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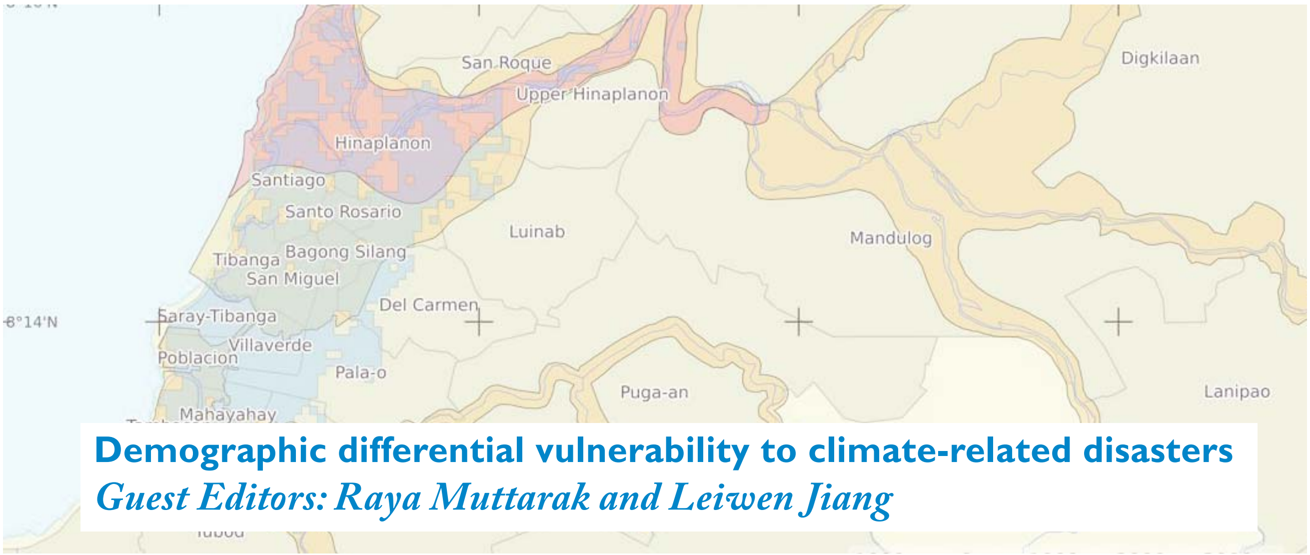

Demographic differential vulnerability to climate-related disasters

Guest Editors: Raya Muttarak and Leiwen Jiang

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Demographic differential vulnerability
to climate-related disasters

Guest editors:
Raya Muttarak and Leiwen Jiang

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INTRODUCTION
What can demographers contribute to the study of vulnerability?

Raya Muttarak, Wolfgang Lutz and Leiwen Jiang*

1 Introduction

The empirical analysis of the vulnerability of people to recent natural disasters is probably the best way to get an analytical handle on estimating the levels of human vulnerability that could result from the intensifying consequences of climate change in the future. This empirical approach is based on the underlying assumption that the vulnerability to past climate-related disasters, such as flooding, storms, and droughts, is isomorphic to the likely future vulnerability to climate change. While the risks and the exposure levels of human populations to extreme weather events may change across regions as climate systems shift, it is also evident that not all people who are living in the same region that is affected by a natural disaster are equally vulnerable to disaster-related mortality or injury. As is the case for other mortality risks, people tend to be differentially vulnerable according to their age, gender, level of education, occupation, and other social and economic variables. This demographic differential vulnerability has, however, not yet been thoroughly studied. This is where we believe that demographers can make an important contribution to the study of the consequences of climate change and this is the rationale for this special issue of the *Vienna Yearbook of Population Research*.

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Our decision to make demographically differentiated vulnerability to climate-related disasters the focus of this special issue is highly timely. Climate action is one of the priorities of the new Sustainable Development Goals (SDGs) endorsed by world leaders at the United Nations (UN) Summit for Sustainable Development in September 2015. The SDG's Goal 13 is to fight climate change by both reducing emissions and promoting adaptive responses to reduce the adverse impacts of the changing climate. As for the latter target, understanding *who* is vulnerable and to *what* is a fundamental question in vulnerability reduction efforts. Here we argue that the concept of vulnerability should only be applied to living creatures, and that the well-being of humans should be at the center of our concern about the effects of climate change. We also point out that vulnerability is differentiated across different sub-groups of a population, and argue that an explicit focus on demographic differential vulnerability should therefore be incorporated into vulnerability reduction policies.

The term vulnerability has been widely used in the context of climate change, but different scholars tend to use it in different ways, often without providing a clear definition. For instance, vulnerability can be defined in terms of exposure (biophysical conditions making people or places vulnerable to hazards), social conditions (measure of resilience to hazards), outcomes (the projected impacts of climate change on a particular exposure unit), or contextual conditions (e.g. economic, political, institutional, and technological structures and processes that influence vulnerability) (O'Brien et al. 2007; Cutter 1996). Generally, the variation in the use of the term vulnerability stems from different research needs, research methods, and normative implications in different disciplines.

In its recent Fifth Assessment Report, the Intergovernmental Panel on Climate Change (IPCC) defined vulnerability as "the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt." (IPCC 2014). In this context, vulnerability is clearly delineated as a characteristic of a *living unit* that influences its susceptibility to being harmed by external shocks, as well as its capacity to anticipate, respond to, cope with, and recover from the impact of such shocks. The term vulnerability has, however, also been used to refer to a physical dimension of a system or a place such as the potential climatic threats on the regions that are affected (IPCC 1996). In accordance with the IPCC definition, we further contend that it is misleading to focus on vulnerability of the systems *per se*, and that the adverse effects on people who are embedded in the systems should be of primary concern. Natural or social systems can, of course, collapse, but whether such an event is seen as threatening or welcome—e.g. the collapse of a dictatorial regime—depends on its effects on human well-being. The concept of social vulnerability therefore emphasizes the inherent properties of human systems that make individuals or groups susceptible to damage from external hazards, as well as people's abilities to respond to and recover from the impacts of disasters (Blaikie et al. 1994; Adger 1999). While the term social vulnerability is commonly used to distinguish the vulnerability of human systems from the vulnerability of non-human (nature) systems, it still does not explicitly state that human beings are the vulnerable unit.

Furthermore, given that the impacts of climate change are not evenly distributed within a regionally defined population, we need a more vigorous incorporation of the concept of **demographic differential vulnerability** into vulnerability analyses and policy measures aimed at reducing vulnerability. Indeed, this approach has already been highlighted as a key to sustainable development by international experts, first in preparation for the United Nations (UN) World Summit on Sustainable Development in 2002 (Lutz and Shah 2002), and a decade later in preparation for the RIO+20 Earth Summit (Lutz et al. 2012). These experts emphasized that vulnerability to environmental changes and the capacity to adapt to these changes vary not only between countries, regions, communities, and households; but also between family members depending on age and gender. Failing to recognize demographic heterogeneity in vulnerability can lead to the formulation of policies that are not appropriately directed at the truly vulnerable groups.

2 Contributions of demography to the understanding of differential vulnerability

Demography has an analytical and methodological tool box and profound knowledge about population dynamics that can be used in several ways to measure demographic differential vulnerability in the context of climate change. First, the topic of differentials across population subgroups has long been a focus in demographic research. Second, the notion of ‘hazard function’, which was originally derived from the risk of dying by age and sex, is central to demographic methodology, and thus lends itself to the study of differential vulnerability. Third, demography is a discipline built upon empirical evidence and facts that are quantifiable. For example, having knowledge of a population’s distribution and composition makes it possible to estimate which members of this population are most at risk to certain natural hazards both in terms of *where* they are and *who* they are. Fourth, demography also provides tools for forecasting. For instance, using multi-dimensional population projection methods it is possible to project into the future the age-sex-education composition of societies, and thus to quantitatively forecast the vulnerable segments of the population within countries and regions. Moreover, it is possible to produce population projections in a probabilistic way—a method that could prove particularly useful for policy planning when uncertainty in population forecasting needs to be accounted for (Lutz et al. 1997; Raftery et al. 2012).

While conventional demographic methods only considered age and sex as demographic factors, education, a characteristic that is highly relevant to reducing vulnerability, has recently been introduced as another demographic component in population projections (Lutz et al. 2014). Research has shown that the changing educational composition of populations stratified by age and sex is a key determinant of future socioeconomic challenges, ranging from total population size (Lutz and KC 2011), to economic growth (Lutz et al. 2008), to disaster mortality (Lutz et al. 2014). Depending on the context, other demographic characteristics, such as labor force participation, marital status, ethnicity, and religion, have also been included in such demographic models.

Indeed, demography is highly relevant to the study of global environmental change since human beings are at the center of the environmental system, both as the driver of and as the unit being affected by climate change. On the one hand, human activities, particularly the burning of fossil fuels, are responsible for the increased concentration of greenhouse gases in Earth's atmosphere, which has contributed to the increasing average global temperatures and consequently caused climate change. On the other hand, the recently observed increases in the intensity and the frequency of extreme weather events, coupled with water scarcity and climate-related food insecurity, appear to be having serious effects on the livelihoods and the well-being of people. The impacts of climate change have already been felt, especially in developing countries with high population growth, poor infrastructure, and a lack of urban planning. It is certainly the case that taking steps to adapt to anticipated climate change—e.g. adjusting planting dates and crop variety, retrofitting buildings, and engaging in disaster risk management—will be necessary to reduce the adverse impacts of climate change. Similarly, mitigation actions, such as technology development and behavioural changes, can help to reduce emissions. However, there is a large degree of heterogeneity within populations, as captured by observable characteristics such as age, gender, education, income, and place of residence; and these demographic differentials may be expected to determine the capacity to mitigate and adapt (Lutz and Striessnig 2015; O'Neill et al. 2010). For instance, it has been shown that countries, communities, households, and individuals with higher levels of education are less vulnerable to natural disasters than their less educated counterparts (Muttarak and Lutz 2014). Different socioeconomic development paths and policies can thus be expected to influence population dynamics and societies' capacities to achieve sustainability and to adapt likewise.

Given the close link between human population and the climate system, demography, as a scientific discipline with powerful methodological tools, can contribute significantly to the estimation and forecasting of population dynamics and population heterogeneity in climate change models. For example, having knowledge of which population subgroups are more likely to be vulnerable to specific types of natural hazards (as shown in this special issue) can assist policy-makers in crafting appropriate interventions aimed at reducing vulnerability. Surprisingly, climate change and differential vulnerability remains a marginal topic of study among demographers (Muttarak et al. 2016). This also results in the underrepresentation of demographers among major scientific efforts related to vulnerability and climate change, including in the IPCC reports.

3 About this special issue 'Demographic differential vulnerability to climate-related disasters'

This special issue is a product of the growing recognition of the need for scholars of population studies and of other social science disciplines to pay greater attention to the issue of demographic differential vulnerability. The special issue is a result of the international scientific conference of the IUSSP (International Union for the Scientific Study of Population) Panel on Climate Change, 'Demographic Differential Vulnerability to Natural Disasters in the Context of Climate Change Adaptation', held in Kao Lak, Phang Nga province, Thailand on 23–25 April 2014. The conference was jointly organized by the College of Population Studies, Chulalongkorn University, Bangkok; the Wittgenstein Centre for Demography and Human Capital (IIASA, VID/ÖAW and WU); and the IUSSP Panel on Climate Change. The conference was funded by the Chula Global Network and the European Research Council ('Forecasting Societies Adaptive Capacities to Climate Change', PI: Wolfgang Lutz, grant agreement: ERC-2008-AdG 230195-FutureSoc).

3.1 Demographic debate

The issue opens with a Demographic Debate section, which is comprised of five contributions from distinguished demographers across different continents. As we mentioned above, the study of environmental change has yet to become popular among demographers. In this section, distinguished demographers from different continents therefore address the following question: **Why are so few demographers working on population and climate change?** The reasons cited in these articles are summarized below:

1. The complexity of climate science and the limitations of data and methods for integrating the environmental and climate context into the microdata commonly used by demographers. With a focus on empirical science, it takes longer time for demographers to address new research questions such as climate change if appropriate data are not available (Hayes; Hunter and Menken).
2. The lack of interdisciplinary collaboration, despite the interconnectedness of the issues of population and climate change. This results in inadequacy of the climate models (e.g. the integrated assessment models (IAM) of the IPCC) in accounting for the social and demographic components (Gage; Hayes; Hunter and Menken; Peng and Zhu).
3. The discomfort with addressing population and environment issues given the historical involvement of demographers in the controversial debates during the late 1960s and 1970s on the limits to population growth, which were triggered by concerns about the limits to natural resources. As these debates raised complex and sensitive policy questions, demographers have become reluctant

to engage with climate change and environmental issues (Gage; Mcdonald; Peng and Zhu).

4. The research topics surrounding climate change, such as production and consumption and disaster vulnerability, are more directly related to other social science disciplines (e.g. economics, political science, geography) than demography. As anthropogenic climate change is a ‘social problem’ inherently related to human values, demographers are required to go beyond a mere emphasis on empirical relationships between population and climate systems when investigating this issue (Hayes; Peng and Zhu).
5. Limitations in funding, especially because funders of climate change research tend to value natural science approaches more than social science approaches (Peng and Zhu).

Although demographers have shown relatively little interest in climate change research until now, one common message across the five contributions to the Demographic Debate section is the promising potentials for population researchers to engage in climate change research following recent developments in data and methodological tools. In addition, as Hunter and Menken pointed out, conventional research topics in demography, such as fertility, mortality, and migration, are linked to global environmental change. The recognition of these common interests should spur the involvement of population scholars in the field of climate change research. Moreover, a few population scholars have already engaged in climate change research, and have introduced the population dimension into climate change modelling. Activities of the IUSSP Climate Change Panel, coupled with recent initiatives—such as an initiative in China that established new degree programs explicitly focusing on population and environment—should encourage younger generations of demographers to participate in the field of climate change research.

The Demographic Debate section concludes with an essay by Wolfgang Lutz that highlights the contributions demographers can make to research on sustainable development, especially by providing estimates and forecasts of population dynamics, which are fundamental to policy design. This essay is accompanied by a reprint of the two statements made by distinguished international scientists on the importance of placing human populations, and the composition and the distribution of these populations, at the center of sustainable development research (Lutz and Shah 2002; Lutz et al. 2012). Indeed, climate change and sustainable development are closely related, as both of these socioeconomic development paths result not only in different levels of greenhouse gas emissions, but in differential adaptive capacities depending on the composition and the distribution of populations (Lutz and Striessnig 2015; KC and Lutz 2014a). It is therefore clear that demography is a scientific discipline that can make important contributions to our understanding of the complex relationship between human populations and the climate system, and of what society will look like in the future based on population projections.

3.2 Research articles

The nine original and fully refereed research articles presented in this special issue highlight how scholars of population studies and other relevant disciplines can contribute to our understanding of population and climate change interactions. These articles address the issue of demographic differential vulnerability from different perspectives on vulnerability, drawing upon case studies from across the globe based on unique data and innovative methodologies. This collection of research articles offers both empirical studies and forecasts of future vulnerability based on national- and global-level evidence.

Vulnerability in this context refers to 'outcome vulnerability'; that is, the negative outcome of climate change on a particular unit, or human being, that can be quantified and measured (O'Brien et al. 2007). After establishing that the human being is the unit that is vulnerable, the next question is *what* hazards people are vulnerable to. Premature death is obviously the most undesirable outcome, as it harms the deceased and deprives him or her of all of the benefits of being alive (Feldman 1991). Also, after death the individual has no chance for recovery and no capacity to adapt. Falling ill, losing a job, or losing a crop are also unwelcome events, but they do not kill the individual; there still is a chance for recovery and adaptation. Likewise, the consequences of certain unwelcome episodes, such as catching the flu, may not be entirely negative, as contracting an illness could boost the person's immune system. Death, on the other hand, is universally seen as an unfavorable outcome, and can be measured unambiguously: a person is either dead or alive, and all countries have clear legal definitions of death. This focus on premature human mortality also makes the measurement and the assessment of vulnerability much easier, as death is a globally valid metric. There are several ways to operationalize the notion of premature mortality, such as through estimating age-sex specific years of life lost due to premature mortality and disability, as was done in the Global Burden of Disease study (Murray and Lopez 2013).

In this special issue, Zagheni et al. and Zhao et al. explicitly investigated mortality risks from climate extremes, such as hydrological hazards (flood and storm) and extreme temperatures, which are likely to be further aggravated by climate change. Focusing on mortality from extreme temperatures in Taiwan in the 1970s, Zhao et al. showed that both unusually cold temperatures in winter and unusually hot temperatures in summer were associated with higher mortality. However, the mortality patterns differed by age group and cause of death, with older people being more likely to die from cardiovascular disease during extreme cold episodes, and children and young adults being more likely to die from drowning during hot spells. These mortality patterns have, however, changed in recent decades due to socioeconomic developments in Taiwan, which brought about improvements in health care, living environments, safety management, and disease prevention practices. Similarly, the analysis of cause-of-death data for 63 countries in the years 1995–2011 by Zagheni et al. found that mortality from hydro-meteorological disasters declined over this period as a result of improvements in human development. Contradicting the common belief that women are more vulnerable to natural disasters than men, Zagheni et al. found that in the case of mortality risks from floods and storms, men, and especially young adult men, had much higher mortality levels than women. The findings on age-sex differentials in mortality risks from different types of natural disasters thus have important implications for designing appropriate policy responses to address the differential vulnerability of different demographic subgroups.

Apart from understanding *who* is vulnerable to *what*, equally importantly *where* people live determine their exposure to natural hazards. For instance, even older people and young children, who are generally more likely to die from tsunamis than people in other age groups, are not more vulnerable if they live in an area that is not exposed to tsunami hazards. The articles by de Sherbinin and Bardy and by Ignacio et al. contribute spatial perspectives to the analysis of differential vulnerability. In particular, the two articles address the important question of whether the subgroups of the population who are socioeconomically disadvantaged—e.g. people who have low incomes, low levels of education, or high unemployment rates; or are members of ethnic minority groups—are also more likely to live in areas with higher levels of exposure to natural hazards. In geography, this question is often approached by developing an index of social vulnerability, or a composite measure of various demographic and socioeconomic characteristics of a geographical unit, to identify a vulnerable area. The articles by de Sherbinin and Bardy and by Ignacio et al. contribute to the empirical advancement in the field by further investigating how well the social vulnerability indices correspond with actual losses and damages after a disaster strikes. This exercise allowed for the validation of the social vulnerability indices, which is rarely done in vulnerability assessment studies (Fekete 2009).

De Sherbinin and Bardy employed census data to develop social vulnerability indices of two major cities, New York City and Mumbai, which are considered to be among the top 10 port cities most exposed to coastal flooding. Exploiting the events of Hurricane Sandy in 2012 for New York City and of the Maharashtra floods in 2005 for Mumbai, the article investigated whether the areas with higher social vulnerability scores were also more likely to be inundated. This was found to be the case for Mumbai, but not for New York City. While these findings may be attributable in part to data limitations and the different spatial resolutions used, the two cities may also differ in terms of settlement preferences, with, for instance, wealthy households in New York preferring to live along the coastline. Indeed, the findings from the case study of the Tropical Storm Washi flood in the southern Philippines in 2011 by Ignacio et al. suggest that the areas along the riverbanks most prone to severe flooding were predominantly inhabited by the middle class. In addition to adopting only a composite score of the social vulnerability indices commonly used in other studies, Ignacio et al. decomposed the indices in order to determine which demographic and socioeconomic factors contributed to disaster vulnerability. They found that physical characteristics that determine exposure to flooding, such as elevation from the coast and slope, explained the losses and the damages better than the socio-demographic characteristics of the areas. Given the extreme nature of the flood event they investigated, exposure was an important determinant of vulnerability. Nevertheless, Ignacio et al. pointed out that it is still important for policy-makers responsible for crafting disaster risk reduction measures to consider the differential capacity of the population to get out of harm's way.

Risk perceptions, attitudes toward climate change, and climate-related behaviors also vary considerably by demographic and socioeconomic characteristics. Understanding public attitudes and perceptions is essential not only for formulating education and communication strategies, but for successfully implementing risk reduction or adaptation strategies. For instance, identifying the factors that influence household hurricane evacuation decisions can contribute to the development of effective protective actions for hurricanes (Huang et al. 2015). The article by Meijer-Irons offers a unique analysis of panel surveys from rural Thailand that compared subjective assessments of environmental risks with objective measures of environmental and climate conditions, such as the vegetation health index. In particular, Meijer-Irons showed that subjective perceptions of environmental risks depend on household characteristics and economic activities. Households that, relative to the average, were large, had a high level of involvement in agriculture, and had a large number of members who were working-age women or older people, were more likely to report that their income losses were due to environmental shocks, after controlling for objectively measured climate conditions of the areas. This finding implies that policies aiming to address the impacts of environmental change should take into account the issues that are most crucial to different subgroups of people who are vulnerable to environmental shocks. The paper by Muttarak and Chankrajang investigated the relationships between climate change perceptions and climate-relevant behaviors, i.e. the actions individuals take to minimize the problem of global warming (mitigation actions) in Thailand. Their results showed that while concerns about global warming were associated with climate-relevant behaviors, this association applied to actions that involved making technical and behavioral changes (e.g. using energy-efficient electrical devices, using a cloth bag instead of a plastic bag, and planting trees), but not to those actions that involved saving electricity and water (e.g. turning off unused lights and turning off the tap while brushing teeth). Similarly, educational differences were found for the former set of behaviors, but not for the latter. The findings further showed that achieving technical and behavioral changes generally involved making consistent efforts to change behavior, knowing what actions to take, and having a certain level of concern about anthropogenic impacts on climate change; whereas saving electricity and water was often undertaken simply for economic reasons. Educational differentials in climate actions thus depend on the motivations for carrying out the action.

Finally, the final three papers in the special issue offer a forecast of the future vulnerability and adaptive capacities of societies through the lens of human capital based on a multi-dimensional population projection exercise and the application of the newly developed Shared Socioeconomic Pathways (SSPs). Population and human capital projections were carried out following the five scenarios as defined by the SSPs (KC and Lutz 2014b). The SSP narratives described alternative socioeconomic development pathways that influence population dynamics and human capital formation for different world regions. Building upon recent solid evidence on the role of human capital (measured as education) in reducing vulnerability to natural disasters (Muttarak and Lutz 2014; Lutz et al. 2014) – from mortality, morbidity, disaster responses, coping strategies to recovery –, the three articles showed that differences in population size and composition in the different SSPs are expected to result in varying degrees of vulnerability in the future.

Based on the estimation of disaster mortality for the years 1970–2010 covering 174 countries, Striessnig and Loichinger confirmed that countries with a higher proportion of women with at least secondary education experienced far fewer deaths due to climate-related extreme natural events. The results were then translated into the predicted number of deaths, and the future fatalities are projected according to changes in the educational composition of population derived from the five SSPs scenarios in each major world region. Striessnig and Lochinger found that future disaster deaths vary considerably in the SSP scenarios, especially for Latin America and the Caribbean, Asia, and Africa, where the room for educational expansion is greater than it is in other regions. Similarly, Crespo Cuaresma and Lutz further extended our understanding of future societies' adaptive capacity by projecting how the Human Development Index (HDI) varies under different SSP scenarios. The HDI is composed of three components: income, educational attainment, and life expectancy (as a proxy for health). Previous studies have shown that each of these components is a key determinant of vulnerability to natural disasters (Striessnig et al. 2013; Patt et al. 2010). Indeed, the paper by Zagheni et al. in this issue demonstrated that disaster-related mortality steadily declines as a country's HDI level increases. Exploiting the new life expectancy and educational attainment projections by the Wittgenstein Centre for Demography and Global Human Capital (Lutz et al. 2014), coupled with the projections of income per capita growth by Crespo Cuaresma (2015) under the five SSP scenarios, Crespo Cuaresma and Lutz were for the first time able to produce HDI projections for 154 countries up to the end of this century. As in the article by Striessnig and Loichinger, the HDI projection exercise found that the degree of vulnerability to climate change varies based on different development trajectories.

Finally, the article by Loichinger, KC, and Lutz presents an innovative application of multi-dimensional population projections to forecast future adaptive capacities at the sub-national level, using the Phang Nga province located in the south of Thailand as a case study. The size and the composition of the population of Phang Nga, the Thai province most severely affected by the Indian Ocean tsunami in 2004, is projected by age, sex, level of education, and labor force participation. This four-dimensional module made it possible to forecast the level of adaptive capacity of the Phang Nga province using the relatively comprehensive understanding of population dynamics and future changes in distribution and composition of the population of Phang Nga. As has been shown that individuals with higher levels of education were better prepared for disasters (Muttarak and Pothisiri 2013; Hoffmann and Muttarak 2015), given the shift in the educational composition of the province's labor force toward higher levels, it may be assumed that the population will have higher levels of disaster preparedness in the future.

These nine original research articles not only enrich our understanding of different dimensions of demographic differential vulnerability in various geographical contexts; they also demonstrate how demographic methodological tools and data can be applied to the study of vulnerability. In particular, the application of demographic knowledge in investigating and forecasting demographic differential vulnerability is a key contribution of demographers to the vulnerability research community. Although the research in this field is still in its infancy in the context of mainstream population studies, as was highlighted in the Demographic Debate section, there is considerable potential for the further development of climate change research in demography. It is clear that advancements in research on population and environment with a focus on demographic differentials must be made by younger generation of demographers, who—relative to their older colleagues—are less influenced by historical polemics on population control, and are more prepared to incorporate new challenges like climate change issue into their research.

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DEMOGRAPHIC DEBATE

Why are so few demographers working on population and climate change?

Invited comments

Vienna Yearbook of Population Research 2015 (Vol. 13), pp. 15–17

Engagement of demographers in environmental issues from a historical perspective

Peter McDonald*

The premise of this Demographic Debate is derived from a claim made by the IUSSP Panel on Population and Climate Change that when they were organising meetings in 2012 and 2014, very few demographers offered to contribute papers to the meetings. To further investigate this claim, I looked at the program of the 2015 meeting of the Population Association of America, the most recent international population conference. There were several sessions with the word 'environment' in the title, but after inspecting the papers in these sessions I found that that term was very broadly defined. There were papers at this PAA meeting on localised environmental issues, and, over the years, it has not been uncommon for demographers to engage in research related to localised environmental issues such as air pollution, pollution of water systems, flooding, clean water and sewerage, depletion of aquifers, soil erosion, deforestation, destruction of natural habitats, and congestion. It appears that demographers are relatively comfortable working at this localised level. But there were no sessions at the 2015 PAA meeting with 'climate change' in the title, and only five or six papers at the conference even mentioned climate change; primarily in the context of migration as an adaptation to climate change. Only one paper dealt directly with demography and climate change mitigation. Thus, the premise seems to have substance.

A historical perspective may be useful. In the late 1960s, the dominant paradigm in demography was that developing countries needed to lower their high fertility rates because this would promote economic growth as both public and private expenditures were redirected away from meeting the needs of children and towards more productive forms of economic investment. The expansion of education and of agricultural production were also components of this model, which had been developed through a series of major studies at Princeton University in the 1940s and the 1950s (see, most importantly, Coale and Hoover 1958). The model was taken up vigorously by the United States government during the Cold War as a means of combating the spread of communism. But it can also be argued that a

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similar motivation inspired the family planning programs of China and Vietnam (Potts 2006). The remarkable economic progress made over the past 50 years in the Asian countries that followed this approach is evidence of its cogency (Bloom and Williamson 1997).

The most severe challenge to this paradigm has been an environmental protection argument that rose to prominence around 1970 known as ‘limits to growth’ (Ehrlich and Ehrlich 1970, Meadows et al. 1972). Ironically, both the economic growth and the limits to growth proponents were advocating zero population growth, but one side was making the argument to promote economic growth, while the other side was making the argument to slow or stop economic growth. I was a doctoral student in demography at the time when this debate arose, and I went to hear Paul Ehrlich speak when he visited the ANU (Australian National University). It is fair to say that my teachers at the time subscribed to the Princeton approach, and that they were strongly opposed to the limits to growth argument. Working in Indonesia in the 1970s, I also agreed with the economic growth through population control argument, as, I think, did most demographers. Whatever one makes of the subsequent history—including of the Simon-Ehrlich bet and the relative outcomes of the two arguments—the point that I want to make here is that the bitterness of this debate left demographers somewhat cautious about engaging with environmental issues. More cynically, it could be observed that funding in the population field was more associated with the economic growth side of the debate than with the limits to growth side.

The limits to growth argument is predominantly Malthusian; i.e. that resources are limited and that their depletion will have disastrous consequences. At the time, the issue of planet-wide climate change resulting from the burning of fossil fuels was well-established, but was still somewhat tentative (see Spengler 1960; Ehrlich and Ehrlich 1970: 239–242; and Ward and Dubos 1972, Chapter 13). Today, we as a planet have managed to deal with the resource issue, particularly the issue of energy and mineral resources, although ensuring that people have basic necessities such as food and water is a major challenge for the future, especially in poor countries with high rates of population growth. On the other hand, climate change has become the dominant scientific paradigm of the age, and very few demographers could be considered ‘climate change deniers’. But as a reaction to this history of sometimes bitter controversies, centres of population research around the world, with some notable exceptions, have not invested in specialists in population and environment research. Social and economic issues dominate the policy-related agendas of population specialists, and these issues are, of course, important. My view is, however, that the balance will change and that younger demographers, not daunted by the historical tensions in population and environment research, will take up population and climate change research. This direction needs to be fostered, and I tried to do so by establishing the IUSSP Panel on Population and Climate Change. However, universities and other centres of population research should be making more appointments in this area of research.

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The next best time for demographers to contribute to climate change research

Anastasia J. Gage*

According to the medium variant projection of the United Nations World Population Prospects: 2015 Revision, the world population is on course to increase from 7.3 billion as of mid-2015 to 9.7 billion in 2050 and to 11.2 billion in 2100 (United Nations, 2015). Much of this growth will occur in developing countries, 35 of which are expected to experience a tripling of their populations between 2015 and 2100. These demographic trends and population dynamics have important, though complex, relationships with climate change itself, as well as with the vulnerability of populations to the negative effects of climate change, efforts to mitigate and adapt to climate change, development, and health.

To date, however, the contributions of demographers and population scientists to international discourse around the interrelationship between population and climate change have been rather limited. As the Population and Sustainability Network (2014) has noted, although the fields of population, development, global health, and climate change are highly interconnected, the collaboration between scholars from these fields has so far been insufficient. This failure to work together makes it difficult to consider how each of these areas of research is linked to climate change.

It is indisputable that population affects climate change. The results of an expert group meeting on population dynamics and climate change organized by the United Nations Population Fund (UNFPA) and the International Institute on Environment and Development (IIED) demonstrate clearly that the size, the structure, and the dynamics of populations influence and are influenced by climate change (UNFPA and IIED, 2009). So why are so few demographers participating actively in international policy discussions about potential responses to climate change? At a basic level, demographers seek to understand the size, composition, and flow of populations; as well as the biological, socioeconomic, political, and environmental processes that influence those changes. Many variables that can influence the

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trajectory of global greenhouse emissions—including urbanization, age structure, household size, and socioeconomic group—are squarely within the domain of demography. To date, these factors have been omitted from the Intergovernmental Panel on Climate Change Models of possible pathways for carbon dioxide emissions until the end of the 21st century; instead, these models have focused narrowly on population size and growth.

Understanding the links between population dynamics and climate change, and ensuring that conclusions regarding these relationships are evidence-based, will involve the identification, collection, and integration of data at the global, regional, and country levels. Demographers are well-positioned to provide substantive and methodological guidance and knowledge about population size and growth, emissions, population vulnerability and adaptation, migration, and urbanization; and to address the challenges inherent in incorporating economic, social, technological, and demographic data into climate change models.

Among the contributions demographers can make to such efforts are evaluating the quality of the relevant data, and promoting modelling for smaller geographic areas to facilitate local-level climate change adaptation and policy formulation. These contributions can help to meet the data analysis needs of policy-relevant research initiatives that seek answers to the following questions: Which populations will be affected? Which places are at risk? What are those risks? How do the risks vary among people and places? The analysis of the 2010 rounds of censuses will provide researchers with the opportunity to overlay climate-related risk maps onto population and socioeconomic data for small disaggregated administrative areas, which will allow them to make finer estimates of the numbers of people who are vulnerable to the impacts of climate change. Supporting the improvement of data streams is clearly within the scope of demography, as is addressing the challenges presented by indicator definitions, missing data, and the measurement of consumption-based versus supply-based emissions.

With more than half of the world's population currently living in urban areas, trends in urbanization have significant implications for consumption patterns, emissions, climate change, and urban adaptation in different parts of the world. Demographers have long explored the components of urban growth and changes in human settlement systems around the world. Yet a number of questions about how demographers are addressing these issues arise. For example, how are demographers contributing to our understanding of how the impact of climate change varies by type of settlement, location, population density, and growth? And, how are demographers shedding light on spatial variation in the vulnerability of the poor to the impacts of climate change, and on the roles of gender and migration?

The debates surrounding population and climate change are, of course, often heated. Although rapid population growth in the global south heightens vulnerability to climate change, the consumption levels and the generation of greenhouse gas emissions by industrialized countries—many of which are experiencing slow population growth or population stabilization—have historically been the key drivers of climate change. Is a desire to avoid being drawn into debates about the role of family planning programs and countries' rights to economic and social advancement leading demographers to downplay the effects of population trends, prospects, and dynamics on climate change, adaptation, and mitigation?

Demographers and population scientists are no strangers to complex and emotional policy controversies. At the 1974 World Population Conference in Bucharest there was sharp disagreement between representatives of developed countries who argued that rapid population growth impeded development, and representatives of developing countries who asserted that population problems are a consequence and not a cause of underdevelopment, and that the solution to these problems lies in the redistribution of resources in a new international economic order. In the current climate change debate, it is important for population scientists to bring to the table lessons learned since the 1994 International Conference on Population and Development about engaging governments to enable people to freely and responsibly choose the number and the spacing of their children by providing them with access to family planning information and contraceptive methods.

A fundamental question is whether and, if so, how the next generation of demographers is being prepared to meet the challenges associated with climate change. To what extent do individual demographers and demographic institutions have the capacity to conduct climate change and spatial analyses, and to integrate satellite imagery, climate modeling, demographic data, and socioeconomic data in studying conditions in the poorest countries of the world—i.e. in countries that are not among the major contributors of greenhouse gases currently, but that are likely to be hardest hit by the negative effects of climate change? Is it time for us to revisit the content of demography and population studies training programs?

I have always viewed the core work we do in demography as a means to an end: that is, providing the evidence needed to inform policies and programs and foster improvements in population well-being. However, recent developments have highlighted the need for demographers to become more active in addressing climate change and environmental degradation, as these phenomena threaten the well-being of current and future generations. There is, therefore, a window of opportunity for demographers to contribute to the ongoing discourse on climate and the environment.

