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Food insecurity and compound environmental shocks in Nepal: Implications for a changing climate

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ABSTRACT

Food insecurity is a key global health challenge that is likely to be exacerbated by climate change. Though climate change is associated with an increased frequency of extreme weather events, little is known about how multiple environmental shocks in close succession interact to impact household health and well-being. In this paper, we assess how earthquake exposure followed by monsoon rainfall anomalies affect food insecurity in Nepal. We link food security data from the 2016 Nepal Demographic and Health Survey to data on shaking intensity during the 2015 Gorkha earthquake and rainfall anomalies during the 2015 monsoon season. We then exploit spatial variation in exposure to the earthquake and monsoon rainfall anomalies to isolate their independent and compound effects. We find that earthquake exposure alone was not associated with an increased likelihood of food insecurity, likely due in part to effective food aid distribution. However, the effects of rainfall anomalies differed by severity of earthquake exposure. Among households minimally impacted by the earthquake, low rainfall was associated with increased food insecurity, likely due to lower agricultural productivity in drought conditions. Among households that experienced at least moderate shaking, greater rainfall was positively associated with food insecurity, particularly in steep, mountainous areas. In these locations, rainfall events disproportionately increased landslides, which damaged roads, disrupted distribution of food aid, and destroyed agricultural land and assets. Additional research on the social impacts of compound environmental shocks is needed to inform adaptation strategies that work to improve well-being in the face of climate change.

1. Introduction

Food insecurity—the lack of access to affordable, sufficient, and nutritious food—is a critical global health challenge and barrier to sustainable development (World Food Summit. (1996), 1996). After declining for several decades, rates of food insecurity have increased in recent years, with two billion people worldwide currently moderately or severely food insecure (FAO, IFAD, UNICEF, WFP, & WHO, 2019). Food insecurity impedes socioeconomic development by negatively impacting physical and mental health as well as educational and economic outcomes (Belachew et al., 2011; Cole & Tembo, 2011; FAO, IFAD, UNICEF, WFP, & WHO, 2018; Gundersen & Ziliak, 2015; Whitaker, Phillips, & Orzol, 2006). In response, the United Nations aimed a Sustainable Development Goals (SDGs) at ending global hunger and ensuring year round access to safe, nutritious, and sufficient food by 2030 (United Nations, 2015).

To achieve food security there must be adequate and stable food production, the ability for individuals to access food, and the capacity for individuals to benefit from the nutrients contained within food. Climate variability as well as extreme weather events have been linked to recent increases in global food insecurity through their effects on each of these components (FAO, IFAD, UNICEF, WFP, & WHO, 2018). Climate change is associated with higher temperatures, changing precipitation patterns, and an increased frequency, duration, and severity of extreme weather events such as floods, droughts, and heat waves (Stocker, Qin, Plattner, Alexander, Allen, Bindoff, & Xie, 2013). This poses significant threats to global food security for both rural and urban populations by impacting agricultural production, food prices, and food system infrastructure (Hertel, Burke, & Lobell, 2010; Lesk, Rowhani, & Ramankutty, 2016; Porter et al., 2014; Wheeler & von Braun, 2013). Droughts in particular have a large impact on

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food production, leading to over 80% of natural hazard-induced crop and livestock losses (FAO, IFAD, UNICEF, WFP, & WHO, 2018). Further, floods and other extreme weather events can impact food security by damaging agricultural land and assets; destroying food storage infrastructure, roads, and transport networks; and increasing the transmission of waterborne diseases that limit the ability for individuals to absorb nutrients from food (Vermeulen, Campbell, & Ingram, 2012; Wheeler & von Braun, 2013). Indeed, the FAO argues that climate change is one of the primary drivers of the recent increase in global hunger (FAO, IFAD, UNICEF, WFP, & WHO, 2018).

Researchers have recently begun calling attention to the fact that climate change is leading to an increased frequency of multiple natural hazards that occur in short succession (AghaKouchak et al., 2018; Zscheischler et al., 2018). For example, in 2016 Ethiopia experienced a severe drought followed by widespread flooding, which killed livestock and displaced already drought-stricken households (FAO, 2016b). In 2018, Japan experienced its worst flooding in decades closely followed by record-breaking heat waves (Gronewald, 2018).In California, a wildfire followed by heavy rainfall triggered deadly mudslides (Addison & Oommen, 2020). Zscheischler et al. (2018) call these occurrences *compound events*, defined as "the combination of multiple drivers and/or hazards that contributes to societal or environmental risk" (p. 470). Exposure to multiple hazards over a short time frame leaves affected populations with less time to recover from an environmental shock before being impacted by a subsequent shock. While numerous studies have examined how individual natural disasters and adverse climatic conditions impact crop production and food security (Iizumi & Ramankutty, 2015; Lesk et al., 2016; Smith & Frankenberger, 2018), little is known about the effects of exposure to multiple environmental shocks in close succession. Indeed, there has been a growing recognition of the need for research on the social and environmental effects of experiencing compound events (Zscheischler et al., 2018).

This paper focuses on Nepal, a country that is acutely vulnerable to the impacts of environmental shocks on food insecurity. Nepal is one of the 20 most disaster-prone countries in the world, with floods, droughts, landslides, and earthquakes causing the majority of damage (Wendelbo et al., 2016). Further, 25% of Nepal's population lives in poverty, over 50% of Nepali households experience food insecurity, and 36% of children aged 6–59 months are chronically malnourished (Bank, 2018; Ministry of Health Nepal, New ERA, & ICF, 2017; World Food Programme, 2018). Two-thirds of Nepalis are employed in agriculture, the majority of which is rain fed (FAO, 2018). Food production is highly dependent on the timing of monsoon onset as well as rainfall amounts, and flooding and landslides are common during periods of heavy rainfall. Additional factors associated with food production and food security in Nepal include forest management practices, road building, and fertilizer access (Gurung, 2021; Paudel & Crago, 2017; Paudel, 2018). The precarity of food production, particularly in mountainous regions, led Nepal to begin providing formal food aid in 1974, and the country remains a large food aid recipient today (Gautam, 2019).

Climate projections for South Asia predict an increase in both above- and below-normal monsoon rainfall, a greater frequency of extreme precipitation events, and an increase in extreme heat during the summer (World Bank, 2013). As a result of climate change, by 2030 Nepal is predicted to experience declines in the production of rice, wheat, and cereal grains, as well as a 5% reduction in real GDP (Bandara & Cai, 2014). Further, research suggests that socioeconomic marginalization—including low-caste status, poverty, and small landholdings—increases the vulnerability of Nepali households to climate-induced food insecurity, indicating that climate change will lead to differential impacts within Nepal (Gautam & Andersen, 2017).

In April 2015, Nepal was hit by a severe earthquake that affected nearly half of the country's 75 districts, 14 of which were impacted severely (WHO, 2015). In this paper, we examine the extent to which exposure to the 2015 earthquake magnified the effects of subsequent monsoon rainfall anomalies on household food insecurity. We investigate how earthquake shaking intensity as well as anomalies in 2015 monsoon rainfall independently and jointly affected food security among households in 2016. We predict that exposure to the earthquake will magnify the negative effects of adverse rainfall conditions on food security, as households who experience a severe environmental stressor are less able to cope with a subsequent stressor. This paper helps to identify how exposure to compound events impacts household food security, which can in turn inform policies to improve health and well-being in the face of climate change.

