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ABSTRACT

Exposure to extreme events has been hypothesized to affect subsequent mortality because of mortality selection and scarring effects of the event itself. We examine survival at and in the five years after the 2004 Indian Ocean earthquake and tsunami for a population-representative sample of residents of Aceh, Indonesia who were differentially exposed to the disaster. For this population, the dynamics of selection and scarring are a complex function of the degree of tsunami impact in the community, the nature of individual exposures, age at exposure, and gender. Among individuals from tsunami-affected communities we find evidence for positive mortality selection among older individuals, with stronger effects for males than for females, and no evidence of scarring. Among individuals from other communities, property loss is associated with elevated mortality risks in the five years after the disaster only for those who were age 50 or older at the time of the disaster.

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INTRODUCTION

Exposure to an extreme event such as a natural disaster has the potential to affect mortality both immediately, if the disaster causes fatalities, but also over the longer term as a result of selective mortality at the time of the event or scarring from exposure to it. Mortality selection occurs when the event removes a segment of the population characterized by differentially high or low levels of vulnerability, so that survivors experience a different mortality schedule than would have otherwise prevailed. Scarring occurs when survivors experience elevated post-event morbidity or mortality because of emotional or physiological damage caused by the event. The two processes potentially interact over time. Selection that alters the distribution of population heterogeneity will influence the subsequent impact of debilitating events; scarring that increases heterogeneity will potentially produce even more selected populations (Vaupel and Yashin 1985). Post-disaster assistance programs may play a role as well, potentially mitigating the impact of scarring over time.

The operation of these dynamics on populations is of central interest to population and health scientists. Demographic studies have illuminated these dynamics through the development of mathematical models that illustrate how mortality rates vary by age and time as a function of the mix of groups characterized by different degrees of frailty and associated mortality schedules (Vaupel and Yashin 1985). A key result in this literature is that hidden heterogeneity leads to a pattern of population-level mortality deceleration at older ages. Recent studies have highlighted the possibility of multiple decelerations (Wrigley-Field 2014) and the potential for heterogeneity to reduce the age at onset of mortality acceleration (Salinari and DeSantis 2015).

Whether mortality after an extreme event is higher or lower than it would otherwise be is fundamentally an empirical question. It is also important. However, existing evidence on health outcomes after disasters is constrained by the lack of population-representative data on individuals with differential exposure who have been followed beyond the immediate impact of the disaster.

Studies that follow survivors after extreme events over the longer term have the potential to provide important insights into how selection and scarring play out over time and across demographic groups.

Using data from such a study, we advance the literature by providing empirical evidence on two interrelated questions. First, what is the extent of mortality selection at the time of a natural disaster, and, second, how do mortality risks for survivors evolve subsequently? The context for our study is the 2004 Sumatran-Andaman earthquake and Indian Ocean tsunami, one of the deadliest natural disasters in recorded history. Many countries were affected, but Indonesia's Aceh province, on the northern tip of Sumatra, was hardest hit. Waves 30 meters high struck within about 30 minutes of the earthquake which was centered off the west coast of Sumatra. The waves inundated parts of the coastline and flooded areas as far as 6 kilometers inland (Paris et al. 2007, 6). Estimates put the death toll at 170,000, almost 5% of Aceh's population. We use data from the Study of the Tsunami Aftermath and Recovery (STAR), a longitudinal survey representative of all individuals living in districts along Aceh's southwest coast and selected districts on the northeast coast at the time of the baseline survey, collected nine months before the December 2004 tsunami. This baseline is combined with detailed information from five annual follow-ups that we fielded beginning 5 months after the tsunami.

Research on mortality at the time of the tsunami has highlighted three key factors that differentiate survival outcomes: location at the time of the tsunami (and in particular the topography of the land and the direction of the waves); age and gender (in part reflecting differences in strength and ability to swim) and household composition (Frankenberg et al. 2011). That work has documented the central role of location and the importance of physical strength, describing the importance of household composition (reflecting the supply of and demands for help), and showing that, conditional on these characteristics, socioeconomic factors were not related to survival at the time of the tsunami. This research provides new evidence on the evolution of mortality risks among survivors during the five years after the disaster, linking those risks to community-level exposure to the waves and to individual-level experiences and losses at the time of the tsunami and to demographic and socio-economic characteristics.

BACKGROUND

Because few surveys provide the longitudinal data necessary to link the evolution of risks after extreme events to exposures, the most common approach in empirical studies is to draw on natural experiments by identifying cohorts whose time or place of birth affects risks of exposure and assembling data on subsequent outcomes for that group and a relevant comparison group. These comparisons potentially reveal the fingerprints of the event's impacts on later life health and mortality (Elo and Preston, 1992, discuss this approach with respect to early-life impacts on adult mortality). Studies vary with respect to event type, the precision of the exposure definition, the age at exposure for the cohorts of interest, the length of the follow up period, and relative focus on documenting and quantifying long-term impacts versus exploring the dynamics of selection and scarring.

Much of this work focuses on the link between early life exposure to famine and mortality later in life. Two studies of the long-run mortality impacts of the Finnish famine of 1866-68 have differed in their conclusions. Kannisto et al. (1997) show that cohorts *in utero* or born just before the famine experience elevated risks of mortality up to age 17, relative to the cohort born after the famine, but not at older ages. Doblhammer, van den Berg, and Lummy (2013) expand the cohorts considered and draw comparisons with Swedish data from the same years, using a Gompertz model that allows for the impact of frailty to vary flexibly across cohorts, reflecting cohort differences in selection processes. Their results suggest significant reductions in life expectancy above age 60 for males born during and just before the famine. For females, the results are less clear. Females born in the 10 years before, but not during, the famine experience lower life expectancies at age 60 relative to their Swedish counterparts.

Song (2010) documents mortality differences through age 22 among Chinese cohorts born before, during, and after the Great Leap Forward famine of 1959-1961. The patterns differ at ages before versus after age 11. Song shows that at ages younger than 11, the pre-famine cohort exhibits higher mortality than the famine cohort, whereas the post-famine cohort exhibits lower mortality. In contrast, between age 11 and 22, mortality for the pre-famine cohort relative to the famine cohort is the same, but mortality for the post-famine cohort is substantially higher. This pattern of cross-over is consistent with the idea that the pre-famine and famine-born cohorts who survive to age 11 are positively selected relative to the post-famine cohort.