It is time to start a dialogue on how demographers will contribute to assessments of the direct and indirect impact of climate change. It is time for demographers to help policy-makers, local leaders, and the public gain a better understanding of how climate change and environmental degradation are influenced by human populations, and how population health and well-being will in turn be influenced by climate change. There is an urgent need for demographic data to be used to support decision-makers in averting, adapting to, and possibly even reversing current warming trends. As demographers, will we help to shape future discourse, policies, and programmatic actions, or will we sit idly by and watch how the effects of climate change unfold?

The best time to plant a tree was 20 years ago. The next best time is now (Chinese proverb).

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Will climate change shift demography's 'normal science'?

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Like any science, the study of population has been guided by *normal science*, as defined within the discipline. As Thomas Kuhn (1962) famously postulated in *The Structure of Scientific Revolutions*, researchers follow *normal science* until a crisis level of unexplainable anomalies is reached—i.e. anomalies that push the limits of current paradigms.

The paradigms guiding population science may, in fact, be increasingly outdated in their exclusion of environmental factors. Yet rather than debating 'narrow-mindedness', we devote this brief essay to a consideration of the conditions required for demographers to make worthwhile contributions to current discussions of climate change.

A valuable example of a recent paradigm shift within population studies is the trend toward studying biological and genetic determinants of population processes. More than 15 years ago, a vigorous debate took place over whether biological/genetic data could provide new opportunities for understanding population processes, whether the relevant theories and data existed, and what forms of training and amounts of funding would be required to support these new research approaches (e.g. Finch et al. 2001). Since then, considerable time and energy have been devoted to training population scientists in these new areas, and to pursuing the opportunities presented by this new line of research. Time will tell whether these efforts have an important impact.

This case provides a useful parallel in answering the question regarding the involvement of population scientists in climate change research. To be sure, demographers have long danced around the more general issue of connections between population development and the environment. In 1998, PAA President Anne Pebley reviewed this tendency and put forward arguments to explain why demographers have avoided directly addressing environmental concerns. In the end,

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Pebley argued that "there are important reasons for demographers to become more involved in research on environmental issues" (1998: 385). As we move further into an era of 'major and still growing impacts of human activities' on ecological systems—a geological epoch informally described as the Anthropocene (Crutzen 2006: 16)—the direct engagement of demographers with environmental issues becomes all the more imperative.

Below we discuss why we believe the time is ripe for population scientists to become more involved in research on climate change. Our argument comprises four key points.

First, while environmental aspects of classic demographic theories have not been emphasized in population research, there is evidence of recent change

Consider Caldwell's classic 'wealth flows' theory of fertility decline and its central theme of children's contributions to household economies (Caldwell 1976). The role of children's labor within agricultural households was key to Caldwell's argument, although most subsequent research on fertility even in resource-dependent settings ignored the role of environmental reliance. Recent research in rural Kenya added to our understanding of the connection between fertility and the environment by showing that land shortages appear to have played a role in the nation's dramatic fertility decline (Shreffler and Dodoo 2009).

A similar critique could be made of migration research, which has until recently largely ignored environmental determinants. The failure to include these determinants is surprising given that contextual factors are critical to many classic migration theories such as push-pull, Wolpert's stress threshold model (1966), and Speare's residential satisfaction framework as related to migration decision-making (1974). Spurred by climate change concerns, migration scholars have, however, recently made substantial progress in bringing environmental factors into migration research, with some generalizable findings emerging, including evidence on the distinctions between the migratory impacts of short-term environmental events and long-term challenges such as drought. In addition, a recent conceptual framework by Black and colleagues (2011) presents a nice overview of how these short- and long-term environmental pressures interact with macro forces (e.g. political, economic, social), and in turn interact with personal and household characteristics to shape migration decision-making.

Second, the data and the methodological challenges that have discouraged demographers from integrating environmental considerations are being addressed

The integration of environmental issues within population research requires us to know not just who people are, but where they are. Yet much of the readily available microdata often used by demographers have not had geographic identifiers that allow for the attachment of data reflecting local environmental conditions and changes in those conditions. As Barbara Entwisle argued in her PAA Presidential Address on linking neighborhoods and health, this kind of research requires 'putting people into place' (2007: 687).

Some researchers have identified opportunities within other data sources to examine population-environment connections. One example is Gray and Mueller's (2012) use of data from the Chronic Poverty and Long Term Impact Study collected by the International Food Policy Research Institute to examine the impacts of flooding on migration in rural Bangladesh. Another example is the use by Hunter, Twine, and colleagues of geographic information within the Agincourt Health and Demographic Surveillance Site data to study migration as related to proximate natural resources in rural South Africa (Hunter et al. 2012; see review by Fussell et al. 2014). These types of analyses could be used to examine demographic scenarios under different climate futures.

In addition, methodological advancements also allow for the integration of contextual factors within micro-level analyses. For example, multi-level models, spatial analytical techniques, and agent-based approaches are increasingly being applied to gain a better understanding of population-environment connections.

Third, there are demographers who are emphasizing climate change

There are examples of important inroads made by demographers in studying both the influences of climate on population processes and the role of population in climate change. These pathways lead to other logical entry points for combining population and climate change concerns.

A particularly prominent example is the work of O'Neill and colleagues in bringing demographic nuances, such as issues of aging and urbanization, into models of economic production and consumption, based on the premise that these factors will ultimately drive climate changing carbon emissions (e.g. O'Neill et al. 2010). This type of demographic research can directly inform climate science by improving our understanding of the demographic trends that underlie human-induced climate change. This line of inquiry represents a much-advanced version of the classic IPAT model of Impact = Population $*$ Affluence $*$ Technology (Ehrlich and Holdren 1971).

Yet another example is the effort by Balk, Montgomery, and colleagues (2010) to improve the spatial dimensions of population projections, which can, for example, help us identify population densities in low-lying coastal regions of Bangladesh. Such work is critical to the formulation of policies and programs designed to reduce vulnerability to climate change, particularly sea level rise.

At the household level, research on migration from rural Mexico has recently integrated climate measures to help explain future migratory potentials under shifting environmental futures (e.g. Nawrotzki, Riosmena and Hunter 2013). Insights from this work can improve targeted policies and programs aimed at enhancing household resilience.

Fourth, there are opportunities for including climate change issues in population research

Demographers might be encouraged to consider the ways in which climate affects their topics of study, including fertility and migration. Climate change may be of particular relevance for populations with high levels of dependence on local environments. Demographers can also contribute useful expertise to the study of climate change vulnerability and adaptation, helping to improve our understanding of who is in harm's way, and what types of responses may be anticipated or desired. Demographers may also be encouraged to apply their population expertise more directly to the study of climate drivers, along the lines of the work of O'Neill.

Any of these entry points into population-climate research can benefit from the incredible array of newly available data that allow us to link population and environmental processes in ways that were not previously possible. For example, demographers could draw upon microdata from TerraPopulus, an initiative to link international census data with information on land and climate data (www.TerraPop.org). A rapidly expanding pool of macro- and microdata resources are also available through the Center for International Earth Science Information Network (CIESIN), a center within the Earth Institute at Columbia University (http://www.ciesin.org/). Finally, as climate scientists continue to recognize the critical nature of demographics, opportunities are growing for important collaborations between population and climate researchers. Demographic scholars already engaged in research on projections and projection methodology would be likely be candidates for collaborations with climate scientists involved in projecting future emissions.

Science is a social product—and the social landscape is changing

The pursuit of knowledge is shaped by societal values, norms, and interests (Merton 1973). Across the world, values, norms, and interests are shifting as climate scientists continue to generate evidence of human-induced change and public concerns about climate change continue to grow. Policy-makers are responding: consider the recent Dutch court ruling mandating that the government increase efforts to combat climate change. At a more fundamental level, the socio-political landscape in which we conduct our research is changing, and the new emphasis on understanding the social, economic, and political dimensions of climate change calls for new ways of doing demography. Shifting temperatures and rainfall will alter migration probabilities, while natural disasters and sea level rise will affect patterns of population health.

Even so, until the case is made that climate change is important to our science and that we have or can develop adequate tools for taking climate change into account, demographers, like other social scientists, will continue on their usual research paths. The many new opportunities to take advantage of geographically referenced microdata should help to bring climate issues into demographic research. But who is in the best position to make the case for the inclusion of climate factors? It is likely to be those demographers who have already engaged in climate research, climate scientists who see the need for demographic nuance, and, crucially, funding agencies willing to invest in population-climate scholarship. We must make the case for the integration of climate into population research and of population into climate science so that both disciplines can move forward from their current normal science stances. It is our hope that this debate contributes to establishing that case.

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Barriers to involvement of Chinese demographers in climate change research

Xizhe Peng and Qin Zhu*

The population and its development trends are important topics in the fields of climate change mitigation and adaptation. Although academic communities (like the IUSSP) have encouraged them to do so, few demographers have devoted themselves to research on climate change.

In China, only a handful of demographers are engaged in climate change research. According to our review of literature published in Chinese core journals in the past decade (2005–2014), there are 17,210 papers with the keyword ‘climate change’, ‘carbon emissions’, or ‘emission of CO_2’. Of these papers, only 254 (1.5%) also had the keyword ‘population’ or ‘demography’, and only 41 (0.2%) are classified as population studies.

Why are so few demographers focusing on climate change research? Within the context of China, we will discuss the knowledge structure and research methods of demographers, the incentive system for scientific research, the population development trends, and the relationship between population and climate change.

First, narrowly defined, the focus of demography is on theories and analytical methods of population change, including fertility, mortality, and the spatial distribution of the population. The field of climate change involves much wider horizons with grand narratives that go beyond the core demographic themes, such as industrial development, energy utilization, ocean and land coverage, and environmental change. It is difficult to use only demographic techniques when examining complicated climate change issues. At the same time, the demographic factors considered in climate change studies are generally represented by a single variable (the change in population size), and even this variable is often treated as exogenous by researchers from other disciplines. This narrow perspective tends to discourage demographers’ participation in such studies. In addition, many of the individuals who have received professional training in demography also work as

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economists or sociologists, and thus make use of theories and methods of economics and sociology, as well as those of demography. As these disciplinary boundaries are not always clear, some of the demographic studies on climate change may not have been classified as demographic.

Second, the existing funding system tends to 'value natural sciences but undervalue social sciences'. As in China demography is considered a social science discipline, demographers are often at a disadvantage when applying for funding for climate change studies, which are dominated by natural scientists. Furthermore, the actual funding of individual projects for climate change is much lower if the funding source distributes funds for social science rather than 'hard science' projects, even if they have similar designs and technical components. This is true in general not only of demographic studies, but also of studies in most other social science disciplines. This situation has existed over the past few decades, mainly due to both the government's priorities and the market demand for research on the natural sciences and applied technologies. These scientific research incentive mechanisms have not only affected the enthusiasm of demographers for climate change research; they have further widened the disparities in research opportunities and quality between the social sciences (such as demography) and the natural sciences. This lack of funding and of governmental support may negatively affect the ability of demographers to take the lead in the field of climate change research.

Third, the development of demography in China as an academic discipline has been largely associated with the effort to control population that has played a central role in China's modernization process. It is therefore understandable that fertility-related research, including studies on family planning programs, have long dominated the research agenda. China's strong economic growth over the past three decades has, however, greatly reduced the public's concerns about the Earth's carrying capacity and 'the Malthusian trap', and has changed people's understanding of the relationship between population and pressure on resources and the environment. Chinese society is experiencing a profound social transformation. Today, Chinese demographers are overwhelmingly occupied with researching large-scale migration, rapid urbanization, and other emerging population issues, such as future labor shortages and aging. Demographers' capacity to focus on the issue of climate change is certainly limited by demands that they address these new and emerging population-related challenges. Moreover, while public awareness of climate change is rising in China, it is often considered as a medium- to long-term issue.

Last but not least, the characteristics of climate change mitigation and adaptation limit the role demographers can play in this research field. In terms of climate change mitigation, demographic factors mainly have indirect effects. For example, while changes in the population may be expected to lead to changes in patterns of production and consumption, these kinds of shifts, and the related benefits to and cooperation between countries, are research topics that are typically addressed by economists and political scientists. In terms of climate change adaptation, demographic factors can also be indirectly reflected through ecological protection, population migration, disaster prevention, and other human behaviors.

The contributions of ecologists, disaster prevention specialists, and geographers appear to be more relevant in these research fields, leaving demographers with no particular comparative advantages.

While a range of factors that are likely to discourage demographers from engaging in research on the link between population and climate change have been discussed here, this does not mean that demographers have no contribution to make to this field. Indeed, as more demographers are highlighting the role of demography in climate change, this relationship is increasingly being recognized. Chinese demographers have made significant contributions to China's climate change research and to the formulation and implementation of relevant government policies. Journal articles written by demographers are widely cited by climate change researchers, although the number of such articles is relatively small. Through the joint efforts of Chinese demographers and scientists in other disciplines, a discipline known as 'population, resources, and environmental economics' has been formally established by China's education authority, and degree programs have been set up in more than a hundred Chinese universities. Students who are enrolled in this discipline come from a variety of academic backgrounds, and population study is a core component of these programs. An interdisciplinary academic journal, 'China Population, Resources and Environment', has published articles in the field of population and climate change. It is expected that the younger generation of demographers in China will become increasingly involved in climate change research. The population studies community should provide better guidance to young demographers, and develop more collaborations with other disciplinary networks. These efforts will not only enrich our scientific knowledge on climate change; they will promote the development of demography itself.

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Population dynamics and climate change: A challenging frontier for the intrepid demographer

Adrian C. Hayes*

I am grateful to the editors for inviting me to contribute to the Demographic Debate Section of this *Vienna Yearbook of Population Research* Special Issue on Demographic Differential Vulnerability to Natural Disasters in the Context of Climate Change. They have asked me to address the question: Why are so few demographers working on climate change? This begs the question of what they might mean by 'so few', but I will return to that issue in a moment. To begin with I want to outline three demanding challenges that any intrepid demographer—or any other social scientist for that matter—faces if she wants to work on anthropogenic climate change with the aim of making a significant contribution to our scientific understanding of its causes and consequences.

First, the Earth's climate system is extremely complex, and climate science brings together theories, data, and methodologies from a wide array of the physical sciences, including physics, chemistry, meteorology, biology, ecology, and geology. No single researcher can master all of these fields of inquiry comprehensively, but anyone who wants to understand how human populations are altering the climate will need a firm grasp of the climate system's basic dynamics. This means acquiring sufficient knowledge of the component parts of the system, of their respective physical properties, and of how these properties interact. In addition, it is important to understand how the whole system is driven by solar energy. Comprehending climate science can thus represent a steep learning curve for a demographer, not least because demographers (like most social scientists) are trained to focus on the socially meaningful aspects of populations, not on their physical properties. But it is precisely the physical nature of what populations do that our intrepid demographer will need to embrace in her research if she is to improve our understanding of how humans are changing the climate. It may be worth noting in passing that many popular accounts of climate change written for the proverbial layperson will not take

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our demographer very far in developing her understanding of the basics of climate science, as they can be misleading: for example, they may explain the so-called greenhouse effect, but without clarifying why this term is in fact a gross misnomer, as the British physicist R.W. Wood demonstrated experimentally in 1909 that the reason the typical garden greenhouse is hot inside is *not* primarily because of the radiative properties of the glass!

Second, it is not enough for our intrepid demographer simply to get more physical; she will also need to find or fashion a conceptual framework capable of integrating the physical with the social. The framework used in the integrated assessment models (IAM) of the IPCC will not satisfy many demographers (or other social scientists) because it gives little attention to basic social facts like agency, the heterogeneity of populations, inequality, vested interests, and conflict. These gaps are understandable given the preponderance of physical scientists in the work of the IPCC: they have made heroic efforts to master the complexity of the climate system, but have no mandate or inclination to recognize and master the complexity of human populations and societies. Our intrepid demographer will need a framework that can help rectify this imbalance.

A number of conceptual frameworks purporting to integrate the human and the natural have found their way into population and environment studies over the last 50 years. This literature can be mined to help fashion a suitable framework for population-climate research. The limitation of many population-environment perspectives is, however, that they identify population-environment interactions in terms of broad associations (for example, between human consumption of goods and services on the one hand and pollution and the depletion of natural resources on the other), without uncovering exactly what happens at the interface of these actions (by, for example, giving a more calibrated assessment of the environmental consequences of discrete choices). When it comes to fashioning a more satisfactory integration framework, my money is on recent advances in social-ecological approaches that embrace population, society, the natural environment, and the built environment (Hummel et al. 2009). Each of these components has embedded within it a distinct kind of resource or form of capital—human, social, natural, or physical—that is essential for human action. In this perspective, the basic story of population-environment interactions is about how these four forms of capital are produced, exchanged, and consumed in social-ecological systems (SESs). In the case of anthropogenic climate change, our demographer will need to consider SESs across all scales, from the individual household to global society.

The third major challenge is clarifying social values and their role in formulating the problem. Interest in anthropogenic climate change is growing around the world, not because of a rise in scientific curiosity, but because it poses an existential threat. Climate change is a very special and increasingly urgent *social problem*. However, if climate change is to be recast as a social problem, then researchers need to be clear and explicit about which and whose social values need to be taken into account and protected, and under what circumstances. Is the problem essentially a question of protecting human lives, livelihoods, lifestyles, or standards of living?

How do we weigh the interests of those currently living against the interests of future generations? And how do biodiversity and the health of ecosystems fit into the equation? The ethics of climate change are far from settled, but they appear to depend on much more than conventional cost-benefit analysis. Sensing the need to season the scientific consensus with some ethical reasoning, Working Group III of the IPCC invited two moral philosophers to join the team of lead authors to write chapter three of its report for the Fifth Assessment (the chapter is titled, 'Social, Economic, and Ethical Concepts and Methods'). To make a significant contribution to the policy debates surrounding climate change, our intrepid demographer will need to endogenize human values in her perspective and not focus simply on the empirical relationships between population and climate. The social problem that the global community wants to solve can only be adequately formulated and addressed with reference to human rights and values.

Having recognised the magnitude of these challenges, we can perhaps begin to understand why relatively few demographers are working on climate change. Moreover, the number of researchers is smaller in demography than in many other social sciences, and few of these researchers are trained in population and environment or in the demography of climate change. Most demographers choose subfields more firmly grounded in the discipline (and for which substantial funding is available), such as fertility (whether it is too high or too low), changing family structures, adolescence, labour force participation, the epidemiological transition, population ageing, urbanisation, and international migration. It is also worth noting that demographers are generally less inclined to rush into new fields of inquiry than some other social scientists, not because they are narrow-minded, but because they take their commitment to *empirical* science very seriously, and are not inclined to speculate on topics before they have adequate data. As Caldwell (1995) put it in his 1994 Borrie Lecture: "Demographers are more closely tied to the real world. They believe that most propositions – or at least important parts of them – can be quantified and that, once this is done, tests of validity can be devised. This is not always right, and it is a weakness as well as a strength, but it does prevent too many flights of fancy and it makes most demographers intelligible to others." It is therefore perfectly understandable that only a few demographers currently focus on climate change. Is this regrettable, and, if so, what can be done about it?

In 2011 the IUSSP established a new scientific panel on climate change (with a mandate to the end of 2014). The members were Susana Adamo, Wolfgang Lutz, Leiwen Jiang, and myself as chair. Our aims were to consolidate on-going research into population and climate change, and to encourage wider and deeper interest in climate change among our colleagues. The outcomes of our efforts are hard to quantify, but I believe we were largely successful. Our first international seminar, held in Canberra in November 2012, covered a wide range of issues concerning population dynamics and climate change. We concluded there is "a major window of opportunity at present for population research on climate change if we position our research vis-à-vis the new generation of climate scenarios" being used by the IPCC, specifically the so-called shared socioeconomic pathways (SSPs) (Hayes and

Adamo 2014). The SSPs can be thought of "as hypotheses arising about the relative importance of different processes in shaping mitigation and adaptation challenges" (Hunter and O'Neill 2014). A selection of the papers presented at the first seminar were published in a special issue of *Population and Environment* in March 2014. Our second seminar, held in Kao Lak in April 2014, focused specifically on adaptation research, and was hosted jointly by Chulalongkorn University and the Wittgenstein Centre. This seminar built on and expanded an already well-established research program focusing on differential vulnerability to natural disasters (Butz et al. 2014). Papers from this seminar are published in this special issue of the *Vienna Yearbook*. I believe these two special issues provide compelling evidence of the fruitfulness of research undertaken by demographers working on climate change today, and, perhaps even more importantly, they make a credible case that many more exciting research opportunities for demographers are likely to emerge in the future. Some previous attempts by demographers to enter environmental debates ended in frustration because it was not clear what demographers had to offer besides population estimates and projections (Caldwell 1995). The papers in these two volumes demonstrate overwhelmingly that this limitation no longer applies. As long as the current momentum in population and climate change research is maintained and the three major challenges mentioned earlier are addressed, it is, I believe, likely that many more demographers will be working in this area in the future.

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Two statements on population and sustainable development produced by global scientific panels in 2002 and 2012

Wolfgang Lutz*

When discussing the involvement of demographers in the analysis of population and climate change interactions, it is useful to remind ourselves that within the last 15 years there were two major attempts to summarize the state of the art on the role of population in sustainable development by high-powered international panels, and to communicate them to decision-makers at the highest levels. Such efforts were made in the context of decadal conferences of heads of states and governments convened by the United Nations System under the broad topic of 'Sustainable Development'. The first of these conferences, the 'Earth Summit', was held in 1992 in Rio de Janeiro under the chairmanship of Maurice Strong. Among the outcomes of this conference was the 'Framework Convention on Climate Change (FCCC)', which is the only binding global agreement on climate change that has been reached so far. Even the recent Paris climate change agreement of December 2015, in which countries agreed to limit global warming to relatively safe levels of less than two degrees Celsius (°C), is only partially legally binding.

In 2002, the leaders of the world gathered again in Johannesburg to assess the progress made since Rio, and to adjust their policy priorities. In preparation for this summit meeting, IIASA (International Institute for Applied Systems Analysis), together with the UNU (United Nations University) and the IUSSP (International Union for the Scientific Study of Population), and with financial support from the UNFPA (United Nations Population Fund), assembled a group of leading scholars working on population-related issues to produce a statement, which is given below. This Global Science Panel was under the joint patronage of Maurice Strong and Nafis Sadik, and was coordinated by Wolfgang Lutz and Mahendra Shah. A shortened version of this statement was also published in Nature (Lutz and Shah 2002). The members of the panel are listed as authors below.

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Ten years later, in preparation for the Rio+20 Conference in 2012, another high-level scientific panel was convened by IIASA with support from the UNFPA. The task was to re-assess, confirm, or complement the earlier statement to reflect the most recent state of research in this field. It was coordinated by Wolfgang Lutz and William Butz. The resulting statement is given below the first one. A shortened version of this statement was published in Science (Lutz et al. 2012).

The theme of this Special Issue is essentially in line with these two statements, which emphasize how population dynamics and demographic differences influence both human impacts on the environment and people's capacity to adapt to environmental change. The current issue of the Vienna Yearbook of Population Research includes vigorous empirical contributions that help us better understand the role of demographic challenges in achieving sustainable development, and that may be of use in designing differentiated policy responses that address the specific needs of population subgroups.

1 Population in sustainable development: Statement of a Global Science Panel in preparation of the Johannesburg Summit on Sustainable Development 2002

Members:
R. E. Bilsborrow, J. Bongaarts, P. DasGupta, B. Entwisle, G. Fischer, B. Garcia, D. J. Hogan, A. Jernelov, Z. Jiang, R. W. Kates, S. Lall, W. Lutz, F. L. MacKellar, P. K. Makinwa-Adebusoye, A. J. McMichael, V. Mishra, N. Myers, N. Nakicenovic, S. Nilsson, B. C. O'Neill, X. Peng, H. B. Presser, N. Sadik, W. C. Sanderson, G. Sen, M. Shah, M. F. Strong, B. Torrey, D. van de Kaa, H. J. A. van Ginkel, B. Yeoh, and H. Zurayk. 2002.

> *If we do not put the human population at the core of the sustainable development agenda, our efforts to improve human well-being and preserve the quality of the environment will fail. The Johannesburg Summit must heed the first principle of the 1992 Rio Declaration – that "human beings are at the centre of concern for sustainable development" – by taking full account of how population and society interact with the natural environment.*

Sustainable development aims at improving human well-being, particularly by alleviating poverty, increasing gender equality, and improving health, human resources, and stewardship of the natural environment. Because demographic factors are closely linked to these goals, strategies that consider population have a better chance of success.

The International Conference on Population and Development in Cairo in 1994 recognized that population policy should be oriented toward improving social conditions and expanding choices for individuals. The key recognition was that focusing on people – their rights, capabilities, and opportunities – would have multiple benefits for individuals, for society, and for their sustainable relationship with the environment. Hence in Johannesburg, consideration of sustainable development policies must include population growth and distribution, mobility, differential vulnerability, and the empowerment of the people, especially women.

A demographically diverse world

We live in a world of unprecedented demographic change. Global population increased by 2 billion during the last quarter of the 20th century, reaching 6 billion in 2000. Despite declining fertility rates, population is expected to increase by another 2 billion during the first decades of the 21st century. Nearly all of this growth will occur in developing countries and will be concentrated among the poorest communities and in urban areas.

We also live in a world of unprecedented demographic diversity. Traditional demographic groupings of countries are breaking down. Over the next 25 years increases in population in sub-Saharan Africa, South Asia, and the Middle East are expected to be larger than in the past quarter century, and growth in North America will be substantial as well. In contrast, in most European countries and in East Asia, population growth has slowed or stopped, and rapid population aging has become a serious concern. Mortality also varies widely across regions, with the burden of infectious disease, including HIV/AIDS, being particularly heavy in Africa. In addition, levels of mobility, urbanization, and education differ substantially among and within regions, affecting economic and health outlooks.

This diversity presents different challenges requiring differentiated responses. The most urgent of these occur where rapid population growth, high levels of poverty, and environmental degradation coincide.

Population matters to development and environment

Research has shown that changes in population growth, age structure, and spatial distribution interact closely with the environment and with development. Rapid population growth has exacerbated freshwater depletion, climate change, biodiversity loss, depletion of fisheries and other coastal resources, and degradation of agricultural lands. Fertility decline in high-fertility countries, by slowing population growth, can make many environmental problems easier to solve. It can also have important economic benefits by reducing the number of children relative to the working-age population, and creating a unique opportunity to increase investments in health, education, infrastructure, and environmental protection.

In high-income countries, the environmental impact of population growth and distribution must be considered jointly with high consumption rates. Even in countries where little growth is envisioned, unsustainable patterns of consumption have global implications for the environment and human well-being, and must be addressed with appropriate policies.

Before the end of this decade, the majority of the world's population will live in urban areas. Urbanization can improve people's access to education, health, and other services. But it also creates environmental health hazards, such as water and air pollution, and by increasing consumption levels, can have environmental impacts in distant rural areas as well.

The mobility and spatial distribution of populations, especially at local and regional scales, is a significant determinant of sustainability. Where the population lives and works relative to the location of natural resources affects environmental quality. The expansion of the agricultural frontier and other human activity is encroaching on fragile ecosystems in many parts of the world.

Policy must account for differential vulnerability within populations

Deteriorating environmental conditions and extreme events do not affect all countries, populations, or households in the same way. Even within a household, the effects may differ by age and gender. Consideration of vulnerability must therefore focus not only on countries but also on the most vulnerable segments of the population within countries.

Many factors contribute to vulnerability, including poverty, poor health, low levels of education, gender inequality, lack of access to resources and services, and unfavorable geographic location. Populations that are socially disadvantaged or lack political voice are also at greater risk. Particularly vulnerable populations include the poorest, least empowered segments, especially women and children. Vulnerable populations have limited capacity to protect themselves from current and future environmental hazards, such as polluted air and water and catastrophes, and the adverse consequences of large-scale environmental change, such as land degradation, biodiversity loss, and climate change.

Vulnerability can be reduced by promoting empowerment, investing in human resources, and fostering participation in public affairs and decision-making.

Empowerment through education and reproductive health benefits people and the environment

Two policies have multiple benefits for individual welfare, for social and economic development, and for the environment. One is investment in voluntary family planning and reproductive health programs. Since research has shown that many women in high fertility countries have more children than they actually want, these programs allow couples to have the number of children they desire, thus reducing unwanted childbearing and lowering fertility rates. Lower fertility leads to slower population growth, allowing more time for coping with the adverse effects of that growth, and easing stress on the environment.

The other top policy priority is education. Education enhances individual choice, fosters women's empowerment, and improves gender equality. Better-educated people are in better health, and often contribute to greater environmental awareness. The increased economic productivity and technological advance that education induces can lead to less pollution-intensive production. It may also reduce vulnerability to environmental change by facilitating access to information and the means to protect oneself. Furthermore, in countries with rapid population growth, the fertility-depressing effect of education contributes to reducing the scale of human impact on the environment.

These two policies – education and reproductive health programs – are in high demand by individuals almost universally because their multiple benefits are clear. They also empower individuals to make informed choices. Efforts to achieve sustainable development should give them the highest priority.

Strengthening interdisciplinary training and research

To facilitate the joint consideration of population, development, and environment, more interdisciplinary research and education addressing these topics is necessary at all levels. The different disciplines should also conduct their studies in ways that make the results mutually accessible. Training about the nature of these interactions is a priority issue for the policy-making community, media, and scientists.

2 Demographic challenges for sustainable development

The Laxenburg declaration on population and sustainable development

Members:
W. Lutz, W. Butz, M. Castro, P. DasGupta, P. Demeny, I. Ehrlich, S. Giorguli, D. Habte, A. C. Hayes, L. Jiang, D. King, D. Kotte, M. Lees, P. Makinwa-Adebusoye, G. McGranahan, V. Mishra, M. Montgomery, K. Riahi, S. Scherbov, P. Xizhe, B. Yeoh. 2011.

Statement of a Global Expert Panel (October 2011).

Human beings are at the centre of concern for sustainable development.

This was the view expressed in the 1992 Rio Declaration on Environment and Development, which we reaffirm. Therefore, consideration of the changing numbers, characteristics, and distributions of human beings on the planet must be at the core of any serious analysis of challenges and opportunities for sustainable development.

Any analysis of sustainable development must recognize the differences among people in terms of their impacts on the environment and their vulnerabilities to risk, which depend on their age, gender, location, and other socioeconomic characteristics. New evidence indicates that human capital, enhanced through education and health (including reproductive health), can make a substantial difference in people's contributions to sustainable development and their capacity to adapt to environmental change.

Only by accounting for and addressing demographic factors will it be possible to achieve sustainable development. Investments in human capital should be emphasized alongside other measures to promote sustainable development, a 'green economy', and adaptation to environmental change.

The current demographic divide

Over the last half century, world population has more than doubled, from 3 billion in 1960 to 7 billion today. Because of the young age structure in low- and middle-income countries, continuing population growth in the coming decades is a virtual certainty, even in the unlikely event that birth rates fall precipitously in these countries. Consequently, the world's population will very likely be between 8 and 11 billion by 2050, depending primarily on the speed of future fertility decline. But this population growth will not occur evenly across the globe.

Indeed, traditional demographic groupings have broken down. While the population of sub-Saharan Africa is likely to increase by a factor of three to five over the course of this century, Eastern Europe is already on a declining trajectory. China, due to its very rapid recent fertility decline, is likely to reach a peak population in 10–20 years and then enter an era of population decline. Along with China and other developing countries with low fertility, the industrialized countries face the challenges of population aging and changing living arrangements, including the adjustments that need to be made to social security and health care systems. Meanwhile, life expectancies are on the rise in most countries, even those worst hit by HIV/AIDS. Mortality decline is a long-term trend that research indicates will likely continue, both in countries where people now live the longest and in those where life expectancy is much shorter. Levels of mobility, urbanization, and education also differ substantially among and within regions, adding significant dimensions to the demographic divide.

Nearly all of the world's population growth will occur in the cities and towns of today's poor countries, primarily because of rural-to-urban migration combined with high national population growth. Meanwhile, the populations of many low-fertility countries will be declining. The demographic divide between rapidly growing urban populations in poor countries and slow growth or decline in industrialized countries is historically unprecedented.

These demographic differences fundamentally affect people's contribution to environmental burdens, their ability to participate in sustainable development, and their adaptability to a changing environment. Different demographic challenges require differentiated responses. The developmental challenges are by far the most significant where population growth and poverty are the highest, education is the lowest, and vulnerabilities to environmental change are the greatest. Negative impacts on the environment tend to be the most significant where people's material consumption levels are at their highest.

Demographic factors in the transition to a green economy

Efforts to meet the legitimate needs and aspirations of rapidly growing populations in developing countries and to reduce poverty will entail higher consumption and production; if inappropriately managed, these efforts will further increase pressure on the natural environment. As well as increasing carbon emissions through fossil fuel combustion with current technologies, population growth also often contributes to depletion and degradation of essential life-support systems, including deforestation, depletion of aquatic resources, air pollution, loss of biodiversity, and degradation of agricultural lands. It is important to reduce such negative impacts on the environment and the global climate in order to derive multiple benefits for local as well as global sustainable development. Fertility decline in high-fertility countries, by slowing population growth, makes many environmental problems easier to solve and development easier to achieve. Some of these benefits operate through the changing age structure that declining fertility induces. If the number of children relative to the working-age population is reduced, the demographic dependency ratio falls, creating an opportunity to increase investments in health, education, infrastructure, and environmental protection. It has been shown empirically that this demographic bonus, if properly utilized, can help propel countries out of poverty. Research in the last decade suggests that education increases people's life opportunities in general, greatly contributes to technological and social innovation, and creates the mental flexibility required for a rapid transition to a green economy. This applies to both low- and high-income countries. Hence, the enhancement of human capital from early childhood to old age through formal and informal education and life-long learning is now known to be a decisive policy priority. The majority of the world's population now lives in urban areas, and urbanization is certain to continue. As recent research has affirmed, urbanization often improves people's economic productivity and their access to education, health, and other services. However, urban population growth also presents challenges for urban planning and good governance: challenges that are especially acute in environmentally fragile locations. For the African and Asian countries where urban growth is most rapid, reducing vulnerability will require the urban transition to be achieved without the creation of undue environmental hazards or social inequality.

Investing in the tide of global youth

A striking demographic challenge is the rapidly increasing tide of young people entering the labor markets of developing countries with high aspirations but limited opportunities to find productive employment. Globally, there are 1.2 billion young men and women aged 15–24, the typical age for entering the labor market. And there are many more young people to come. In sub-Saharan Africa alone, the population aged 15–24 will likely increase from its current level of 170 million to 360 million by mid-century. With youth unemployment rates already high, assuring proper education and creating jobs for those hundreds of millions of young people are top priorities. If not given the chance for a decent life, these masses of young people without much hope for the future can pose a serious threat to social and political stability. But if they are provided with education and appropriate jobs, the young possess enormous potential for innovation, including the ability to adopt new technologies that accelerate economic progress and speed up the transition to a green economy. With a long life ahead of them, young people are likely to have genuine interest in sustainability because they themselves would experience the repercussions of unsustainable trends. Ages 15–24 are when people marry and begin to have children. Increasing education and employment will have a predictably major impact on fertility decline through postponed marriage and childbearing, thereby reducing future population growth in the developing world. Hence, ensuring appropriate investment in young people—which must begin in early childhood when the seeds of future development are planted—must be an essential component of broader policy packages to promote global sustainable development.