2. The 2015 Nepal earthquake and monsoon season

On April 25, 2015, a 7.8 magnitude earthquake struck the Gorkha District of central Nepal, followed by more than 250 aftershocks greater than 3.0 in magnitude over the subsequent weeks (Kargel et al., 2016). The earthquake and aftershocks led to over 4,000 landslides, caused approximately 9,000 deaths and 23,000 injuries, destroyed over half a million homes, and displaced two million people (Basnyat, Tabin, Nutt, & Farmer, 2015; Government of Nepal National Planning Commission, 2015; Kargel et al., 2016). The Gorkha earthquake was the worst quake to hit Nepal in over 80 years (Government of Nepal Ministry of Home Affairs, 2015). Thirty-one of Nepal's 75 districts were affected, with 14 districts facing the most severe impacts.

Nepal is a highly mountainous and landslide-prone country, with terrain ranging from low-lying alluvial plains called the Terai, to hilly regions of the Middle Himalaya, to the mountainous High Himalaya (Bhandary, Yatabe, Dahal, Hasegawa, & Inagaki, 2013; Petley et al., 2007). Households in hilly and mountainous areas were most adversely affected by the quake (Thorne-Lyman et al., 2018). Further, Kathmandu, Nepal's capital city, was among the hardest hit areas, though poor rural areas were most adversely impacted due to inferior housing construction (Government of Nepal National Planning Commission, 2015). The agriculture sector experienced the most severe impacts from the earthquake, followed by the tourism, commerce, and industry sectors (Wendelbo et al., 2016). The earthquake threatened food production and access in the worst affected areas, as households lost crops as well as stored grain and seeds, livestock were killed, and roads and markets were destroyed (Webb, West, & O'Hara, 2015).

The humanitarian response to the earthquake was rapid and well-funded. Numerous countries, international organizations, and NGOs donated services, money, equipment, and food to help with recovery. For example, in the six weeks following the earthquake, the United Nations World Food Programme (WFP) provided food assistance to two million people in the 14 most severely affected districts, and over the following year the WFP worked to rebuild irrigation systems and repair roads and mountain trails (World Food Programme, 2016). In addition, the FAO aided 1.5 million people in the six worst affected districts by providing seeds and grain storage bags, repairing livestock shelters, and rehabilitating irrigation schemes (FAO, 2016a). Further, the Nepali government, along with national and international partners, implemented a successful Emergency Nutrition Response that targeted young children and their mothers (Aguayo, Sharma, & Subedi, 2015). International aid projects were directed towards places with greater earthquake damage and poorer housing conditions, however aid was also biased toward areas near Kathmandu as well as municipalities with a higher proportion of upper caste individuals (Eichenauer, Fuchs, Kunze, & Strobl, 2020). This suggests that aid allocation decisions did not always correspond to areas with the highest levels of socioeconomic vulnerability.

The earthquake occurred shortly before the onset of the 2015 monsoon season, which typically extends from early June through late September. Nepal normally receives about 80% of its annual rainfall during the monsoon, with heavy rainfall events leading to flooding and landslides, and low rainfall reducing crop and livestock production. The majority of landslides are triggered by monsoon rain events, with most fatal landslides occurring in the hill regions of central and eastern Nepal (Petley et al., 2007). Sea surface temperatures in the tropical Pacific were warm during the fall/winter months of 2014 and the warming continued into 2015, with 2015/16 experiencing the strongest El Niño since 1997/98 (Ineson et al., 2018). During the 2015 monsoon season, Nepal received about 25% less rainfall than average, with the most severe drought conditions occurring in the center-west regions (World Meteorological Organization, 2016). These deficits are consistent with what can be expected during El Niño years (Shrestha, Wake, Dibb, & Mayewski, 2000; Sigdel & Ikeda, 2013). Most areas of the country experienced drier-than-average conditions during the 2015 monsoon, which led to decreased agricultural production and increased food prices (Ministry of Agricultural Development, FAO, & WFP, 2016).

In addition to the thousands of landslides that directly resulted from the earthquake and aftershocks, rain events during the 2015 monsoon triggered more landslides, as the hilly terrain in areas affected by the earthquake was more likely to become destabilized by heavy rainfall (Qiu, 2016). Despite the weaker-than-normal monsoon season, individual rain events led to landslides at rates 10–20 times that of a typical monsoon season, with landslides concentrated in the areas hardest hit by the earthquake (Qiu, 2016; Rosser, Densmore, & Oven, 2016).

3. Methods

3.1. Data

To understand the joint effects of earthquake exposure and monsoon rainfall anomalies, we linked data from the 2016 Nepal Demographic and Health Survey (DHS) to data on earthquake shaking intensity as well as high-resolution rainfall data from the 2015 monsoon season. The Nepal DHS uses a stratified clustered sampling design to select representative household samples at the national, provincial, and rural/urban levels. Each of Nepal's seven provinces was divided into rural and urban areas for a total of 14 sampling strata, and then 383 enumeration areas (clusters) were selected with approximately 30 households interviewed in each cluster (Ministry of Health Nepal, New ERA, ICF, 2017). Households were administered a questionnaire, and each woman aged 15 and 49 residing in the household completed an additional questionnaire. Data were collected between June 2016 and January 2017 from 11,040 households in 73 of Nepal's 75 districts (Ministry of Health Nepal, New ERA, ICF, 2017). DHS data contain information on food security as well as geographic coordinates of the sampling clusters, length of time in residence among surveyed women, and an array of household- and community-level variables. Our analytic sample consists of 11,029 households with non-missing values on variables of interest.

We created a measure of household food insecurity based on the Household Food Insecurity Access Scale (Coates, Swindale, & Bilinsky, 2007), and following the technique used by the Nepal DHS (DHS Program, 2014). Heads of household were asked a set of nine questions that addressed how often during the prior 12 months they or any members of their household: worried about not having enough food, were unable to eat preferred foods, ate a limited variety of food due to lack of resources, ate smaller meals, ate fewer meals, lacked food to eat, went to sleep hungry, or had to go an entire day and night without eating. Households were then classified into four categories: food secure, mildly food insecure, moderately food insecure, and severely food insecure. Among the analytic sample, 47% of households were food secure, 21% were mildly food insecure, 22% were moderately food insecure, and 10% were severely food insecure. We further dichotomized these group into moderately/severely food insecure (32%) and food secure (68%) households.

We included a measure of earthquake ground shaking intensity developed by the US Geological Survey (USGS) Earthquake Hazards Program (USGS, 2015). The USGS's ShakeMap measures the distribution and severity of earthquake ground shaking using a combination of recorded macroseismic intensity data from seismic sensors and estimated intensity through interpolation techniques (Worden & Wald, 2016). The ShakeMap intensity scale ranges from one (not felt, no damage) to ten (extreme, heavy damage). The qualitative descriptions that accompany each number represent estimates of "perceived shaking" and "potential damage", respectively. However, the ShakeMap data are not derived from observations of an earthquake's impacts on people or infrastructure (Worden, Thompson, Hearne, & Wald, 2020). The maximum intensity of the Gorkha earthquake was eight (severe, moderate/heavy damage), with large areas of the country experiencing intensities ranging from five (moderate, very light damage) through seven (very strong, moderate damage). Fig. 1 displays the ground shaking intensity data for the Gorkha earthquake.