Relatively few papers consider the impacts of nutritional deprivation at ages beyond early childhood in relation to mortality in later life. Horiuchi (1983) is an exception. He uses vital statistics data to examine mortality at older ages for cohorts exposed to severe food shortages associated with World War I. Horiuchi identifies a pattern of relatively high "late life" mortality for males born in Germany in 1901-02 who experienced severely constrained access to food in adolescence. Similar patterns exist for males in Austria and France but not for males in countries more distal to the conflict, or for females anywhere. Horiuchi hypothesizes that nutritional deprivation in adolescence differentially affects growth of blood vessel structures in males (whose biological capacity to store fat is lower than for females), which has consequences for the development of and mortality from cardiovascular disease at older ages.

The impact of adult exposure has also been assessed with respect to the mortality of individuals who as Prisoners of War (POWs) experienced disease outbreaks, severe food shortages, and other harsh conditions. Page and Brass (2001) use federal records to track the experiences of returned POWs from World War II and the Korean War. They document an initial pattern of lower death rates from heart attacks and strokes (relative to a control group of veterans who were never POWs), which persists for three decades but then reverses. Above age 75, the risk of death from heart disease is higher for former POWs than for the controls. Costa (2012), using historical records from Union Army prisoners of war, finds that the impact of imprisonment on subsequent mortality varies by age of imprisonment. Among soldiers older than 30, those who survived prison camps have lower risks of death at older ages than the controls, whereas for those younger than 30 at imprisonment, risks of morbidity and mortality at older ages are higher than for the controls. Costa documents extremely high levels of mortality within camps, particularly among those older than 30. She concludes that whether selection or scarring is dominant is likely to vary as a function of mortality levels during the event itself. This theme also emerges in the literature on early life famine exposures.

An important limitation of these studies is a paucity of knowledge about the actual experiences of individuals during the events being investigated, how those experiences vary across individuals, and whether that variation predicts subsequent mortality. Place or time of birth (or records of imprisonment) in combination with historical evidence regarding the timing and content of an event are used to assign individuals or cohorts to membership in the "treatment" groups, but historical evidence is often fragmentary and the distinctions between the exposed and unexposed are not always clear (Doblhammer et al., 2013, for example, discuss various pre-famine factors that might have affected health of the pre-famine cohorts). It is also not clear in these studies that exposure can be thought of as random with respect to other factors that might affect subsequent mortality (see Costa, 2012, for an insightful discussion of this question in the context of Civil War POWs).

Only a small number of studies have investigated natural disasters, though such events are increasing in frequency and impact and exposure is associated with increased levels of physical, psychosocial, and economic stress (Borque et al. 1988, Rodriguez et al. 2006; Phifer, Kaniasty, and Norris 1988; Uscher-Pines 2009; Wachtendorf et al. 2006). Studies of earthquake survivors provide evidence that exposure is linked to subsequent chronic diseases and mortality after several years. Armenian, Melkonian, and Hovanesian (1998) analyze morbidity and mortality in the four years after an Armenian earthquake for a relatively complete group of Ministry of Health employees (based on records of pre-quake employment) who were surveyed two times after the earthquake. Though the study is not population-based, it is unusual in that it considers the impacts of different types of exposures. Among males, but not females, being in a building at the time of the quake is associated with a higher risk of mortality in the first year after the earthquake. For both sexes, injury or death of a family member and property losses are associated with higher odds of developing hypertension, heart disease, diabetes, or arthritis in the first six months after the disaster.

Nakagawa et al. (2016) consider deaths from acute myocardial infarction (AMI) in the three years after the 2004 Niigata-Chuetsu earthquake in Japan, based on death records from areas defined as treatment and control based on reported damage. They find that after the earthquake, AMI mortality in the treatment area increased significantly for both men and women relative to the pre-earthquake levels, but no change occurred in the control area. The study cannot adjust for selective migration, which is problematic given greater out-migration from the treatment area.

The studies of earthquakes suggest that exposure during adulthood to a highly destructive disaster can elevate morbidity and mortality from chronic diseases in the next several years. They are silent on the possible role of mortality selection at the time of the event, but selection is presumably not important because disaster fatalities appear to have been low for these particular populations. Though earthquakes have been responsible for a number of extremely high-fatality disasters over the past decade, we know of no work apart from this study that documents their impacts on subsequent mortality for survivors.

Building on this work, our research makes several key contributions to the literature. First, mortality surrounding the 2004 event was extremely concentrated both spatially and temporally and we can identify exposure to risks with much greater precision than has been possible in most studies. Second, because we have detailed information on both the exposure levels of communities where people lived and individual-level experiences of stressors during the event, we can separate the impact of mortality selection, a process that alters the composition of survivors, from scarring, which occurs to individuals as a result of what happened specifically to them. In contrast, most studies that focus on selection versus scarring rely on one spatially- or temporally-based measure to proxy for both forces; we use multiple measures of exposure. Third, because we have pre-disaster data that is population-representative and attrition among tsunami-survivors is very low (less than 5%), our results are unlikely to be contaminated by selective sample composition that arise in surveys based on samples constructed after the event or for vital events data from relatively local areas or periods that may be affected by migration.

CONTEXT

On the morning of December 26, 2004, a powerful earthquake occurred about 150 miles off the coast of Sumatra, displacing a trillion tons of water, which produced a series of tsunami waves. In Aceh, communities were engulfed along 800 kilometers of coastline, destroying infrastructure and killing more than 170,000 people.

Impacts varied considerably within local areas. The height and inland reach of water from the tsunami depended on slope, wave features, water depth, and coastal topography (Ramakrishnan et al. 2005). Along parts of the west coast of Aceh, the water removed bark from trees as high as 13 meters (Borrero 2005). At the beachfront in Banda Aceh, the province's capital and largest city, water depths reached approximately 9 meters; further inland they rarely exceeded the height of a two story building (Borrero 2005). In some areas the water scoured the earth’s surface, removing all buildings and almost all vegetation. The worst-affected areas were low-lying communities within a few kilometers from the coast, and these were largely destroyed. Where rivers emptied into the ocean, the water moved inland as much as six to nine kilometers, but encroached only 3-4 kilometers in other locations (Kohl et al. 2005; Umitsu et al. 2007). In areas further inland, at higher elevations, or topographically sheltered in some way, flooding damaged many structures and deposited enormous quantities of debris, but larger proportions of the population survived. For some communities the tsunami had few if any direct effects, although the earthquake was felt throughout Aceh and caused damage in areas the water never reached.