Differential vulnerability of people must shape appropriate policy

Environmental degradation and climate change do not affect all countries and all geographic regions in the same way. Vulnerability also varies significantly among people living in the same region, according to their socioeconomic circumstances. Even within a household, effects can differ importantly according to age and gender. Policies to reduce vulnerability must therefore focus on the most vulnerable segments of the population within countries and regions. Region-specific or even urban/rural-specific policies alone no longer suffice. Ignoring the more particular demographic dimensions of vulnerability will misdirect the focus of policy and dilute its impacts. The spatial distribution of populations among regions, between village and city, and across cities is a significant dimension of sustainable development. Migration within and between countries has always been an integral part of the human response to changing economic, social, and environmental conditions. This pattern is likely to continue, not only due to increased economic opportunities facilitated by improved information and transport systems and globalization of production and labor markets, but also exacerbated by population displacement and relocation due to environmental degradation and civil conflict. The principal demographic factors that increase vulnerability are poverty, poor health, low levels of education, gender inequality, declining family support for the elderly, and unfavorable geographic location. Populations with these characteristics also often lack a political voice, putting them at even greater risk.

Within these populations, women and children are usually the poorest and least empowered. Vulnerability is reduced and adaptive capacity enhanced where there is investment in poor people's human capital, particularly their education, and most particularly the education of girls and women, whose importance in these adoptive and adaptive processes is now known to be especially great. Policies that do not include features focused on these people will likely not succeed.

Five action implications for sustainable development

1. Recognize that the numbers, characteristics, and behaviors of people are at the heart of sustainable development challenges and of their solutions.
2. Identify sub-populations that contribute most to environmental degradation and those that are most vulnerable to its consequences. In poor countries especially, these sub-populations are readily identifiable according to age, gender, level of education, place of residence, and standard of living.
3. Devise sustainable development policies to treat these sub-populations differently and appropriately, according to their demographic and behavioral characteristics.
4. Facilitate the inevitable trend of increasing urbanization in ways that ensure that environmental hazards and vulnerabilities are under control.
5. Invest in human capital—people's education and health, including reproductive health—to slow population growth, accelerate the transition to green technologies, and improve people's adaptive capacity to environmental change.

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Differential mortality patterns from hydro-meteorological disasters: Evidence from cause-of-death data by age and sex

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Abstract

This paper evaluates the heterogeneous impact of hydro-meteorological disasters on populations along the dimensions of age, sex, and human development. The analysis is based on previously untapped cause-of-death data over the period 1995–2011 that were obtained from the WHO mortality database, and were based on the civil registration records of 63 countries/territories. Using these data, we evaluate patterns of mortality related to meteorological disasters in the spirit of model life tables. We observe that mortality rates from hydro-meteorological disasters for men are consistently higher than for women across all age groups, and that the differential by sex is larger for adults than for young children or the elderly. Furthermore, the sex differential in mortality becomes smaller with improvements in human development. Comparing our disaster fatalities with those recorded in the Emergency Events Database (EM-DAT), we find that the number of deaths from hydro-meteorological disasters was underestimated in the WHO database, especially in the case of high-impact events. In the paper we discuss issues of data quality and data harmonisation for the study of the differential demographic impact of natural disasters. One of our main goals is to stimulate an interdisciplinary debate in this area.

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1 Introduction

There is evidence that both the frequency and the intensity of extreme weather events, such as storms, floods, and droughts, have been increasing in recent decades (IPCC 2007), with floods being the most common type of natural disaster worldwide. In addition to having severe effects on livelihoods, property, and the economy; floods cause very large numbers of fatalities. Flooding is most commonly caused by heavy rainfall or by other weather events; in coastal areas in particular, flooding is often caused by storm surges associated with tropical cyclones. During the past three decades, up to 230,000 deaths worldwide have been attributed to floods, while an estimated 447,000 deaths have been linked to storms, particularly tropical cyclones (EM-DAT 2010). Although the death toll from individual flood or storm events is generally lower than it is from other destructive disaster events, like mega-earthquakes or tsunamis, the frequency of disasters resulting from floods and storms has increased in recent decades. Accordingly, in 2012 hydro-meteorological disasters were responsible for the largest share of natural disaster fatalities, accounting for 39% of global disaster mortality in that year (Guha-Sapir et al. 2013).

At first glance, the risk of death from storms and floods would appear to depend on their meteorological characteristics (e.g. the speed of onset, the scale, the duration, the velocity of the flow, and the depth of the water). However, the topography of the area, the land-use patterns, and the antecedent moisture conditions also matter (Ahern et al. 2005). In addition to geophysical characteristics, the level of economic development has been found to be significant in determining human and economic losses from natural disasters (Fankhauser and McDermott 2014; Toya and Skidmore 2007). Compared to more developed countries, developing countries generally suffer much higher death tolls from floods and cyclones because they often have poor infrastructure and badly constructed housing, high-density settlements, a lack of early warning systems, and poorly devised evacuation and shelter procedures (Doocy et al. 2013a). The fact that most deaths from cyclones in less developed nations are storm surge drowning fatalities that occur during the impact phase implies that deaths from storms are, to a certain degree, preventable (Shultz et al. 2005).

Likewise, it has been shown that flood- and storm-related mortality is not distributed evenly across population subgroups. Gender, age, ethnicity, and socio-economic status are reported to be associated with the risk of mortality from hydro-meteorological disasters. While most studies have found that the elderly are more vulnerable to floods (Jonkman et al. 2009; Myung and Jang 2011; Thacker et al. 2008), it has also been reported that very young children, especially in low-income countries, have higher flood-related mortality (Pradhan et al. 2007). Similarly, for storm-related deaths, both children and older adults are exposed disproportionately to higher mortality risks (Brunkard et al. 2008; Bern et al. 1993; Chowdhury et al. 1993). With respect to gender, in developed countries men are generally more likely to die from flood- and storm-related causes, whereas in less developed countries women appear to have a higher risk of mortality (Alderman et al. 2012; Doocy et al. 2013a, 2013b). In addition, studies have shown that flood-related mortality in different age groups is not distributed evenly between men and women: while the vast majority of females who die in floods are elderly women (Coates 1999), in many countries flood-related deaths are most common among adult men (Ashley and Ashley 2008; Coates 1999). Gender differences in risk-taking behaviours may account for observed differences in the mortality outcomes of men and women in certain types of natural disasters (Kruger and Nesse 2004).

Given that demographic characteristics play a significant role in determining risk exposure levels during hydro-meteorological disasters, identifying who is more likely to perish during floods and storms would allow for the implementation of appropriate risk reduction measures that target the relevant vulnerable groups. The existing empirical studies of demographic differentials in disaster-related mortality are, however, overwhelmingly based on hazard events in the United States (Ashley and Ashley 2008; Jonkman et al. 2009; Jonkman and Kelman 2005; Thacker et al. 2008) and a few other developed countries (FitzGerald et al. 2010; Coates 1999). The literature on age-sex differences in disaster-related fatalities in developing countries, where mortality registration systems often underreport deaths or are not widely available, is scarce. Likewise, there are only a few cross-national studies on demographic differential mortality from natural disasters that include both developed and less developed nations. In addition, most of the existing studies on the impacts of economic development on the scale of loss and damage from natural disasters do not consider how the level of development affects different population subgroups.

Accordingly, our aim in this study is to (1) estimate the impact of hydro-meteorological disasters (i.e. floods and storms) on mortality among different population subgroups, and (2) investigate the relationship between development and age-sex differences in reducing fatalities from hydro-meteorological disasters. We use a mostly untapped resource in the disaster literature: i.e. cause-of-death data by age and sex from the WHO (World Health Organization) Mortality Database. The estimation of hydro-meteorological disaster deaths from the WHO data is then validated with the commonly used disaster data source, the Emergency Events Database (EM-DAT). Principal component analysis is employed to describe age-sex patterns in mortality from floods and storms across 63 countries/territories from 1995 to 2011. Using this approach, we are able to describe age-sex mortality profiles related to hydro-meteorological disasters for many countries at the same time.

Furthermore, a first-difference approach is employed to estimate how changes in the level of development (measured by the Human Development Index) relate to changes in the mortality rates of men and women in different age groups. This identification of patterns of disaster-related mortality by age, sex, and level of development is particularly important, as understanding these patterns could help us anticipate the extent to which future societies will be able to cope with natural disasters as their demographic compositions and levels of socio-economic development change.

The remainder of the paper is organised as follows. In Section 2 we describe the data used for the analysis, while in Sections 3 and 4 we present the methods and the results. We first show the results from the WHO data, and then present a validation of our analysis by comparing our findings with the numbers of deaths from hydro-meteorological disasters reported by the EM-DAT. In Section 5 we discuss potential further uses of the WHO data, as well as the value of the kinds of analyses we performed. We close with a discussion and a summary of our results.

2 Data

2.1 Cause-of-death data by age and sex

To perform our analysis, we needed information on cause-specific mortality by age and sex. We identified a data source that has been almost untapped in the disaster literature: i.e. death registrations by age, sex, and cause of death. The data are published in a harmonised format by the WHO, which gathers vital statistics from civil registration systems submitted to the WHO annually by the national authorities of member countries. The database goes as far back as 1950. Numbers of deaths by country, year, sex, age group, and cause of death are provided. Causes of death are classified according to the International Classification of Diseases (ICD), a system of diagnostic codes developed to classify diseases and categorise medical terms reported by physicians and coroners on death certificates for international compatibility and statistical purposes. The most up-to-date revision of the ICD classification is ICD-10, which has been used by WHO member states since 1994. The data are freely available for download online via the WHO mortality database website.[1]

Disaster-related deaths are classified in ICD-10 under the label 'exposure to forces of nature'. This broad category includes deaths related to excessive natural heat or cold, earthquakes, volcanic eruption, landslides, etc. In the current study we consider two groups of causes, 'cataclysmic storm' (code X37) and 'flood' (code X38), which are natural hazards that are likely to become more common and more severe due to climate change (Nicholls 2004). These two categories include deaths that are both directly and indirectly related to hurricanes, storms, floods, tornadoes, and tidal waves. Direct mortality from floods and storms refers to deaths caused by the environmental force of a disaster (e.g. a storm surge, wind, and flooding). Indirect mortality refers to deaths attributable to unsafe conditions caused by a disaster (e.g. electrocutions from downed power lines and hazardous roads) or by a loss or a disruption of usual services caused by a disaster (e.g. loss of electrical services). We have data on mortality from 'cataclysmic storm' and 'flood' for 63 countries/territories for the period 1995–2011. Figure 1 shows a map of countries

[1] http://www.who.int/healthinfo/mortality_data/en/

Figure 1:
Map of countries where data on causes of death related to 'cataclysmic storm' (X37) and 'flood' (X38) are available in WHO ICD-10 (1995–2011)

for which data are available in ICD-10. The sample is skewed towards high-income countries that have efficient vital registration systems and most countries in Latin America. However, a few developing countries in southeast Asia and Africa are also included.

2.2 Mortality from natural disasters data

Maintained by the Centre for Research on the Epidemiology of Disasters (CRED) since 1988, the Emergency Events Database (EM-DAT) is a database that has been compiled specifically to monitor disasters worldwide. In addition to having data on disasters that have occurred across the world from 1900 to the present, the EM-DAT also contains information on loss and damage, including the number of people killed and the number of people affected in a particular disaster. The data are collected from various sources, with priority given to data from UN agencies, followed by data from the Office of U.S. Foreign Disaster Assistance (OFDA), national governments, and the International Federation of Red Cross and Red Crescent Societies. An event qualifies as a disaster and is included in the EM-DAT database if it fulfils at least one of the following criteria: 1) 10 or more people are reported killed, 2) 100 or more people are reported affected, 3) the government declares a state of emergency, or 4) the government appeals for international assistance.

While both natural disasters and technological disasters are recorded in the EM-DAT, here we focus only on mortality from hydro-meteorological disasters, i.e. floods and storms. This allows us to compare deaths from floods and storms registered in the WHO data with those in the EM-DAT data for each country.

3 Patterns of flood and cataclysmic storm mortality

3.1 Methods

We identify patterns of mortality by age and sex from cataclysmic storms (X37) and floods (X38) using data from the WHO database. Our method is based on classic demographic approaches developed in the context of model life tables. We use an approach inspired by the Lee and Carter (1992) model for forecasting mortality in the United States and the model life table system for sub-Saharan Africa (INDEPTH Network 2004). Since we are interested in the distribution of deaths related to storms and floods by age for each sex respectively, we subtract the average profile of deaths by age for all countries from the number of deaths for a given age group a during the year t for each geographic region among all of the 63 countries/territories in the ICD-10 database. We then model this quantity as the product of age-specific profiles and time-variant indexes:

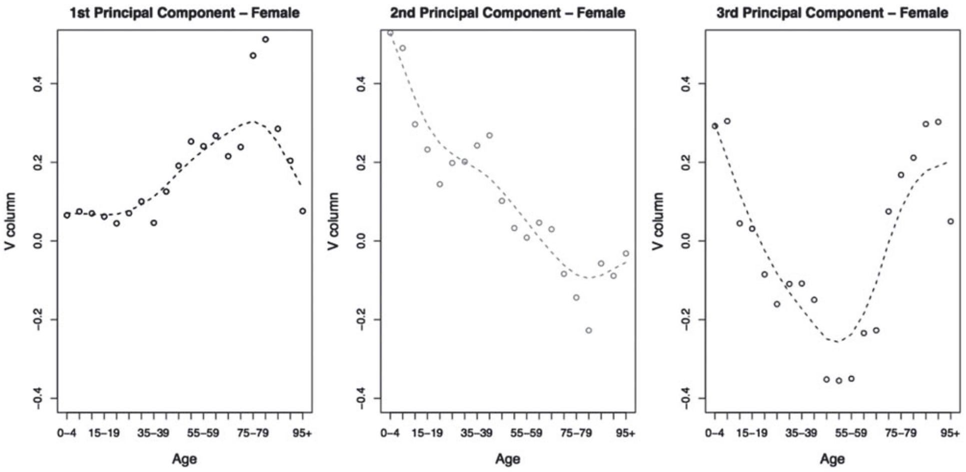
$$D^{i}_{(a,t)} - D_{(a,t)} = B_{1(a)}k_{1(t)} + B_{2(a)}k_{2(t)} + B_{3(a)}k_{3(t)} + e \tag{1}$$

where $D^{i}_{(a,t)}$ is the number of deaths related to hydro-meteorological disasters in country i, for age group a, during year t. $D_{(a,t)}$ is the average number of deaths related to hydro-meteorological disasters for age group a, during year t, across all countries considered. $B_{1(a)}$, $B_{2(a)}$, and $B_{3(a)}$ are vectors of age profiles of deaths associated with the first, the second, and the third principal components of the demeaned death data, respectively. $k_{1(t)}$, $k_{2(t)}$ and $k_{3(t)}$ are vectors of time trends.

In order to estimate the B and k terms, we use Principal Component Analysis (PCA), which is equivalent to a Singular Value Decomposition (SVD) on the demeaned profiles of deaths by age and sex for all countries in the dataset. The goal is to summarise the available data in order to extract meaningful information about profiles by age for the available countries. The analysis is done for men and women separately. Our approach is consistent with a long history of demographic modelling of age schedules. For a detailed explanation of the estimation procedure, the relationship between SVD and PCA, as well as a presentation of a number of demographic applications, see Clark (2015).

We decided to use the first three principal components, as they explain a relatively large proportion of the variance (~50%) in the observed profiles, and allow for a simple demographic interpretation. Including more components would explain a larger proportion of the variance, but would not provide additional insights. We thus decided to use a relatively parsimonious model. The main reason why the first principal components do not explain a larger portion of the variance is that because disasters are relatively rare phenomena, the data contain a large number of age-country-year combinations with zero deaths. As a result, the overall variance of the data points is quite large. In other words, the data are very noisy, and for a number of countries we may observe spikes in the number of deaths due to a single event, followed by several years of very low death counts.

Figure 2:
First three principal components of demeaned number of deaths related to floods and cataclysmic storms for females. Dashed lines represent smoothed values



Source: Own calculations based on ICD-10, WHO mortality database.

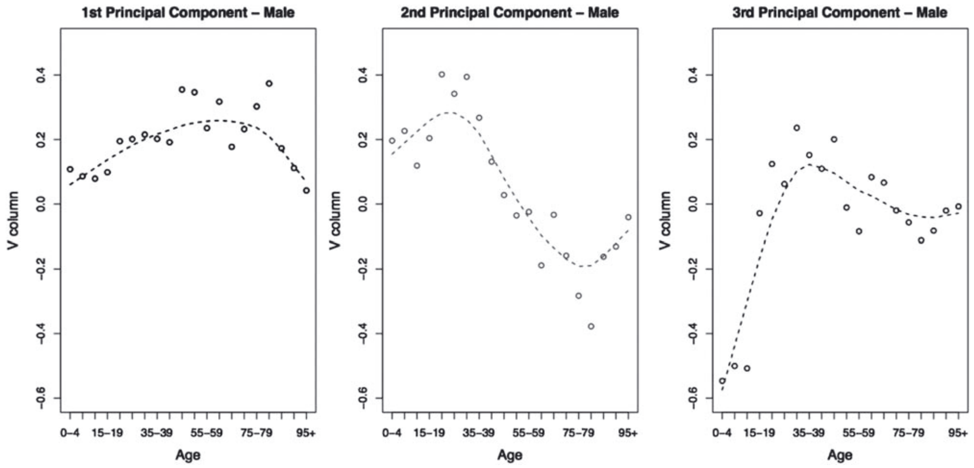
3.2 Results

Figure 2 shows the first three principal components of the demeaned number of deaths related to floods and cataclysmic storms for females. The first component indicates a death profile by age that is strongly skewed towards the elderly. The second component is skewed towards young children. The third component emphasises this bimodal distribution of deaths by having negative values for observations for adults and positive values for children and the elderly.

Figure 3 shows the first three principal components of the demeaned number of deaths related to floods and cataclysmic storms for males. The first component shows that storm- and flood-related mortality for males spreads out rather evenly across age groups. The second component is moderately skewed towards very young children. The third component reveals a relatively large number of deaths for adult males that are not observed for females.

The mortality profiles by age differ considerably between men and women. While the three principal components for females together show that most deaths from floods and storms typically occur among young girls and elderly women, the male death profile shows a somewhat different pattern, with mortality being higher among adolescent and adult males. This bump in the number of deaths among male adults may be attributable to a greater proneness to risky behaviour or a lower ability to assess risks among males than among females (Byrnes et al. 1999; Croson and Gneezy 2009). In addition, because men are more likely than women to engage in outdoor work and leisure activities, they are more exposed to natural hazards, such as flood and storm events.

Figure 3:
First three principal components of demeaned number of deaths related to floods and cataclysmic storms for males. Dashed lines represent smoothed values



Source: Own calculations based on ICD-10, WHO mortality database.

The first three principal components account for more than 50% of the variance in the data and capture the key summary profiles of mortality from floods and storms for men and women. The observations have very high levels of variance because of the nature of disaster data. For some countries, we observe only a small number of deaths over the course of several years, resulting in a large number of age-specific cells that contain zeroes. The additional principal components explain the remaining variance due to the large number of zeroes in the data, but do not have any relevant structure, and do not add much information to our analysis.

We also evaluated the first three principal components of death rates in addition to looking at death counts. When we consider mortality rates, the results are qualitatively similar. However, a larger proportion of the variance is explained by a first principal component that captures old-age mortality for both men and women. The combination of high disaster death counts among the elderly with relatively small population sizes for older age groups leads to an increased emphasis on old-age mortality. Ideally, we would have data on deaths and the numbers of people exposed to risk. We do not, however, have that information; we only have data on country-level population size by age and sex, as available from the World Population Prospects: the 2012 Revision (United Nations 2013). Thus, even major events like Hurricane Katrina may have small effects on mortality rates when the denominator is the entire U.S. population. Likewise, relatively small floods or storms may have large effects on the mortality rates of small countries, even when the death counts are not high. Death counts and death rates have different advantages and disadvantages in the context of our analysis. In this section, we emphasised results based on death counts. In the next section, we will look more closely at death rates.

Gender differences in mortality from floods and storms

The principal component analysis indicates that there are substantial differences in the age-specific mortality profiles of men and women. However, the PCA does not allow us to quantify whether men have higher or lower mortality rates from floods and storms than women. In the subsequent analysis, we therefore compare the age-specific mortality rates from hydro-meteorological disasters of men and women for each country over the period 1995–2011. Figure 4 presents the results from selected countries that represent the general patterns of hydro-meteorological disasters by age and sex, in terms of both death distribution and death rates per 1000 of population.

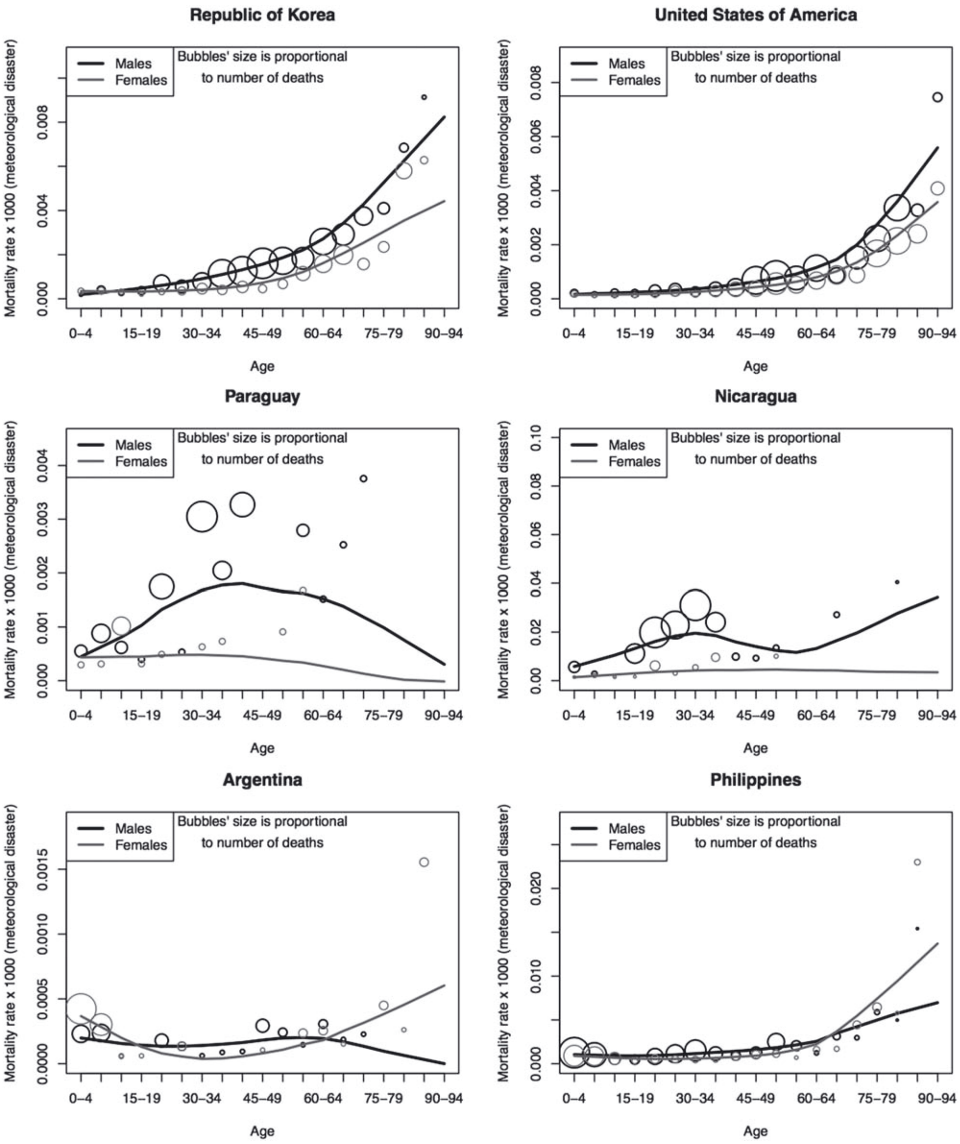
Countries in which a higher proportion of the population are elderly, such as South Korea, Japan (not shown), and the United States, show a monotonic increase in mortality with age. Most of the deaths occur among adults or the elderly, with more male fatalities occurring among the older age groups in particular. Paraguay, Nicaragua, and Cuba (not shown) are examples of the second pattern, in which the highest mortality rates and the largest numbers of deaths are among male adults. In Argentina, the Philippines, Mexico, Brazil, and Guatemala (not shown), the largest numbers of deaths from the hydro-meteorological disasters are, in absolute terms, of young children. In Argentina, Mexico, and Brazil, the mortality rates are higher among young children and the elderly, especially females. But in the Philippines and Guatemala, which have young population age structures, the mortality rates for young children are not very high, even though the largest numbers of deaths are, in absolute terms, of children.

Turning to gender differences in fatalities from floods and storms for all countries with $\geq$10 deaths over the period 1995–2011, as presented in Figure 5, we find that in most countries the absolute number of deaths is larger for males than for females. Men might be more vulnerable to flood- and storm-related mortality than women because they generally exhibit more risky behaviours and engage in more dangerous activities than women. Note that for most countries, the number of deaths from floods and storms does not exceed 200 in the period observed. However, in tropical cyclone-prone areas such as Mexico, Japan, the Philippines, and the United States, the numbers of registered deaths from floods and storms are large, and male mortality levels are always higher than female mortality levels.

4 Meteorological disaster mortality and development

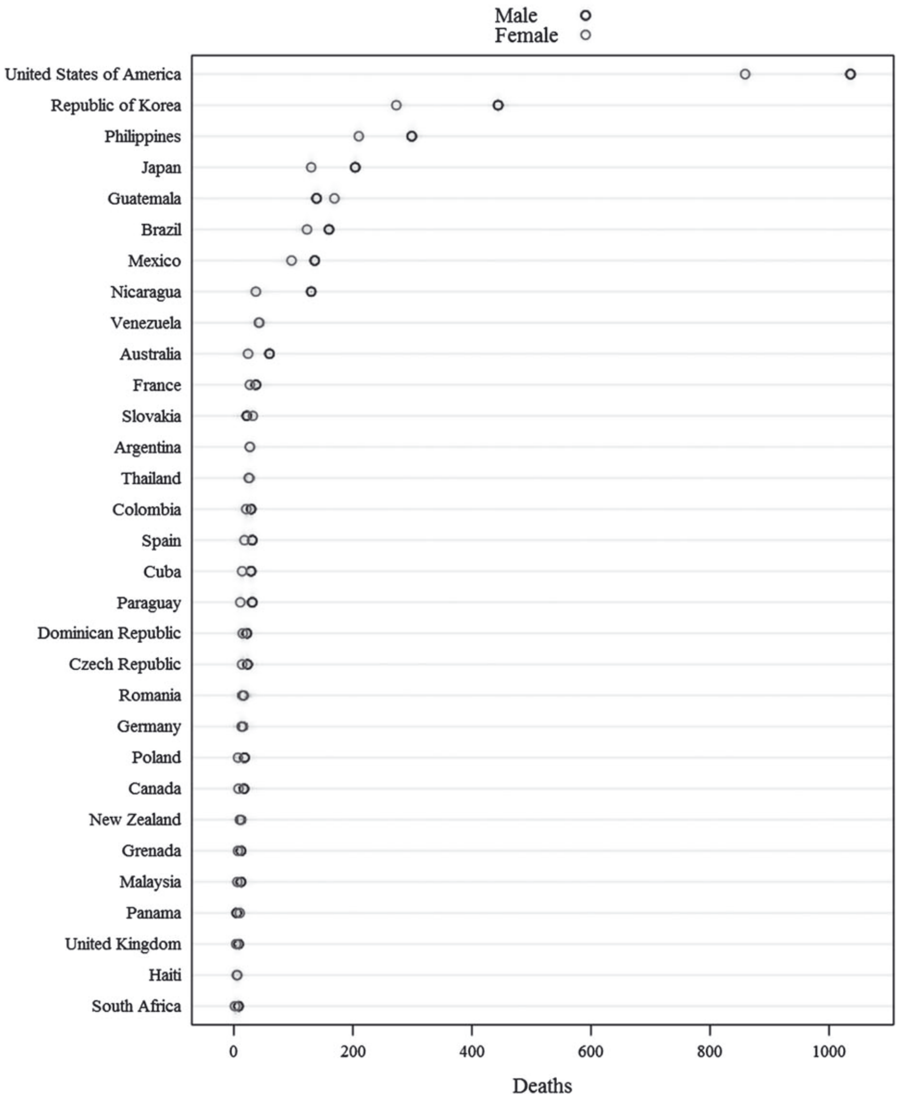
Having found evidence for a gender difference in mortality from hydro-meteorological disasters, we examine the question of whether the observed reduction in loss of life due to economic development follows the same patterns for men and women and for different age groups. Development is measured by the UNDP Human Development Index (HDI), a composite index of life expectancy, educational levels, and economic prosperity. In order to have a larger sample that

Figure 4:
Profiles of flood and cataclysmic storm mortality for selected countries, by age and sex. The bubbles indicate mortality rates (× 1000). The size of the bubbles is proportional to the actual number of deaths and has been rescaled for each country separately. Thus, comparisons of number of deaths across countries, based on the size of the bubbles, are not possible. The solid lines are the smoothed values



Source: Own calculations based on ICD-10 WHO mortality database (for death counts) and UN WPP 2012 (for population counts).

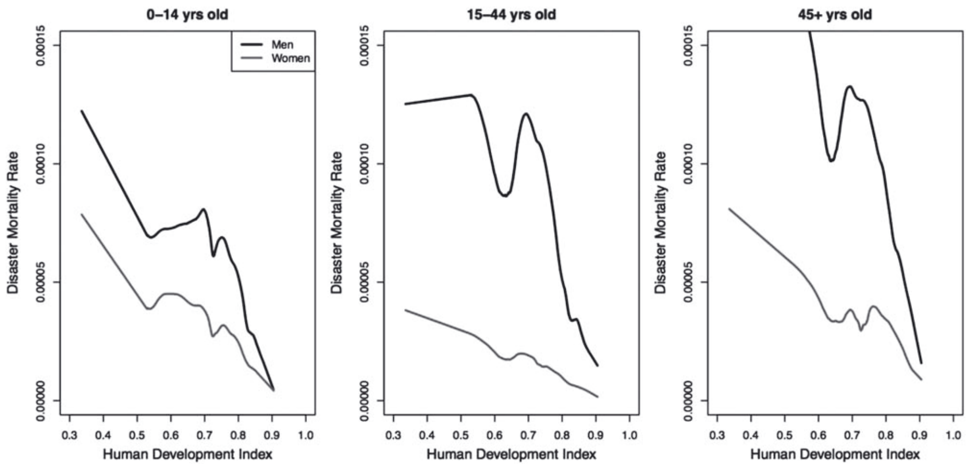
Figure 5:
Total number of deaths from floods and storms by gender for selected countries with ≥ 10 deaths over the period 1995–2011



Source: Own calculations based on ICD-10 WHO mortality database.

covers a longer time period than the ICD-10 data alone can provide, we include data from three previous classifications: ICD-7, ICD-8, and ICD-9. Those datasets extend as far back as 1970. However, in the older versions of the ICD, deaths related to cataclysmic storms or floods were not classified with a specific code. Thus, we select causes of death potentially related to meteorological disasters; i.e.

Figure 6:
Relationship between meteorological disaster mortality and Human Development Index, by age and sex



'accidental drowning and submersion'. Since drowning accounts for the majority of the fatalities from floods, and, to a lesser extent, storms (Jonkman and Kelman 2005), deaths from drowning may naturally increase in the event of flash floods and coastal floods.

Figure 6 presents the relationships between the HDI and hydro-meteorological-related deaths by age groups (i.e. aged <15 years, 15–44 years and ≥45 years) and gender. We observe a strong negative correlation between hydro-meteorological disaster mortality and the HDI that holds across all age groups. With respect to gender, we find that although mortality rates are higher for men than for women, the speed of change for males is, on average, faster. Thus, we expect that differences by gender will become narrower across countries as human development increases.

In order to statistically quantify the relationship between hydro-meteorological disaster mortality and the HDI, we estimate a first-difference type model, with indicator variables for age groups and sex:

$$\begin{aligned}(d_{ia,t} - d_{ia,t-1}) = B_0 + B_1(\mathrm{HDI}_{ia,t} - \mathrm{HDI}_{ia,t-1}) + B_2 I_{\mathrm{F}} + B_3 I_{\mathrm{F}}(\mathrm{HDI}_{ia,t} - \mathrm{HDI}_{ia,t-1}) \\ + B_4 I_{0-15} + B_5 I_{0-15}\mathrm{HDI}_{ia,t} + B_6 I_{45+} + B_7 I_{45+}\mathrm{HDI}_{ia,t} + e \qquad (2)\end{aligned}$$

where $d_{ia,t}$ is the hydro-meteorological disaster death rate (per 1000 people) for country i, population subgroup a (age and sex), at time t. I_{F} is a dummy variable for females, I_{0-15} is a dummy variable for age group 0–15, and I_{45+} is a dummy variable for the age group 45 and above. Death rates were computed using data on mid-period population size as the denominator. These data come from the World Population Prospects: the 2012 Revision (United Nations 2013). Table 1 presents the results from the first-difference estimator of mortality rates from floods and storms, controlling for changes in the level of HDI.