To ensure confidentiality, the DHS randomly displaces the GPS locations of rural clusters by between zero and five km (with 1% of clusters displaced by between zero and ten km) and urban clusters by between zero and two km. The displacement is restricted so that the cluster remains within the same district. There is therefore the potential for misclassification of earthquake intensity values for clusters that have displaced GPS locations. To account for this, we created a 2 km buffer around each urban cluster and a 5 km buffer around each rural cluster and assigned the earthquake intensity category that occupied the maximum proportional area within the buffer. The cluster is therefore given the earthquake intensity category with the greatest probability of containing the true cluster location (Perez-Heydrich et al., 2013).

We grouped the earthquake intensity data into three categories: no to light shaking (intensity values of zero to four), moderate to strong shaking (intensity values of five or six), and very strong to severe shaking (intensity values of seven or eight). Among the analytic sample, 33% of households experienced no to light shaking, 43% of households experienced moderate to strong shaking, and 24% of households experienced very strong to severe shaking. As mentioned above, 14 of Nepal's districts experienced the most severe impacts in terms of deaths, injuries, and damage to infrastructure and humanitarian assistance was concentrated on these districts. (Government of Nepal Ministry of Home Affairs, 2015). Among the analytic sample, zero households that experienced light or no shaking were located in the 14 most affected districts, 6% of households that experienced moderate to strong shaking were located in these districts, and 82% of households that experienced very strong to severe shaking were located in these districts.

To understand the effects of monsoon rainfall anomalies, we used data on total daily precipitation from the Climate-Weather Research and Forecasting Model (CWRF) (Liang et al., 2012). CWRF provides 30-km gridded data from 1980 to 2015, and the data have been shown to capture summer monsoon rainfall well over South China, which borders Nepal (Liang et al., 2019). We linked the rainfall and DHS data at the cluster level using GPS points. We took the centroid of each 30-by-30 km grid point and linked the cluster to its nearest centroid. Because the spatial resolution of the rainfall

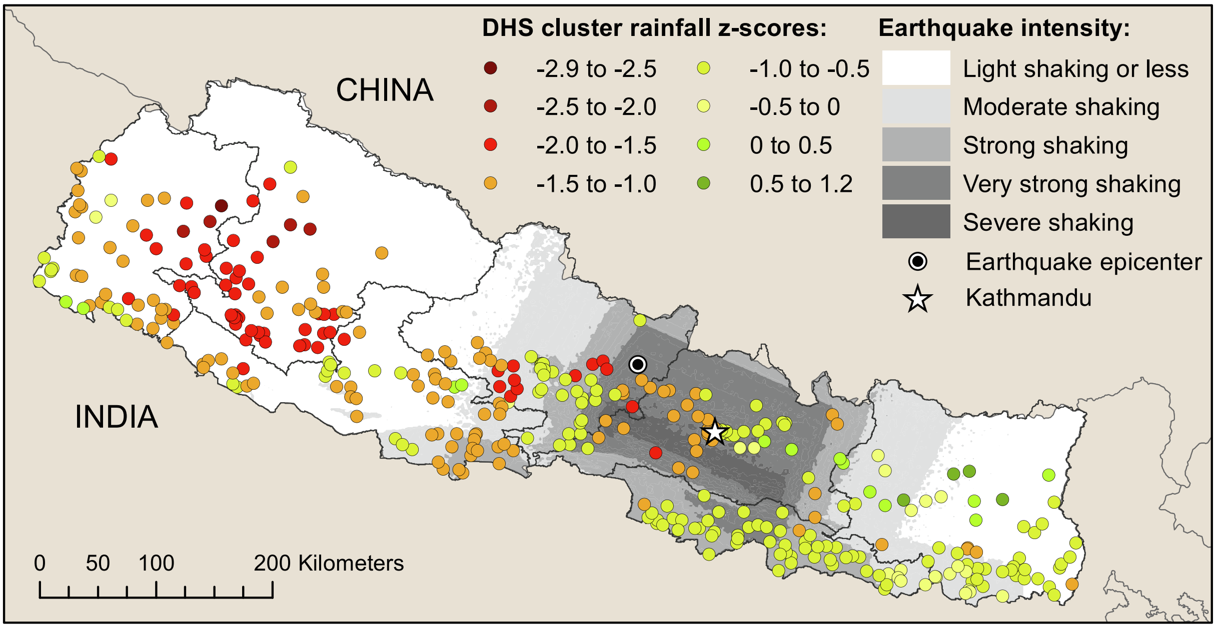

Fig. 1. Map of Nepal including province boundaries, Gorkha earthquake shaking intensity, and 2015 rainfall z-scores for the DHS clusters.

data (30 km) is much larger than the maximum potential displacement of clusters (10 km), we expected minimal misclassification of rainfall exposure, and therefore did not adjust for cluster displacement.

We created a measure of rainfall anomalies during the 2015 monsoon season by first calculating the average total rainfall across the monsoon months (June through September) in each cluster for a 36-year baseline period of 1980 to 2015. We then calculated z-scores for 2015 monsoon rainfall based on deviations from the baseline period. A z-score of −2 would therefore indicate that the total monsoon rainfall in 2015 in a given DHS cluster was two standard deviations below the cluster's long-term average total monsoon rainfall. Fig. 1 displays cluster-level rainfall z-scores for the 2015 monsoon season, which range from −2.9 to 1.2.

To account for additional social and environmental factors that are associated with food security, we included a set of control variables at the household level (age of household head, whether the household head is female, education of household head, and whether the household owns agricultural land), DHS cluster level (urban/rural status, altitude, and slope), and district level (Human Development Index (HDI)). Average slope of the DHS cluster was obtained from the DHS Program's geospatial covariates dataset (Mayala, Fish, Eitelberg, & Dontamsetti, 2018). Slope, measured in degrees, indicates how rugged the terrain is around each cluster. We created a dichotomous variable for clusters with the steepest terrain, coding all clusters in the 90th percentile or above (with an average slope equal to or greater than 11.86 degrees) as steepest, and all other clusters as less steep. However, it is important to note that many of the clusters in the "less steep" category are hilly and are therefore also vulnerable to landslides.

HDI data were obtained from Nepal's 2014 Human Development Report, and serve as a composite measure of socioeconomic development based on life expectancy, years of schooling, literacy, and gross national income per capita (Government of Nepal National Planning Commission, 2014). Large spatial inequalities in HDI exist within Nepal. The far western regions, as well as some districts in the southeastern part of the country, experience the lowest HDI levels, while districts in central Nepal, including Kathmandu and surrounding areas, experience the highest levels.

3.2. Analysis

We then estimated a set of binary logistic regression models predicting the likelihood of moderate or severe food insecurity. The two main predictor variables are (1) a categorical measure of earthquake shaking intensity (no to light shaking, moderate to strong shaking, and very strong to severe shaking); and (2) 2015 monsoon rainfall z-score at the cluster level. In addition to the joint effects of earthquake exposure and rainfall, we estimated models with earthquake-rainfall interactions and earthquake-rainfall-slope interactions in order to examine whether exposure to the earthquake magnifies or attenuates the effects of rainfall anomalies on food security, and whether this relationship varies by the slope of the terrain in which the cluster is located.

We included interview month fixed effects to account for seasonal variation in food insecurity and province fixed effects to account for spatial differences in food insecurity across Nepal's seven provinces. In addition, we included household-, cluster-, and district-level controls, described above, to account for baseline differences in food security between households that vary on these dimensions. Lastly, we accounted for the DHS Program's complex sampling design in our models by adjusting for stratification, clustered sampling, and sampling weights (using Stata's *svyset* command). Including sampling weights ensures that the results are nationally representative and accounting for stratified and clustered sampling adjusts standard errors for the non-independence of households within the same DHS enumeration area.