DATA

We focus on individuals living in 11 districts (*kabupaten*) at the time of the tsunami who participated in the baseline survey, a large, nationally representative socioeconomic survey (SUSENAS) conducted by Statistics Indonesia in February/March 2004. SUSENAS, which collected information on demographic and socioeconomic characteristics of all household members from a key household member, has participation rates exceeding 99%. The first STAR follow-up survey was conducted between May 2005 and July 2006. We conducted four annual follow-ups thereafter.

In the STAR follow-ups, we have established survival status for 99% of the baseline respondents by triangulating multiple sources of information, including interviews with household and family members (whose reports we deem most reliable), community leaders, and neighbors (who are essential for households for which we have not located any original members). We developed this procedure in the first follow-up and employed it in subsequent follow-ups, updating the few errors as they have been revealed (Frankenberg et al. 2013). In each follow-up, every household member age 11 and older is interviewed. The first two follow-ups (and the fifth) included detailed information on experiences at the time of the tsunami. All waves include extensive questions on physical health, psycho-social well-being, and behavioral responses to the event, including displacement and migration, as well as information about individual and household demographics and socioeconomic status.

We examine mortality of 6,687 adults 35 years and older at baseline (few younger respondents died during the five years after the tsunami). We interviewed just over 95% of those who survived to the first follow up survey. All predictors are constructed from the pre-tsunami baseline or, in the case of exposures to the tsunami, from the first follow-up. The post-tsunami survivor sample consists of 5,640 individuals who were followed until they died or survived at least 5 years.[3]

To help interpret evidence on the relative contributions of scarring and selective mortality, we compare age- and gender-specific mortality during the tsunami with mortality in the five years after the tsunami.

At the community level, tsunami wave characteristics and coastline topography were key determinants of death and destruction at the time of the tsunami. We have constructed a community-specific indicator of geographic exposure based on the location of each respondent's community at the time of the tsunami that combines information on elevation above sea level, proximity to the coastline, and tsunami wave height at the closest coastal point.[4] In the analyses we distinguish respondents who were living at the time of the tsunami in communities that were directly affected by the tsunami ("tsunami-affected") from respondents who were not ("other"). As we show below, this dichotomy captures tsunami-related exposures. A key advantage of this dichotomization is that it is based on plausibly exogenous characteristics that are outside the control of the respondents at the time of the tsunami and therefore unlikely to be related to behaviors that affect either tsunami or post-tsunami mortality.[5] The measure may also be correlated with exposure to assistance programs in the tsunami's aftermath. If these programs affect health, our estimates will represent the combined impact of destruction and reconstruction.

We estimate models that predict five-year mortality as a function of both community- and individual-level measures of exposure to the tsunami. In these models we include more fine-grained

[3] Attrition rates are low because we tracked movers to their new destinations. We lost only 3.5% of tsunami survivors as a result of failing to find movers, another 1.3% either refused or could not be contacted; these rates are similar for respondents from tsunami-affected and other communities.
[4] Estimates of wave height draw on data on tsunami run-up heights compiled by the National Oceanic and Atmospheric Association (NOAA).
[5] Our main results do not depend on this particular dichotomization. For example, our conclusions are the same if the sample is split by whether or not tsunami-related deaths occurred to community members. They are also the same if we restrict "other" communities to those relatively close to the coast.

exposures that draw on reports from the first post-tsunami survey of individual experiences of the tsunami and its immediate aftermath.

Comparing mortality during and 5 years after the tsunami

Figure 1 displays the percentage of the population that died within 5 days of the tsunami (panel A) and during the next 5 years (panel B), distinguishing those who were living in communities subsequently affected by the tsunami (in red) from those in other communities (in blue). The samples are also stratified by gender and by age at the time of the tsunami into prime age and older adults (35-49 year olds versus 50 years and above).

Mortality resulting from the tsunami was extremely high in tsunami-affected communities, but negligible in the other communities. In affected communities, one in eight prime-age males died. For females and older males the ratio is one in every five or six. The very high level of mortality for each of these groups is testimony to the tsunami's devastating impact in the communities that bore its full force—communities from which substantial shares of the population were removed, perhaps selectively.

Tsunami-related mortality is higher for older relative to prime age adults and for females relative to males. The gender gap is largest (and statistically significant) among prime age adults (Frankenberg et al. 2013). Similar findings have been reported in other post-tsunami studies in India, Indonesia, and Sri Lanka (Oxfam 2005; CNN 2005; Doocy et al. 2007).

Part of the explanation for women's elevated mortality during the tsunami likely lies in sex differences in swimming ability, physical strength, and stamina. Yeh (2010) develops a physical model of water flow characteristics during a tsunami in combination with age- and sex-specific physiological attributes to show that age-sex differences in vulnerability are substantial.

Social factors are potentially relevant as well. Relative to men, in Aceh and South Asia women are much less likely to know how to swim and their clothing is more likely to restrict their movements (Neumayer and Plumper 2007). But many have speculated that women's family roles may have contributed as well, with the gender difference in mortality arising because females died trying to save their children and other family members (MacDonald 2005). In Yeh's model the vulnerability gap between men and women widens further when women's attributes are adjusted to incorporate evacuation with a small child. Frankenberg et al. (2011) explored variation in mortality with household composition. Death is less likely if a person from a physically stronger demographic group – such as a prime-age male – is available to help and death is more likely in the presence of people in even more need of assistance – such as older women.

These factors all suggest that the force of mortality during the tsunami operated differently by age and sex, raising the possibility that the nature of selection varied across these groups as well. Indeed, if swimming skills were critical but effectively non-existent among women, their deaths may have been far more random than were men's.

Panel B of Figure 1 displays, for tsunami survivors, the percent that died in each group during the five years after the tsunami. The patterns are completely different from those at the time of the tsunami. First, for prime age males, older males, and prime age females mortality is *lower* for individuals from tsunami-affected communities than for individuals from other communities. The survival advantage for those from tsunami-affected communities is particularly large (and statistically significant) for older males.

In the post-tsunami environment, more demographically typical patterns of mortality by gender and age reassert themselves. To spotlight age, Figure 2 presents nonparametric estimates of mortality in the five years after the tsunami by age and community type, stratified by sex. Among males (left-hand panel), mortality at all ages is higher for those who, at the time of the tsunami, were living in communities beyond the disaster's reach. After the late 40s the gap increases steadily with age, reaching nearly 10 percentage points by age 75. One interpretation is that males who were living in tsunami-affected areas and survived the disaster are positively selected and, if they were scarred by the experiences in ways that our community-level measure captures, those effects are strongly dominated by selection. As a result, males who were living in tsunami-affected areas have lower subsequent mortality rates.