Table 1:
First-difference estimates of mortality rate (× 1000) from meteorological disasters given changes in the Human Development Index. The model is estimated using data from ICD-7, ICD-8, ICD-9, and ICD-10 for 81 countries, for the period 1970–2010

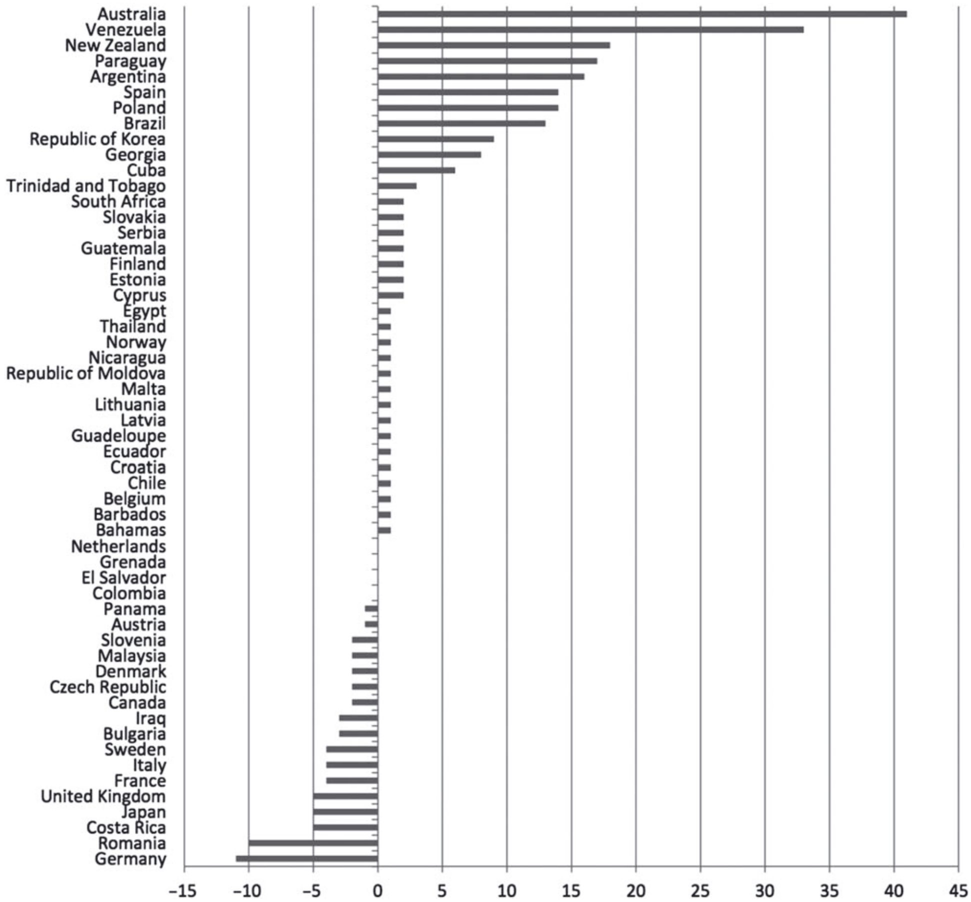
Variable	Coefficient estimate	*p*-value
Intercept	-0.0098^{*}	0.0188
Difference in HDI	-0.7380^{***}	0.0000
Female	+0.0011	0.1155
Female × Difference in HDI	$+0.5550^{***}$	0.0000
Age 0–15	+0.0047	0.4299
Age 0–15 × HDI	−0.0060	0.4422
Age 45+	−0.0056	0.3336
Age 45+ × HDI	+0.0060	0.4666

Note: The data used for this analysis include the following causes of death: victim of cataclysmic storm, all places (ICD-10: X37); victim of cataclysmic flood, all places (ICD-10: X38); accidental drowning and submersion (ICD7: A146; ICD9: B521,C096; ICD10: 1098); accident caused by fire and explosion of combustible material (ICD7: A143); accidents due to natural and environmental factors (ICD9: B520, C095).

We found the coefficients B_1 and B_3 to be highly significant. These results confirm our observations based on visualisations of trends in Figure 7. There is a strong negative relationship between the mortality rate and the HDI. The slope is less steep for women than for men. The estimated coefficients for age groups are not statistically significant. However, we observe that the coefficient for the interaction of age group 0–15 and the HDI is negative, whereas the coefficient for the age group 45+ is positive. These findings may be interpreted as showing that mortality patterns are shifting with development: as development increases, disaster mortality rates may be expected to decrease at a faster pace for children than for the elderly, relative to the adult population.

It is important to highlight that the statistical analysis that we presented is intended to provide a quantitative summary of the trends observed in Figure 6. Using a first-difference model allows us to account for individual country effects. However, there are a number of limitations that we would like to acknowledge. The adjusted R^2 for the first-difference model is quite small, at 2%. This indicates that the ability of the model to explain the variance in the data is quite limited. As we described above, our analysis relies on data for ICD classifications 7, 8, 9, and 10. Classifications based on ICD 7, 8, and 9 do not include a clear distinction between hydro-meteorological mortality and other related causes of death, like drowning. Therefore, we might be overestimating the effect of development on hydro-meteorological mortality. We ran the same model (described in equation 2) on data from ICD-10 only for countries and years with HDI values greater than 0.7. We observed that from a qualitative point of view, there is still a negative

Figure 7:
Absolute differences in the number of meteorological deaths reported by WHO and EM-DAT when there were < 10 deaths per single disaster event



relationship between mortality and HDI values, and between first differences in mortality and first differences in HDI values. However, none of the coefficients in our regression model are statistically significant. The lack of statistical significance is likely to be related to the reduced sample size. Moreover, as we discuss in the next sections, estimates of mortality rates from floods and storms in the WHO ICD-10 database tend to underestimate mortality more for relatively low HDI levels. As the underestimation is potentially greater for low HDI levels, a regression analysis that is based on ICD-10 data only may be expected to generate a flatter and less significant slope for the relationship between hydro-meteorological mortality and HDI values. We felt that including additional data sources would be sensible in this situation. However, it is important to be aware that adding more data sources could lead to an overestimation of the effect of development on hydro-meteorological mortality. In sum, we cannot provide definitive evidence regarding the relationship between development and meteorological disaster mortality. Nonetheless, we hope that our analysis represents a first step in that direction. Further research with additional datasets is needed to consolidate our initial findings.

5 Validating deaths from hydro-meteorological disasters estimated from the WHO database

To our knowledge, this is the first time the WHO mortality database has been used to estimate age-sex differentials in deaths from hydro-meteorological disasters. However, since the WHO mortality data are based on cause-of-death statistics obtained from country civil registration systems, fatalities from natural disasters might be undercounted, especially deaths that are only indirectly related to floods and storms, such as fatal car accidents, heat stroke, heart attacks, or other conditions associated with a lack of medical supplies; unsafe conditions; or a disruption of usual services. Such deaths are typically not linked to the original disaster in countries' civil registration systems. In this section, we compare the aggregated number of deaths from floods and storms reported by the WHO with those recorded by the EM-DAT over the period 1995–2011 for each country with available data.

Figure 7 presents the differences in the absolute number of hydro-meteorological disaster-related deaths reported by the WHO and the EM-DAT when deaths in the WHO database were <10. In most countries (34 countries), the number of fatalities from floods and storms identified was greater in the WHO database than in the EM-DAT. In 17 countries, the number of flood- and storm-related deaths was found to be higher in the EM-DAT data, but the difference in most countries (15 countries) was no greater than five deaths in absolute terms. The number of fatalities was the same in the WHO database and the EM-DAT for four countries: Colombia, El Salvador, Grenada, and the Netherlands.

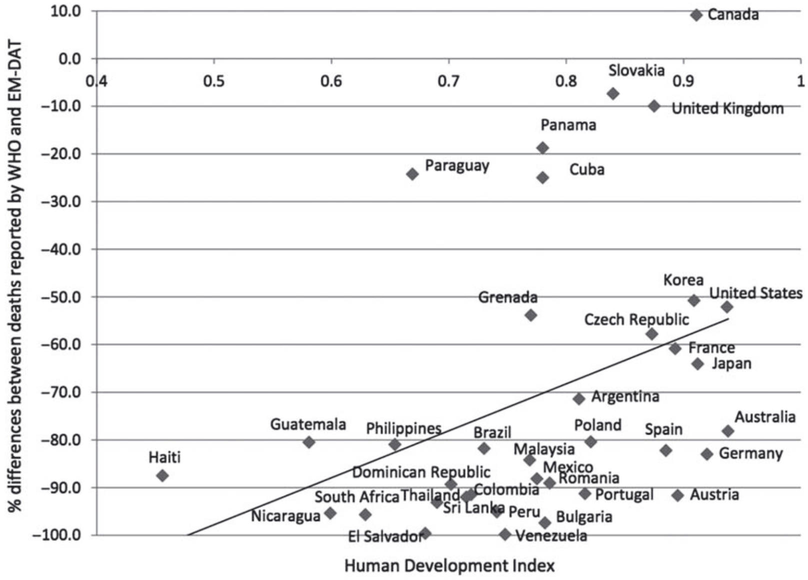
On the other hand, in cases of 10 or more reported deaths, the differences between the WHO and EM-DAT data are in the opposite direction. Table 2 presents a list of countries with ≥10 deaths per disaster event from meteorological disasters, including the percentage difference between the number of deaths reported by the WHO and the EM-DAT data sources. Except for Canada, the numbers of deaths from floods and storms reported by the WHO over the period 1995–2011 were monotonously lower than the numbers reported by the EM-DAT for the remaining 35 countries. The percentage differences ranged from as small as −7.0% to −99.9%.

Deaths from low-impact meteorological disasters were undercounted by the EM-DAT due to the nature of the CRED's data collection procedures. One criterion used by the CRED for determining whether an event qualified as a disaster is that 10 or more people are killed in a particular event. Thus, based on this definition, small disaster events are underrepresented in the EM-DAT database.

Table 2:
Number of deaths from floods and storms reported by WHO and EM-DAT over the period 1995–2011 for each disaster event with ≥10 deaths in WHO database

Country	WHO	EM-DAT	% difference
Canada	12	11	9.1
Slovakia	50	54	−7.4
United Kingdom	9	10	−10.0
Panama	13	16	−18.8
Paraguay	25	33	−24.2
Cuba	15	20	−25.0
Republic of Korea	708	1439	−50.8
United States of America	1895	3958	−52.1
Grenada	18	39	−53.8
Czech Republic	27	64	−57.8
France	63	161	−60.9
Japan	314	874	−64.1
Argentina	38	133	−71.4
Australia	12	55	−78.2
Poland	9	46	−80.4
Guatemala	306	1571	−80.5
Philippines	509	2678	−81.0
Brazil	263	1447	−81.8
Spain	11	62	−82.3
Germany	17	100	−83.0
Malaysia	12	76	−84.2
Haiti	11	88	−87.5
Mexico	233	1967	−88.2
Romania	26	238	−89.1
Dominican Republic	37	347	−89.3
Portugal	4	46	−91.3
Colombia	43	506	−91.5
Austria	1	12	−91.7
Sri Lanka	2	25	−92.0
Thailand	50	727	−93.1
Peru	4	82	−95.1
Nicaragua	166	3601	−95.4
South Africa	8	186	−95.7
Bulgaria	1	39	−97.4
El Salvador	1	275	−99.6
Venezuela	39	30117	−99.9

Figure 8:
Relationships between percentage differences in hydro-meteorological deaths reported by WHO and EM-DAT when deaths were ≥10 per single disaster event and HDI. Pearson's *r* = 0.374, *p* = 0.025



On the other hand, we find that in the WHO database the numbers of deaths from high-impact disaster events are systematically lower. While the WHO mortality database relies on civil registration data from the respective national authorities, the CRED obtains death estimates from various sources, both official and non-official. The number of fatalities might be overestimated or underestimated for a number of reasons, such as in order to attract international assistance or to cover up disaster management failures. Another reason for the discrepancy between the WHO and the EM-DAT data is related to how missing persons (i.e. people whose bodies were not recovered) are recorded. In some disaster events this number can be very high, but unlike the CRED, the WHO database does not include these cases.

One extreme example of a discrepancy between the numbers of deaths recorded by the WHO database and the EM-DAT is the case of Venezuela: for this country, the EM-DAT reported 30,117 deaths from hydro-meteorological disasters, whereas the WHO database reported only 37 deaths. This enormous gap between the two datasets is due to a single storm event in December 1999, in which heavy rainfall triggered thousands of landslides on steep slopes of the Sierra de Avila north of Caracas, as well as flooding and massive debris flows in the State of Vargas along the Caribbean coast. The early estimated death toll was between 5,000 and 50,000, while the figure that is now generally recognised as accurate is around 30,000 (the number recorded by the EM-DAT) (Wieczorek et al. 2001). The WHO database does not report the deaths of people who were buried in the landslides or swept away to sea by the mud, debris flows, and flooding, since the vast majority of bodies were never recovered, and were therefore not registered as deaths in the standard vital registration system. Moreover, an accurate assessment of the exact number of people who perished was impossible due to the lack of recent census figures for Vargas in the period before the disaster event.

In developed countries with much better civil registration and vital statistics systems (Mahapatra et al. 2007), it is possible that the discrepancies in the numbers of fatalities reported by the WHO mortality database and the EM-DAT are smaller. Accordingly, we display in Figure 8 a scatterplot of the relationship between the HDI and the percentage differences between the number of deaths reported by the WHO database and the EM-DAT over the period 1995–2011. The relationship between the two factors is significant and positive (Pearson's $r = 0.374$, $p = 0.025$). This suggests that the higher the HDI, the smaller the discrepancy between the numbers of fatalities documented in the WHO database and the EM-DAT.

6 Discussion

Using the age- and sex-specific cause-of-death data from the WHO cause-of-death mortality database, we estimated patterns of differential hydro-meteorological disaster mortality, as well as their relationships with levels of societal development. The first objective of the study was to describe age-sex differentials in mortality patterns from floods and storms. We observed heterogeneous patterns of mortality that could be summarised in the spirit of model life tables as constituting three main families. In some countries, children and the elderly—and especially girls and older women—were the most affected groups. In other countries, male adults were at highest risk of death from meteorological disasters.

When focusing on the aggregated number of flood- and storm-related deaths by sex, we found that in almost all countries male fatalities were higher than female fatalities. This finding contradicts previous results on deaths from natural disasters by Neumayer and Plümper (2007), who reported that more women were killed than men, and that women were killed at younger ages than men. Apart from the fact that we only considered flood and storm events while Neumayer and Plümper included all types of natural disasters, our study estimated mortality by gender directly using sex-specific death records from the WHO mortality database, whereas Neymayer and Plümper estimated sex-specific fatalities using data on the gender gap in life expectancy, while taking into account the intensity of each disaster. Hence, it is plausible that women are not always more vulnerable to natural disasters than men, especially in the context of disasters such as floods and storms, in which men are more likely than women to engage in active risk-taking behaviour, and to be exposed to the disaster. For example, the fact that men are more likely to be engaged in outdoor work or leisure activities than women (Bradshaw 2004) could play a role in determining mortality. In contrast, in sudden-onset disasters like earthquakes or tsunamis, mortality tends to be higher among women than men.

The second important goal of our study was to investigate the relationship between development and disaster mortality, and how this relationship differs by age and gender. Consistent with previous studies (Patt et al. 2010; Striessnig et al. 2013), we found a strong negative relationship between mortality and development, as measured by the HDI. Our study further adds to extant findings that the decline in mortality rates from hydro-meteorological disasters occurred at a faster pace for men than for women. Meanwhile, we found no strong evidence that the speed of the reduction in mortality rates, given a change in the HDI, differed between age groups. Our finding that the mortality reduction corresponding to improvements in the HDI was greater for men than for women could be due to unequal access to resources, whereby men were able to benefit more than women from socio-economic development (Denton 2002; Nelson et al. 2002). This result could also be related to the fact that mortality rates from meteorological disasters were simply higher for men than for women, which implies that there is more room for improvement for men than for women.

The finding that countries that are more developed, as measured by the HDI, tend to experience lower levels of disaster mortality suggests that development could play a key role in reducing vulnerability to natural disasters. The factors that drive development (e.g. health, education, income) tend to be protective factors against disasters as well. However, the whole chain of causal relationships is not completely clear. More educated people may have a better understanding of the risks associated with disasters than their less educated counterparts (Muttarak and Lutz 2014, Lutz et al. 2014). People with higher socio-economic status may have more resources to protect themselves or to escape from disaster-prone areas than those with lower status (Fussell et al. 2010). Richer societies may have means to prepare for disasters and to co-ordinate interventions that poorer societies lack (Kahn 2005). Being in good health could increase the probability of survival during disastrous events (Brooks et al. 2005). Moreover, levels of exposure to the risks associated with disasters may be lower in more developed countries than in less developed countries. Regardless of the specific mechanisms at play, from a policy perspective it is important to consider development as one of the tools for enhancing the capacity of societies to adapt to future climate change, and to the more frequent extreme weather events that are expected to result from climate change.

Using the WHO mortality database, we were able to identify which demographic groups are more vulnerable to meteorological disasters, and whether the impact of development on disaster-mortality reduction varies between gender and age groups. However, the WHO data are not without limitations. First, although the WHO mortality database is the most respected official source for comparative analyses we are aware of, the sample of countries is biased. Developing countries with poor or non-existing civil registration systems are not represented, and our results should not be generalised to those countries. Indeed, it has been shown that flood and storm mortality is concentrated in the less developed and heavily populated nations of southeast Asia and the western Pacific (Doocy et al. 2013a, 2013b), where WHO data are scarcely available. The demographic differentials in flood- and storm-related mortality observed in this study could thus be biased. For instance, if women are more likely to die from hydro-meteorological disasters in less developed countries, our analysis would not have been able to capture such a mortality pattern.

Second, since the age- and sex-specific cause-of-death data provided by the WHO are obtained from civil registration systems, the number of fatalities from hydro-meteorological disasters may have been undercounted owing to 1) how the cause of death was identified and 2) whether there were large numbers of missing persons associated with a disaster event. Indeed, our validation procedures for comparing the numbers of fatalities reported by the WHO with those reported by the EM-DAT showed that, especially in high-impact disaster events, the WHO database systematically reported lower numbers of deaths than the EM-DAT. If this bias in disaster mortality was distributed evenly across population subgroups, our analysis of age-sex differentials in mortality patterns would still be valid, since our interest was in demographic profiles of deaths rather than the absolute numbers of deaths *per se*. Given the lack of other global data sources, we were unable to directly test if this was the case. It should be noted that it is also possible that deaths were underreported in the EM-DAT for some countries, especially those in Africa where data reporting is poor (Guha-Sapir and Hoyois 2012). If this is the case, the true number of fatalities from floods and storms identified in the WHO mortality database would be even lower than our estimates.

Third, although mortality is an indicator of disaster impact that is directly measurable, fatalities from natural disasters have become more preventable with social and economic development, and disaster-related mortality has declined over time (Goklany 2009). Subsequently, in the absence of high-impact disasters, mortality might not be a valid indicator of natural disaster impacts. In addition to having direct effects, floods have a number of indirect effects, including morbidity and livelihood disruption, which may be associated with additional, unaccounted mortality. Although these indirect effects are important, they are less important than the direct effects. Direct mortality, like mortality related to drowning, accounts for the great majority of fatalities from hydro-meteorological disasters. Non-mortality measures, like economic damage or injuries, could also be considered. However, measures such as economic losses may be strongly dependent on the level of GDP of specific countries, and these kinds of estimates tend to be inexact (Downton and Pielke 2005). Estimates of direct mortality are, by contrast, more precise. Moreover, we can assume that societies around the world attach considerable value to human life, although differences may exist. Therefore, the number of deaths is an appropriate indicator for comparative analyses.

7 Conclusion

Understanding the relationships between demographic differential vulnerability and socio-economic development helps us assess the potential impact of climate change on mortality, and how that impact differs at various stages of development for countries in different regions of the world. This information is important because it allows us to evaluate the potential capacity of societies to cope with climate change in the future, and to identify the groups within a population who are at greater risk of suffering from the consequences of climate change.

Our study has shown that flood- and storm-related fatalities can follow different patterns across the globe. One pattern indicates that mortality risks are higher among young children and the elderly, and especially among females; while another pattern shows that mortality risks are higher among young adult males. Documenting the differences across countries can help us understand why some groups are at a greater disadvantage in some countries than in others. Our results also suggest that the reductions in disaster-related mortality that generally accompany improvements in the HDI are not distributed evenly between men and women. Understanding the social, economic, and geographic factors that explain the differential impact of disasters could help to reduce the unequal distribution of the consequences of climate change.

In addition to the substantive results discussed in the paper, this article highlights the limitations of currently existing datasets and the importance of combining all available data sources in order to improve our understanding of the differential demographic impact of natural disasters. We presented novel findings, but we also acknowledged the substantial uncertainty associated with the data. We hope that this article will stimulate further research with additional datasets that will help us gain a better understanding of the heterogeneous demographic impact of natural disasters.

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Daily mortality changes in Taiwan in the 1970s: An examination of the relationship between temperature and mortality

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Abstract

Growing evidence indicates that world temperatures have increased in recent history, and that this trend is likely to continue in the future. The rise in global temperatures has been accompanied by an increase in extreme weather events, which often have devastating environmental, economic, demographic, and social effects. As concern about the impact of climate change has grown in recent years, there has been a considerable increase in the number of studies published on the effects of extreme temperatures. However, detailed, systematic, and historical investigations into the relationship between temperature and mortality relationship are still difficult to find. This study fills some of these gaps. By examining the impact of extreme temperatures on mortality in Taiwan in the 1970s, our aim is to answer the following questions: (1) Is a lower or a higher temperature recorded in winter or summer related to higher daily mortality? (2) Is mortality higher in particular years with extreme temperatures than it is in the corresponding periods of other years with normal temperatures? (3) Finally, if more extreme temperatures are indeed associated with higher mortality, what kinds of people tend to face higher mortality risks? This study shows that variations in daily mortality were related to changes in temperature in Taiwan over the study period. Cold temperatures in the winter, hot temperatures in the summer, and unusually cold or hot temperatures were all associated with higher mortality. In comparison with other times of the year, the proportions of people who died at old or very young ages were relatively high during cold periods. The proportions of deaths caused by cardiovascular diseases were also

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relatively high, and these deaths contributed to the high mortality levels in winter time. Meanwhile, during the hot periods relatively high proportions of children and young people died of injuries or poisoning, and relatively high proportions of people died of respiratory diseases; both of these causes of death were closely related to mortality increases in the summer. In comparison with recent decades, however, these patterns were more observable in the 1970s, when the public health and the socioeconomic development levels in Taiwan were not as advanced as they are today.

1 Introduction

There is growing evidence that global temperatures have increased in recent years, and that this trend is likely to continue in the foreseeable future. The rise in global temperatures has been accompanied by an increase in extreme weather events, which often have devastating demographic, economic, environmental, and social effects (Hale et al. 2003; Goklany 2007; Deschenes and Moretti 2009; Hayhoe and Farley 2009; Steffen et al. 2013; Hajat et al. 2014). The heatwaves in India and Pakistan in May-June 2015 provided evidence that extreme temperatures coupled with poor public health systems and infrastructure can result in sharp increases in mortality. As concerns about the effects of climate change on the future of the planet and on humankind have grown, there has been a considerable increase in the number of studies published on the effects of extreme temperatures.

Previous studies have reported that there is a close association between temperature and mortality (Anderson and Bell 2009; Chung et al. 2009; Deschenes 2013). However, the relationship tends to be nonlinear. An unusually low or high temperature in winter or summer is often accompanied by higher mortality (Basu and Samet 2002; Chung et al. 2009; Guo et al. 2011). The extent to which this is the case varies across regions (Curriero et al. 2002; Deschenes 2013; McMichael et al. 2008). The optimal or threshold temperature (a temperature at which the risk of mortality reaches the lowest level) is usually related to the latitude and the temperature level of the area (Curriero et al. 2002). Studies have also suggested that the effects of hot temperatures on mortality are more immediate, while the effects of cold temperatures on mortality tend to accumulate over time, or become more observable after some delay (Deschenes 2013). In addition, Rocklov, Ebi, and Forsberg have found "the mortality impact of persistence of extreme high temperatures to increase proportionally to the length of the heat episode in addition to the effects of temperature based on the temperature-mortality relationship" (Rocklov et al. 2011). Notable variations have also been found when the association between temperature and mortality has been examined by causes of death. For example, links have been demonstrated between extreme temperatures and increases in cardiovascular and respiratory mortality, but links between temperature levels and cancer mortality have been more difficult to observe (Basu and Samet 2002; Astrom et al. 2011; Song et al. 2008). Similarly, some researchers have found that older people are most vulnerable to extreme temperatures (Basu and Samet 2002), while others have found associations between extreme temperatures and elevated mortality among children under four years old (Nakai et al. 1999; Vaneckova et al. 2008).

While great efforts have been made in recent years to study the impact of extreme temperatures on population health and mortality, detailed and systematic investigations into long-term changes in the temperature-mortality relationship are still difficult to find, especially in less developed countries. This study is designed to further improve our knowledge about these issues by examining the impact of extreme (both cold and hot) temperatures on mortality in Taiwan in the 1970s. We aim to answer the following research questions: (1) Is a lower or a higher temperature recorded in winter or summer related to higher daily mortality in the study population? (2) Is a more extreme (either cold or hot) temperature recorded in a particular year related to higher mortality than in the same period in other years? (3) If a more extreme temperature is indeed associated with higher mortality, which population sub-groups tend to have a higher mortality risk under the given temperature conditions?

When studying the association between temperature and population health and mortality, the concept of an ‘extreme’ or an ‘unusual’ temperature needs to be clearly defined. This is not, however, a straightforward task, because it often requires a careful consideration of the absolute level of temperature, the magnitude of temperature changes, and the duration of the cold or the hot temperature. These factors can have numerous combinations, and they interact with other meteorological or air quality factors. The effects of these factors, and of their combinations and interactions, also differ significantly across different geographic areas and climate zones (Wu et al. 2011). For these reasons, there is no standard or widely accepted definition of what constitutes an extreme temperature or an episode of extreme temperatures in the available studies.

The methods used to examine the effects of weather conditions on population health and mortality are also insufficiently developed. Most of the available studies have been conducted from one of the following perspectives. First, some studies have looked at cold or hot temperatures over a certain period, such as a year; and have investigated the health or mortality effects of these cold or hot temperatures. These studies have generally examined variations in temperatures and the associated differences in mortality levels, and have modelled the relationship between them (Medina-Ramón and Schwartz 2007; Zenobetti and Schwartz 2008; McMichael et al. 2008; Hajat et al. 2012; Hales 2012). Second, other studies have looked at whether extreme cold or hot temperatures during the same season or during the same period of different years led to excess mortality. Studies of this kind have, for example, investigated the health and mortality effects of heatwaves in Chicago in 1995, in Paris and other parts of Europe in 2003, or in other areas or at other times (Pirard et al. 2005; Kaiser et al. 2007; Tong et al. 2010; Tong et al. 2012). In this study, we analyse the effects of high or low temperatures from both methodological perspectives. Our definitions of extreme or unusual temperatures, measurements of mortality, and methods of analysis will be further discussed in related sections.

2 The study populations and climate in Taiwan

In this study, we examine the relationship between temperature and mortality in northern and southern Taiwan over the period 1971–1980. The data used in this research have been provided by the Department of Statistics, the Ministry of Interior, the Central Weather Bureau, and the Environmental Protection Administration of Taiwan Executive Yuan, Taiwan; or were published on their websites. In this study, northern Taiwan includes Taipei, New Taipei (previously Taipei County), Taoyuan, and Keelung; and southern Taiwan includes Tainan, (previously Tainan City and Tainan County), and Kaohsiung (previously Kaohsiung City and Kaohsiung County). These categories are different from the official classifications, which also include some other areas.[1] At the beginning of 1971, northern Taiwan had a total population of 4.06 million, while southern Taiwan had a total population of 3.07 million; these respective figures had risen to 5.88 and 3.75 million by the end of 1980, and to 9.10 million and 4.66 million by the end of 2014 (Department of Statistics, Ministry of Interior 2015). As is shown in Table 1, nearly 197,000 deaths were recorded in northern Taiwan and slightly more than 157,000 deaths were recorded in southern Taiwan over the study period. The table also provides other information about mortality and weather conditions for the study period.

Taiwan has a warm and humid climate. During the 20th century, the average temperature in Taiwan was 23 degrees Celsius (°C) (The Central Weather Bureau of Taiwan 2015). The weather conditions vary from the north to the south. Northern Taiwan has a subtropical climate with moderate temperatures, and rain is common in the region in the winter months. In southern Taiwan the temperatures are higher on average, and rain is less common than in the north.

The distance between Taipei (a major city in northern Taiwan) and Kaohsiung (a major city in southern Taiwan), where the two selected weather stations are located, is about 300 kilometres. For the study period, the mean daily temperature ranged from a minimum of 6.5°C to a maximum of 32.4°C, and the average daily mean temperature was 22.8°C in the north. The average daily air pressure was 1012.8 hPa, and the average daily humidity was 76.9%rh. In the south, the mean daily temperature ranged from a minimum of 8.3°C to a maximum of 32.3°C. The average daily mean temperature was 24.5°C, or 1.7°C higher than in the north. In southern Taiwan, the average daily air pressure was 1011.1hPa, and the average daily humidity 79.6%rh. The humidity level was slightly higher in the south than in the north.

[1] According to the official classification used by the Executive Yuan, northern Taiwan consists of Taipei, New Taipei, Taoyuan, Keelung, Hsinchu City, Hsinchu County, and Yilan County; and southern Taiwan consists of Tainan, Kaohsiung, Chiayi City, Chiayi County, Pingtung County, and Penghu County. Because we have used only weather condition data collected from two weather stations, one in Taipei and the other in Kaohsiung, we have selected a smaller number of areas that are relatively close to these two major centres and that have relatively large population sizes.

Table 1:
Weather conditions and mortality in the northern and southern Taiwan over the study period

	Northern Taiwan	Southern Taiwan
Max. daily mean temperature	32.4°C	32.3°C
Min. daily mean temperature	6.5°C	8.3°C
Ave. daily mean temperature	22.8°C	24.5°C
Max. daily mean air pressure	1031.3 hPa	1027.1 hPa
Min. daily mean air pressure	977.5 hPa	981.4 hPa
Ave. daily mean air pressure	1012.8 hPa	1011.1 hPa
Max. daily mean humidity	98.0%rh	98.5%rh
Min. daily mean humidity	45.0%rh	43.0%rh
Ave. daily mean humidity	76.9%rh	79.6%rh
Max. daily death count	101	81
Min. daily death count	23	17
Ave. daily death count	53.9	43.0
Number of deaths (1971–1980)	196,848	157,094

Note: Max., Min. and Ave. are abbreviations for maximum, minimum and average.

3 Is a lower or a higher temperature recorded in winter or summer related to higher daily mortality?

A total of 350,000 deaths were recorded in the two study areas from 1971 to 1980. During this period, daily death counts ranged from 23 to 101 in northern Taiwan and from 17 to 81 in southern Taiwan, as shown in Table 1. We start our investigation by examining the question of whether these very large variations were related to changes in temperature using the following analyses.

We first compute the daily mortality ratio, which is the daily death count to the average daily death count of the year; and use this ratio to indicate the relative level of daily mortality. We chose this indicator because it is less affected by the considerable changes in the number of deaths and in the level of mortality over the study period. All of the days in a year are then ranked by the mean daily temperature and are divided into 10 groups, with each group consisting of about the same number of days. The range of the daily average temperatures for the 10 groups is shown in Table 2. It is worth noting that there are some differences in the temperature ranges of the two study areas. Finally, we calculate the average daily mortality ratio for each of the 10 groups. The total number of days, the range of daily death counts, and the average daily mortality ratio for each group are also presented in Table 2.

An issue that needs to be taken into consideration in the study of the temperature-mortality relationship is the possibility that the effect of temperature on mortality is often delayed. Determining the length of such a lag effect is complicated, because it

Table 2:
Daily temperature and mortality in northern and southern Taiwan, 1971–1980

Northern Taiwan										
Temperature range °C	−14.85	14.85–17.20	17.20–19.40	19.40–21.35	21.35–23.40	23.40–25.30	25.30–27.20	27.20–28.40	28.40–29.45	29.45+
Number of days	368	367	363	372	362	364	370	359	366	362
Daily death count range	34–91	34–101	26–92	28–88	29–91	29–79	23–86	26–95	31–88	32–81
Average daily mortality ratio	1.125	1.073	1.041	1.009	0.972	0.931	0.937	0.935	0.974	1.003
Southern Taiwan										
Temperature range °C	−18.45	18.45–20.47	20.47–22.30	22.30–24.20	24.20–25.75	25.75–26.80	26.80–27.55	27.55–28.10	28.10–28.80	28.80+
Number of days	371	360	370	361	373	383	367	357	355	356
Daily death count range	25–74	26–81	23–69	19–66	24–71	22–61	24–72	20–67	17–75	21–74
Average daily mortality ratio	1.112	1.045	1.021	0.983	0.969	0.960	0.955	0.962	0.989	1.005

may be expected to vary depending on the cause of death, the health care facility, the geographic area, and other factors. Although these questions have been discussed in many papers, so far there is no conclusive answer about the length of lag that should be used in studies of this kind. We have examined the link between changes in daily mortality and the temperatures recorded in the preceding days, and found that in cold periods the correlation coefficient between the daily death count and the temperature recorded three days previously is slightly stronger, whereas in hot periods the correlation coefficient between daily mortality and the temperature recorded on the reference day or one day before the reference is slightly stronger. In the following analyses we use as a proxy the temperature recorded two days prior to death to capture the lag effect of temperature on mortality.

The results presented in Table 2 show a strong relationship between the daily temperature and the mortality level. Although winter in Taiwan is fairly mild, the number of deaths recorded in the coldest 10 per cent of days is about 1.13 times higher than the annual daily average in northern Taiwan. In southern Taiwan, the ratio is, at 1.11, slightly lower; which may be because the average daily temperature is a couple of degrees higher in the south than in the north. In both northern and southern Taiwan, daily mortality decreases when the average temperature increases, but this relationship begins to change when the temperature reaches 23.40–25.30°C in the north and 26.80–27.55°C in the south: at these thresholds, the average daily mortality ratio falls to its lowest level in each region, of 0.931 and 0.955, respectively. After the 'optimal' temperature has been reached, changes in daily mortality generally show a positive relationship with temperature increases. For the group of days with the highest temperatures, the average daily mortality ratio is slightly higher than 1.00 in both northern and southern Taiwan.

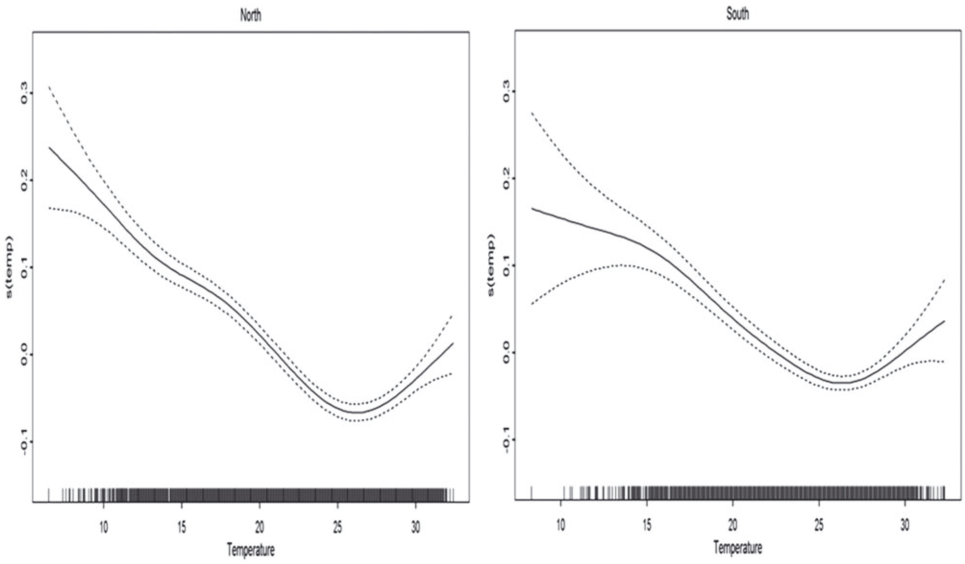
The results from the relatively simple descriptive analysis are supported by multivariate analyses using a generalised additive model that accounts for the relevant environmental indicators, as specified below.

$$E(Y|X,T) = a + S(T) + \sum_{n=1}^{4} S_i(X_i) \tag{1}$$

Here Y is predicted daily death count, a is the intercept, S and S_i are smooth functions, T is the time index, X_1 is *lag*1 death, X_2 is *lag*2 temperature, X_3 is humidity, and X_4 is air pressure.