4. Results

Table 1 presents descriptive statistics stratified by level of earthquake shaking intensity. The prevalence of moderate to severe food insecurity was highest in areas that experienced no to light shaking, which is consistent with the fact that these regions tend to be poorer than other parts of Nepal. Forty-one percent of households in the areas least affected by the earthquake were food insecure, versus approximately 28% of households in the other two groups. About half of household heads in each group were in the 34-to-56-year age range and approximately 30% of households were female headed. Households who experienced no to light

Table 1
Descriptive statistics by level of earthquake shaking.

	No to light shaking				Moderate to strong shaking				Very strong to severe shaking			
	Mean/ proportion	SD	Min	Max	Mean/ proportion	SD	Min	Max	Mean/ proportion	SD	Min	Max
Moderate/severe food insecurity	0.41		0	1	0.27		0	1	0.28		0	1
Monsoon rainfall z-score	−1.06	0.65	−2.87	1.21	−0.81	0.41	−1.94	0.71	−0.95	0.28	−1.57	0.23
Age of household head:												
15–33 years	0.25		0	1	0.21		0	1	0.27		0	1
34–56 years	0.51		0	1	0.53		0	1	0.49		0	1
57–95 years	0.23		0	1	0.26		0	1	0.24		0	1
Female-headed household	0.34		0	1	0.30		0	1	0.30		0	1
Education of household head:												
No education or preschool	0.40		0	1	0.42		0	1	0.32		0	1
Primary	0.26		0	1	0.21		0	1	0.22		0	1
Secondary	0.26		0	1	0.27		0	1	0.28		0	1
Higher	0.09		0	1	0.10		0	1	0.18		0	1
Household lives in rural area	0.49		0	1	0.42		0	1	0.19		0	1
Household owns land	0.88		0	1	0.73		0	1	0.71		0	1
Altitude (m above sea level)	979.02	693.83	71	3110	391.17	524.71	68	2636	1066.30	492.91	111	2264
Cluster has steep slope	0.11		0	1	0.05		0	1	0.13		0	1
District-level HDI	0.46	0.04	0.36	0.53	0.47	0.05	0.39	0.58	0.55	0.08	0.39	0.63
Number of households	4859				4324				1846			
Weighted number of households	3587				4781				2652			

shaking were more likely to live in rural areas and to own land. Thirteen percent of households that experienced very strong to severe shaking lived in clusters with the steepest slopes, versus 5% of households that experienced moderate to strong shaking and 11% of households that experienced no to light shaking. Among households that experienced very strong to severe shaking, variability in monsoon rainfall z-score was lowest, average altitude was highest, household head education was highest, and average HDI was highest. The last two points reflect the fact that Kathmandu and other wealthier areas were among those most severely affected by the earthquake.

Table 2 presents results from models predicting the likelihood of moderate/severe food insecurity based on earthquake intensity and 2015 monsoon rainfall anomalies. Model 1 examines the joint effects of earthquake exposure and rainfall conditions and we do not find significant relationships between rainfall or earthquake shaking intensity and food insecurity. However, when we introduce an interaction term between earthquake intensity and rainfall in Model 2, the results become significant. This indicates that there is indeed a relationship between monsoon rainfall anomalies and food insecurity, and that this relationship varies by shaking intensity experienced by a household.

Fig. 2 presents predicted probabilities of moderate/severe food insecurity based on interactions between earthquake intensity and rainfall z-score. Among households that experienced no to light earthquake shaking, there is a strong negative relationship between rainfall z-score and the likelihood of food insecurity. For example, a household that experienced a rainfall z-score of −2 has a 41% predicted probability of food insecurity, whereas a household that experienced a rainfall z-score of 0.5 has a 20% predicted probability of food insecurity. This suggests that during a year with lower-than-average monsoon rainfall, food security is strongly positively associated with rainfall among households not recovering from earthquake damage.

In contrast, among households that experienced moderate to strong shaking, the relationship between rainfall z-score and food insecurity is positive, with a 19% predicted probability of food insecurity at a z-score of −2 and 40% at a z-score of 0.5. Among house-

Table 2
Odds ratios of the likelihood of moderate or severe food insecurity based on earthquake shaking intensity and rainfall anomalies during the 2015 monsoon season.

	Model 1		Model 2	
Earthquake intensity [No to light shaking is baseline]				
Moderate to strong shaking	0.928		1.790	*
Very strong to severe shaking	1.001		2.166	*
Rainfall z-score	0.932		0.657	***
Moderate to strong shaking X Rainfall z-score			2.347	***
Very strong to severe shaking X Rainfall z-score			2.650	**
Household head age [34–56 years is baseline]				
15 to 33 years	1.277	**	1.265	**
57 to 95 years	0.770	***	0.778	***
Female-headed household	0.725	***	0.732	***
Household head education [none/preschool is baseline]				
Primary	0.612	***	0.621	***
Secondary	0.323	***	0.329	***
Higher	0.129	***	0.132	***
Household lives in rural area	1.115		1.127	
Household owns agricultural land	0.565	***	0.560	***
Altitude of cluster	1.000	***	1.000	***
Cluster has steep slope	1.044		1.106	
District-level HDI	0.127		0.236	
N	11,029		11,029	

Notes: Models also include fixed effects for province and month of interview.
+ p < 0.1 * p < 0.5 ** p < 0.01 *** p < 0.001

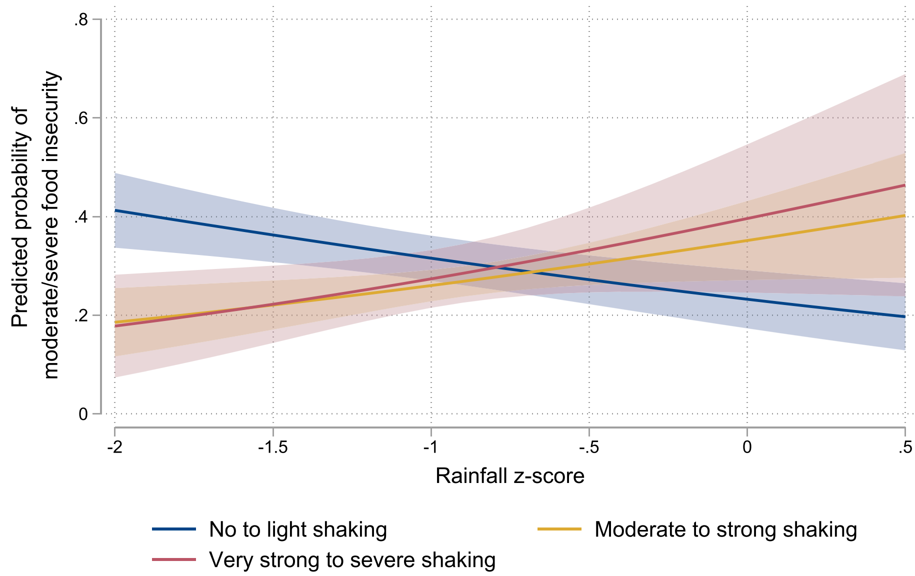

Fig. 2. Predicted probabilities of moderate or severe food insecurity based on earthquake intensity-rainfall z-score interactions, including 95% confidence intervals.

holds that experienced very strong to severe shaking, the link between rainfall z-score and food insecurity is also positive, with an 18% predicted probability of food insecurity at a z-score of −2 and 46% predicted probability at a z-score of 0.5. This indicates that rainfall was a key risk factor for food insecurity in areas of moderate to severe earthquake shaking.