In contrast, females from tsunami-affected communities have no clear survival advantage in the subsequent five years (right hand panel). Possibly deaths during the tsunami were so much more idiosyncratic for women than men that positive selection did not operate. It is also possible that the women who survived in tsunami-affected communities were so weakened by their experiences during the tsunami that the scarring offset any survival advantage.

To investigate the potential role for scarring we turn to multivariate models that harness detailed individual-level information on tsunami exposures.

METHODS

We begin by contrasting the correlates of mortality during the tsunami with those for mortality after the tsunami. For each individual i, the model

$$\theta_{ic} = \alpha + \beta T_c + \gamma X_{ic} + \varepsilon_{ic} \qquad [1]$$

is estimated by ordinary least squares. We analyze two dichotomous dependent variables: death at the time of the tsunami and, among the subset of survivors, death over the course of the next five years. In each case the dependent variable is multiplied by one hundred so that results are interpretable as percentages. In this model T_c indicates whether the respondent's pre-tsunami community was affected by the tsunami. The vector X_{ic} includes individual background characteristics measured at the pre-tsunami baseline: age (in single years), education, whether the respondent was married, household expenditures per capita (a well-established measure of economic resources), and controls for household composition (Deaton 1997). Unobserved heterogeneity is captured by ε_{ic}. Estimates of variance-covariance matrices and all test statistics take into account clustering at the enumeration area level and are robust to arbitrary forms of heteroskedasticity (Huber 1981).

For individuals who survived the tsunami, we also examine how individual exposures to its direct impacts are related to death over the next five years by extending the model:

$$\theta_{ic} = \alpha + \beta T_c + \lambda E_{ic} + \gamma X_{ic} + \varepsilon_{ic} \qquad [2]$$

where the vector of covariates E_{ic} consists of four measures of exposure based on individual reports of experiences and losses at the time of the tsunami. We focus on exposures that capture the immediate exogenous impact of the event rather than on how the lives of survivors unfolded in its aftermath, so as to spotlight the impact of disaster-related experiences that were beyond the control of the respondents. First, we base a binary variable on self-reports of one or more potentially traumatic or immediately life-threatening experiences: (1) sustaining an injury, (2) struggling in the water, (3) seeing family members struggle, (4) seeing family members disappear, (5) seeing friends struggle, or (6) seeing friends disappear. For shorthand, we refer to this indicator as "direct/immediate experience" of the tsunami. Second, two binary variables indicate whether (1) the respondent lost a spouse between the baseline and first follow-up interview and (2) whether the tsunami killed a parent, sibling, or child of the respondent. Third, a binary variable indicates whether the respondent lost his/her home. In combination, these variables summarize exposure to the immediate visceral horrors of the event and to loss of family networks and assets.

To explore whether the factors associated with survival differ across the five-year period, we re-estimate the model in equation 2 for two periods: 2005-2007 and 2008-2009. To more precisely highlight the role of personal exposure, we also estimate models that draw only on variation in exposure across individuals within the same community:

$$\theta_{ic} = \alpha + \lambda E_{ic} + \gamma X_{ic} + \mu_c + \varepsilon_{ic} \qquad [3]$$

where μ_c is an enumeration area (EA) fixed effect that absorbs the influence of all community-specific variation that does not change over time and affects the outcome in a linear and additive way. This includes the extent of damage in the community because of the earthquake and tsunami, post-tsunami reconstruction, and pre-tsunami levels of infrastructure and economic activity.

This model does not allow the impacts of personal exposures in communities in which sizable segments of the population perished to differ from the impacts in communities without significant mortality at the time of the event. The extent of local area mortality is likely related to the intensity of an individual's experiences and to assess whether impacts vary in this respect, we re-estimate model 3, stratifying by our dichotomous measure of community-level impact.

RESULTS

Exposure to the tsunami and characteristics of survivors

Table 1 presents descriptive statistics for the analytical samples of individuals alive before the tsunami (panel A) and the subgroup of survivors (panel B), stratified by whether the community was affected by the tsunami (before the tsunami slightly over half the sample lived in a tsunami-affected community). Regardless of community type, the sample is roughly evenly divided between males and females and the average age is 50 years. Just over four-fifths were married at the baseline interview. Education levels are somewhat higher in the tsunami-affected communities, where adults have attained an average of 7.2 years of education, versus 6.5 in other communities. Just under 17% of respondents were killed during the tsunami in exposed communities, versus 0.6% in other communities.

With respect to the individual level measures of exposures, each of the four experiences is much more common among respondents from tsunami-affected communities than from other communities. About one in five respondents from communities that were exposed directly experienced the tsunami themselves, versus one in twenty-five for those from “other” communities. Nearly one quarter of respondents from affected communities lost a parent, sibling, or child in the disaster, whereas 10 percent of those from other communities did. Finally, in the five years after the tsunami 7 and 8 percent of adults died in affected and other communities, respectively.

Multivariate Models of Mortality

Mortality at the Time of the Tsunami

Table 2 presents results of regressions that relate the risk of dying at the time of the tsunami and, among survivors, during the five years after the tsunami to our community-level measure of tsunami exposure, individual background characteristics measured at baseline (age, education, marital status, and economic resources), and personal exposure at the time of the disaster. Results are stratified by age group and gender, as in the descriptive statistics presented earlier.

With respect to mortality at the time of the tsunami (columns 1-4), the results for residence (at baseline, before the disaster) in a community that was affected by the tsunami reproduce the patterns of death rates depicted in Figure 1. Excess mortality for those from tsunami-affected communities varies from just over 11 percentage points for males aged 35-49 to almost 19 percentage points for females aged 50 and older.

Among prime age males and females, none of the measures of background characteristics is related to mortality during the tsunami. Notably, higher levels of socioeconomic status, as characterized by education and per capita household expenditures, do not offer protection from the tsunami. The story is somewhat different for older individuals. Among older men, being married at baseline is associated with lower rates of tsunami mortality. But being from a household with more economic resources is positively associated with mortality during the tsunami (the result is marginally significant). Additionally, being a member of a household with relatively more adult females is positively associated with mortality (consistent with results described in Frankenberg et al., 2011). For older women, socioeconomic status is also positively related to mortality. In addition, higher levels of education are associated with higher rates of mortality ($p<.10$). These results likely reflect compositional differences across communities, with relatively well-off older individuals living in communities that were located relatively closer to the coast.