The results obtained from this analysis suggest that there is a non-linear relationship between temperature and mortality, as indicated by the graph in Figure 1. In the plot, X is the temperature and the smooth function $S(X)$ shows the impact of the temperature on mortality, while holding the impact of other variables in the model constant. Here the impact is expressed in terms of the number of deviations from its mean, which is indicated by zero in the Y axis. The figure shows that when the temperature is low, the relationship between a change in the temperature and daily mortality is negative. But after the optimal temperature (approximately 26°C in both northern and southern Taiwan) has been reached,

Figure 1:
Daily temperature and mortality in northern and southern Taiwan



an increase in the temperature is positively related to an increase in mortality. The results also show that there are some differences in the temperature-mortality relationship in the two regions. There is a slightly larger increase in mortality in northern than in southern Taiwan when the temperature falls below 25°C, which may be attributable to the slightly colder weather in the north. These results are consistent with the findings presented earlier.

4 Is a more extreme temperature recorded in a particular year related to higher mortality?

Temperatures recorded in the same period or season of different years can vary greatly. Are these variations also related to changes in the daily mortality level? For example, can periods with unusually cold or hot temperatures observed in a particular winter or summer (or other season) be shown to be associated with higher mortality than the corresponding periods or seasons of other years with normal temperatures?

To investigate these questions, we compared recorded temperatures for the same period across different years. To identify unusually cold or hot periods, both the temperature levels and the durations of these exceptionally high or low temperatures had to be taken into consideration. We first computed the average daily temperatures for every episode or period ranging from one to 20 days for the whole study period.

For example, over the entire period of 3653 days there were 3652 episodes of two successive days. We computed the average daily temperature for each of these two-day episodes. We also did the same calculation for each episode of other specified numbers of days. This procedure enabled us to identify the hottest and the coldest periods with the specified duration over the entire study period. We then calculated the average daily mortality ratios for those coldest or hottest periods of one to 20 days, and noted the years in which these extreme temperature episodes occurred. Finally, we computed the average daily mortality ratios for the same periods of other years, and compared them with those recorded in the year in which the most extreme temperatures were observed.

Table 3 shows the coldest periods with durations of three, seven, 10, or 14 days; along with the dates when they occurred, the average daily mortality ratios for these periods, and the average daily mortality ratios for the same periods of other years.[2] The results indicate that unusually cold temperatures were correlated with higher mortality in general, and especially during periods when the cold temperatures lasted for a longer time. For the coldest periods with seven, 10, or 14 days in northern Taiwan and the coldest periods with three, seven, 10, or 14 days in southern Taiwan the average daily mortality ratios varied from 1.18 to 1.29 in the years when these coldest spells were recorded. All of these ratios were markedly higher than the average daily mortality ratios in the other years, which were between 1.05 and 1.10. The only exception to this general pattern was found for a three-day episode of extreme cold observed in northern Taiwan from 25 to 27 February 1974: despite being very cold, the average daily mortality ratio during this episode was slightly lower than the ratio in other years.

Table 4 presents similar results showing the associations between hot or unusually hot temperatures and daily mortality. In northern Taiwan, the periods with the hottest three, seven, or 10 days had average daily temperatures of between 31.3°C and 32.0°C. The average daily mortality ratios of these periods varied between 1.02 and 1.10, and were higher than the ratios for other years, which varied between 0.93 and 1.01. For the hottest 14-day episode recorded in August 1980, the average daily mortality ratio was 0.97, or the same as the ratio observed in other years. In southern Taiwan, the hottest periods of seven, 10, or 14 days were all recorded in late June and early July 1980, with average daily temperatures ranging from 31.3°C to 32.0°C. The average daily mortality ratios for these episodes were 1.08 or 1.09, and thus were higher than the ratios for the same periods in other years. However, for the hottest three-day period between 28 and 30 June 1980 the average daily mortality ratio was 0.95, and was therefore lower than the ratios for the same periods of the other years. Compared with the ratios for the coldest periods, the average daily

[2] As we mentioned in the last paragraph, we have computed average daily temperature and daily mortality ratios for every episode ranging from one to 20 days for the whole study period. The results are consistent with those shown in Tables 3 and 4, which (because of space restrictions) present only the results for episodes with durations of three, seven, 10, or 14 days.

Table 3:
Average daily mortality ratios in periods with cold or unusually cold temperatures

Northern Taiwan				
Length of duration	3 days	7 days	10 days	14 days
Coldest period	25/2–27/2/1974	27/2–4/3/1972	25/1–3/2/1971	25/1/–7/2/1971
Average mean temperature °C	7.7	9.4	10.1	10.4
Average daily mortality ratio	1.11	1.29	1.21	1.25
Average daily mortality ratio for other years	1.14	1.06	1.07	1.10
Southern Taiwan				
Length of duration	3 days	7 days	10 days	14 days
Coldest period	25/2–27/2/1974	27/2–4/3/1972	26/2–6/3/1972	25/1–7/2/1971
Average mean temperature °C	10.5	12.7	14.3	14.7
Average daily mortality ratio	1.18	1.22	1.24	1.22
Average daily mortality ratio for other years	1.07	1.06	1.05	1.06

mortality ratios for the hottest periods were generally lower. Thus, the temperature-mortality relationship seems to have been weaker and its patterns were less clear for hotter than for colder weather. This is likely due to the fact that even in summer, temperatures are not particularly high in Taiwan. When there is a heatwave, the temperatures rarely reach the levels that are routinely recorded in some other parts of the world.

We have also examined the distribution of average daily mortality ratios against the average daily temperatures recorded in the cold and hot periods specified in the two tables. The results provide further support for the conclusions reached above. There are, however, exceptions. For example, in northern Taiwan the average daily mortality ratio for the coldest three-day period was actually lower than the ratio for the corresponding periods of many other years. This may be because the daily mortality level is affected not only by the temperature level, but by many other factors as well.

5 Which population groups are more vulnerable to the extreme temperature?

Cold temperatures in winter and hot temperatures in summer—especially if they are unusually low or high—have been shown to be closely related to higher mortality. These findings are confirmed by the evidence presented in Tables 5 and 6. In the two tables, we divide a year into three periods. The cold period consists of the days

Table 4:
Average daily mortality ratios in periods with hot or unusually hot temperatures

Northern Taiwan				
Length of duration	3 days	7 days	10 days	14 days
Hottest period	3/9–5/9/1977	21/7–27/7/1980	12/7–21/7/1971	20/7–2/8/1980
Average mean temperature °C	31.97	31.52	31.27	31.13
Average daily mortality ratio	1.04	1.02	1.10	0.97
Average daily mortality ratio for other years	0.93	0.96	1.01	0.97
Southern Taiwan				
Length of duration	3 days	7 days	10 days	14 days
Hottest period	26/6–28/6/1980	21/6–27/6/1980	20/6–29/6/1980	15/6–28/6/1980
Average mean temperature °C	32.02	31.39	31.35	31.11
Average daily mortality ratio	0.95	1.08	1.09	1.08
Average daily mortality ratio for other years	1.04	1.03	1.03	1.01

from 16 December to 15 March. The hot period lasts from 16 June to 15 August. The remaining days of the year are grouped into a third, or 'other' period. This division is largely based on our examination of the mean temperatures recorded in these periods, their slight variations across different years, and their effectiveness in revealing the links between temperatures and variations in mortality among sub-populations.

Tables 5 and 6 show that the highest average daily death counts in a given year are in the cold period, followed by in the hot period. The lowest mortality levels are observed in the other period of the year. These patterns and the evidence presented in the preceding sections led us to ask the question of which groups are more vulnerable: i.e. which sub-populations are more likely to die during extreme temperature episodes? To answer this question, we calculated the percentage distributions of mortality by age groups and major causes of death for each of the three specified periods and for the study period as a whole; the results of these analyses are also presented in Tables 5 and 6.

The proportions of people who died at age 65 or above were higher in the cold period than in the other two periods of the year. In contrast, the proportions of people who died between ages one and 34 (as well as the proportion of infants who died before age one in the south) were higher in the hot period than in the other periods of the year. This pattern, which was observed for both northern and southern Taiwan, indicates that older people were more vulnerable to cold weather conditions, while younger people were more vulnerable to hot weather conditions. When the deaths were examined by causes of death, we found that the proportions of people who died due to cardiovascular diseases (CVD) were higher in the cold period than at

Table 5:
Percentage distributions of deaths by different times of the year, northern Taiwan

	Cold period	Hot period	Other time	Average
Average daily death count	58.50	53.73	51.99	53.89
By age groups (%)				
0	6.05	5.55	5.34	5.57
1–34	12.61	18.39	15.32	15.10
35–64	39.48	39.34	40.64	40.11
65+	41.85	36.71	38.70	39.22
By major causes of death (%)				
Cancers	16.44	18.47	18.69	18.05
CVD	32.20	25.77	29.14	29.40
Respiratory diseases	8.54	9.29	7.93	8.32
Injuries and poisoning	12.16	16.72	14.67	14.34
Others	30.66	29.74	29.57	29.89

Table 6:
Percentage distributions of deaths by different times of the year, southern Taiwan

	Cold period	Hot period	Other time	Average
Average daily death count	45.64	43.20	41.84	43.00
By age groups (%)				
0	6.29	7.29	6.49	6.57
1–34	13.29	17.04	15.89	15.40
35–64	36.04	36.77	37.17	36.80
65+	44.39	38.90	40.45	41.22
By major causes of death (%)				
Cancers	13.25	15.03	14.92	14.50
CVD	30.30	25.22	27.21	27.69
Respiratory diseases	10.64	11.39	10.08	10.45
Injuries and poisoning	12.22	15.19	14.64	14.10
Others	33.59	33.17	33.15	33.27

other times of the year. However, the percentages of people who died of injuries and poisoning and of respiratory diseases were higher in the hot period than in the other periods. These results reveal that compared with other times of the year, people were more likely to die of cardiovascular diseases in the cold period, and were at greater risk of dying from injury or poisoning in the hot period. Even after examining the

Table 7:
Vulnerability indices by age groups and causes of death in cold and hot periods, 1971–1980

	Cold period		**Hot period**	
	North	**South**	**North**	**South**
By age groups				
0	1.09	0.96	1.00	1.11
1–34	0.84	0.86	1.22	1.11
35–64	0.98	0.98	0.98	1.00
65+	1.07	1.08	0.94	0.94
By major causes of death				
Cancers	0.91	0.91	1.02	1.04
CVD	1.10	1.09	0.88	0.91
Respiratory diseases	1.03	1.02	1.12	1.09
Injuries and poisoning	0.85	0.87	1.17	1.08
Others	1.03	1.01	0.99	1.00

mean daily death counts, we found that these conclusions applied to the populations living in both the north and the south.

To compare the vulnerability levels to extreme temperature conditions of the populations living in northern and southern Taiwan, we calculated a simple vulnerability index for the cold and hot periods: i.e. the ratio of the proportion of deaths of a specified age or causal group out of all deaths for the cold or hot period to the proportion of deaths of the same age or causal group for the whole study period. In general, a higher index value indicates a higher mortality risk (relative to the percentage of deaths among the same age or causal group in the total deaths of the study period). According to the vulnerability indices shown in Table 7, in the cold period the elevated mortality risks for people aged over 65 and for people with cardiovascular diseases were fairly similar in northern and southern Taiwan. In the hot period, the mortality risk among people aged 1–34, and the proportions of people who died of injury or poisoning or of respiratory diseases, were higher than in the other periods in both northern and southern Taiwan; although the gaps appear to have been greater in the north than in the south. In addition, in the cold period the mortality risk among infants under age one was higher than the average of the whole period in northern Taiwan, but not in southern Taiwan. The opposite was the case in the hot period. These observed differences should be further investigated in future studies.

To further examine the populations who were especially vulnerable in hot weather, we analysed the link between the relatively high proportion of people who died at ages 1–34 and the major causes of death. The results of the analysis provide further evidence in support of our previous conclusions. For example, we found that among people aged 1–34, injury or poisoning accounted for 52.6 per cent of deaths in the hot period, but just 45.6 per cent of deaths during the cold period. This gap is mainly attributable to the large number of deaths caused by drowning: in the hot period, the total number of drowning deaths was 2007, or more than three drowning deaths per day. These deaths accounted for 36.3 per cent of all injury or poisoning deaths among this age group. If the level of mortality caused by drowning in the hot period had been similar to the level in the cold period, then the total number of deaths due to injuries and poisoning that occurred in the hot period would have decreased by approximately 26 per cent. Injury and poisoning deaths would have accounted for 45.1 per cent of total deaths in the same age group, or slightly less than the 45.6 per cent of total deaths in the cold period.

We also examined the temperature-mortality relationship and levels of vulnerability to extreme temperature conditions in urban (cities) and rural (counties) areas, and in male and female populations. The vulnerability indices for cold and hot periods of the year are computed for cities and counties, and for males and females in northern and southern Taiwan; the results are presented in the four tables in the appendix of the paper. These results confirm the suggestions made above. In comparison with other times of the year or annual averages, the proportions of deaths among people aged 65 and over and of deaths caused by CVD were relatively high in the cold period. Meanwhile, the proportions of deaths among people aged 1–34 and of deaths caused by injury or poisoning or respiratory diseases were relatively high in the hot period. The variations in these patterns between urban and rural populations and between male and female populations were relatively small. However, in the hot period the vulnerability index for deaths caused by respiratory diseases was higher in the cities than in the counties in both northern and southern Taiwan. During the same period in both regions, the vulnerability index for deaths caused by respiratory diseases was higher among females than among males. It is beyond the scope of this paper to further analyse gender differentials in deaths due to this cause, but we will examine these differences in a future study.

6 Concluding remarks

This study has shown that variations in daily mortality were related to changes in temperature in both northern and southern Taiwan over the study period. Generally, cold temperatures in the winter, hot temperatures in the summer, and unusually cold or hot temperatures were all associated with higher mortality. However, daily mortality was generally higher in winter than summer.

Compared with other times of the year, the proportions of people who died at old and at very young ages were relatively high during the cold period. The proportions of deaths caused by CVD were also relatively high during this period, and contributed to the high mortality observed in winter time. People with these characteristics were thus more vulnerable to low temperatures. During the hot period, however, relatively high proportions of children and young people died of injury or poisoning. The proportions of deaths caused by respiratory diseases were also relatively high. These causes were closely related to the increase in mortality in summer time. People with these characteristics were more vulnerable during the hot season.

The analysis of the increase in summer mortality in Taiwan in the 1970s also makes clear that during this period the major reason for the rise in mortality in the hot season was not the increase in CVD mortality among elderly people, which might have been related to hot temperatures; but to other factors such as drowning among children and young adults, which may have been attributable to the poor or less effective safety management practices at the time. Since then, considerable efforts have been made to improve these practices. There has thus been a significant decline in deaths from drowning, and this decrease has contributed considerably to the reduction in summer mortality (Wang 1999 and 2007; Chen 2008).

The present paper has some limitations that should be acknowledged. While we focused on the relationship between temperature variability and mortality in Taiwan in the 1970s, we were unable to take into account the effects of other factors that may have contributed to mortality risk levels, such as air quality. We could not include these data because they did not become available until the mid-1990s, and their exclusion may have had some effects on our results. Furthermore, the research findings reported in this paper offer insights into the temperature-mortality relationship and demographic differential vulnerability at a time when Taiwanese society was undergoing a demographic transition, and the country's level of socioeconomic development was less advanced than it is today. Thus, our observations of trends from more than three decades ago do not represent the temperature-mortality relationship patterns of today. Indeed, our investigations into this relationship have shown that it has not remained constant, but has undergone substantial changes since the 1980s. Big summer mortality peaks have largely disappeared in recent years. These changes are attributable to major changes in causes of death, improvements in health care and in living environments, and progress in safety management and disease prevention practices. (Zhao et al. 2015).

As we mentioned in the introduction of this paper, in recent years there has been a substantial increase in the discussion of the effects of global warming and associated extreme temperature events, such as heatwaves, on health and mortality. Some studies have also projected the extent of health or mortality effects into the future (Hajat et al. 2014). While such studies have greatly enriched our knowledge of related issues, it is notable that some of the reported results are based on observations made in one or two years, or in even shorter periods. It is also important to note that the temperature-mortality relationship has not been constant, but has undergone considerable changes. Furthermore, some temperature-related health and mortality risks can be prevented or considerably reduced. For example, in the summer of 2003 western European countries experienced a heatwave that resulted in more than 70,000 excess deaths (Robine et al. 2008). According to Fouillet and others (2008: 309), in France the high death toll was largely attributed to "an overall lack of reactivity by people (insufficient protective reflexes and help for the elderly), health professionals (poorly known diseases related to heat), the health system (difficulty perceiving the signals, lack of prevention recommendations) and the media (alarmist messages but no information on prevention)". In order to prevent this kind of heat-related disaster from happening again and to reduce the health effects of future heatwaves, a National Heat Wave Plan was set up by the Directorate General for Health. Thanks to the implementation of this plan and other related efforts, the impact on mortality of the 2006 heatwave was significantly lower (Fouillet et al. 2008).

Our study also highlights that it is crucial to consider demographic differentials in mortality risk from extreme temperature when developing disaster risk reduction strategies. We have shown that people of different age groups were exposed mortality risks differentially in hot and cold periods. Preventive policies that take into account the needs of specific sub-populations are essential for reducing premature deaths caused by extreme weather conditions and other environmental hazards.

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Appendix

Table A.1:
Vulnerability indices by age groups and causes of death in cold and hot periods in northern Taiwan, 1971–1980

	Cold period		Hot period	
	Cities	**Counties**	**Cities**	**Counties**
By age groups				
0	1.09	1.08	0.99	1.00
1–34	0.85	0.82	1.19	1.20
35–64	1.00	0.97	0.97	0.99
65+	1.04	1.09	0.96	0.93
By major causes of death				
Cancers	0.91	0.91	1.00	1.03
CVD	1.10	1.10	0.91	0.87
Respiratory diseases	1.00	1.05	1.17	1.11
Injuries and poisoning	0.84	0.85	1.16	1.14
Others	1.03	1.02	0.98	1.00

Table A.2:
Vulnerability indices by age groups and causes of death in cold and hot periods in southern Taiwan, 1971–1980

	Cold period		Hot period	
	Cities	**Counties**	**Cities**	**Counties**
By age groups				
0	0.95	0.96	1.13	1.07
1–34	0.86	0.86	1.08	1.14
35–64	1.00	0.97	0.97	1.00
65+	1.08	1.08	0.98	0.94
By major causes of death				
Cancers	0.93	0.90	1.01	1.06
CVD	1.08	1.10	0.90	0.91
Respiratory diseases	0.99	1.03	1.15	1.07
Injuries and poisoning	0.89	0.85	1.04	1.09
Others	1.01	1.01	1.03	0.99

Table A.3:
Vulnerability indices by age groups and causes of death in cold and hot periods in northern Taiwan, 1971–1980

	Cold period		Hot period	
	Males	**Females**	**Males**	**Females**
By age groups				
0	1.09	1.07	0.95	1.06
1–34	0.83	0.84	1.23	1.14
35–64	1.00	0.96	0.98	0.98
65+	1.07	1.06	0.93	0.96
By major causes of death				
Cancers	0.92	0.90	1.01	1.02
CVD	1.10	1.08	0.87	0.91
Respiratory diseases	1.06	0.98	1.08	1.21
Injuries and poisoning	0.84	0.89	1.19	1.01
Others	1.04	1.01	0.97	1.02

Table A.4:
Vulnerability indices by age groups and causes of death in cold and hot periods in southern Taiwan, 1971–1980

	Cold period		Hot period	
	Males	**Females**	**Males**	**Females**
By age groups				
0	0.96	0.95	1.11	1.07
1–34	0.85	0.88	1.12	1.10
35–64	1.00	0.95	0.98	1.01
65+	1.08	1.07	0.95	0.95
By major causes of death				
Cancers	0.94	0.88	1.05	1.03
CVD	1.10	1.09	0.90	0.92
Respiratory diseases	1.03	1.00	1.06	1.14
Injuries and poisoning	0.87	0.87	1.07	1.06
Others	1.01	1.01	1.00	1.00

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Assessing the effectiveness of a social vulnerability index in predicting heterogeneity in the impacts of natural hazards: Case study of the Tropical Storm Washi flood in the Philippines

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Abstract

As global warming and climate change predictions become increasingly certain, there is mounting pressure to gain a better understanding of disaster risk. Climate change is seen as a major contributing factor in the recent increases in the losses and damages attributed to hazard extremes. Vulnerability is one of the key components of risk. Yet identifying who the vulnerable segments of the population are, and to which specific hazards different groups are vulnerable, remains a challenge. Measuring social vulnerability has become an active area of research, with scholars attempting to capture the differential vulnerabilities of the population exposed to certain hazards. To address these research challenges, we developed in this study social vulnerability indices at the most basic level of governance in the Philippines using raw, individual-level census data for the entire country. Our goal in conducting this research is to establish relationships between the derived vulnerability measurements and flood exposure and the impacts of coastal flash floods triggered by Tropical Storm Washi in the southern Philippines in December 2011. We find that exposure rather than vulnerability appears to play a greater role in the magnitude of the losses and damages resulting from this particular type of hazard at the localized scale.

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1 Introduction

The Hyogo Framework for Action states that "the starting point for reducing disaster risk and for promoting a culture of disaster resilience lies in the knowledge of the hazards and the physical, social, economic, and environmental vulnerabilities to disasters that most societies face, and of the ways in which hazards and vulnerabilities are changing in the short and long term, followed by action taken on the basis of that knowledge" (UNISDR 2005, p. 7). However, the promotion of resilient and adaptive societies requires a shift in focus away from natural hazards and extreme events, and toward the identification, assessment, and ranking of vulnerability (Lavell et al. 2003; Birkmann 2006a; Birkmann 2006b; IPCC 2012). Risk identification through the assessment of vulnerability can facilitate the emergence of a common understanding of responses to risk among stakeholders and actors, and thus represents one of the initial stages in the processes of risk reduction, prevention, transfer, and climate adaptation in the context of climate extremes (IPCC 2014).

Measuring vulnerability is, therefore, an increasingly important component of effective disaster risk reduction strategies (Birkmann and Wisner 2006). In the current context of more frequent disasters and mounting environmental degradation, the quantitative assessment of vulnerability is a crucial issue that the scientific community must address as they seek to provide effective strategies for creating a more sustainable and resilient world (Kasperson et al. 2001; Convertino et al. 2013).

Social assessments can illustrate the vulnerability levels of communities using quantitative evaluation algorithms, and produce indices with the goal of providing effective deterministic tools for assessing the potential impact of natural hazards on society. This fundamental approach is intended to tackle the major challenge of validating these indices with specific regard to the parameters connected to the losses and damages suffered by communities impacted by extreme hazard events.[1] However, while social vulnerability indices are increasingly being developed and applied, the available data and methods for their validation remain limited (Fekete 2009).

Although the validation data needed for direct vulnerability assessment models are still lacking, indirect evaluation procedures connected to actual disaster observations and forensic studies may constitute a valid surrogate for information on the affected areas. For example, an open testing laboratory may be used to calibrate and tune vulnerability models in ex-post disaster conditions (see Birkmann and Fernando 2008). Thus, in validating the effectiveness of vulnerability indices with regard to the social impact of hazards on the exposed population, we use disaster information gathered from different and diverse sources (e.g. disaster maps, remote

[1] Loss and damage refers to the adverse impacts of climate change that communities have not been able to cope with or adapt to, which include economically quantifiable and non-measurable costs (Morrissey and Oliver-Smith 2013; Warner and van der Geest 2013).

sensing, social media). The literature reveals that several attempts have been made in the past to quantitatively map physical exposure and related risks on exposed populations.

In the work by Peduzzi et al. (2009), tropical cyclones, earthquakes, droughts, and flood hazards (accounting for 94% of total hazards in the period 1980–2006) were evaluated with respect to population spatial distribution in order to characterize the associated physical exposure at the country scale. Using statistical tools (e.g. fitting, regression), the authors tested a total of 23 vulnerability indicators, such as the human development index, GDP per capita, and other readily available datasets. The resulting disaster risk model, which the authors validated using actual data reported from global data providers like the EM-DAT (CRED 2012), demonstrated as expected a strong correlation between vulnerability and disaster impact, especially for analyses at increasing spatial scales.

Cardona (2007) introduced a complex series of indices for the Americas designed to provide decision-makers with the ability to compare disaster risk impact with respect to management capacities across different spatial and time scales. Such studies represent a trend toward the use of index characterization and selection procedures that are strongly dependent on data specifications and availability, which are the most common and fundamental challenges for this type of research (Fekete 2009; Cardona 2007).

Explaining the complex relationships between hazards, exposure, and vulnerability by means of indirect analyses requires researchers to conduct extensive comparative investigations of several different parameters and physical and social processes in different climatic and socioeconomic conditions that compare data and results for different countries and at different time and spatial scales (Peduzzi et al. 2009). In addition, given the relatively large within-country variance in vulnerability levels and the locale-specific nature of the hazards themselves (Cutter et al. 2008), researchers need to upscale and/or downscale the disaster risk analysis to examine the specific area and conditions of exposure in relation to the different levels of vulnerability of the affected population. The literature review by Fekete (2009) showed that there were several past attempts at the sub-regional or the sub-national level to depict social vulnerability in quantitative terms, but that most of these studies lacked validation and the degree of resolution required to accurately capture the social and economic impacts on the actual communities at risk.

While obtaining proper data that provide higher levels of detail remains a major challenge, the more the spatial resolution increases, the more the available data seem to be inappropriate for evaluating levels of vulnerability. The temporal dimension is also important for periodically updating levels of vulnerability, as it can allow for a monitoring of trajectories or changes over time.

Given the importance of accurate risk evaluation and management efforts from the global to the local scale, it is crucial that decision-makers at all governance levels have detailed vulnerability information that can guide them in developing appropriate actions to strengthen community capacity and resilience to hazards under changing socioeconomic and climate conditions (IPCC 2012).

The main goal of this paper is to evaluate the social impacts of a natural hazard—i.e. coastal river flooding—using a quantitative assessment procedure that utilizes a census-based social vulnerability index (*SVI*) developed for the Philippines at its most basic level of governance, the *barangay*. The proposed approach tests the relationships between social vulnerability and coastal river flood hazard (*CRFH*) exposure using actual flood disaster loss and damage data from two case study sites. We seek to determine whether there are relationships between the risk elements of vulnerability and exposure and the negative impacts of a hazard event.

The remainder of the paper is organized as follows. In the next two sections we describe the data and the methods we use to develop and validate the *SVI*. We then present the results of the application of the *SVI* estimation and validation procedure for the case study based on the loss and damage data on major floods caused by Tropical Storm (TS) Washi in mid-December 2011 in Iligan and Cagayan de Oro Cities in Mindanao in the southern Philippines. In the last section we discuss our findings and provide concluding remarks.

2 Data

2.1 Data for SVI estimation

This research is based on several datasets from a diverse set of sources. Conducting a comprehensive technical survey of barangay boundaries for the Philippines has always been a challenge because of the countless boundary conflicts between local government units at the barangay, municipal, and provincial levels (PIA 2012). Fortunately, in 2009 the Global Administrative Areas (GADM) initiative was established as part of a global effort to provide geographic bases for text-based locality descriptions and for mapping census data (GADM 2009). Although the available GIS polygon dataset for the Philippines is only indicative, it provides an overview of local governance jurisdictions at the national scale. Using these data, it is possible to identify for the purposes of conducting more in-depth analyses a collection of barangays in a municipality that normally have more accurate local boundary delineations maintained by the respective local government units.

For this study, we derived indicators of social vulnerability at the barangay level from the data fields of the raw, disaggregated 2010 Census of Population and Housing of the Philippines. The total household population of the Philippines as of 2010 was 92,097,978 (46,458,988 males and 45,638,990 females). One-third (33.3%) of the population were under age 15, while 59.9% were between the ages of 15 and 59. The remaining 6.8% of the population belonged to the elderly category (aged 60 and older), as defined by Philippine law (Republic of the Philippines 1992). A total of 22,926,492 adults aged 18 and older (24.9%) had not completed secondary education, while a total of 1,442,586 (1.6%) individuals had disabilities. The dataset also included a total of 20,171,899 individual households and a total of 21,745,707 housing units.

2.2 Validation data

The data used for the site-specific validation were compiled by the Social Welfare and Development Offices and the Disaster Risk Reduction and Management Council Offices for both cities, as well as by the respective regional administrative offices. The data were gathered with the specific purpose of surveying the losses and damages that occurred during the Tropical Storm (TS) Washi event, which caused unprecedented flooding in the Northern Mindanao region of the Philippines in mid-December 2011. The dataset includes demographic profiles of dead and missing persons, as well as a comprehensive survey of the individuals affected by the flood in terms of injuries and damage to property. The dataset also includes a survey of housing units that were damaged to varying degrees.[2] It is important to note that the level of detail of the surveyed information differed between locations, with the data for Cagayan de Oro City being less comprehensive than the data for Iligan City, particularly in terms of the demographic and geographic specifications of the individuals affected by the flood. Nevertheless, a significant amount of information is available, and the data are sufficient to allow us to perform statistical analysis on the two flooding case studies. The barangay GIS polygon data provided by the Planning and Development Offices of the two cities give more accurate information on the barangay boundaries maintained by the local government than the publicly available GADM dataset.

3 SVI estimation method and results

In this section we describe the method used to develop the social vulnerability index derived from the presented disaggregated census data. The empirical measurements of social vulnerability combine a number of indicators that can be used to obtain characteristics or parameters that describe a social system's state of vulnerability (Cutter et al. 2008). The *SVI* for the Philippines presented here is based on the 2010 Census of Population and Housing, with the barangays being used as the basic unit of analysis, and three types of information being provided per barangay: i.e. individual members, households within the barangay, and housing units aggregated at the barangay level (Ignacio and Henry 2013a). Because we have access to disaggregated or raw data for both population and housing characteristics, we are able to combine the social and the housing-based indicators in developing an *SVI*

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[2] The database identifies three degrees of flood damage to housing units: 1) inundation, or flooding without damage to the housing structure; 2) partial damage, or minor damages sustained by the housing unit; and 3) total damage, or damage that renders the housing unit irreparable.

that spans all 42,020 of the populated barangays in the Philippines. Barangay aggregations are the best way of locating census data at the most detailed unit possible, which is critical for identifying the populations exposed to particular hazards. Although the barangay boundaries used for the nationwide mapping are arbitrary, the boundaries used in the case study sites have an acceptable level of accuracy, as they have been provided by the respective city governments. In this research we focus on a discrete geographical level of aggregation (the barangay) in assessing the site-specific impacts of flood hazard on a population, and thus minimize the problems associated with the modifiable areal unit problem (MAUP) detailed by Openshaw (1983).

The *SVI* scores are estimated at the national level as percentile scores. For the case study sites, geographic subsets of the *SVI* for the barangays comprising Iligan and Cagayan de Oro Cities are extracted from the national database to allow us to perform a more detailed analysis of the *SVI* vis-à-vis hazard impacts on the population at the local scale. The indices are measured separately using corresponding indicators that are based on the pertinent census fields (see Appendix B for the complete list of census fields).

Utilizing the relevant fields provided by the 2010 raw census data, 18 indicators were derived (Table 1) and simple additive indices or composite indicators based on individuals, households, and housing characteristics were developed and computed for the barangays. Many of these indicators were selected based on groups generally known to have high levels of vulnerability, as illustrated in Cutter et al. (2003: pp. 246–249). Our social vulnerability concepts were derived based on the existing literature, and on whether they could be measured from the available census fields.

Demographic groups such as the very young, the very old, the disabled, single-parent households, and low-income earners are thus seen as vulnerable (King and MacGregor 2000). Because the legal working age is 15 in the Philippines, the dependent age range is defined as ages 0–14 (Racelis and Salas 2008). People aged 60 and older are classified as senior citizens (Republic of the Philippines 1992). Following the work of Cutter et al. (2003), the additional indicators we considered are average household size, low adult educational attainment (no secondary school diploma), the share of females, and the percentage of households headed by women. An additional variable, the proportion of females aged 20–39 who had a secondary education or higher, was included following the work of Streissnig et al. (2013), who found that this variable has a positive relationship with vulnerability reduction. Lutz et al. (2008) showed that the proportion of younger women who have a junior secondary or higher education is important in social and economic development, as these women play key roles in family matters ranging from child-rearing to family health, household decision-making, and changes in labor force participation.[3]

[3] According to the Philippine Commission on Women (2014), women have higher functional literacy rates than men, and have a relatively high labor force participation (49.8% in 2013).

Table 1:
Social vulnerability proxy variables derived from the 2010 census data fields

Variable	Description	Type of Data (per barangay)	Corresponding vulnerability concept
female	% Female	Total individuals	Gender
children	% Children (under age 15)	Total individuals	Age
elderly	% Elderly (aged 60 and older)	Total individuals	Age
adult<secondary	% Adults with no secondary degree	Total individuals	Education
unregistered_birth	% With no birth registration	Total individuals	Social dependence
female_20–39 yrs<secondary	% Non-secondary graduate females aged 20–39	Total individuals	Education/Gender
female_head	% With female household head	Total households	Gender/Family structure
with_disabled	% Household with disabled person	Total households	Special Needs population
head<secondary	% With non-secondary graduate household head	Total households	Education
single_head	% With single household head	Total households	Family structure
average_size	Average household size	Total households	Family structure
no_overseas_worker	% Household with no overseas worker	Total households	Social dependence
poor_roofing	% Houses with poor roofing materials	Total housing units	Residential property
poor_walling	% Houses with poor walling materials	Total housing units	Residential property
no_tenure	% Houses with no tenure	Total housing units	Renters/Social dependence
age>30 years	% Houses older than 30 years	Total housing units	Residential property
need_repair	% Houses needing repair	Total housing units	Residential property
small	% Houses having area<10 sqm	Total housing units	Socioeconomic status

Other vulnerability proxies based on Cutter's work were derived from the housing database: e.g. poor roofing materials, poor walling materials, lack of tenure, needing repairs, old structures, and small house floor area. Finally, since the raw database is in a disaggregated form, other combinations of variables linked to social vulnerability are evaluated: households in which the adults lack high school diplomas and households that receive no support from overseas foreign workers. More than 10% of the population of the Philippines are working abroad (Commission on Filipinos Overseas 2010), and these overseas workers provide significant resources to their families in the form of remittances.