Given the associations between earthquake damage in mountainous areas, rainfall, and landslides, we then estimated a model that includes interactions between earthquake intensity, rainfall z-scores, and the slope of the cluster's terrain (see Table A1 for results). Fig. 3 presents predicted probabilities of moderate/severe food insecurity based on these interactions. Among households living in districts that experienced no to light shaking, we continue to see a negative relationship between rainfall z-score and food insecurity, and the relationship is slightly stronger among those who lived in clusters with less steep slopes. Among households that experienced moderate to strong shaking, there is a small positive relationship between rainfall and food insecurity in less steep areas and a large positive relationship for households in areas with the steepest terrain. Lastly, for households that experienced very strong to severe shaking, we find a positive relationship between rainfall z-score and the likelihood of food insecurity for both slope categories, and this relationship is stronger for those living in areas with the steepest terrain.

5. Robustness checks

We estimated five supplementary models as robustness checks. The first accounts for potential misestimation of earthquake and rainfall exposure due to migration, which is potentially important given that the earthquake led to the displacement of two million people. Research suggests that most people returned to their home communities in the weeks and months following the earthquake, and a study using mobile phone data found that in the 14 most severely-affected districts, only between 5% and 15% of people remained away from their homes by July 2015 (Wilson et al., 2016). The household questionnaire, conducted between June 2016 and January 2017, did not include a question on the length of residence in the cluster among household members, however the woman's questionnaire asked how long each woman had lived in her current place of residence as well as the district where she had lived prior. Using these data, we restricted our analysis to non-migrant households, defined as those in which at least one female household member either lived in the current place of residence for at least two years or moved there from another location within the same district. Among the 8,889 households in which the woman's questionnaire was completed, 97% fell into the non-migrant category. Results among this subgroup were consistent with the main specification (see Model 4 in Table A2 and Panel 1 of Fig. A1 in the Appendix for results).

The second model accounts for potential long-term effects of exposure to the 1988 Udaypur earthquake, which severely impacted four districts of Nepal (Chaulagain, Gautam, & Rodrigues, 2018; Paudel & Ryu, 2018). The 1988 earthquake negatively affected long-term educational attainment among those exposed in early childhood (Paudel & Ryu, 2018), and exposure to severe earthquake damage may also have implications for vulnerability to the 2015 earthquake. To account for this, we estimated a model that excluded households from the four districts severely impacted by the 1988 earthquake (Ilam, Morang, Saptari, and Bhakapur). Results among this subgroup were consistent with the main specification (see Model 5 in Table A2 and Panel 2 of Fig. A1 in the Appendix for results).

The third model substitutes a continuous measure of earthquake shaking intensity for the categorical measure used in the main models. The continuous measure, from which we originally derived the three shaking intensity categories, ranged from zero to eight and increased in intervals of 0.2. Results, presented in Model 6 in Table A3 and Fig. A2 of the Appendix, are consistent with the main models.

Next, to account for potential non-linearity in the effects of rainfall anomalies on food insecurity, we estimated a model that included a quadratic rainfall specification. Results, presented in Model 7 of Table A3 and Fig. A3 of the Appendix, are generally consistent with the main models. Among households that experienced no to light shaking, we see a negative linear relationship between rainfall z-score and the probability of food insecurity. Among households that experienced very strong to severe shaking, we see some evidence of nonlinearity, though the overall relationship remains consistent with the linear specification. The risk of food insecurity remains highest at greater levels of rainfall, however there is also a modest increase in risk at the lowest levels of rainfall. This indicates that both severe drought as well as near normal monsoon rainfall undermined food security among this group.

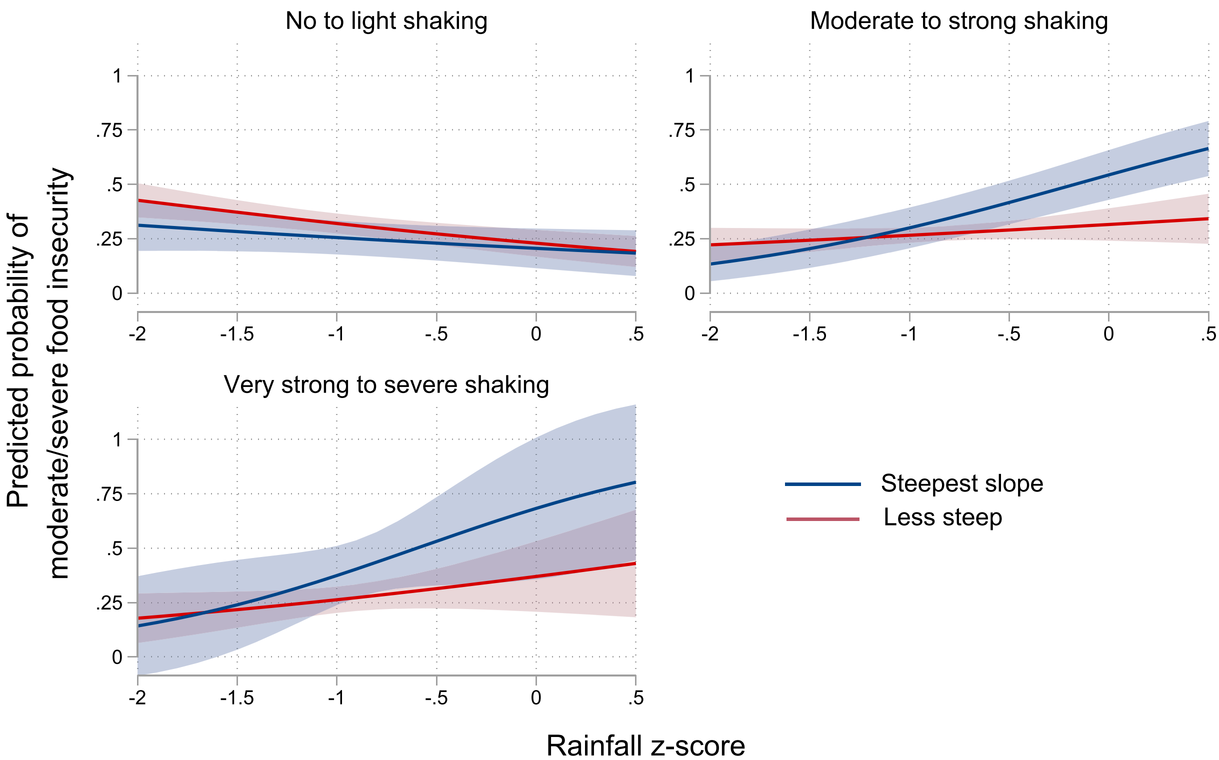

Fig. 3. Predicted probabilities of moderate or severe food insecurity based on earthquake intensity-rainfall z-score-slope interactions, including 95% confidence intervals.

Lastly, to further account for variation in terrain steepness, we have added a supplementary model that divides cluster slopes into three categories: the lowest 10th percentile (least steep slope), the 10th through 90th percentiles (moderate steepness), and the highest 90th percentile (steepest slope). The results, presented in Appendix Table A4 and Fig. A4, offer a few interesting insights. First, we see that there are no clusters in the "least steep slope" category that experienced very strong to severe shaking. This is consistent with the fact that the most severe earthquake shaking was concentrated in hilly and mountainous areas. Second, in areas that experienced moderate to strong shaking, there is a positive relationship between rainfall and food insecurity among households in clusters with moderate slope steepness, and a slight negative relationship among households in the least steep areas. This is consistent with notion that hilly areas were also at risk of post-earthquake rainfall-induced landslides, and that this risk was minimal in areas with the least steep slopes.