Mortality in the Five Years after the Tsunami

Turning to mortality after the tsunami (columns 5-8), among survivors, being from a community affected by the tsunami is no longer associated with higher mortality. In fact, a clear survival advantage emerges for older men from tsunami-affected communities (column 6). Their probability of dying is on average 5 percentage points lower than that of men from other communities. For the other three groups, no appreciable differences in mortality emerge across community types.

Figure 2 illustrated that in the five years after the tsunami, death probabilities rose rapidly with age. The regressions in Table 2 indicate that apart from age, other factors such as socioeconomic status and marital status are not significantly related to mortality in the five years after the disaster. This is the case for both prime-age and older adults.

As we have noted, our community-level measure is a very strong, positive predictor of mortality at the time of the tsunami, but afterwards, it is significantly associated with mortality only for older men, and this effect is negative. Possibly this measure reflects a combination of two effects: positive mortality selection ("survival of the fittest") and the negative impacts of exposure to stress because of the tsunami. Community exposure, however, is only a rough proxy for what individuals actually experienced during the disaster. To address this we include direct measures of traumatic experiences and loss of family and assets.

The addition of these fine-grained individual exposure measures (columns 9-12) does not change the impact of being from a tsunami-affected community. Among older males, community exposure continues to be negatively and significantly associated with mortality (column 10). For prime age males, the coefficient on community exposure is also negative and now larger and marginally significant (column 9). Among women, community exposure is not significantly related to mortality.

With respect to these detailed individual-level measures, none is significantly related to subsequent mortality for prime age men and women. For those under age 50, individual experiences during the tsunami do not appear to have weakened survivors in ways that influence their risk of death over the next five years.

For older survivors, some of the individual exposures are related to subsequent mortality. But their impact is to *reduce* mortality risks, not to heighten them, as one would expect if scarring or debilitation was important. For older males, the impacts of both immediate/direct exposure to the tsunami and loss of close kin are negative, statistically significant, and substantively large. For older women, direct experience of the tsunami is not statistically significant but it is substantively large. These indicators seem to identify individuals with characteristics associated with greater longevity.

Effects by Period

We have shown that the impacts of individual exposures to the tsunami are inconsequential for younger adults and are associated with lower mortality for older individuals, particularly for older males. However, these effects may vary over time. To investigate this question, we divide the five year follow-up period into an earlier period, 2005-2007, and a later period, 2008-2009 (conditional on surviving to 2008). We re-estimate Model 2, stratifying by age and sex, and by period (Table 3).

Among individuals under 50 years of age no evidence emerges of exposure impacts for either period (columns 1-4). For older men, death of a parent, child, or sibling is associated with lower mortality in the first two years after the tsunami, whereas being from a tsunami-affected community or direct experience of the tsunami predicts lower mortality in the latter half of the period. For older women, direct experience of the tsunami emerges as a marginally significant predictor of lower mortality in the first two years of the event. On the other hand, losing a home is positively related to mortality during the subsequent two years ($p<0.10$). This impact of home loss is our only indicator of scarring from the event.

Exposure Impacts within Communities

Our measure of community-level exposure is unlikely to capture all variation across communities in the tsunami's impact. To more fully control for community-level impacts and thereby sharpen the spotlight on individual exposures, we turn to specifications that add a community fixed effect. To increase our power, we pool males and females, but we retain the age stratification given that in the post-tsunami period, exposure impacts appear to differ by age group. These results are presented in Table 4.

For completeness we first estimate the model on the pooled samples without the community fixed effects. Among prime age adults, there is a small but negative impact of being from a tsunami-affected community ($p<0.10$), indicating some positive mortality selection for this group (column 1). Consistent with our previous results, none of the personal exposure measures are related to subsequent mortality. Among older adults being from a tsunami-affected community is not related to subsequent mortality, but there is a strong negative impact of having lost close kin in the disaster.

The next specifications include a community fixed effect. In these models, our estimates reflect the effects of particular exposures for individuals within a community relative to individuals from the same community who were not similarly exposed. These results sweep out common elements shared by all residents from the community and thus control more completely for variation across communities in tsunami destruction.

If exposures to traumatic experiences and to loss cause debilitation in and of themselves, then for individuals from the same community, those with more harrowing exposures and greater losses should be more likely to die than those with more muted exposures. But this is not what we see. For prime age adults (column 2), none of the personal exposures matters, even within communities. For older adults (column 6), direct experience with the tsunami continues to serve as a marker for attributes associated with greater longevity.

In all of these models we have combined individuals from tsunami-affected and other communities and controlled for community-level features either through our geographic exposure measure or with a fixed effect. These approaches do not allow for the possibility that the impact of individual exposures varies across communities. Such an interaction may well characterize our particular context, given that the tsunami-affected communities lost a sizable share of their population and were the focus of a major reconstruction effort, whereas these phenomena were largely absent in the other communities. To explore this question we re-estimate equation 3 separately by whether the community was tsunami-affected. For the "other" communities we drop the indicators for direct experience of the tsunami and for death of a spouse, as very few individuals report those exposures.

For adults between the ages of 35 and 49 stratifying by community type does not change the finding that exposures are not predictive of subsequent mortality (columns 3 and 4). In both sets of communities the coefficients are small and not statistically significant.

The stratification does shed light on the processes at play for older adults. In tsunami-affected communities, direct experience of the tsunami is associated with an 8 percentage point reduction in mortality risk over the next five years, and loss of close kin is associated with a 6 percentage point reduction. These are large effects. For older adults from other communities, loss of a home is associated with an almost 8 percentage point increase in mortality. This result for housing loss is a strong indicator of scarring, suggesting that in the communities where disaster-related mortality did not change population composition, subsequent survival prospects for older adults were affected by asset loss. In combination, the results suggest that for older adults in this context, positive mortality selection was the dominant force in communities where disaster-related mortality occurred, but that where it did not, disaster related experiences took a toll on survival over the next five years.

CONCLUSION AND DISCUSSION

The evolution of mortality risks in the aftermath of events that expose populations to conditions of extreme stress or hardship is central in demography, but the availability of data with which to directly examine such evolutions is rare. We use unique data that is representative of an at-risk population pre-exposure, that establishes survival status in the face of a major high mortality natural disaster, and that follows survivors for five years afterward. We are able to examine the determinants of mortality both at and after the event, which allows us to assess the roles of selection and scarring in unusual detail.

We find that for adults, the key determinants of surviving the disaster itself are the exposure of one's community at the time of the disaster (defined by the intersection of geography and tsunami wave height at the coast), sex, and to a lesser extent age. Prime-age males are the group most likely to survive the tsunami. Socioeconomic status played little role in determining survival during this disaster.

