of short-term movement in a developing region and implications for disease transmission. *Epidemiology, 29*(1), 117–125. https://doi.org/10.1097/EDE.0000000000000751

MacPherson, D. W., Gushulak, B. D., Baine, W. B., Bala, S., Gubbins, P. O., Holtom, P., & Segarra-Newnham, M. (2009). Population mobility, globalization, and antimicrobial drug resistance. *Emerging Infectious Diseases, 15*(11), 1727–1732. https://doi.org/10.3201/EID1511.090419

Majowicz, S. E., Hall, G., Scallan, E., Adak, G. K., Gauci, C., Jones, T. F., O'Brien, S., Henao, O., & Sockett, P. (2008). A common, symptom-based case definition for gastroenteritis. *Epidemiology and Infection, 136*(7), 886–894. https://doi.org/10.1017/S0950268807009375

Marsden, P. V. (1987). Core discussion networks of Americans. *American Sociological Review, 52*(1), 122. https://doi.org/10.2307/2095397

Meyers, L. A., Pourbohloul, B., Newman, M. E. J., Skowronski, D. M., & Brunham, R. C. (2005). Network theory and SARS: Predicting outbreak diversity. In *Journal of theoretical biology* (Vol. 232, pp. 71–81). https://doi.org/10.1016/j.jtbi.2004.07.026, 1.

Neville, F., & Reicher, S. (2011). The experience of collective participation: Shared identity, relatedness and emotionality. *Contemporary Social Science, 6*(3), 377–396. https://doi.org/10.1080/21582041.2012.627277

Newman, M. E. J. (2006). Modularity and community structure in networks. *Proceedings of the National Academy of Sciences, 103*(23), 8577–8582. https://doi.org/10.1073/pnas.0601602103

Páez, D., Basabe, N., Ubillos, S., & González-castro, J. L. (2007). Social sharing, participation in demonstrations, emotional climate, and coping with collective violence after the March 11th Madrid bombings. *Journal of Social Issues, 63*(2), 323–337. https://doi.org/10.1111/j.1540-4560.2007.00511.x

Payment, P., Richardson, L., Siemiatycki, J., Dewar, R., Edwardes, M., & Franco, E. (1991). A randomized trial to evaluate the risk of gastrointestinal disease due to consumption of drinking water meeting current microbiological standards. *American Journal of Public Health, 81*(6), 703–708. https://doi.org/10.2105/AJPH.81.6.703

Perry, B. L., & Pescosolido, B. A. (2010). Functional specificity in discussion networks: The influence of general and problem-specific networks on health outcomes. *Social Networks, 32*(4), 345–357. https://doi.org/10.1016/j.socnet.2010.06.005

Pustejovsky, J. E., & Spillane, J. P. (2009). Question-order effects in social network name generators. *Social Networks, 31*(4), 221–229. https://doi.org/10.1016/j.socnet.2009.06.001

Rimé, B., Kanyangara, P., Yzerbyt, V., & Paez, D. (2011). The impact of Gacaca tribunals in Rwanda: Psychosocial effects of participation in a truth and reconciliation process after a genocide. *European Journal of Social Psychology, 41*(6), 695–706. https://doi.org/10.1002/ejsp.822

Roderick, P., Wheeler, J., Cowden, J., Sockett, P., Skinner, R., Mortimer, P., Rowe, B., & Rodriques, L. (1995). A pilot study of infectious intestinal disease in England. *Epidemiology and Infection, 114*(2), 277–288. http://www.ncbi.nlm.nih.gov/pubmed/7705491.

Roy, S. L., Beach, M. J., & Scallan, E. (2006). The rate of acute gastrointestinal illness in developed countries. *Journal of Water and Health, 4*(Suppl 2), 31. https://doi.org/10.2166/wh.2006.017

Shakya, H. B., Christakis, N. A., & Fowler, J. H. (2014). Association between social network communities and health behavior: An observational sociocentric network study of latrine ownership in rural India. *American Journal of Public Health, 104*(5), 930–937. https://doi.org/10.2105/AJPH.2013.301811

Shakya, H. B., Christakis, N. A., & Fowler, J. H. (2017). An exploratory comparison of name generator content: Data from rural India. *Social Networks, 48*, 157–168. https://doi.org/10.1016/j.socnet.2016.08.008

Shelton, R. C., Lee, M., Brotzman, L. E., Crookes, D. M., Jandorf, L., Erwin, D., & Gage-Bouchard, E. A. (2019). Use of social network analysis in the development, dissemination, implementation, and sustainability of health behavior interventions for adults: A systematic review. *Social Science & Medicine, 220*, 81–101. https://doi.org/10.1016/J.SOCSCIMED.2018.10.013

Silvapulle, M. J. (1981). On the existence of maximum likelihood estimators for the binomial response models. *Journal of the Royal Statistical Society: Series B, 43*(3), 310–313. http://www.jstor.org/stable/2984941.

Small, M. L. (2013). Weak ties and the core discussion network: Why people regularly discuss important matters with unimportant alters. *Social Networks, 35*(3), 470–483. https://doi.org/10.1016/j.socnet.2013.05.004

Small, M. L., & Sukhu, C. (2016). Because they were there: Access, deliberation, and the mobilization of networks for support. *Social Networks, 47*, 73–84. https://doi.org/10.1016/j.socnet.2016.05.002

Steijvers, L. C. J., Brinkhues, S., Hoebe, C. J. P. A., Van Tilburg, T. G., Claessen, V., Bouwmeester-Vincken, N., Hamers, F., Vranken, P., & Dukers-Muijrers, N. H. T. M. (2021). Social networks and infectious diseases prevention behavior: A cross-sectional study in people aged 40 years and older. *PLoS One, 16*(5). https://doi.org/10.1371/JOURNAL.PONE.0251862

Swann, W. B., Jetten, J., Gómez, Ã., Whitehouse, H., & Bastian, B. (2012). When group membership gets personal: A theory of identity fusion. *Psychological Review, 119*(3), 441–456. https://doi.org/10.1037/a0028589

Tong, A., Sainsbury, P., & Craig, J. (2007). Consolidated criteria for reporting qualitative research (COREQ): A 32-item checklist for interviews and focus groups. *International Journal for Quality in Health Care, 19*(6), 349–357. https://doi.org/10.1093/INTQHC/MZM042

Valente, T. W. (2017). Putting the network in network interventions. In *Proceedings of the national academy of sciences of the United States of America*. https://doi.org/10.1073/pnas.1712473114

Wesolowski, A., Buckee, C. O., Engø-Monsen, K., & Metcalf, C. J. E. (2016). Connecting mobility to infectious diseases: The promise and limits of mobile phone data. *Journal of Infectious Diseases, 214*(suppl 4), S414–S420. https://doi.org/10.1093/infdis/jiw273

WHO, & UNICEF. (2004). Clinical management of acute diarrhea. In *American journal of public health*.

Xu, B., Zhang, Y., Chen, L., Yu, L., Li, L., & Wang, Q. (2021). The influence of social network on COVID-19 vaccine hesitancy among healthcare workers: A cross-sectional survey in Chongqing, China. *Human Vaccines & Immunotherapeutics, 17*(12), 5048–5062. https://doi.org/10.1080/21645515.2021.2004837

Zelner, J. L., Trostle, J., Goldstick, J. E., Cevallos, W., House, J. S., & Eisenberg, J. N. S. (2012). Social connectedness and disease transmission: Social organization, cohesion, village context, and infection risk in rural Ecuador. *American Journal of Public Health, 102*(12), 2233–2239. https://doi.org/10.2105/AJPH.2012.300795