6. Discussion

In this paper, we examined the independent and compound effects of the 2015 Nepal earthquake and monsoon rainfall anomalies on household food insecurity in 2016. We predicted that exposure to more intense earthquake shaking as well as low monsoon rainfall would have independent, as well as additive, effects on food insecurity. Contrary to expectations, when examining these effects independently, neither earthquake exposure nor rainfall anomalies were significantly associated with food insecurity. Like Thorne-Lyman et al. (2018), we found no evidence that households that experienced greater earthquake shaking intensity were significantly more likely to be food insecure. This may be due in part to large disbursements of food aid and recovery assistance to the most severely affected areas. While other aspects of recovery—namely the rebuilding of housing and infrastructure—have been criticized (Ojha, Baldry, & Shrestha, 2017), our findings suggest that the extensive and multipronged national and international efforts to prevent hunger and restore agricultural production may have generally been successful (United Nations, 2016).

However, when we accounted for the compound effects of earthquake exposure and rainfall, notable findings emerged. We expected to find a stronger relationship between drought conditions and food insecurity among households most severely impacted by the earthquake, as experiencing multiple environmental stressors in close succession would lead to greater impacts on food production and income. Among households in areas that experienced no to light earthquake shaking, experiencing lower-than-average monsoon rainfall in 2015—a year in which the country received about 25% less rain than normal—was positively associated with food insecurity. This relationship reflects the link between dry conditions, reduced agricultural production, and increased food prices (Ministry of Agricultural Development, FAO, WFP, 2016).

In contrast, and contrary to our expectations, we discovered a positive relationship between rainfall anomalies and food insecurity among households that experienced moderate to strong shaking and an even stronger positive relationship among households that experienced very strong to severe shaking. This is likely due to fact that the 2015 monsoon season, despite being drier than normal, led to landslides at rates 10–20 times that of a normal monsoon season, with landslides concentrated in the areas hardest hit by the earthquake (Qiu, 2016; Rosser et al., 2016). Monsoon rainfall events triggered landslides in hilly areas already destabilized by the earthquake, thereby damaging agricultural assets and roads, which disrupted food production as well as the distribution of food aid. Indeed, a UN report noted that landslides caused by monsoon rainfall blocked access to most mountain passes, which delayed the provision of aid, especially to remote villages (United Nations Office for the Coordination of Humanitarian Affairs, 2015).

To further explore the linkages between monsoon rainfall anomalies and landslides in earthquake-affected areas, we examined how the relationship between rainfall, earthquake shaking, and food insecurity varied by the slope of the cluster, an indicator of terrain steepness and landslide vulnerability (Bhandary et al., 2013). We discovered that among households that experienced moderate to strong shaking, greater monsoon rainfall was strongly positively associated with food insecurity in areas with the steepest terrain. Households in areas with less steep terrain experienced a weaker positive relationship between rainfall and food insecurity, suggesting that rainfall likely increased risk in these places as well, many of which are hilly. Further, in areas that experienced very strong to severe shaking, monsoon rainfall was positively associated with food insecurity in all slope categories, and this relationship was stronger for households in the steepest areas. These results indicate that households in clusters with the steepest terrain who experienced at least moderate earthquake shaking as well as greater rainfall during the 2015 monsoon season were most vulnerable to food insecurity, likely related to landslides triggered by rainfall events.

This is the first study to examine the compound effects of natural disasters and rainfall anomalies on food insecurity. Climate change is leading to an increased frequency of compound events, which are defined as multiple natural hazards that occur in short succession (AghaKouchak et al., 2018; Zscheischler et al., 2018). It is therefore critical to better understand how exposure to multiple natural hazards jointly affects human health and well-being. Using a large, nationally-representative sample of households as well as high resolution climate data, we were able to understand the linkages between monsoon rainfall anomalies, earthquake shaking intensity, and food insecurity among households across Nepal. Though the frequency and severity of earthquakes are not related to climate change, earthquakes exemplify additional threats that can interact with climate change driven hazards to create compound events.

This study is subject to one primary limitation—the examination of a single natural disaster as well as a single monsoon season. Data on a greater number of compound events would provide additional variability and therefore enable a more comprehensive understanding of how exposure to multiple environmental shocks in close succession impacts food insecurity. For example, an earthquake followed by a wetter-than-normal monsoon season may jointly affect food security differently than what we observed in our data. Additional research on the social and health impacts of compound events is therefore needed to better prepare for and mitigate the increasing risks associated with climate change.

7. Conclusions

Prior studies have documented an increased frequency, duration, and severity of extreme weather events including droughts, floods, hurricanes, wildfires, and heat waves, and this trend is projected to continue into the future in response to ongoing anthropogenic climate change (Stocker et al., 2013). This will lead to new challenges for health and well-being, as populations are increasingly exposed to compound events. Compound events are relevant for natural systems (e.g., earthquakes destabilize hillsides, thereby increasing the risk of rainfall-induced landslides) as well as human systems (e.g., households recovering from an earthquake are more vulnerable to subsequent monsoon-induced landslides). In the context of Nepal, the rapid aid response to the 2015 earthquake was likely critical in preventing large increases in food insecurity, though landslides during the 2015 monsoon season may have limited the effectiveness of aid distribution. Rainfall conditions were associated with food insecurity across the country, though these effects differed by level of earthquake exposure and terrain steepness.

Nepal is predicted to experience an increase in both above- and below-normal monsoon rainfall and a greater frequency of extreme precipitation events, leading to more severe droughts, floods, and landslides (World Bank, 2013). While Nepal received large amounts of aid to assist in the recovery from the Gorkha earthquake, extreme weather events such as floods and droughts are unlikely to garner similar levels of assistance. A greater frequency of environmental shocks, without accompanying resources for adaptation and recovery, will leave vulnerable populations across the world increasingly vulnerable to food insecurity and undernutrition. In order to design effective adaptation strategies to improve global health and promote sustainable development in the face of climate change, it is essential to better understand how exposure to compound events impacts populations across different geographic, cultural, and socioeconomics contexts.

CRediT authorship contribution statement

Heather Randell: Conceptualization, Methodology, Formal analysis, Writing - original draft, Visualization. **Chengsheng Jiang:** Conceptualization, Methodology, Formal analysis, Writing - original draft, Visualization. **Xin-Zhong Liang:** Resources, Funding acquisition, Writing - review & editing. **Raghu Murtugudde:** Writing - review & editing. **Amir Sapkota:** Conceptualization, Supervision, Writing - review & editing.

Conflict of Interest Statement

The authors declared that they have no conflict of interest.

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Appendix A

Table A1
Odds ratios of the likelihood of moderate or severe food insecurity with interactions between earthquake exposure, rainfall anomalies during the 2015 monsoon season, and steep slope of cluster.