In the five years after the disaster, community-level geographic exposure continues to influence mortality. It is especially important for males. Males who were living in highly vulnerable areas before the disaster but survived face substantially lower mortality risks in the next five years. The survival advantage is greater for older males than for prime age males. We do not see the same evidence of positive selection for females. It is possible that deaths of females during the tsunami occurred more randomly than selectively, in which case post-tsunami mortality patterns should not be affected by who was killed in the disaster. Although the community exposure measure may also be reflecting the impact of exposure to assistance programs, it seems unlikely that these programs explain the results we see given the differences between males and females and the parallel results for individual exposures.

We also consider the roles that individual experiences and losses during the tsunami may play in determining subsequent mortality risks. For the most part, these experiences do not appear to raise mortality risks. For prime-age males and females, the individual exposure measures do not predict subsequent mortality. For older males and females, some of the exposures are related to subsequent mortality, but they reduce rather than heighten mortality risks, both across individuals from different communities, and across individuals from within the same community. The picture becomes slightly more complicated, however, when we stratify by whether the community was affected by the tsunami. In tsunami-affected communities, personal exposure measures are associated with lower mortality risks over the five years after the disaster, but in other communities the relationship is positive.

Some aspects of our results mirror those from other studies. As did Costa (2012) in the context of Civil War POWs, we find that patterns of mortality relative to the comparison group vary by age at exposure, with stronger evidence of positive selection among men who were 50 and above at the time of the tsunami. Several studies (Horiuchi, 1983; Armenian et al., 1988; Doblhammer et al., 2011) find that patterns differ for males and females, as do we, although these studies tend to find that males are somewhat more vulnerable to elevated mortality after a shock (we find that positive mortality selection was stronger for males).

Our study considers mortality in the five years after the tsunami. Relative to a number of the papers we discuss, our follow-up period is quite short. Charting the continued evolution of relative mortality risks will be important as more of our sample reaches ages where chronic diseases (which exposure to stress has been shown to increase) are the major sources of mortality.

Several other differences distinguish the Indian Ocean tsunami from the events that are the focus of other papers. First, the other papers on earthquakes focus on events where mortality from the event itself was much lower for the population under study than was the case for the disaster we examine. Second, the papers on famines and POW experiences center on exposures that were drawn out for several years. Mortality caused by the tsunami was concentrated over a very narrow window of time, and was almost entirely the result of drowning. Unlike famines and imprisonment, death from the tsunami did not occur after months of exposure to harsh conditions. This difference may alter the potential role for debilitation, in that the tsunami was not a disaster during which debilitation and death co-evolved in a slow and progressive way, killing some and leaving others tottering on death's doorstep.

A related point is that in the period after the tsunami, individuals from tsunami-affected communities may well have continued to accrue experiences that altered their mortality trajectories. Some of these were undoubtedly negative, such as displacement, life in makeshift housing, and a period of severe inadequacies in food and drinking water. But others were likely positive, such as infusions of aid, improvement in health care via reconstruction of infrastructure, housing assistance, and livelihood restoration projects. In this paper, we have focused only on features of the disaster experience that we can plausibly treat as exogenous. But the evolution of exposures among survivors after the event and the role they play in shaping the evolution of health and mortality is extremely important, if complicated, and we will turn to this question in future work.

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Figure 1
Percentage of adults who died at time of the tsunami and in the 5 years after tsunami
By gender, age group and location at the time of tsunami