An index can be simply constructed as an additive combination of several indicators, assuming that all of the components reflect the underlying construct equally (Carmines and Woods 2003). As indices attempt to condense a complex reality into simple terms, they can serve as good measures (Diener and Suh 1997). There are, however, limitations to composite indices, as they do not indicate the structure or the causes of the vulnerabilities, and they do not specify the degree to which each individual indicator affected the overall outcome (Adger et al. 2004). Weighting schemes for indicators have been suggested based on a number of approaches and techniques, such as expert opinion and principal components analysis (Nardo et al. 2005; Cutter et al. 2003; Rygel et al. 2006). Although there is a general consensus regarding the overall factors that influence social vulnerability to natural hazards, scientists and professionals tend to disagree on the selection of specific indicators and on weighting schemes (Gall 2007). Given these limitations and for the sake of simplicity, an approach of an equal weighting of indicators was adopted.

The selected indicators for *SVI* are combined into three equally weighted indices per data type:

$$SVI_{\mathrm{in}} = \frac{(I^1_{\mathrm{in}} + I^2_{\mathrm{in}} + \cdots + I^i_{\mathrm{in}})}{i} \tag{1}$$

$$SVI_{\mathrm{hh}} = \frac{(I^1_{\mathrm{hh}} + I^2_{\mathrm{hh}} + \cdots + I^i_{\mathrm{hh}})}{i} \tag{2}$$

$$SVI_{\mathrm{hs}} = \frac{(I^1_{\mathrm{hs}} + I^2_{\mathrm{hs}} + \cdots + I^i_{\mathrm{hs}})}{i} \tag{3}$$

where SVI_{in}, SVI_{hh} and SVI_{hs} correspond to the individual, the household and the housing unit social vulnerability indices respectively; while I^i_{in}, I^i_{hh}, and I^i_{hs} correspond to the individual, the household and the housing indicators respectively. A total of six indicators per data type are derived to compute the respective composite *SVIs* per barangay. As most of the values of the individual indicators are represented as percentages that correspond directly to increasing levels of vulnerability, the average household size indicators are normalized based on the maxima and minima of the entire dataset at the national level for consistency.

Figures 1 to 3 map the different *SVI* results, which show quintiles ranging from very high to very low *SVI* types for a sample geographical area covering Iligan and

Cagayan de Oro Cities in Northern Mindanao. The quintile ranges used are based on the entire national dataset and illustrate the states of measured vulnerability in these areas compared to the national values. It is worth noting that barangays farther from the city centers tend to have higher relative *SVI* values.

4 Defining zones of flood exposure

In its Fifth Assessment Report, the IPCC defines disaster risk as the convergence and interplay of hazard, vulnerability, and exposure (Field et al. 2014). As in this paper we seek to evaluate the impacts of a natural hazard in terms of the measurable factors associated with risk (i.e. vulnerability), measuring the level of exposure to a hazard can help determine whether this risk factor has greater significance in determining the level of vulnerability in the overall outcome of the TS Washi flood disaster.

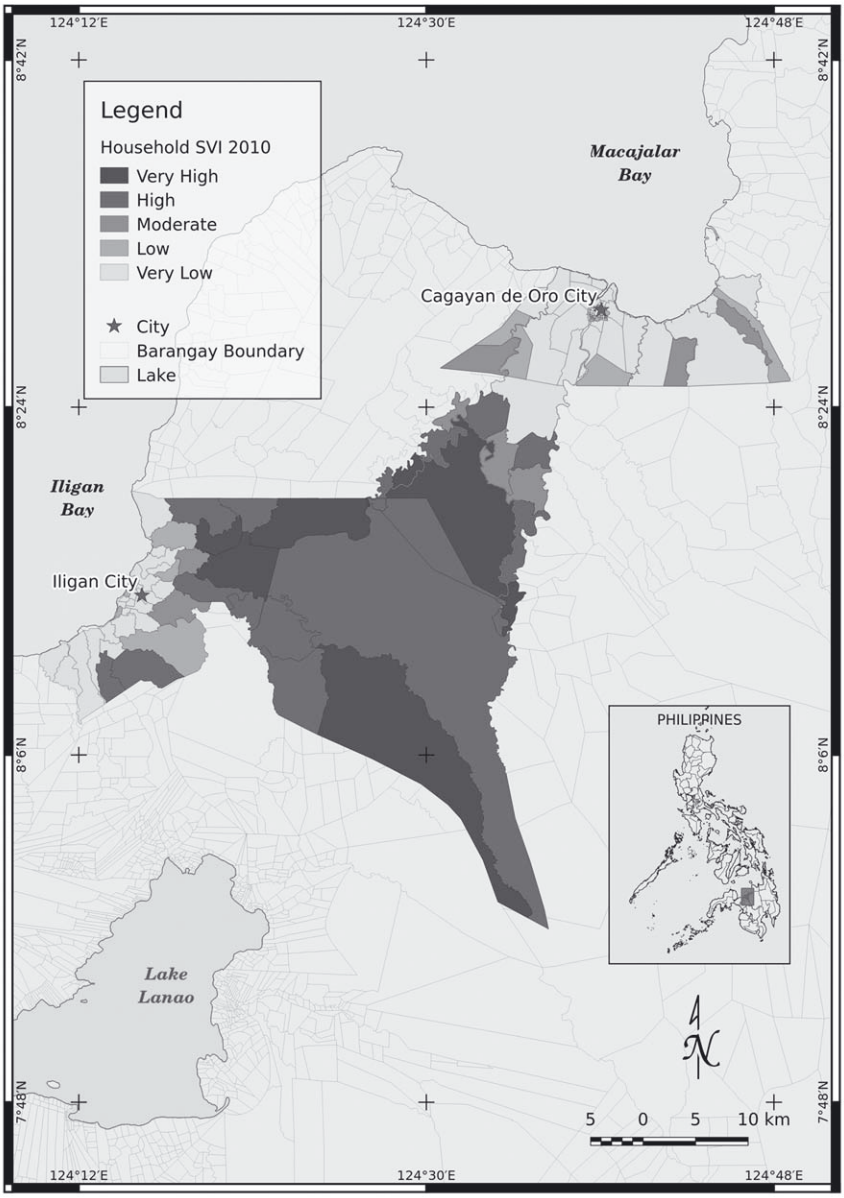
As we mentioned above, the Planning and Development Offices of Iligan and Cagayan de Oro Cities provided geographic information system (GIS) data that show the barangay boundaries more accurately. The data for the domain on the TS Washi flood-affected areas were provided by the Planning and Development Office of Iligan City, while the data for the Cagayan de Oro City flood zones were provided by the Xavier University Engineering Resource Center (2011). Both datasets were based on ground surveys of the extent of flood damage. Additional geospatial data on features such as elevations and rivers were taken from standard topographic maps at a 1:50,000 scale published by the National Mapping Resource Information Authority (NAMRIA) of the Philippine government. In addition, global-scale data were gathered, including digital elevation models (DEMs) produced by the Shuttle Radar Topography Mission (SRTM) (Farr et al. 2007) and aerial photographs and satellite imagery from national and international geospatial data providers. This diverse and heterogeneous set of geospatial information was processed to develop a robust and homogeneous GIS database that provides an *a priori* representation of the areas exposed to flood hazards, along with the social and demographic characteristics of these areas based on the census data.

In the case of the TS Washi disaster, flash floods were the main reason for the loss of life and the destruction of property. In order to delineate flash flood hazard exposure zones, the simple model developed by Ignacio and Henry (2013b) was considered and adapted. A combination of two basic geomorphic parameters extracted from the SRTM DEM define the primary areas of *CRFH*, which is a function of elevation from the coast and slope:

$$CRFH = E_{10m} \cap S_{2\%} \tag{4}$$

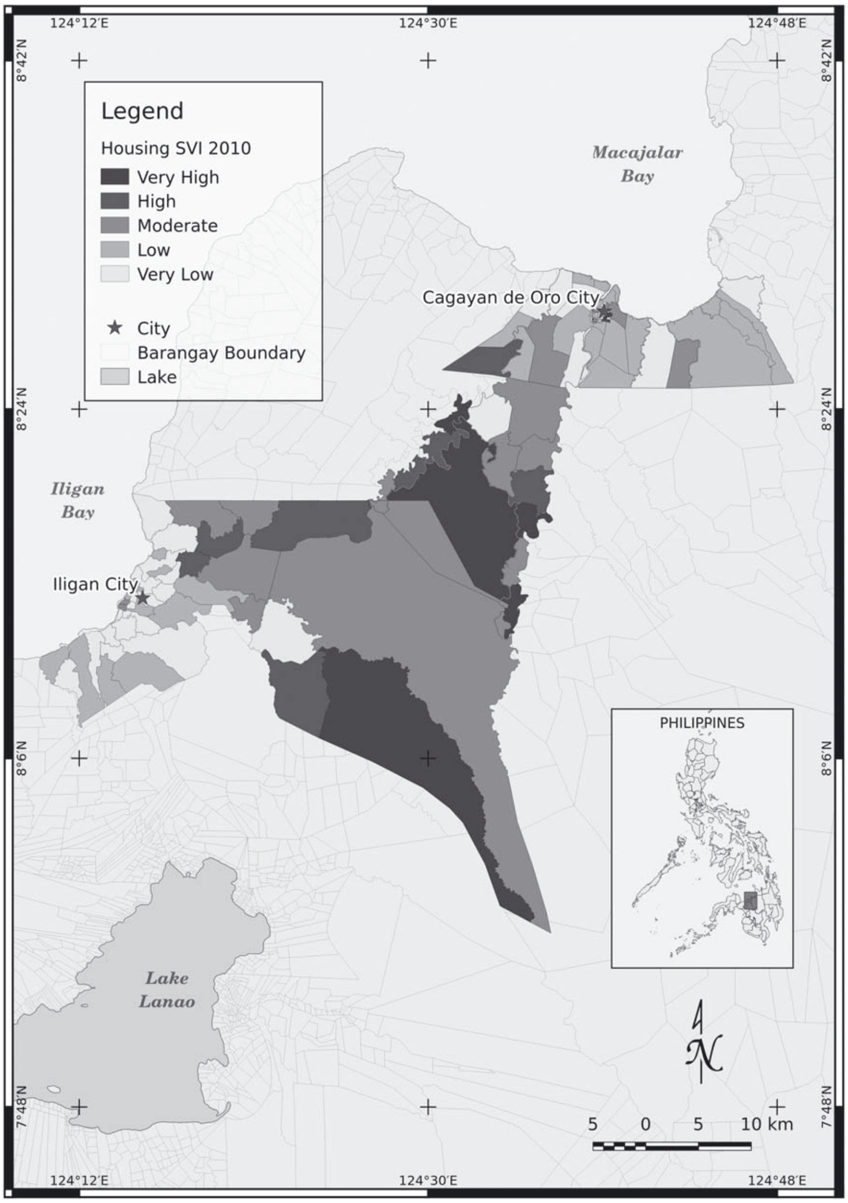
where E_{10m} and $S_{2\%}$ are the coastal areas with, respectively, an elevation lower and equal to 10 m.a.s.l. and slope gradients of 2% or lower. Note that the original elevation threshold of 5 m defined by Ignacio and Henry has been increased to effectively represent the TS Washi flooded zones. The *CRFH*, measured in

Figure 1:
SVI_{in} distribution in Iligan and Cagayan de Oro Cities



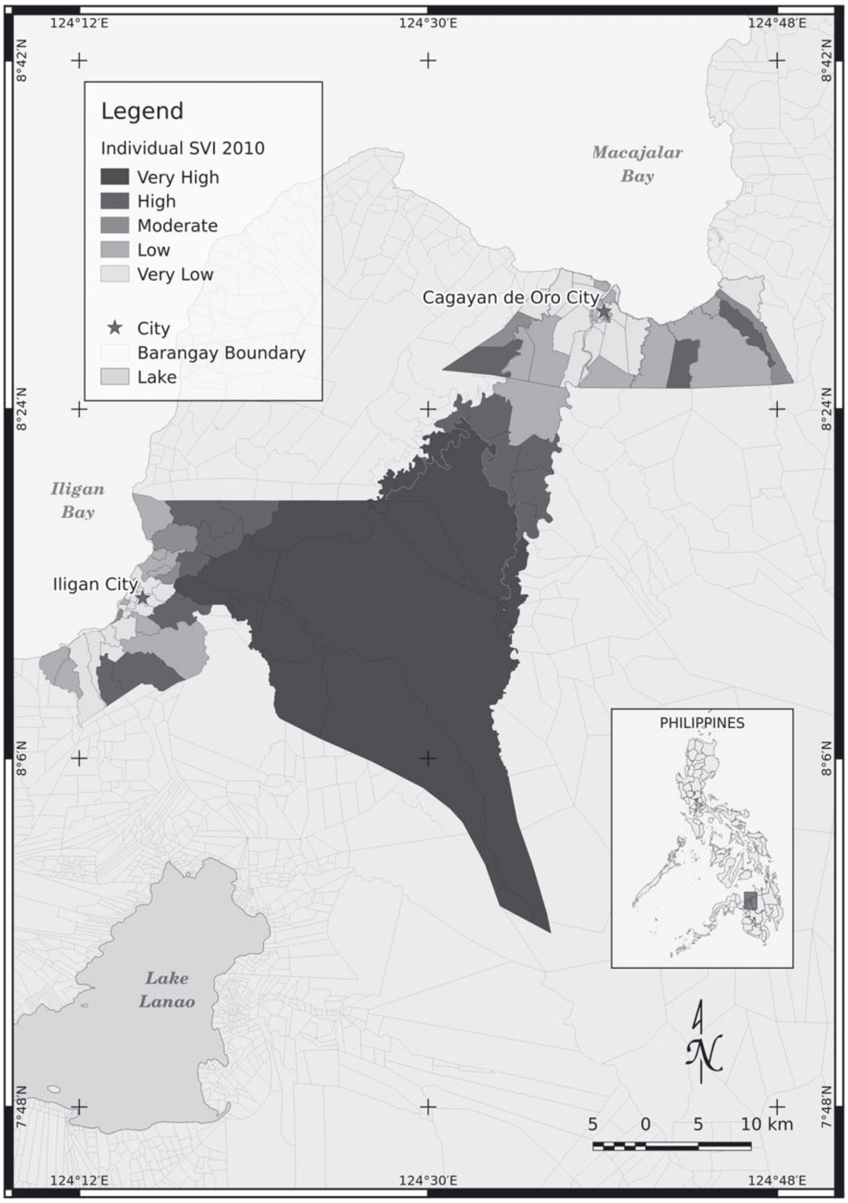
Source: Compiled by the author.

Figure 2:
SVI_{hh} distribution in Iligan and Cagayan de Oro Cities



Source: Compiled by the author.

Figure 3:
SVI_{hs} distribution in Iligan and Cagayan de Oro Cities



Source: Compiled by the author.

hectares, is a simple attempt at delineating the flood plain areas of the coast-draining rivers with flash flood potential using the best available data. The *CRFH* zones are then used to identify the flood-prone barangays using standard GIS overlay tools. We considered using more complex terrain analysis for flood plain mapping (Nardi et al. 2006; Nardi et al. 2013; Manfreda et al. 2014), and developing and applying a spatially distributed, physically based hydrologic and geomorphic flood plain delineation approach (Grimaldi et al. 2004; Grimaldi et al. 2012; Grimaldi et al. 2013). But for the hydrogeomorphic setting of the coastal areas of Northern Mindanao in the southern Philippines, we selected a simple approach based on the geometric parameters of differential elevation and slope, as this approach seems to be the most efficient way of identifying low-lying river bottoms and potentially flooded zones given the flat nature of the domain of interest (Nardi et al. 2008).

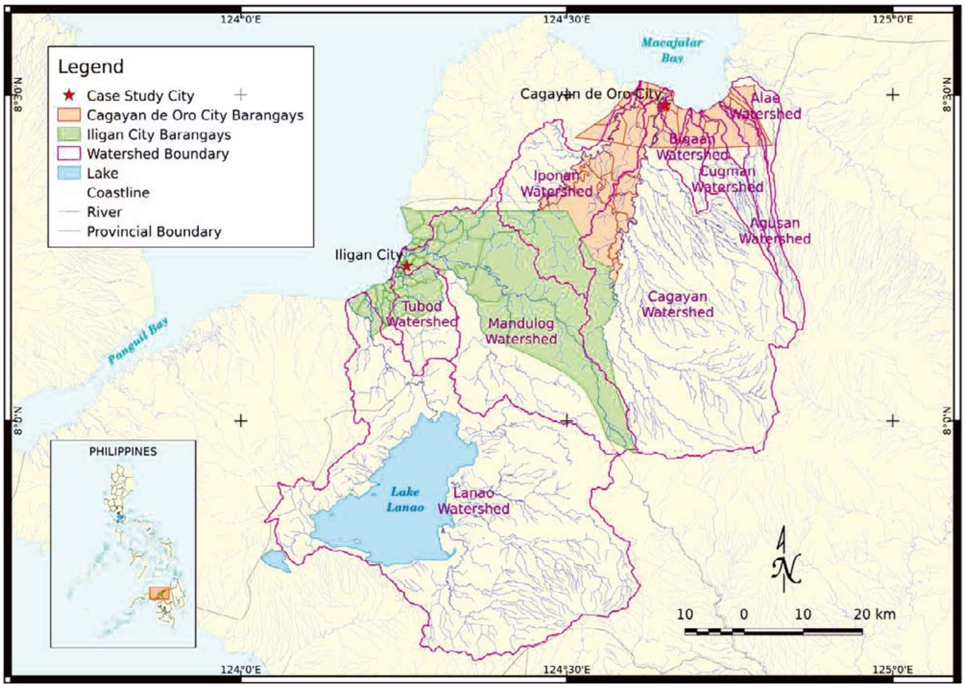
5 Case studies: Iligan and Cagayan de Oro and the TS Washi flood

Iligan and Cagayan de Oro Cities are selected as case studies (Figure 4). Iligan City is located in the Northern Mindanao region of the Philippines. It includes 44 barangays or villages with a total area of 813.37 km^2 and a household population of 321,156; as of May 2010. Three major river systems – the Mandulog, the Tubod, and the Lanao – flow through the coastal barangays before emptying into Iligan Bay. Cagayan de Oro City is located northeast of Iligan City, and is also on the coast of Northern Mindanao. It has 80 barangays with a total area of 488.9 km^2 and a household population of 598,803; as of May 2010. Two major rivers flow through the western portion of Cagayan de Oro City: the Iponan and the Cagayan. These rivers and a series of smaller coastal watersheds all drain into Macajalar Bay.

On December 16, 2012, TS Washi passed through Northern Mindanao, an area that is rarely hit by typhoons. Precipitation of 180.9 mm accumulated in 24 hours, making this an event with a return period of once in 75 years (RDC-X 2012). Flash floods affected several communities along the coast of Northern Mindanao, with the densely populated urban centers of Iligan and Cagayan de Oro Cities reporting the highest rates of loss and damage.

According to the Northern Mindanao Regional Disaster Risk Reduction and Management Office (DRRMO) of the Philippine government, in Iligan City alone 148 people died and 1,023 people went missing. A total of 94,611 individuals were affected, given the population specifications within the flood hazard zone of the Mandulog and Tubod river systems. The flood totally destroyed 4,448 housing units and partially destroyed 5,884 housing units, while a total of 10,582 houses were hit by the flood waters. For Cagayan de Oro City, the official data show that 569 people died and 363 people went missing. A total of 47,526 individuals living within the flood hazard areas of the larger Cagayan river were significantly affected. The flood totally destroyed 3,998 houses and partially destroyed 6,162 houses, and a further

Figure 4:
Barangays and Watersheds of Iligan and Cagayan de Oro Cities



Source: Philippine National Mapping Resource Information Authority (NAMRIA) 1:50,000 topographical maps; Iligan and Cagayan de Oro City Planning and Development Offices; Environmental Science for Social Change; and www.gadm.org (compiled by the author).

2,981 houses were inundated with no significant damage reported. A full report of the TS Washi impact on the two case study areas can be found in Appendix A.

6 Results

6.1 Regression analysis for the determinants of the flood impact

For a comprehensive and homogeneous representation of the flood social impacts, a multiple regression analysis is implemented using the *SVI* variables and the coastal risk flood hazard (*CRFH)* as predictors. The multiple linear regression model is defined as follows:

$$y_j = \alpha + \sum_k \beta_k x_k + \epsilon \tag{5}$$

Table 2:
Correlation matrix of predictor variables for Iligan City

	SVI_{in}	SVI_{hh}	SVI_{hs}	CRFH
SVI_{in}	1.000			
SVI_{hh}	0.843	1.000		
SVI_{hs}	0.850	0.856	1.000	
CRFH	−0.399	−0.417	−0.395	1.000

where y_j represents the three outcomes of interest: i.e. (1) number of dead + missing; (2) number of affected individuals; and (3) levels of damage to housing units; and x_k represents the various predictors (SVI_{in}, SVI_{hh}, SVI_{hs}, and *CRFH*).

Table 2 displays the Pearson's R correlation matrix among the different predictors for Iligan City, which shows that SVI_{hs} is highly correlated with SVI_{hh} and SVI_{in} with 0.856 and 0.850 correlation values respectively. Even if the principle of multicollinearity applies here, the different *SVI* variables are not combined to describe the single *SVI* outcomes for independently evaluating the different aspects of vulnerability at the individual, the household, and the housing level.

As a result of the high correlations, several ordinary least square (OLS) simple regression models are used for each variable individually in the form:

$$y = \alpha + \beta x + \epsilon \tag{6}$$

where y represents the outcome variables and x represents the different *SVI*, as well as the *CRFH* predictors. Since the purpose of this analysis is to establish whether there is a predictive relationship between the *SVI* or the *CRFH* and the outcomes resulting from the hazard event, and because the SVI is a continuous variable, the OLS simple regression can establish whether there are relationships between the assumed predictors and the outcomes.

6.2 SVI for Iligan and Cagayan de Oro cities

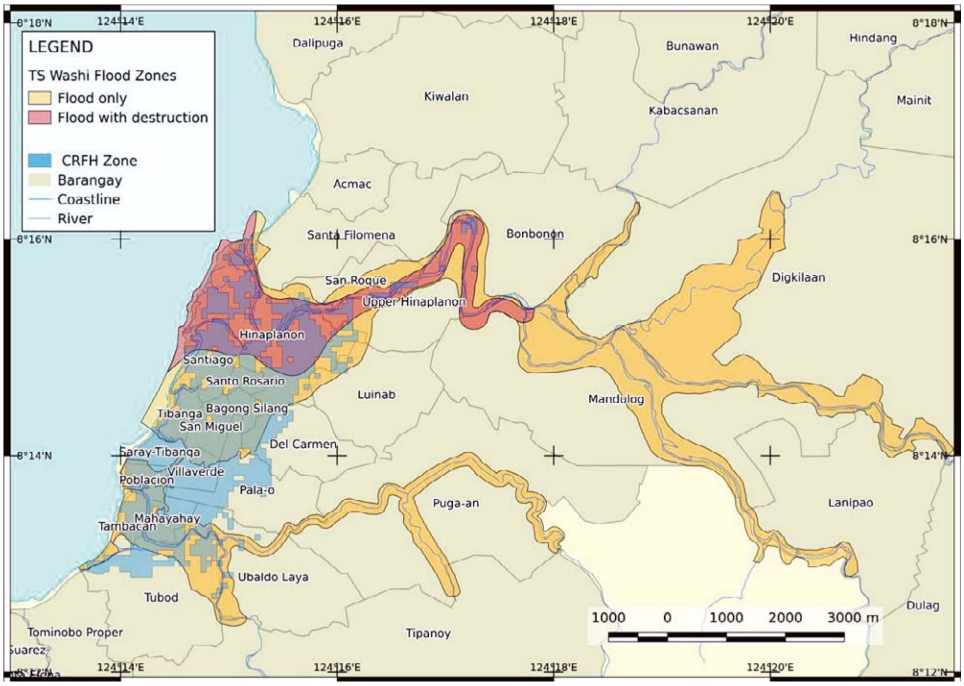
Table 3 presents a statistical summary of the three *SVI* composite variables for Iligan and Cagayan de Oro Cities, respectively, based on the 2010 census fields. As the resulting scores are based on the percentages of individuals, households, or housing units per barangay (except for the average household size indicator), the results are comparable at the barangay level for each single *SVI*. The summary statistics show relatively similar average and median values for the two cities. The index scores for each barangay served as input predictor variables in the regression models, which will be discussed in detail below.

Figure 5 shows the extent of flood damage to the barangays, as delineated by the Iligan City Planning Office after the disaster. The destructive flooding region,

Table 3:
Summary statistics of the SVI scores for the barangays of Iligan and Cagayan de Oro Cities

City	Variable	*n*	mean	sd	median	min	max
Iligan	SVI_{in}	44	26.50	9.84	22.41	16.65	55.69
Iligan	SVI_{hh}	44	36.10	3.74	34.52	30.40	42.71
Iligan	SVI_{hs}	44	18.67	7.44	16.78	8.15	40.21
Cagayan de Oro	SVI_{in}	80	21.45	5.7	20.18	10.42	39.23
Cagayan de Oro	SVI_{hh}	80	35.01	3.44	34.65	25.4	44.02
Cagayan de Oro	SVI_{hs}	80	19.02	9.09	17.32	5.32	61.49

Figure 5:
Flood zones and CRFH areas along the Mandulog and the Tubod rivers in Iligan City



Source: Iligan City Planning and Development Office; NAMRIA 1:50,000 Topographic Maps (compiled by the author).

shown in red, is specifically located along the Mandulog flood plain in the north of the region, while the inundated zones with non-destructive conditions depicted in an orange color are mainly distributed along the Mandulog and Tubod river channels. The *CRFH* areas shown in a semi-transparent blue color have a significant spatial correlation with the flooded zones. Since the *CRFH* areas are provided *a priori* using the available observation data, this information is used as a predictor variable in the linear regression model to allow us to compare its influence on the outcomes of the flood impact, as expressed in terms of the losses and damages incurred.

The *CRFH* areas within the watersheds of the Mandulog and the Tubod rivers measured 883 hectares. The Hinaplanon barangay had the largest share of these areas, with 182 hectares (20.6%); followed by Palao, with 84 hectares (9.5%); and Santiago, with 80 hectares (9.1%). The *CRFH* areas included 20 barangays that experienced flooding during TS Washi. Only five barangays that were flooded were not associated with the *CRFH* areas, as they were located relatively far away from the river outlets. The same analysis was conducted for Cagayan de Oro City, but it is not included in this section for the sake of brevity.

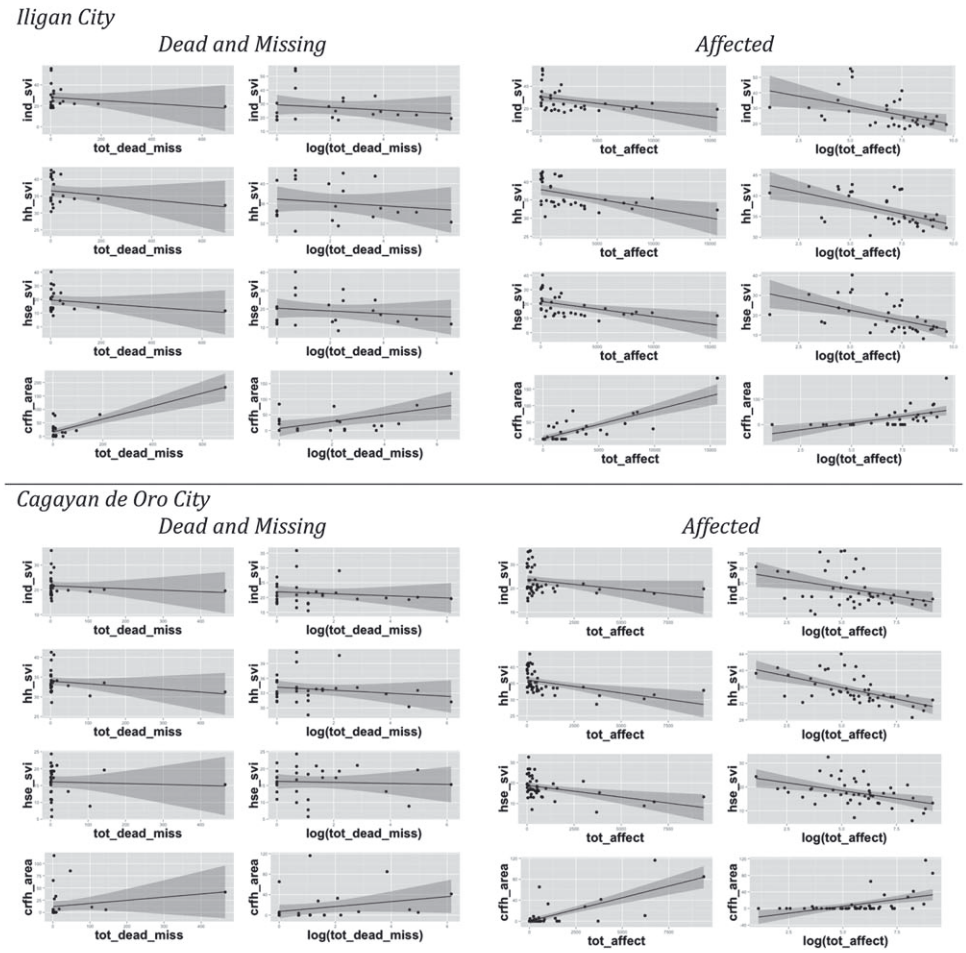
6.3 Flood impact with respect to social vulnerability and exposure

The *SVI* and the *CRFH* variables are represented using the selected OLS regression model. As the numbers of samples are limited for the two sites, the distribution of the raw output data is highly skewed, but the application of the log function for interpolating the social impact behavior as a function of the driving force of the flooding scenario provides a comprehensive linear relationship between the predictors and the outcomes; as we can see in Figures 6, 7, and 8. Figure 6 graphically represents the log function results in comparison with the different variable plot pairs of the raw data with respect to the outcomes of the dead + missing people and the affected people for the two sites.

Figure 7 presents SVI_{hs} with respect to the different housing damage types, comparing the raw and the log-treated outcomes. Figure 8 presents the *CRFH* area with respect to the different housing damage types and their logs, which shows a consistent improvement in the relationships between the variable pairs. This justifies the use of OLS regression models to characterize the relationship between the predictors and the outcomes.

Table 4 shows the results of the simple OLS linear regressions of the log values of the outcomes on the predictor variables for each of the case study sites. The regressions of the dead and missing outcome on the predictors do not seem to exhibit statistically significant results, but this is expected considering the low number of dead and missing victims per barangay. But for the affected people the statistical significance of the regression estimates is strong. This finding is supported by the more comprehensive loss and damage data that were gathered from the individuals affected by the disaster (see Appendix A). Moreover, the number of affected individuals per barangay is much higher with respect to the numbers of dead

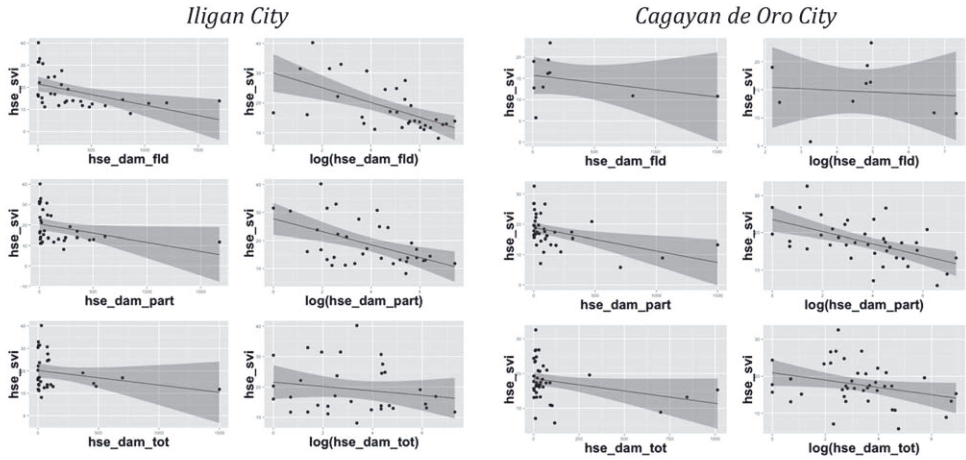
Figure 6:
Comparison of scatterplots of SVI and CRFH vs. raw and log of dead + missing and affected showing the corresponding regression line and confidence regions in Iligan and Cagayan de Oro Cities



Source: Compiled by the author.

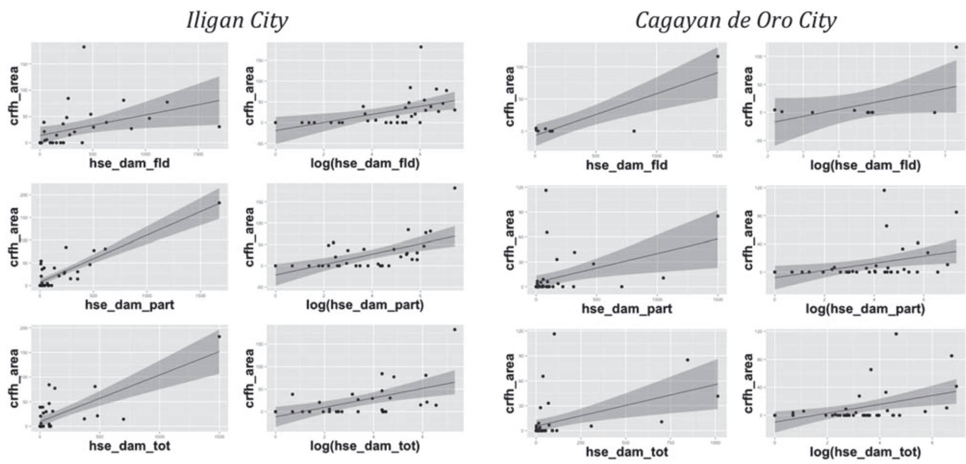
and missing for both case study sites (see Appendix A Tables A.1 and A.3). The regression of flood damage types on SVI_{hs} and $CRFH$ reveal strong relationships as well particularly for the partially damaged house category. SVI_{hs} is also strongly linked with the flooded house variable for Iligan City, but there do not seem to be enough cases in Cagayan de Oro City (n = 10) to statistically characterize the connection.

Figure 7:
Comparison of scatterplots of SVI_{hs} vs. raw and log of housing damage types showing the corresponding regression line and confidence regions in Iligan and Cagayan de Oro Cities



Source: Compiled by the author.

Figure 8:
Comparison of scatterplots of *CRFH* vs. raw and log of housing damage types showing the corresponding regression line and confidence regions in Iligan and Cagayan de Oro Cities



Source: Compiled by the author.