	Model 3	
Earthquake intensity [No to light shaking is baseline]		
Moderate to strong shaking	1.548	+
Very strong to severe shaking	1.977	
Rainfall z-score	0.632	***
Cluster has steep slope	0.870	
Moderate to strong shaking X Rainfall z-score	2.012	**
Very strong to severe shaking X Rainfall z-score	2.605	**
Steep slope X Rainfall z-score	1.195	
Steep slope X Moderate to strong shaking	2.969	**
Steep slope X Very strong to severe shaking	4.214	+
Steep slope X Moderate to strong shaking X Rainfall z-score	1.828	
Steep slope X very strong to severe shaking X Rainfall z-score	1.831	
N	11,029	

Notes: Models also include control variables and fixed effects for province and month of interview.
+ $p < 0.1$ * $p < 0.5$ ** $p < 0.01$ *** $p < 0.001$

Table A2
Supplementary models of the likelihood of moderate or severe food insecurity based on earthquake shaking intensity and rainfall anomalies during the 2015 monsoon season, excluding migrant households (Model 4) or households in districts severely affected by the 1988 earthquake (Model 5).

	Model 4 - Excluding migrant households		Model 5 - Excluding 1988 earthquake districts	
Earthquake intensity [No to light shaking is baseline]				
Moderate to strong shaking	1.836	*	1.525	
Very strong to severe shaking	1.964		1.805	
Rainfall z-score	0.645	***	0.675	**
Moderate to strong shaking X Rainfall z-score	2.565	***	2.307	***
Very strong to severe shaking X Rainfall z-score	2.565	**	2.518	**
N	8641		10,213	

Notes: Models also include control variables and fixed effects for province and month of interview.
+ p < 0.1 * p < 0.5 ** p < 0.01 *** p < 0.001

Table A3
Supplementary models of the likelihood of moderate or severe food insecurity based on a continuous measure of earthquake shaking intensity (Model 6) and quadratic rainfall anomalies (Model 7).

	Model 6	
Earthquake intensity	1.164	**
Rainfall z-score	0.465	***
Earthquake intensity X Rainfall z-score	1.185	***
N	11,029	
	Model 7	
Earthquake intensity [No to light shaking is baseline]		
Moderate to strong shaking	1.896	**
Very strong to severe shaking	2.829	**
Rainfall z-score	0.776	
Rainfall z-score^2	1.135	
Moderate to strong shaking X Rainfall z-score	3.143	***
Very strong to severe shaking X Rainfall z-score	7.026	**
Moderate to strong shaking X Rainfall z-score^2	1.219	
Very strong to severe shaking X Rainfall z-score^2	1.924	
N	11,029	

Notes: Models also include control variables and fixed effects for province and month of interview.
+ p < 0.1 * p < 0.5 ** p < 0.01 *** p < 0.001

Table A4
Supplementary models of the likelihood of moderate or severe food insecurity with interactions between earthquake exposure, rainfall anomalies during the 2015 monsoon season, and three-category slope variable.

	Model 8	
[No to light shaking is baseline]		
Moderate to strong shaking	1.067	
Very strong to severe shaking	10.730	**
Rainfall z-score	0.324	
Slope category [least steep is baseline]		
Moderate steepness	1.002	
Steepest slope	0.745	
Moderate to strong shaking X Rainfall z-score	2.637	
Very strong to severe shaking X Rainfall z-score	6.006	*
Moderate slope X Rainfall z-score	1.938	
Steepest slope X Rainfall z-score	1.954	
Moderate slope X moderate to strong shaking	1.605	
Moderate slope X very strong to severe shaking	0.192	+
Steepest slope X moderate to strong shaking	5.049	+
Moderate slope X moderate to strong shaking X Rainfall z-score	0.821	
Moderate slope X very strong to severe shaking X Rainfall z-score	0.444	
Steepest slope X moderate to strong shaking X Rainfall z-score	1.646	
N	11,029	

Notes: Models also include control variables and fixed effects for province and month of interview.
+ p < 0.1 * p < 0.5 ** p < 0.01 *** p < 0.001

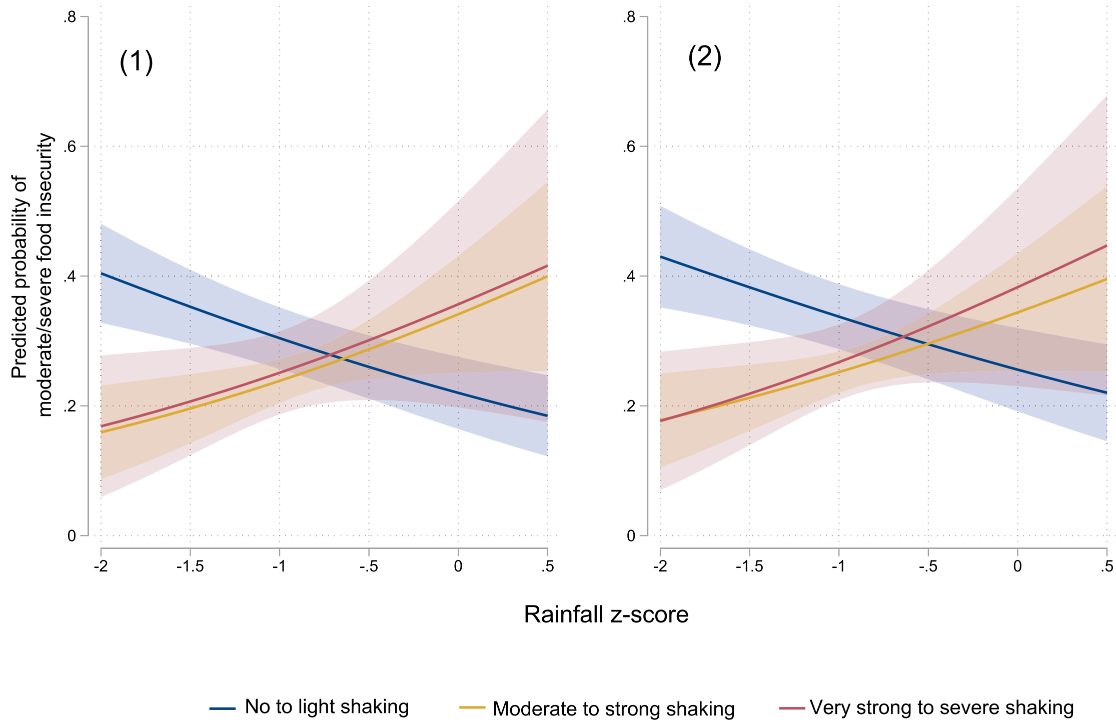

Fig. A1. Predicted probabilities of moderate or severe food insecurity based on earthquake intensity-rainfall z-score interactions, excluding migrant households (Panel 1) or excluding households in districts severely affected by the 1988 earthquake (Panel 2), with 95% confidence intervals.