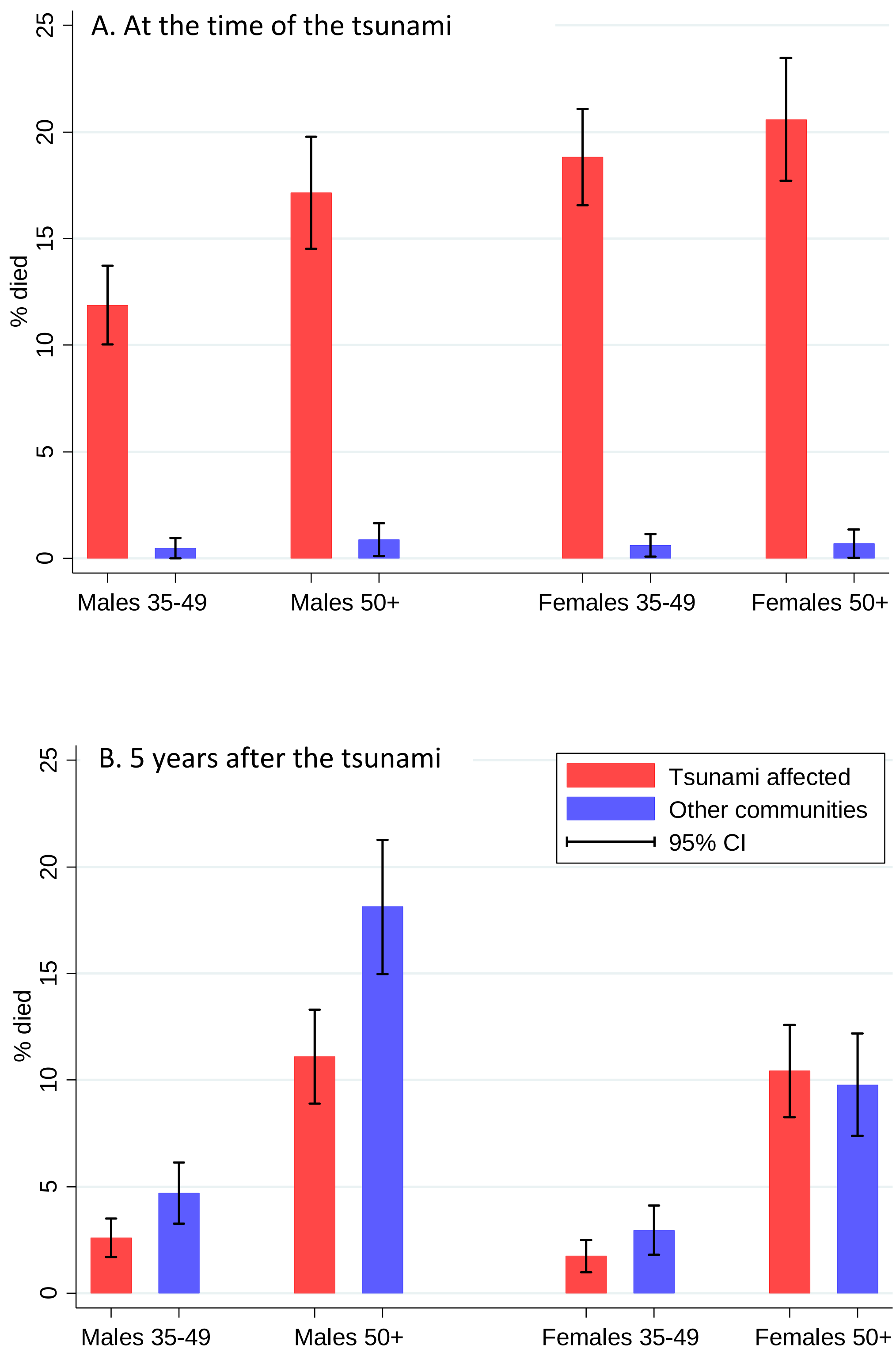
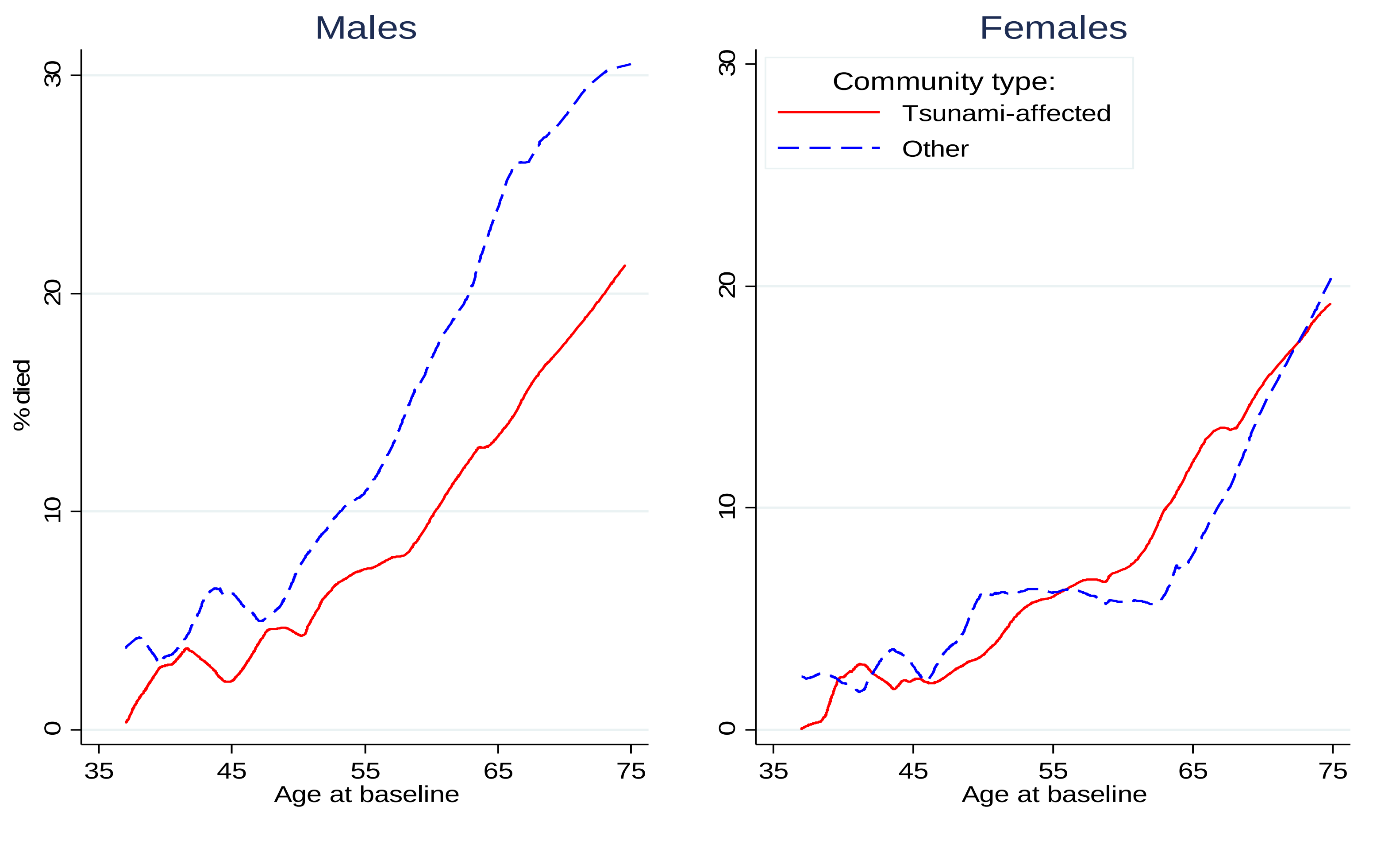


Figure 2. Mortality (% died) in the five years after the tsunami
By gender, age and location at the time of the tsunami



Non parametric estimates

Table 1

Descriptive Statistics for Survivors of the Tsunami (Adults aged 35 and Older), % or mean (SD)

	Tsunami-Affected	Other
A. Baseline Sample		
Female	49.1	49.8
Age	49.7 (0.19)	50.2 (0.22)
% Married	82.1	82.0
Years of Education	7.2 (0.07)	6.5 (0.08)
Died in the tsunami	16.7	0.6
N	3,886	2,801
B. Survivors to first interview		
Direct experience of tsunami	19.6	4.0
Parent, Sibling, or Child killed	23.9	9.9
Widowed by Tsunami or B ivw	7.9	4.5
Lost Home in Disaster	37.7	13.3
Died during the follow-up period	7.0	8.1
N	3,005	2,635