Table 4:
Simple regression results of loss and damage vs. vulnerability and exposure. Numbers in parentheses are standard errors

	Predictor variable			
Outcome variables	SVI_{in}	SVI_{hh}	SVI_{hs}	$CRFH$
Log dead and missing				
Iligan City	−0.0301	−0.0809	−0.0411	0.0219*
n = 22	(0.0387)	(0.1081)	(0.0520)	(0.0086)
Cagayan de Oro City	−0.0497	−0.1047	−0.0209	0.0161
n = 30	(0.2314)	(0.1085)	(0.0694)	(0.0105)
Log affected				
Iligan City	−0.0878**	−0.2963***	−0.1332**	0.0308***
n = 35	(0.0291)	(0.0759)	(0.0374)	(0.0077)
Cagayan de Oro City	−0.1209*	−0.3124***	−0.1525**	0.0394***
n = 46	(0.0456)	(0.0646)	(0.0456)	(0.0099)
Log flood housing damage				
Iligan City			−0.1436***	0.0245**
n = 32			(0.0353)	(0.0080)
Cagayan de Oro City			−0.0310	0.0253.
n = 10			(0.1137)	(0.0133)
Log partial housing damage				
Iligan City			−0.1180**	0.0288***
n = 34			(0.0336)	(0.0069)
Cagayan de Oro City			−0.1870***	0.0285*
n = 39			(0.0467)	(0.0113)
Log total housing damage				
Iligan City			−0.0452	0.02937***
n = 32			(0.0449)	(0.0080)
Cagayan de Oro City			−0.0945.	0.0301**
n = 41			(0.0470)	(0.0099)

Note: Significance codes: 0 =‘***’; 0.001 = ‘**’; 0.01 = ‘*’; 0.05 = ‘.’

In terms of the relationships between the variable pairs in the regression models, Table 4 consistently shows inverse relationships between the three composite *SVI* variables and the outcomes. These relationships are graphically represented in the scatterplots of Figures 6, 7, and 8, which show the negative slopes of the regression lines. These results reveal an unexpected trend with respect to the direct relationships between social vulnerability and the magnitude of losses and damages, particularly in the regression of affected individuals and partial housing damage. This rather surprising finding is unlikely to be due to poor data quality, since the data on the affected individuals and the types of housing damage are usually reliable, given the more consistent survey information provided by the survivors and by the post-disaster observations of damage to the housing units.

In order to further investigate which factor in the SVI contributes to the results shown in Table 4, a further set of regression analyses is presented on the decomposed *SVI* variables; i.e. on the six individual indicators that comprise each of the *SVIs* (see Table 1). Table 5 provides the summary of the results using the procedure that was implemented for the overall SVI indices. The outputs confirm these trends, thus validating the regression model behavior for the dead and missing outcomes with no statistically significant relationship between the variable pairs—except for the *no_tenure*[4] variable for Iligan City, which also has a relatively high standard error. It is worth noting that education-related regressors (i.e. *female_20–39yrs<secondary*[5] and *head<secondary*[6]) for the affected population outcomes show a consistent dependency link between the two case studies. The *poor_walling*[7] indicator variable for SVI_{hs} also exhibits a consistent degree of significance in many of the outcomes. The *no_overseas_worker*[8] variable is also significant and consistent between the two sites. However, in line with the pattern presented in Table 4, the relationships for all the mentioned regressors are also consistently inverse in relation to the log of the outcomes.

A final series of models is formulated and applied that combine the component variables for each of the *SVIs* as regressors in a multiple linear regression model, defined by the equation:

$$\log y_j = \alpha + \sum_m \beta_m x_m + \epsilon \tag{7}$$

where $\log y_j$ represents the log of the outcomes (i.e. number of dead + missing, affected individuals, and levels of damage to housing units), and x_m represents the various indicators for each of the *SVI* variables, as listed in Table 1. The purpose of this last test is to check for the simultaneous influence of the decomposed *SVI* variables on the log of the outcomes, and to determine which variable has the most impact.

Table 6 lists the results of the multiple linear regressions of the log of the outcomes on the decomposed variables. The results are not as expected. We find that for the two case study sites the *head<secondary*[9] and *poor_walling*[10] variables are significantly consistent for the affected population outcome. These two variables

[4] % of houses with no tenure.
[5] % of women aged 20–39 who were not high school graduates.
[6] % with a non-high school graduate household head.
[7] % of houses with poor walling materials.
[8] % of households with no overseas worker support.
[9] % with a non-secondary graduate household head.
[10] % of houses with poor walling materials.

Table 5:
Simple OLS linear regression results for component variables of *SVIs* for the log of outcomes

Outcome variables	Predictor variables					
	Individual-based social vulnerability indicators					
Log dead and missing	female	children	elderly	adult<secondary	unregistered_birth	female_20–39yrs<secondary
Iligan City	0.0388	−0.0107	−0.0500	−0.0168	−0.0128	−0.0113
n = 22	(0.2835)	(0.0723)	(0.1968)	(0.0394)	(0.0149)	(0.0151)
Cagayan de Oro City	0.4857	−0.0709	0.0131	−0.0324	−0.1007	−0.0122
n = 30	(0.2733)	(0.0857)	(0.2779)	(0.0380)	(0.2728)	(0.0196)
Log affected	female	children	elderly	adult<secondary	unregistered_birth	female_20–39yrs<secondary
Iligan City	0.6417**	−0.1478**	0.1800	−0.1082***	−0.0225.	−0.0369**
n = 35	(0.1806)	(0.0518)	(0.1618)	(0.0267)	(0.0122)	(0.0111)
Cagayan de Oro City	0.1622	−0.0731	0.0639	−0.0696**	−0.1136	−0.0328*
n = 46	(0.1255)	(0.0481)	(0.1863)	(0.0252)	(0.1294)	(0.0124)
	Household-based social vulnerability indicators					
Log dead and missing	female_head	with_disabled	head<secondary	single_head	average_size	no_overseas_worker
Iligan City	0.0074	−0.0740	−0.0060	−0.0194	−0.0069	−0.0358
n = 22	(0.0834)	(0.0916)	(0.0150)	(0.0703)	(0.1134)	(0.1275)
Cagayan de Oro City	0.0273	0.0737	−0.0151	0.0247	−0.1065	−0.0595
n = 30	(0.0675)	(0.1685)	(0.0159)	(0.0590)	(0.1507)	(0.1130)
Log affected	female_head	with_disabled	head<secondary	single_head	average_size	no_overseas_worker
Iligan City	0.1593**	0.0865	−0.0398***	0.0994.	−0.0999	−0.2632*
n = 35	(0.0572)	(0.0848)	(0.0102)	(0.0546)	(0.1090)	(0.1056)
Cagayan de Oro City	0.00089	−0.1212	−0.0281**	−0.00697	−0.0529	−0.3281**
n = 46	(0.0357)	(0.1175)	(0.0100)	(0.0296)	(0.0771)	(0.0934)

	Housing-based social vulnerability indicators					
Log dead and missing	poor_roofing	poor_walling	no_tenure	age<30yrs	need_repair	small
Iligan City	−0.0218	−0.0055	1.0203*	−0.0402	0.0010	0.0134
n = 22	(0.0193)	(0.0159)	(0.4164)	(0.0380)	(0.0484)	(0.0363)
Cagayan de Oro City	−0.0424	−0.0039	−0.0311	0.0012	0.0612	0.0063
n = 30	(0.0403)	(0.0187)	(0.0344)	(0.0312)	(0.0433)	(0.0399)
Log affected	poor_roofing	poor_walling	no_tenure	age<30yrs	need_repair	small
Iligan City	−0.0340*	−0.0436***	−0.0081	0.0400	−0.0473	−0.0422
n = 35	(0.0161)	(0.0107)	(0.2880)	(0.0298)	(0.0340)	(0.0286)
Cagayan de Oro City	−0.0358	−0.0483***	−0.0222	−0.0065	0.0094	−0.0188
n = 46	(0.0263)	(0.0129)	(0.0244)	(0.0241)	(0.0278)	(0.0201)
	Housing-based social vulnerability indicators					
Log flood housing damage	poor_roofing	poor_walling	no_tenure	age<30yrs	need_repair	small
Iligan City	−0.0463**	−0.0442***	0.5310	0.0454	−0.0480	−0.0584.
n = 32	(0.0141)	(0.0110)	(0.3634)	(0.0288)	(0.0349)	(0.0312)
Cagayan de Oro City	0.1263	−0.0098	−0.0739	−0.0575.	0.0728	0.0553
n = 10	(0.1101)	(0.0404)	(0.2333)	(0.0285)	(0.0470)	(0.0956)
Log partial housing damage	poor_roofing	poor_walling	no_tenure	age>30yrs	need_repair	small
Iligan City	−0.0361*	−0.0306**	0.1012	0.0070	−0.0391	−0.0450.
n = 34	(0.0143)	(0.0110)	(0.2637)	(0.0280)	(0.0313)	(0.0261)
Cagayan de Oro City	−0.0225	−0.0582***	−0.0306	0.0020	−0.0348	−0.0290
n = 39	(0.0302)	(0.0142)	(0.0258)	(0.0328)	(0.0323)	(0.0213)
Log total housing damage	poor_roofing	poor_walling	no_tenure	age>30yrs	need_repair	small
Iligan City	−0.0107	−0.0150	0.1937	0.0263	−0.0406	−0.0017
n = 32	(0.0175)	(0.0138)	(0.2962)	(0.0507)	(0.0360)	(0.0308)
Cagayan de Oro City	−0.0250	−0.0336*	−0.0007	−0.0107	0.0147	−0.0137
n = 41	(0.0259)	(0.0133)	(0.0243)	(0.0285)	(0.0288)	(0.0194)

Note: Significance codes: 0 = '***'; 0.001 = '**'; 0.01 = '*'; 0.05 = '.'

Table 6:
Multiple OLS linear regression results for component variables of *SVIs* for the log of outcomes

Outcome variables	Predictor variables					
	Individual-based social vulnerability indicators					
Log dead and missing	female	children	elderly	adult<secondary	unregistered_birth	female_20–39yrs<secondary
Iligan City	0.1391	0.0957	−0.4736	0.1256	−0.0058	−0.0950
$n = 22$	(0.6188)	(0.3007)	(0.5273)	(0.2101)	(0.0504)	(0.1089)
Cagayan de Oro City	0.6899	−0.1565	0.3333	0.1162	0.1040	−0.0210
$n = 30$	(0.5035)	(0.2625)	(0.5264)	(0.1913)	(0.3646)	(0.0766)
Log affected	female	children	elderly	adult<secondary	unregistered_birth	female_20–39yrs<secondary
Iligan City	0.7436*	−0.2429	−1.0743**	−0.1434	−0.0677*	0.0876
$n = 35$	(0.3531)	(0.3376)	(0.3376)	(0.1200)	(0.0284)	(0.0607)
Cagayan de Oro City	−0.1007	0.0218	−0.2858	−0.1063	0.0248	0.0095
$n = 46$	(0.2307)	(0.1019)	(0.2906)	(0.0971)	(0.1511)	(0.0439)
	Household-based social vulnerability indicators					
Log dead and missing	female_head	with_disabled	head<secondary	single_head	average_size	no_overseas_worker
Iligan City	0.1815	−0.1083	−0.0294	−0.2401	−0.0707	0.09476
$n = 22$	(0.4057)	(0.1194)	(0.0544)	(0.2876)	(0.1787)	(0.2806)
Cagayan de Oro City	0.0325	0.1408	−0.0261	−0.0704	−0.0989	0.0114
$n = 30$	(0.2873)	(0.1903)	(0.0308)	(0.2641)	(0.1743)	(0.1674)
Log affected	female_head	with_disabled	head<secondary	single_head	average_size	no_overseas_worker
Iligan City	0.1161	−0.0471	−0.0938*	−0.2297	0.0706	0.3145
$n = 35$	(0.2455)	(0.0804)	(0.0385)	(0.1710)	(0.1190)	(0.2044)
Cagayan de Oro City	−0.0506	−0.0838	−0.0621**	−0.0907	0.0131	−0.0264
$n = 46$	(0.1691)	(0.1081)	(0.0212)	(0.1320)	(0.0884)	(0.1325)

	Housing-based social vulnerability indicators					
Log dead and missing	poor_roofing	poor_walling	no_tenure	age>30 yrs	need_repair	small
Iligan City	−0.0268	−0.0006	1.0450*	−0.0575	0.0280	0.0376
n = 22	(0.0254)	(0.0235)	(0.4605)	(0.0405)	(0.0447)	(0.0387)
Cagayan de Oro City	−0.1058	0.0179	−0.0487	−0.0374	0.0360	0.0079
n = 30	(0.0737)	(0.0280)	(0.0392)	(0.0395)	(0.0529)	(0.0463)
Log affected	poor_roofing	poor_walling	no_tenure	age>30yrs	need_repair	small
Iligan City	0.0090	−0.0638**	0.0187	−0.0394	−0.0235	0.0300
n = 35	(0.0210)	(0.0202)	(0.2643)	(0.0331)	(0.0312)	(0.0317)
Cagayan de Oro City	−0.0006	−0.0598**	−0.0491*	−0.0369	0.01643	−0.0026
n = 46	(0.0301)	(0.0162)	(0.0225)	(0.0241)	(0.0247)	(0.0204)

	Housing-based social vulnerability indicators					
Log flood housing damage	poor_roofing	poor_walling	no_tenure	age>30yrs	need_repair	small
Iligan City	−0.0112	−0.04424.	0.1951	−0.0201	−0.0154	0.0180
n = 32	(0.0217)	(0.0247)	(0.3410)	(0.0320)	(0.0330)	(0.0397)
Cagayan de Oro City	0.1524	−0.0240	0.1867	−0.0522	0.0653	−0.0670
n = 10	(0.3306)	(0.0816)	(0.4466)	(0.0550)	(0.0612)	(0.1839)
Log partial housing damage	poor_roofing	poor_walling	no_tenure	age>30yrs	need_repair	small
Iligan City	−0.0179	−0.0329	0.0337	−0.0582.	0.0238	−0.0038
n = 34	(0.0213)	(0.0222)	(0.2610)	(0.0321)	(0.0306)	(0.0337)
Cagayan de Oro City	0.0334	−0.07781***	−0.0548*	−0.0133	−0.0154	−0.0009
n = 39	(0.0294)	(0.0171)	(0.0222)	(0.0304)	(0.0278)	(0.0205)
Log total housing damage	poor_roofing	poor_walling	no_tenure	age>30yrs	need_repair	small
Iligan City	0.0110	−0.0282	0.2214	−0.0181	−0.0379	0.0298
n = 32	(0.0269)	(0.0263)	(0.3409)	(0.0746)	(0.0395)	(0.0396)
Cagayan de Oro City	−0.0002	−0.0412*	−0.0251	0.0465	0.0296	−0.0050
n = 41	(0.0322)	(0.0177)	(0.0254)	(0.0334)	(0.0306)	(0.0221)

Note: Significance codes: 0 = '***'; 0.001 = '**'; 0.01 = '*'; 0.05 = '.'

correspond to educational attainment and house structure stability, respectively; and both variables again have a negative relationship with the affected population dependent variable. For *head<secondary*, this means that the greater the percentage of household heads who had not finished secondary school, the lower the number of people affected. Like for the *poor_walling* variable, the inverse relationship obtained means that the higher the percentage of houses with poor walling materials, the lower the number of people affected. It is interesting to note that these two variables were also shown to have highly significant inverse relationships in the previous simple linear regression results (Table 5) for both case study sites, and for the same affected population outcome.

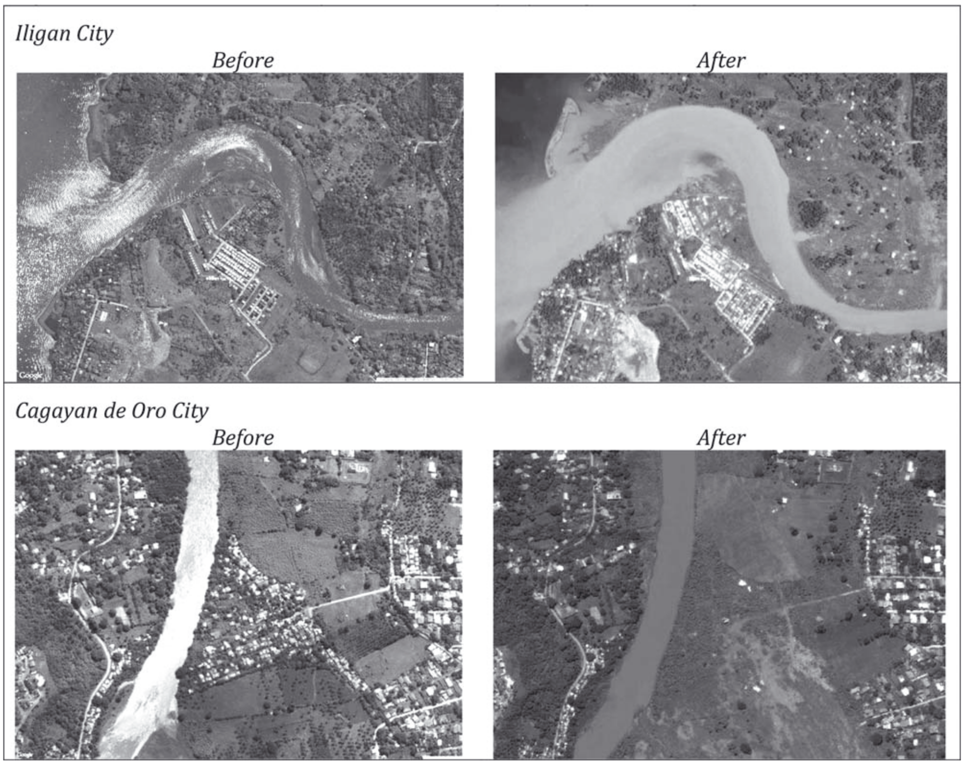
The result for the education variable can also be interpreted as follows: the higher the educational attainment of the household heads in the barangay, the higher the number of affected people. Like for the housing stability variable, we find that the more stable the walling materials of the houses in the barangay, the higher the number of affected individuals in the barangay. While these findings initially seem counterintuitive, based on observations conducted by combining a visual interpretation of satellite imagery (Figure 9) and GPS-based ground surveys comparing conditions before and after the disaster, it is apparent that the middle-class community zones located along the riverbanks were the main areas hit by TS Washi. Thus, it seems that the physical impact of a flood of this magnitude is much more significant than the demographic and socioeconomic characteristics of the affected population. In practical terms, it appears that the *CRFH* zones, which are defined by the hydrogeomorphic conditions that are the most prone to severe flooding, are mainly inhabited by the middle class, a socioeconomic group who are generally less vulnerable than the poor. In technical terms, the *CRFH* plays a major role as the defining variable for *a priori* exposure, significantly influencing the magnitude of loss and damage for both of the case study sites.

7 Conclusion and recommendations

The level of detail of the data compiled for this research, coupled with their broad coverage, made it possible to produce a geographically comprehensive and detailed social vulnerability assessment for the whole Philippines at the level of its most basic unit of governance, the barangay. Furthermore, the availability of raw and disaggregated census data allowed for the development of very specific indicators to capture social vulnerability that are adapted to the Philippine context. In this research, we attempted to develop vulnerability metrics at a relatively fine scale, while also including the validation of such quantitative and qualitative measurements with respect to the impacts of this type of flash flood hazard.

An ex-post validation of how social vulnerability and exposure determine flood impact at a detailed geographical level using the case study areas of Iligan and Cagayan de Oro Cities has revealed that the element of scale is a major factor to consider when making such assessments. Risk assessment at the national scale using

Figure 9:
Pre and post TS Washi flood satellite images for Iligan and Cagayan de Oro Cities



Source: Before images © Google; After images © Bing.

country-level data is important for collectively determining risk levels across nations and prioritizing needs. However, since hazards—and particularly flash floods—are spatially defined at the local level, identifying the populations who are exposed to such hazards through methods such as *CRFH* area delineation can help to reduce risk. Although it has been established that there are direct relationships between vulnerability and disaster impact at the country level (Peduzzi et al. 2009), it is important that this evidence is applied at very local geographic scales when seeking to identify the populations who are most vulnerable to coastal flooding.

Although levels of social vulnerability may be measured accurately through indices such as those developed in this paper, the findings from this research suggest that the component of flood hazard exposure is more important in determining the magnitude of losses and damages than social vulnerability metrics. As the regression results revealed, the statistically significant social vulnerability indicators were actually inversely related to the outcome of the disasters. This does not, however, necessarily signify that there is an inverse correlation between social vulnerability and the tendency to be adversely affected by hazard events. In our analysis we found that having low SVI values does not connote a propensity to being affected by coastal river flooding, because middle-class housing had expanded into areas that had not been properly classified as flood-prone. The results show that exposure is more influential in determining losses and damages from disasters at this scale of analysis, and that other factors may be more significant than social vulnerability.

Using an *SVI* derived for counties in Germany exposed to river flooding, Fekete (2009) found a significant relationship between the vulnerability index scores and the affected groups per county. However, the nature and the scale of the floods Fekete considered were different from those investigated in this research. In the type of event being investigated here—i.e. an extreme flood event triggered by intense rainfall, and with a relatively low return probability (75 years)—much smaller watersheds were affected. It is possible that due to the very extreme nature of the flood event being investigated here, differential social vulnerability, as captured in the *SVI* scores, did not significantly influence the outcomes.

The very high significance of the *CRFH* variable shows that, in this context, exposure matters greatly. In the framework of the IPCC model on disaster risk, exposure is one of the major components in the management of risk. In an extreme hazard event such as TS Washi, differential vulnerability may disappear, and the most important component of the risk management framework shifts to the exposure of the population, and their ability to get out of harm's way. This observation also applies to recent events such as the 2004 Indian Ocean tsunami, the 2011 Tohoku tsunami, and the 2013 Super Typhoon Haiyan in the Central Philippines. The extreme nature of these events caused the exposure component to be the most significant determinant of the loss and damage levels, as the whole exposed population eventually became vulnerable, regardless of the initial states of vulnerability of the communities.

The delineation of the coastal river flood hazard (*CRFH*) areas is important in identifying communities that are at high risk of being affected by coastal river flash floods. Once these areas are identified, government and other interest groups can then allocate resources to preparing for disasters, as such preparedness actions can spell the difference between life and death. In some cases, people might even need to be relocated to areas away from the flash flood danger zones. There should be a greater focus on urban expansion and development in hazard zones, with government agencies identifying the high-risk areas and declaring no-build zones in areas that are highly exposed.

The lack of consistent and uniform information at the barangay level throughout the country led us to use census data to develop proxy variables for vulnerability. We derived composite indicators of social vulnerability from the existing census fields in an effort to capture aspects of social vulnerability in the population. But in the end, the census database was designed with very specific objectives in mind, and we have to accept these limitations when we try to use the data for purposes other than those for which they were originally intended. Furthermore, as census data are collected every 10 years with an inter-decadal subset in-between, a more regular and more frequently updated survey specifically designed to measure vulnerability assessment and resilience building may be needed. As concern about climate change impacts grows, particularly in a country like the Philippines, which is exposed to a wide range of hazards and has relatively high levels of vulnerability (Welle et al. 2012), a regular vulnerability assessment would be a very useful tool for planning and for empowering communities as they slowly adapt to a rapidly changing environment.

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Appendix A: Losses and damages in the case study areas resulting from TS Washi

A.1 Iligan city

Missing persons Table A.1 shows the profile of the 1,023 missing persons reported in 19 barangays. The results show that most of the missing were reported in Hinaplanon (59.3%), while smaller shares were reported in Santiago (17.3%) and Santa Filomena (7.2%).

The missing were almost evenly spread between the sexes, although the share of the females is slightly higher than the share of males (56% vs 44%). The mean age of the missing was relatively young, at around 23 years old, with almost no significant difference between the sexes. Of the missing, one in five were children under five years old, around 40% were under age 15, and an equal percentage were in the prime ages of 15–59. At least 6% of the missing were people aged 60 and older. There were more females than males among the missing for all age groups except for infants (<one year old).

Dead persons A total of 148 people were reported dead in 12 barangays. Most of of the cases were in Hinaplanon (59.4%), followed by in Santa Filomena, (13.5%) and in Upper Hinaplanon (10.1%). In terms of the sex structure, slightly more females (57.4%) than males (42.6%) perished as a result of the flooding. The average age of those who died was 30.8, with the women who perished being about four years older than the men (32.7 vs. 28.2, respectively). The gender difference in age was, however, not statistically different.

A closer examination of the age structure of the mortality statistics indicates that there were three cases of infant mortality (i.e. of infants aged under one year) associated with this natural disaster. Almost one-fifth of those who died were aged 1–4, another one-fifth were in the 5–14 age group, while 44% were in their prime years (ages 15–59). A disproportionate share of those who died were older people (17.7%). As of the 2010 census, older people constituted only 5.7% of the population in the 12 barangays that reported deaths.

An analysis of the age structure of the mortality by sex also reveals that more older females (10.8%) than older males (6.7%) died. Almost 19% of the females

Table A.1:
Iligan City barangays with registered dead and missing victims

Barangay name	Total missing and % of tot. pop.		Total dead and % of tot. pop.		Total affected and % of tot. pop.		2011 population*
Hinaplanon	84	0.57%	607	4.14%	15,636	106.74%	14,648
Santiago	11	0.12%	177	1.85%	8,461	88.59%	9,551
Santa Filomena	20	0.26%	74	0.97%	3,074	40.40%	7,608
Mandulog	2	0.07%	38	1.34%	1,647	58.05%	2,837
Upper Hinaplanon	15	0.23%	34	0.51%	5,717	85.78%	6,665
San Roque	5	0.12%	32	0.79%	3,854	95.51%	4,035
Bonbonon	–	–	12	0.81%	872	58.84%	1,482
Digkilaan	1	0.02%	11	0.27%	1,259	30.35%	4,148
Bagong Silang	–	–	10	0.17%	5,153	86.03%	5,990
Abuno	–	–	7	0.15%	139	2.95%	4,717
Tubod	2	0.01%	6	0.02%	8,092	24.20%	33,442
Tambacan	4	0.02%	5	0.03%	9,876	55.62%	17,757
Rogongon	–	–	2	0.04%	1,814	38.07%	4,765
Kalilangan	–	–	2	0.15%	150	11.54%	1,300
Panoroganan	–	–	2	0.05%	163	3.68%	4,424
Dalipuga	–	–	1	0.01%	1,132	5.82%	19,458
Pala-o	–	–	1	0.01%	2,677	28.34%	9,445
Poblacion	–	–	1	0.03%	949	26.42%	3,592
Ubaldo Laya	–	–	1	0.01%	3,569	31.93%	11,179
Luinab	2	0.02%	–	–	392	4.41%	8,893
Santo Rosario	1	0.05%	–	–	1,576	75.05%	2,100
Hindang	1	0.08%	–	–	3	0.24%	1,237
Total	148	0.08%	1,023	0.57%	76,205	42.51%	179,275

Note: *Projected from 2007 and 2010 population census data.

who died were elderly, compared to about 16% of the males. These results indicate that older people, and especially older women, are particularly vulnerable to disaster risks.

Affected persons A total of 94,611 individuals were surveyed and registered with the Iligan City government as having been affected by the flooding. Hinaplanon had the most affected individuals (16.5%), followed by Tambacan (10.4%) and Santiago (8.94%). Our examination of the demographic distribution of the affected persons did not reveal any significant findings with respect to age, sex, or educational attainment.

Table A.2 presents the 22 barangays that had registered missing and/or dead individuals, with additional information on the number of affected individuals in each barangay, together with its 2010 population. An additional 13 barangays not shown in Table A.2 had individuals affected by the flood, but no dead or missing.

Table A.2:
Iligan City barangays that sustained varying degrees of damage to housing units

Barangay	Total damage and % of tot. housing		Partial damage and % of tot. housing		Flooded only and % of tot. housing		Total housing units in 2011*
Hinaplanon	1,499	42.17%	1,675	47.12%	417	11.73%	3,555
Upper Hinaplanon	699	49.47%	352	24.91%	158	11.18%	1,413
Santa Filomena	481	27.38%	179	10.19%	41	2.33%	1,757
Santiago	461	19.80%	611	26.25%	793	34.06%	2,328
San Roque	372	39.91%	286	30.69%	282	30.26%	932
Tubod	125	1.73%	505	6.98%	1,205	16.65%	7,238
Tambacan	107	2.79%	352	9.18%	1,698	44.28%	3,835
Mandulog	90	13.82%	77	11.83%	156	23.96%	651
Rogongon	82	7.93%	33	3.19%	223	21.57%	1,034
Digkilaan	79	8.09%	109	11.17%	98	10.04%	976
Mahayahay	77	3.62%	467	21.95%	1,037	48.73%	2,128
Pala-o	77	3.60%	244	11.42%	268	12.54%	2,137
Bonbonon	77	25.16%	70	22.88%	46	15.03%	306
Ubaldo Laya	52	2.02%	232	8.99%	508	19.69%	2,580
Bagong Silang	29	2.01%	227	15.73%	866	60.01%	1,443
Panoroganan	29	4.30%	7	1.04%	5	0.74%	675
Tibanga	23	1.19%	39	2.02%	38	1.97%	1,933
Kalilangan	15	5.62%	1	0.37%	10	3.75%	267
Dulag	13	5.96%	6	2.75%	–	–	218
Puga-an	12	0.74%	46	2.83%	120	7.38%	1,626
Tipanoy	9	0.30%	83	2.73%	401	13.17%	3,044
Luinab	9	0.45%	19	0.94%	64	3.17%	2,022
Mainit	7	1.23%	9	1.58%	3	0.53%	570
Santo Rosario	6	1.04%	12	2.08%	328	56.85%	577
Dalipuga	4	0.08%	28	0.58%	196	4.08%	4,799
Lanipao	4	0.79%	13	2.57%	16	3.17%	505
Abuno	3	0.27%	14	1.26%	14	1.26%	1,115
Del Carmen	2	0.10%	135	6.78%	630	31.63%	1,992
Kiwalan	2	0.14%	7	0.48%	1	0.07%	1,457
Acmac	1	0.07%	4	0.29%	4	0.29%	1,378
Kabacsanan	1	0.22%	2	0.44%	–	–	453
Hindang	1	0.37%	–	–	–	–	269
Poblacion	–	–	20	1.69%	220	18.57%	1,185
San Miguel	–	–	11	1.14%	482	49.90%	966
Villaverde	–	–	9	0.72%	254	20.42%	1,244
Total	10,582	18.06%	5,884	10.04%	4,448	7.59%	58,608

Note: *Projected from 2000 and 2010 housing census data.

It is worth noting that in Hinaplanon the total number of victims (missing, dead, and affected) was high relative to its projected 2011 population. The projected population based on a geometric growth rate between the census years of 2007 to 2010 should have been only 14,648, while the total number of documented victims was 16,327. The discrepancy can be partly explained by the completion of new housing projects in the barangay, as can be seen in multi-date high resolution satellite images analyzed for the area, as well as in the total number of housing units (Table A.2).

Damage to housing A total of 20,914 housing units were damaged in Iligan City due to the TS Washi flood. The largest share of the damages occurred in Hinaplanon (17.2%), followed by Tambacan (10.3%), and Santiago (8.9%). Table A.4 provides the full details of the number of housing units that experienced varying degrees of damage per barangay, together with the total number of housing units in 2011, as projected from the 2010 census. Totally damaged houses were totally destroyed or washed out; partially damaged houses sustained damage to parts of the structure but were still repairable; while flooded only houses did not incur any structural harm, but items within the houses were damaged, such as furniture, appliances, and other personal belongings.

A.2 Cagayan de Oro city

Missing persons Table A.3 shows the profile of the 363 missing persons reported in 17 barangays. The results show that most of the missing persons were reported in Macasandig (72.2%), while much smaller shares were reported in 13 and Balulang (7.2% in both).

Roughly equal shares of males and females (49% vs 51%) went missing, while the mean age of the missing was even younger than in Iligan City, at around 21.8. Of the missing, around one in four were children under age five, around 50.4% were under age 15, and 36.1% were in the prime ages of 15–59. At least 13.5 % of those missing were aged 60 and older. The sex distribution was nearly equal across all of the age groups.

Dead persons A total of 569 people were reported dead in Cagayan de Oro City. Of this total number, there was no information on the barangay for 90 cases. Thus, only 479 cases could be assigned to 24 barangays. The largest share of these cases were in Macasandig (42.4%), while smaller shares were in 13 (23.8%) and Balulang (15.9%). Slightly fewer males (45.5%) than females (54.5%) perished as a result of the flooding. The average age of those who died was 32.4, with women being about two and a half years older than men on average (33.5 years vs. 31.1 years, respectively). Like in Iligan City, the gender differences across age groups were not statistically significant.

Table A.3:
Cagayan de Oro City barangays with registered dead and missing victims

Barangay	Total dead and % of tot. pop.		Total missing and % of tot. pop.		Total affected and % of tot. pop.		2011 population*
Macasandig	203	0.84%	262	1.09%	3,851	15.98%	24,103
Barangay 13	114	4.96%	29	1.26%	1,392	60.52%	2,300
Balulang	76	0.23%	29	0.09%	6,221	19.10%	32,575
Carmen	35	0.05%	12	0.02%	9,376	12.77%	73,420
Barangay 15	11	0.36%	6	0.20%	504	16.47%	3,061
Consolacion	7	0.07%	1	0.01%	1,005	10.02%	10,032
Puntod	4	0.02%	–	–	2,988	16.52%	18,089
Canitoan	3	0.02%	2	0.01%	1,600	10.21%	15,664
Kauswagan	3	0.01%	–	–	6,752	19.23%	35,112
Iponan	3	0.01%	–	–	3,696	16.82%	21,980
Tablon	3	0.02%	–	–	523	2.83%	18,451
Barangay 14	2	0.51%	1	0.25%	–	–	395
Cugman	2	0.01%	–	–	773	3.71%	20,835
Mambuaya	2	0.07%	–	–	3	0.11%	2,726
Patag	2	0.01%	–	–	–	–	17,230
Bayanga	1	0.04%	8	0.28%	8	0.28%	2,849
Camaman-an	1	0.00%	4	0.02%	38	0.15%	25,001
Lumbia	1	0.01%	1	0.01%	100	0.73%	13,640
Barangay 18	1	0.06%	–	–	816	52.82%	1,545
Bonbon	1	0.01%	–	–	536	5.66%	9,478
Barangay 17	1	0.04%	–	–	508	21.36%	2,378
Baikingon	1	0.04%	–	–	184	7.43%	2,476
Bayabas	1	0.01%	–	–	25	0.18%	13,789
Puerto	1	0.01%	–	–	–	–	12,501
Nazareth	–	–	2	0.02%	258	2.44%	10,563
Tumpagon	–	–	2	0.09%	170	7.30%	2,330
Bulua	–	–	1	0.00%	1,477	4.48%	32,988
Gusa	–	–	1	0.00%	617	2.32%	26,571
Pagatpat	–	–	1	0.02%	428	8.03%	5,328
Barangay 22	–	–	1	0.05%	–	–	1,902
Total	479**	0.10%	363	0.08%	43,849	9.55%	459,312

Note: *Projected from 2007 and 2010 data. **There were 90 victims who could not be located by barangay.