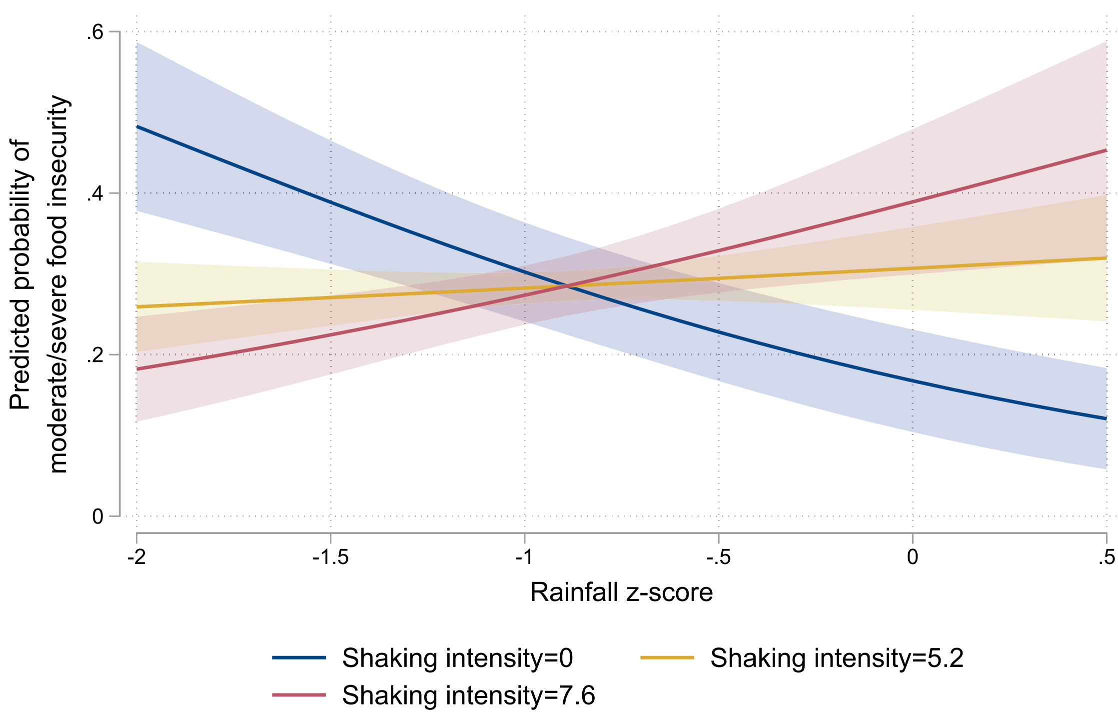

Fig. A2. Predicted probabilities of moderate or severe food insecurity based on earthquake intensity-rainfall z-score interactions, using a continuous measure of shaking intensity, with 95% confidence intervals. Predictions are calculated for a shaking intensity of zero, as well as the 50th (5.2) and 95th (7.6) percentiles of shaking intensity among households in the analytic sample.

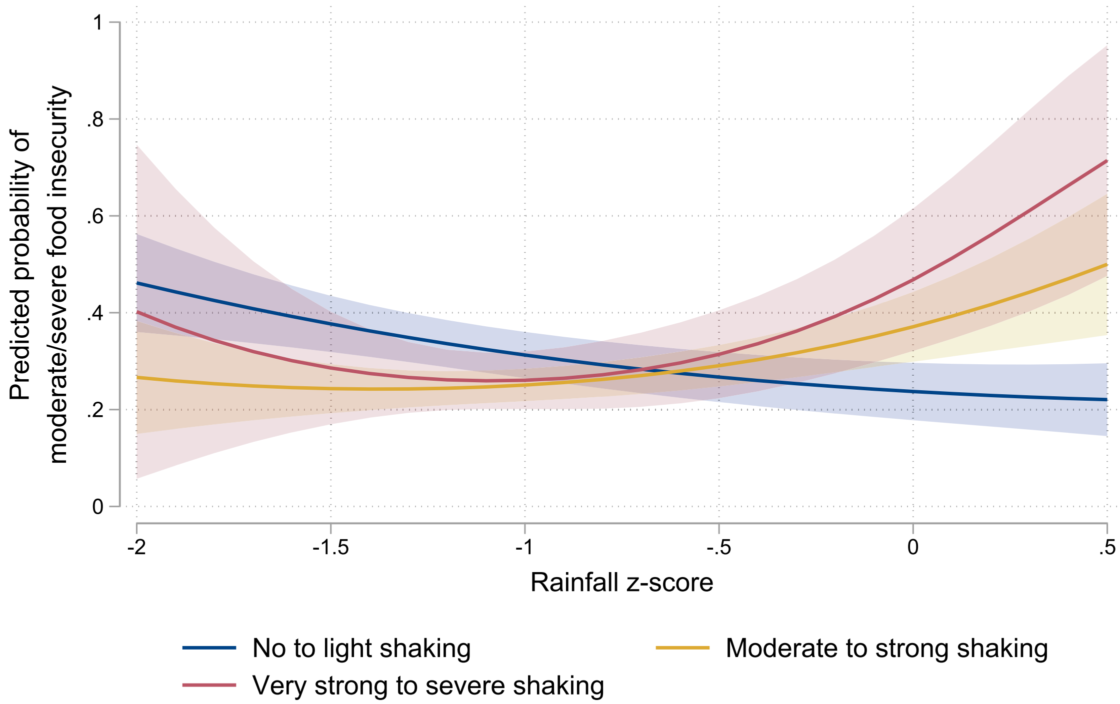

Fig. A3. Predicted probabilities of moderate or severe food insecurity based on earthquake intensity-rainfall z-score interactions using a quadratic rainfall specification, with 95% confidence intervals.

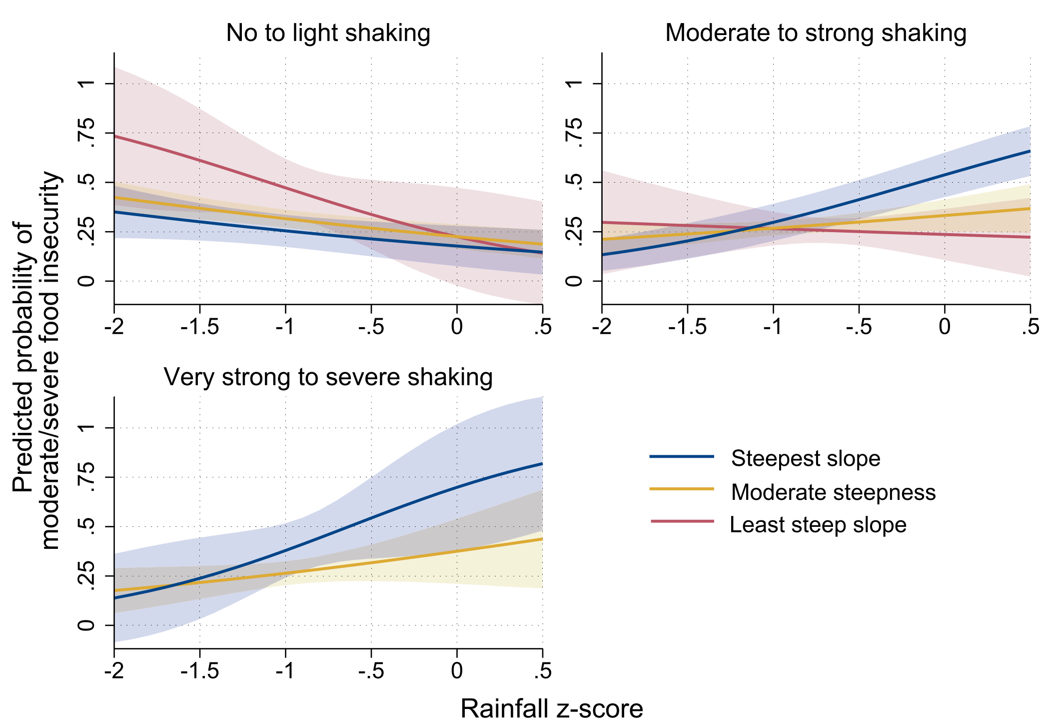

Fig. A4. Predicted probabilities of moderate or severe food insecurity based on earthquake intensity-rainfall z-score-slope interactions using three slope categories, with 95% confidence intervals.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.worlddev.2021.105511.

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