Table 2 Mortality At and After the Tsunami

	At the Tsunami				After the Tsunami							
	Males		Females		Males		Females		Males		Females	
	<50	>=50	<50	>=50	<50	>=50	<50	>=50	<50	>=50	<50	>=50
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Tsunami-affected community	11.22**	15.57**	18.03**	18.82**	-1.18	-5.00*	-0.67	1.87	-1.89+	-4.40*	-0.71	2.1
	[1.73]	[2.33]	[2.54]	[2.63]	[0.92]	[2.12]	[0.77]	[1.77]	[1.04]	[2.23]	[0.79]	[1.97]
Direct experience of tsunami									2.20	-6.39*	-0.03	-4.69
									[1.64]	[2.83]	[1.25]	[3.27]
Parent, Sibling, or Child killed									1.15	-5.47*	0.12	-0.05
									[1.42]	[2.57]	[1.11]	[2.44]
Widowed by Tsunami or B ivw									-1.61	6.59		-0.58
									[2.15]	[4.94]		[3.40]
Lost Home in Disaster									0.66	2.91	0.13	1.50
									[1.20]	[2.54]	[0.94]	[2.06]
Married at Baseline	-4.61	-8.47*	-0.70	0.08	-1.98	-4.10	0.10	0.26	-1.88	-4.84	0.09	0.14
	[3.81]	[4.11]	[2.18]	[2.18]	[3.08]	[5.39]	[1.17]	[1.98]	[3.11]	[5.30]	[1.18]	[2.00]
Education (years)	0.23	0.03	0.22	0.59+	0.04	0.09	0.01	-0.19	0.04	0.10	0.01	-0.16
	[0.15]	[0.27]	[0.25]	[0.351]	[0.11]	[0.29]	[0.11]	[0.28]	[0.11]	[0.29]	[0.11]	[0.29]
per capita HH Expenditure (ln)	0.34	3.79+	0.76	5.23*	-0.76	1.70	0.42	-0.61	-0.85	2.15	0.42	-0.51
	[1.47]	[2.07]	[2.12]	[2.36]	[0.86]	[1.92]	[0.78]	[1.73]	[0.87]	[1.95]	[0.77]	[1.75]
Number of adult males	1.35	-0.10	0.45	-0.53	0.52	0.84	-0.36	1.23	0.51	1.02	-0.36	1.23
	[0.94]	[0.83]	[0.76]	[0.92]	[0.89]	[1.04]	[0.41]	[0.88]	[0.87]	[1.05]	[0.41]	[0.88]
Number adult females	0.01	1.56+	1.36	0.50	0.78	1.39	-0.07	1.59	0.82	1.54	-0.07	1.64
	[0.90]	[0.92]	[0.92]	[1.02]	[0.77]	[1.18]	[0.43]	[1.03]	[0.78]	[1.17]	[0.43]	[1.02]
Number of Children	-0.75	-1.10	-0.95	0.07	0.26	-1.78*	0.27	0.86	0.25	-1.63+	0.27	0.78
	[0.46]	[0.92]	[0.67]	[0.99]	[0.45]	[0.90]	[0.36]	[1.12]	[0.46]	[0.90]	[0.36]	[1.13]
Constant	0.12	-36.96	-1.73	-67.06*	9.65	-10.44	-3.42	4.24	10.62	-15.82	-3.48	2.88
	[19.1]	[27.7]	[27.7]	[31.5]	[12.0]	[25.4]	[9.5]	[22.8]	[12.0]	[25.9]	[9.3]	[23.0]
Observations	1,957	1,428	1,915	1,387	1,704	1,187	1,609	1,140	1,704	1,187	1,609	1,140

Robust standard errors in brackets. Includes controls for age measured in single years.

** p<0.01, * p<0.05, + p<0.1

Table 3 Mortality after the Tsunami, by Time Period

	Less than 50 Years Old				50 years or older			
	Males		Females		Males		Females	
	2005-07	2008-09	2005-07	2008-09	2005-07	2008-09	2005-07	2008-09
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Tsunami-affected community	-1.05	-0.87	-0.30	-0.41	-1.34	-3.74*	1.21	1.10
	[0.67]	[0.87]	[0.59]	[0.55]	[1.62]	[1.85]	[1.44]	[1.57]
Direct experience of tsunami	0.73	1.51	0.34	-0.38	-0.64	-6.29**	-3.31+	-1.51
	[1.12]	[1.345]	[0.80]	[0.98]	[2.59]	[2.07]	[1.98]	[2.77]
Parent, Sibling, or Child killed	0.27	0.90	-0.09	0.21	-5.37**	-0.41	-0.43	0.20
	[0.97]	[1.12]	[0.71]	[0.88]	[1.94]	[2.17]	[1.68]	[1.98]
Widowed by Tsunami or B ivw	-0.61	-1.05			1.54	6.07	-1.39	0.69
	[1.38]	[1.70]			[3.70]	[4.47]	[2.36]	[2.66]
Lost Home in Disaster	-0.16	0.82	0.24	-0.12	0.94	2.49	-1.91	3.43+
	[0.77]	[0.96]	[0.74]	[0.61]	[1.93]	[1.89]	[1.47]	[1.78]
Constant	6.59	4.16	-1.05	-2.47	-0.54	-13.77	-10.36	13.78
	[7.88]	[9.09]	[6.79]	[6.79]	[18.35]	[22.64]	[18.76]	[17.32]
Observations	1,704	1,675	1,609	1,591	1,187	1,091	1,140	1,076

Robust standard errors in brackets. Includes controls for age measured in single years, years of education, marital status at baseline, per capita household expenditures, and household composition.
** p<0.01, * p<0.05, + p<0.1

Table 4 Mortality after the Tsunami by Community Type

	Less than 50 Years Old				50 years or older			
	Combined		Tsunami Affected		Combined		Tsunami Affected	
			Yes	No			Yes	No
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Tsunami-affected community	-1.24+				-0.75			
	(0.65)				(1.59)			
Direct experience of tsunami	1.40	1.29	0.65		-4.47*	-5.96+	-7.95*	
	[1.11]	[1.31]	[1.34]		[2.17]	[3.09]	[3.37]	
Parent, Sibling, or Child Killed	0.74	0.93	1.38	0.08	-2.79	-2.46	-6.13*	0.79
	[0.88]	[1.01]	[1.21]	[1.79]	[1.86]	[2.12]	[2.70]	[3.43]
Widowed by Tsunami or B Ivw	-1.39	-1.96	-0.34		1.52	3.17	6.45	
	[1.36]	[1.38]	[1.88]		[2.79]	[3.08]	[4.85]	
Lost Home in Disaster	0.24	-0.02	0.25	-0.45	1.95	0.44	-2.77	7.61*
	[0.81]	[0.97]	[1.07]	[2.01]	[1.72]	[2.47]	[3.19]	[3.77]
Constant	3.70	10.08	-5.20	26.06	-13.64	0.37	-17.72	17.22
	[7.4]	[10.8]	[12.3]	[17.4]	[17.7]	[29.3]	[45.9]	[37.5]
Community Fixed Effect	No	Yes	Yes	Yes	No	Yes	Yes	Yes
N	3,313	3,313	1,796	1,517	2,327	2,327	1,209	1,118

Robust standard errors in brackets. Includes controls for age measured in single years, years of education, marital status at baseline, per capita household expenditures, and household composition.

** p<0.01, * p<0.05, + p<0.1