Looking at the age structure of the mortality statistics, we found a higher rate of infant mortality in Cagayan de Oro City, at 15 deaths (3.1%), and a smaller share of deaths among those aged 1–4 (7.7%). Seventeen percent of the deaths occurred among the 5–14 age group. Similar to the share found in Iligan City, 43.4% of those who died were between 15 and 59 years of age. A high proportion of the casualties (24.0%) were aged 60 and older. This share was even higher relative to the group's share of the entire population than the share found in Iligan City. As of the 2010 census, older people constituted only 4.9% of the population in the 24 barangays that reported deaths.

An analysis of the age structure of the mortality by sex also revealed that among all those who died, around 12.5% were elderly females while 11% were elderly males. Around 23.2% of the females and 24.1% of the males who died were elderly. There was no statistically significant difference in sex among the elderly casualties, but as was the case in Iligan City, the elderly in general were more vulnerable to flood risk.

Affected persons A total of 47,526 individuals were surveyed and registered with the Cagayan de Oro City government as having been affected by the flooding. Carmen was the barangay that had the most affected individuals (21.4%), followed by Kauswagan (15.4%) and Balulang (14.2%). The available data for the affected population in Cagayan de Oro City was not disaggregated beyond the barangay level, and did not have a further breakdown of demographic characteristics.

Damage to housing A total of 20,914 housing units were damaged in Cagayan de Oro City due to the TS Washi-triggered floods. Most of the housing damages occurred in the barangays of Carmen (17.8%), Balulang (13.3%), and Kauswagan (9.3%). Table A.4 provides the full details of the number of housing units that experienced varying degrees of damage per barangay, together with the total number of housing units from the 2010 census. It is important to note that Macasandig had the highest number of houses that were totally damaged, while in Kauswagan most of the damaged houses were merely inundated.

Table A.4:
Cagayan de Oro City barangays that sustained varying degrees of damage to housing

Barangay	Total damage and % of tot. housing		Partial damage and % of tot. housing		Flooded only and % of tot. housing		Total housing units in 2011*
Macasandig	1,013	17.20%	318	5.40%	–	–	5,890
Carmen	845	4.66%	1,499	8.27%	–	–	18,134
Balulang	700	7.36%	1,050	11.04%	–	–	9,515
Barangay 13	308	55.10%	40	7.16%	–	–	559
Iponan	116	1.76%	707	10.75%	26	0.40%	6,577
Kauswagan	102	1.20%	82	0.97%	1,504	17.72%	8,487
Bulua	92	1.15%	221	2.77%	815	10.22%	7,972
Canitoan	90	2.43%	310	8.36%	–	–	3,710
Barangay 15	73	8.90%	11	1.34%	–	–	820
Consolacion	69	2.52%	172	6.28%	–	–	2,739
Tuburan	53	16.51%	18	5.61%	–	–	321
Pagatpat	52	3.56%	107	7.32%	123	8.42%	1,461
Tablon	49	0.96%	84	1.65%	–	–	5,100

Continued

Table A.4: Continued

Barangay	Total damage and % of tot. housing		Partial damage and % of tot. housing		Flooded only and % of tot. housing		Total housing units in 2011*
Bonbon	39	1.70%	90	3.92%	–	–	2,297
Cugman	37	0.73%	140	2.77%	–	–	5,052
Agusan	36	0.98%	45	1.23%	–	–	3,659
Tumpagon	34	6.10%	–	–	–	–	557
Gusa	31	0.47%	109	1.66%	–	–	6,549
Pigsag-an	29	12.03%	3	1.24%	–	–	241
Puntod	25	0.52%	474	9.91%	–	–	4,783
Nazareth	22	0.75%	10	0.34%	–	–	2,922
Lumbia	20	0.50%	14	0.35%	–	–	3,994
Indahag	17	0.97%	19	1.08%	–	–	1,754
Baikingon	16	2.42%	27	4.08%	–	–	662
Barangay 7	16	11.11%	23	15.97%	–	–	144
Macabalan	15	0.31%	59	1.24%	–	–	4,762
Barangay 6	15	44.12%	7	20.59%	–	–	34
Pagalungan	14	3.16%	2	0.45%	–	–	443
Dansolihon	12	1.01%	4	0.34%	–	–	1,194
Tignapoloan	11	1.12%	1	0.10%	–	–	981
Barangay 10	10	6.85%	56	38.36%	–	–	146
San Simon	9	2.59%	92	26.51%	–	–	347
FS Catanico	9	2.05%	57	12.98%	–	–	439
Barangay 1	7	4.12%	20	11.76%	142	83.53%	170
Barangay 17	3	0.51%	95	16.07%	–	–	591
Barangay 18	2	0.47%	182	42.92%	–	–	424
Camaman-an	2	0.03%	7	0.12%	127	2.13%	5,969
Bayanga	2	0.28%	–	–	–	–	716
Bayabas	1	0.03%	4	0.12%	–	–	3,441
Balubal	1	0.13%	2	0.26%	–	–	779
Mambuaya	1	0.15%	–	–	–	–	683
Lapasan	–	–	1	0.01%	–	–	10,513
Barangay 24	–	–	–	–	139	51.87%	268
Barangay 23	–	–	–	–	85	37.61%	226
Barangay 20	–	–	–	–	11	32.35%	34
Barangay 25	–	–	–	–	9	2.69%	335
Total	2,981	2.19%	6,162	4.52%	3,998	2.93%	136,396

Appendix B: Complete list of fields in the 2010 Census of Population and Housing

Code	Description
reg	Region code
prv	Provincial code
prrcd	Highly urbanized city code
mun	Municipal code
bgy	Barangay code
husn	Housing unit sequence number
hsn	Household sequence number
lno	Line number
rel	Relationship to household head
sex	Sex
age	Age
breg	Birth registration status
ms	Marital status
rlgn	Religion
cit	Citizenship
eth	Ethnicity
dis	Disability
dsee	Functional difficulty in seeing
dhrg	Functional difficulty in hearing
dmob	Functional difficulty in walking/climbing
dmem	Functional difficulty in remembering or concentrating
dslf	Functional difficulty in self-caring
dcom	Functional difficulty in communicating
r5yr	Residence 5 years ago
hgc	Highest academic grade completed
ofw	Overseas foreign worker
type	Housing type
roof	Type of roofing material
wall	Type of outer wall material
repr	State of repair
yrbt	Year built
area	Floor area
tnur	Tenure status
huind	First household in the housing unit

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Social vulnerability to floods in two coastal megacities: New York City and Mumbai

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Abstract

In this paper we assess differential exposure to flooding in two coastal megacities, New York and Mumbai, both of which suffered major flood-related disasters in the past decade. Specifically, we examine whether the most exposed populations are also the most socially vulnerable. First, we developed Social Vulnerability Indices (SoVIs) for each city with census data. We then overlaid the SoVI scores onto flood extent maps for Hurricane Sandy (New York, October 2012) and the Mumbai flash floods (July 2005), as well as for the evacuation zones for New York, to examine patterns of differential exposure. Our results suggest a degree of differential exposure in New York, especially in the highest flood risk areas, and provide fairly clear evidence for differential exposure in Mumbai. However, differences in the input resolution and confidence in the datasets for Mumbai make the results more uncertain. The paper concludes with a discussion of the policy implications and the data needs for urban spatial vulnerability assessments.

1 Introduction

There is growing interest among researchers and policy-makers in the risks to and the vulnerability of cities as the climate changes. This issue is attracting considerable attention in response to mounting evidence that the probability of extreme events of high magnitudes is increasing owing to anthropogenic climate change (Fischer & Knutti 2015, IPCC 2012, IPCC 2007); that the world's population is becoming increasingly urban (UNFPA 2007); and that urban systems are particularly susceptible to certain kinds of climate impacts, such as storm surges, cyclones with high winds, floods, extreme heat, and—over the long term—sea

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level rise (SLR) (Jha et al. 2012, Rosenzweig et al. 2011a). Although vulnerability assessment is gaining increasing attention, the literature on urban areas and climate change tends to be more heavily weighted toward impact and risk assessment, in which the focus is on the likely damage to infrastructure or health impacts on populations from events of various magnitudes (Lane et al. 2013, Rosenzweig et al. 2011a, Preston et al. 2007). A high proportion of these studies focus on flood and storm surge risk (UN HABITAT 2013, Jha et al. 2012, Storch et al. 2011, Kit et al. 2011, Rosenzweig et al. 2011b, Hallegate et al. 2010, Lin et al. 2010, Nicholls et al. 2008, Kleinen and Petschel-Held 2007), although populations who face risks related to heat waves (Wilhelmi et al. 2004, Kinney et al. 2000) and drought (and attendant water scarcity) (McDonald et al. 2011) are also included in some risk assessments.

Climate and risk researchers have often focused on infrastructure impact assessment using top-down expert- or model-driven approaches because they are less complex than approaches that incorporate social vulnerability (Soares et al. 2012, Cutter et al. 2003). Yet social vulnerability to climate change is also high, especially in urban areas with large, concentrated populations and a high degree of social stratification (Romero Lankao and Qin 2010). It is now widely appreciated that differences in demographic characteristics—e.g. income, educational level, race, social class, housing type, and occupation—are key contributors to social vulnerability (WHO 2010). Cutter et al. (2003) defined these characteristics as "social factors that influence or shape the susceptibility of various groups to harm and that also govern their ability to respond".[1] Differential vulnerability based on factors such as race, ethnicity, income, and gender was identified by Soares et al. (2012) as one of nine key concepts in vulnerability research. According to Pelling (2002), "the matter of which groups of people are exposed to living with physical insecurity is not decided by random forces," but rather by patterns of political exclusion, wealth differentials, and power relations. Although there is evidence that urban populations with higher levels of social vulnerability generally suffer greater impacts from climate-related hazards (Reckien et al. forthcoming and 2013, Cutter and Emrich 2006, Laska 2006), there is less research that combines spatial patterns of social vulnerability and exposure to test the hypothesis, articulated by Pelling, that populations with higher levels of social vulnerability are more exposed to climate hazards than populations who are less socially vulnerable.

The goal of this paper is to use spatial methods to test the hypothesis that there are higher levels of social vulnerability in flood-prone areas of New York City and Mumbai. We use the term 'differential exposure' rather than the term 'differential vulnerability' (Soares et al. 2012), which focuses on population characteristics that make some population groups more sensitive to environmental stressors than others.

[1] Throughout this paper, we use the term vulnerability in the sense of social, contextual, or intrinsic vulnerability (O'Brien et al. 2007); rather than in the sense of outcome vulnerability, defined by the IPCC fourth assessment report as comprising exposure, sensitivity, and adaptive capacity (Parry et al. 2007).

There are theoretical reasons that would both support and refute a proposed link between high levels of social vulnerability and flood exposure. On the one hand, areas exposed to floods may have lower housing prices, which tend to attract poorer and less informed populations. There is evidence that this is the case in two highly flood-prone cities: Kampala, Uganda (Sliuzas et al. 2013, Nyakaana 2006) and Lagos, Nigeria (Agbola and Agunbiade 2009). On the other hand, wealthier people may be more exposed to coastal flooding, as property prices are often highest in close proximity to the shore. The collective action literature suggests, however, that wealthier populations are often able to mobilize to obtain the coastal infrastructure needed to protect their homes, and may therefore be less exposed than poorer populations (Adger 2003). Thus, on balance it is possible to argue that in all but the most extreme events the wealthiest populations are the least likely of the income groups to be exposed. We return to these theoretical linkages in our concluding discussion.

We chose to focus on New York City and Mumbai because they represent socioeconomically diverse cities at different ends of the global development spectrum that are highly vulnerable to flood hazards, and because they can be used to illustrate how the spatial resolution of data inputs affects our confidence in the results. First, we summarize recent research on spatial approaches to assessing differential exposure. We then discuss the two cities' levels of vulnerability to flood hazards, followed by a presentation of methods and results. We conclude with a discussion of broader issues related to uncertainty and the spatial resolution of input data in vulnerability assessments, and of the theoretical and policy implications of this research.

2 Literature review

While there is relatively abundant environmental justice (EJ) literature that shows that poor neighborhoods are differentially exposed to environmental hazards in the form of polluting industries, toxic waste sites, and air pollution sources such as highways (e.g. Crowder and Downey 2010, Mitchell and Dorling 2003, Bowen et al. 1995), there is less work that explores differential exposure to climate-related hazards (Reckien et al. *forthcoming*). An early study on differential exposure to climate hazards was conducted by Pelling (2002) in Santo Domingo, Dominican Republic. He employed survey methods to examine local patterns of self-organization and resilience in the aftermath of Hurricane Georges in 1998. However, he focused only on one community that was both low-income and exposed to natural hazards owing to its location on a river bank that experienced flooding during the hurricane. Thus, the research design could not answer the question of whether low-income communities in Santo Domingo were differentially exposed to flood hazards.

In the United States, Hurricane Katrina—which struck New Orleans, Louisiana, in August 2005—was a signature climate event that revealed differential vulnerability, though not necessarily differential exposure. Curtis et al. (2007) used census and public health data to explore the geography and characteristics of poverty in New Orleans prior to Hurricane Katrina, and how the specific locations and living situations of the residents contributed to outcomes. They found that the floods affected comparably well off and poorer communities almost equally, but that the impacts were greater in low-income communities because people living in these neighborhoods lacked transportation options to evacuate. In other regions the results are varied. A first ever global analysis by Winsemius et al. (2015) estimated a 'poverty exposure bias' to floods for 52 countries; i.e. that poor urban populations are often disproportionately represented in flood zones. Researching differential exposure to flood hazards in the UK, Houston et al. (2011) found that socially deprived areas are at slightly higher risk of pluvial flooding (rivers overtopping their banks), particularly in cities with larger rivers in which inner-city neighborhoods tend to be located in low-lying areas. Looking at New York City as a whole, Maantay and Maroko (2009) found that minority populations are not disproportionately represented in the 100-year floodplains, although in some boroughs (Manhattan, the Bronx, and Queens) African-Americans are disproportionately represented. In Cologne, Germany, results from an analysis by Welle et al. (2014) showed a low degree of spatial overlap between areas with high levels of flood exposure and those with high levels of social susceptibility, as measured by four metrics that examine household size and age composition, with an emphasis on the ability of residents to evacuate without assistance.

Other flood-related vulnerability assessments have been less tailored toward assessing differential exposure. Rygel et al. (2006) constructed a Social Vulnerability Index (SoVI) for the city of Norfolk, Virginia (United States), and surrounding areas known to be at high risk of coastal surge and sea level rise (SLR). While they experimented with alternative aggregation methods, they stopped short of assessing differential vulnerability to mapped distributions of flood hazards. Similarly, Kit et al. (2011) and Reckien et al. (2013) mapped slum distributions and flood hazards in Hyderabad, India; and Lane et al. (2013) examined indicators associated with higher flood vulnerability in the hurricane evacuation zones of New York City. Yet neither of these studies tested the hypothesis that populations exposed to floods or within these zones are more socially vulnerable than other populations.

There is a larger body of literature on differential exposure to urban heat stress, and most U.S.-based studies have found that poorer residents are exposed to higher temperatures than more affluent residents because low-income people are more likely to live in crowded conditions and older building stock, and/or live in neighborhoods with a lack of green space. An assessment of differential exposure to urban heat stress by Uejio et al. (2011) in Phoenix and Philadelphia found that heat distress calls in the former city and heat mortality in the latter city were correlated with higher proportions of minority residents and lower housing values. Other studies conducted in Philadelphia confirmed that the populations with high levels of social vulnerability also have relatively high levels of exposure to urban heat stress, as measured by satellite-derived land surface temperatures (Weber et al. 2015, Johnson and Wilson 2009). In a study of Washington, DC, Aubrecht and

Özceylan (2013) created a heat stress vulnerability index (HSVI) composed of census-derived social vulnerability metrics and a heat stress risk index (HSRI), which is a combination of the HSVI and exposure to extreme heat. The HSRI was found to have high values in the poorer neighborhoods of northeast, east, and southeast Washington, DC; and particularly high values in Anacostia and Lincoln Heights, which are low-income, predominantly African-American neighborhoods south of the Anacostia River. De Sherbinin et al. (2012) conducted a spatial analysis of several cities using different poverty and heat/greenness metrics aggregated to high resolution census units. They found a positive correlation between median housing value and greenness in Phoenix, Arizona (greenness is negatively correlated with surface temperature (Imhoff et al. 2010)), and a slight positive correlation between income per capita and satellite-derived surface temperature in Houston, Texas.

In other regions, the evidence for differential exposure to heat stress is less clear. Romero-Lankao et al. (2013) analyzed temperature, air pollution, mortality, and socioeconomic vulnerability data for Bogota, Mexico City, and Santiago (Chile). They found little evidence that areas experiencing greater environmental stressors or health impacts were more likely to have populations with high levels of social vulnerability. In Cologne, Germany, results from an analysis by Welle et al. (2014) showed that there is a relatively high degree of spatial overlap between high heat exposure and lack of coping capacity (as measured by household size and residents' ages), but that there is little overlap with high levels of social susceptibility (as measured by unemployment rates and by the shares of the population who were very young, elderly, or foreign). De Sherbinin et al. (2012) found a positive correlation between poverty levels and vegetation greenness in Hanoi, Vietnam, and virtually no correlation between a multiple deprivation index produced by Baud et al. (2008) and satellite-derived surface temperature in Delhi.[2]

Although the existing literature is sparse, this brief review shows that the evidence on differential exposure by event type (flood or extreme temperatures) and by region is mixed.

3 Overview of the two cities

Over the past decade, New York City (NYC) and Mumbai have been hit hard by natural disasters. In the Mumbai metropolitan area at least 500 people died as a result of the July 2005 Maharashtra flash floods, which dumped more than 900 mm of rainfall on the city in a 24-hour period (Government of Maharashtra

[2] One possible explanation for the differences between U.S. and developing region cities in exposure to heat stress is that higher-income residents have tended to remain in city center areas in many developing countries for ease of access to work and amenities, whereas the U.S. saw the flight of many upper-income populations to the suburbs from the 1950s onwards.

2005). Hurricane Sandy caused 44 deaths in NYC in October 2012 (Goldstein 2013). Owing to their demographic and geographic characteristics, these two cities are among the top 10 port cities most exposed to coastal flooding in terms of the assets and the population exposed (Nicholls et al. 2008).

With a population of 8.25 million spread over five boroughs (about 785 km^2), NYC has multiple waterways that create nearly 965 km of coastline affected by tides and weather. Though street and fluvial flooding affect NYC, coastal flooding represents the main danger. The massive coastal flooding during Hurricane Sandy caused extensive damage to NYC's infrastructure systems and coastal ecosystems, resulting in the loss of property and lives (Horton et al. 2015). Coastal flooding affects residential neighborhoods, businesses, infrastructure, coastal water quality (including sewage and toxic chemicals contamination), and natural ecosystems.

NYC has been a world leader in climate change adaptation planning. In 2008 the city launched the Climate Change Adaptation Task Force and the NYC Panel on Climate Change (NPCC) to develop adaptation strategies for protecting the city's infrastructure from the effects of climate change (Rosenzweig and Solecki 2010). In 2011, the city of New York updated PlaNYC, its plan to improve the city's sustainability, and particularly its resilience to and preparedness for extreme events (i.e. events projected to occur once every 100 years). Despite having identified its vulnerabilities (Horton et al. 2010, Jacob et al. 2007) and recently updated PlaNYC, the city still found itself unprepared for the 14-foot storm surge that occurred during Hurricane Sandy in October 2012 (Lane et al. 2013). A storm surge of this magnitude was considered to be a once-in-500-year event (Aerts et al. 2013).

Mumbai is at an earlier stage in the urban transition, and is facing many of the same environmental consequences of rapid economic growth and industrial expansion that the U.S. experienced six decades ago. Within the last three decades alone, metropolitan Mumbai's population has tripled, from eight million in 1991 to about 20.7 million in 2011 (Census of India 2011). Mumbai is largely located on reclaimed land, and much of the new settlement (industrial, residential, and commercial) has occurred along the coastal areas of Greater Mumbai that are low-lying and flood-prone (de Sherbinin et al. 2007). Although the metropolitan area of Mumbai extends well over 4,400 km^2, population growth has largely been confined to 450 km^2 in an area known as Greater Mumbai.

Over the years, topographic modifications, poor disaster planning, obsolete drainage systems, and poor coastal zone management have all exacerbated flood risk, thereby increasing the vulnerability levels of diverse sections of the population and of coastal ecosystems. In particular, the influx of migrant workers has led to the emergence of large informal settlements in low-lying areas (Parthasarathy 2009), where floods associated with extreme rainfall are highly damaging to human health and well-being, and thus compound existing vulnerabilities (Murthy et al. 2001, Dhage et al. 2006). Urban development is steadily encroaching on wetland ecosystems, which provide flood prevention and other important ecosystem services, while urban effluents often lead to hypoxic and anoxic conditions in coastal waters (Kumar et al. 2008). A study sponsored by the OECD modeled flood risks in

Mumbai based on the July 2005 event (Ranger et al. 2011, Hallegatte et al. 2010). The team estimated the economic costs of the flood at USD 2 billion, and projected that under future development and climate scenarios the costs will triple. They also provided several adaptation options, including improving drainage and increasing insurance penetration.

Although the two cities have very different levels of economic development, both have a high degree of social stratification, which make them useful case studies for an assessment of differential vulnerability to flood hazards.

4 Framework, data, and methods

Our research is framed by the IPCC Special Report on Extreme Events (SREX) conceptual framework, which construes risk as emanating from the intersection of exposure to extreme events and social vulnerability (IPCC 2012). We measured social vulnerability using the approach described by Cutter et al. (2003) and Emrich (2011) for the construction of a Social Vulnerability Index (SoVI). The SoVI is commonly used in the literature to assess social vulnerability, but here we intend to use it as a synthetic measure of poverty and social exclusion to examine differential exposure to floods. The SoVI builds on research that has identified the primary social drivers of sensitivity to, and slow recovery from, natural hazards (Cutter et al. 2003, Carreño et al. 2007, Birkmann et al. 2011), including:

- **Socioeconomic status** (income, political power, prestige): Wealthy people are able to recover from natural disasters and absorb losses more quickly than poor people. Even if the total economic losses are higher for the richest people, the most deprived people face the greatest difficulties in recovering from these events.
- **Gender:** Women often face greater consequences and recover more slowly from natural disasters than men, due to factors such as their greater likelihood of being in sector-specific employment, having low wages, having family care responsibilities, or being pregnant. Single mothers in particular are threatened by natural hazards.
- **Race, ethnicity, culture:** Being part of an ethnic minority or foreign-born community can be helpful in the aftermath of a disaster if social solidarity exists. But in many circumstances being a member of minority group can result in social exclusion and difficulties in accessing government help, relocation, or funding because of isolation, lack of legal status, and low language proficiency.
- **Age:** Because they often suffer from health and mobility problems, the elderly are the most sensitive to disasters of all of the age groups (Al-rousan Tala et al. 2014). Early childhood is also a critical period. Children under age five are particularly vulnerable, and therefore require attention, time, and money from the whole family during both the disaster and the recovery process.

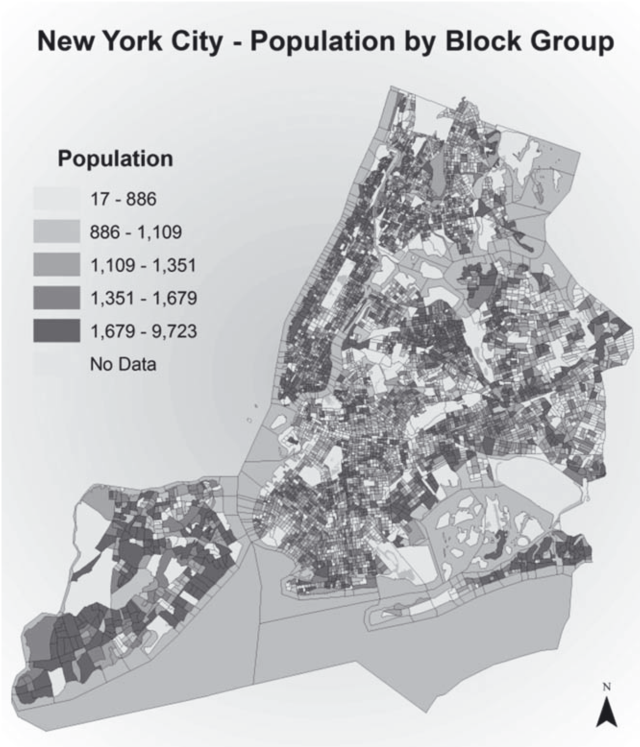
- **Housing stock:** The quality of housing, as measured by rents, may indicate resilience to certain types of hazards.
- **Family structure:** Experiencing a catastrophe and the period of recovery that follows is especially difficult for those responsible for large families and for single-parent households.
- **Education:** Having a low level of education may constrain an individual's ability to understand warning information and access recovery information (Muttarak and Pothisiri 2013).
- **Social dependence:** People who are dependent on social services for survival require additional support in the post-disaster period.
- **Special needs populations:** Infirm, institutionalized, transient, drug-addicted, and homeless people are disproportionately affected during disasters. Because they are difficult to identify and measure, these populations are mostly ignored during the recovery phase.

Obviously, the factors that contribute to social vulnerability will differ depending on the stressor (e.g. floods, extreme heat, or air pollution), but this list covers a wide range of population factors that have been found to be important in vulnerability studies (Carreño et al. 2007, Birkmann et al. 2011). Other factors, such as the robustness of urban infrastructure, the existence of emergency services, and the adequacy of governance and institutions are all important in determining outcomes, but typically cannot be measured through census or survey data. There may also be location-specific factors that contribute to vulnerability, such as the existence of the caste system in India or of systematized gender discrimination.

Guided by these general factors and by the work of Cutter et al. (2003), we constructed Social Vulnerability Indices (SoVIs) in New York City and Mumbai based on available census data. The SoVI was originally developed to compare the hazard vulnerability of U.S. counties, but has been modified to allow for local-scale analyses (Cutter et al. 2006, Schmidtlein et al. 2008) and applications of similar social vulnerability indices outside the U.S. (Fekete 2010, Crooks 2009, Confalonieri et al. 2009). The exposure aspects were measured using the available flood and flood risk data layers for each city. The specific indicators and flood data layers used in each city are described in greater detail in Sections 4.1 and 4.2. Here we provide information on the SoVI approach that is relevant to the two case studies.

The SoVI is calculated using principal components analysis (PCA). This approach uses eigen analysis to summarize the statistical properties of the indicators simultaneously by identifying a set of n uncorrelated principal components (PCs), where n = the number of indicators. The PCs are linear combinations of the indicators that are conceptually similar to a line of best fit through the data cloud. The first PC explains the greatest amount of variation in the n-dimensional data cloud; and the second PC explains the next largest amount of variation, subject to the constraint that it is orthogonal (or uncorrelated) to the first PC. Because the PCs are uncorrelated, the scores associated with each PC encapsulate a unique aspect of social vulnerability represented by the original set of indicators. SoVI scores can

Figure 1:
Population by block group (quintiles)



be interpreted as unit variance or z-scores; zero represents the mean, positive scores represent higher vulnerability, and negative scores represent lower vulnerability.

As suggested by the SoVI recipe (Emrich 2011) and Schmidtlein et al. (2008), we performed the PCA using a varimax rotation and only selected the components with an eigenvalue superior to one (Kaiser Criterion). Varimax rotation tends to load each variable highly on just one component in order to ease component interpretation (Schmidtlein et al. 2008). In both cities we named each of the PCs based on the indicators that loaded most highly on that PC. Demšar et al. (2013) discussed the merits of spatial PCA (sPCA), which takes into account spatial effects with respect to spatial heterogeneity or autocorrelation. We chose not to conduct a sPCA because it is not yet common practice to perform such an analysis in SoVI construction,[3] and we were not convinced that doing so would have yielded significantly improved results, given that our main interest is in how the indicators co-vary over space.

It is a common practice to invert (reverse the directionality) of PCs by multiplying scores by −1 in cases in which higher values can be construed as being associated with lower vulnerability (Emrich 2011, Thornton et al. 2008). Once all of the PCs have the same directionality, they can be averaged together, with each PC given equal weight (which we call an 'Averaged SoVI'). Alternatively, a weighted average can be created in which each PC is multiplied by the variance it explains (which we call a 'Weighted SoVI'). Schmidtlein et al. (2011) stated that the SoVI algorithm does not appear to be substantially influenced by scalar changes, but is sensitive to variations in its construction. The SoVIs we constructed are obviously influenced by the choice of variables and the aggregation method, but a comparison using different approaches to SoVI construction suggested that the results were broadly similar.

In each city, we compare SoVI scores within different flood exposure categories, and in the case of New York, evacuation zones. For each exposure category we calculated a population weighted mean of the Average and the Weighted SoVIs. Figure 1 shows the population by block group. The population-weighted SoVI avoids the potential problem that block groups with very low populations could have a disproportionate influence on the average score by exposure category; since our concern is with the exposure of populations, it is appropriate to apply the population weight using the following formula:

$$\mathrm{SoVI}_Z = \sum_{i=1}^{n}(\mathrm{SoVI}_i * \mathrm{P}_i) \Big/ \left(\sum_{i=1}^{n} \mathrm{P}_i\right)$$

Where:

SoVI_Z = SoVI population-weighted score for the zone Z (exposure category),
SoVI_i = SoVI of the i block
P_i = Population of the i block

With these population-weighted means, we were able to test whether there is a statistically significant difference in the mean scores by exposure category for each of the two cities.

In line with Winsemus et al. (2015) we also tested an additional metric, the 'poverty exposure bias' (PEB), which compares the fraction of the poor population with the fraction of the total population exposed to floods in each city. This summary metric, while not as sophisticated, provides an additional test of differential exposure.

3 We were unable to find a single SoVI analysis that used sPCA. Indeed, Demšar et al. reported that "in surveyed literature we found proportionally few studies that use spatially adapted versions of PCA to analyze their data" (p. 123).

4.1 New York

4.1.1 New York social vulnerability

For New York, we began with a list of relevant variables published on the Hazards and Vulnerability Research Institute's SoVI website[4] (USC undated), but modified the list based on their applicability to the NYC context and flood vulnerability. The choice of variables is obviously important, since not all variables are directly relevant to every type of hazard (Welle et al. 2014). We chose a somewhat liberal approach to the construction of the SoVI for flood exposure, but also tested the importance of individual variables with stronger theoretical ties to flood exposure to see if the results differed substantially. Table 1 provides a list of the variables we removed and our reasons for removing them. We used data from the 2010 U.S. Decennial Census and five-year estimates from the 2006–2010 American Community Survey. The U.S. Decennial Census covers the entire American population on years ending with '0', and includes a reduced set of variables. The American Community Survey (ACS) is an ongoing statistical survey that gathers information on about one in 38 households every year. The Census Bureau releases estimates based on one, three, and five years of data. As recommended on the SoVI website, we used data from the ACS five-year estimates for 2006–2010 because they are more robust and better match the decennial census data. In cases in which the data existed in both datasets, we selected the census data, as they represent a full count and not an estimate.

We recognize that the uncertainty levels in the three-year ACS data are very high at smaller geographies, such as block groups and census tracts (Spielman et al. 2014, Bazuin and Frazier 2013). Thus, we believe that the use of a mix of decennial census variables, five-year estimates, and a relatively large number of variables mitigates the risk of spurious results. Roughly two-thirds (13 out of 21) of the variables were obtained from the decennial census, and seven out of 11 of the variables that were found to be most highly correlated with the top five PCs (and therefore contributed most to the SoVI scores) were from the decennial census.

We collected data at the block group level for both the census and the ACS, which is the smallest unit at which data are reported. The data were from three websites: American Fact Finder, Social Explorer, and Data Ferret.[5] The average population of a block group in NYC is 1,300 inhabitants, and there were 6,198 block groups covering the city's five boroughs, for a total population of approximately 7.8 million people. Table 2 provides the list of the variables we selected together with the broad category, the origin of the data, and the effect on the SoVI.

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[4] The SoVI was developed by Susan Cutter and colleagues at the Hazards and Vulnerability Research Institute.

[5] http://factfinder.census.gov/, http://www.socialexplorer.com/ and http://dataferrett.census.gov/, respectively.

Table 1:
Discarded variables from the SoVI

Variables removed	Reason
Percent Urban Population	Not pertinent in a city, and very low variability
Percent Employment in Extractive Industries (e.g. mining)	Not pertinent in a city, and very low variability
Percent Employment in Services	Not theoretically relevant to flood exposure
Median Housing Value	Too many missing values at block group level
Median Gross Rent	Data not consistent at block group level
Percent Mobile Homes	Not pertinent in a city, and very low variability
Percent Civilian Unemployment	Data not available at block group level
Hospitals Per Capita	Data not available at block group level
Percent of Population Without Health Insurance	Data not available at block group level

The variables were normalized where necessary by transforming raw figures into comparable indicators, such as percentage of population or density. We analyzed the data while focusing on the following: (1) the level of reliability and confidence in the datasets (e.g. the estimations we had on housing prices were not reliable at our block group scale); (2) the correlation among variables, discarding those that are too highly correlated (if two variables cover the same information we do not need both); and (3) removing block groups without data, such as parks and industrial areas, or block groups without housing units (e.g. the Rikers Island jail complex). The result was a single file with 21 variables and 6,199 block groups. A correlation/covariance matrix for all of the variables is found in Tables A.1 and A.2 in the appendix. Finally, we performed the PCA as described in above, and we extracted five factors explaining a total of 71.1% of the variance of our original dataset (see Table 3). We inverted Factor 5, and then developed averaged and weighted SoVI scores, which are shown in Figure 2. The results are broadly similar.

Examining Figure 2, we can see that the most vulnerable block groups are often located together, forming large socially vulnerable areas.

- The eastern part of Brooklyn (Bushwick, Bedford-Stuyvesant, East Flatbush, Brownsville, Canarsie or East New York)
- Northern Manhattan and a large part of the Bronx
- Southeastern Manhattan (Chinatown and the Lower East Side)
- Coney Island and Brighton Beach
- Downtown Flushing in northern Queens

By contrast, most of Staten Island, the southern half of Manhattan (except the Lower East Side neighborhoods) and southeastern Queens have very low SoVIs, and thus show low levels of social vulnerability to climate extremes.

Table 2:
List of variables used for New York's SoVI

Variable	Category	Origin	Effect on SoVI
Percent Black	Race/Ethnicity	Census	+
Percent Native American	Race/Ethnicity	Census	+
Percent Asian	Race/Ethnicity	Census	+
Percent Hispanic	Race/Ethnicity	Census	+
Percent of Population Under Age 5 or Over Age 65	Age	Census	+
Percent of Children Living in Married Couple Families	Family Structure	Census	−
Median Age	Age	Census	+
Percent of Households Receiving Social Security	Age, Dependency	ACS	+
Percent Poverty	Income	ACS	+
Percent of Households Earning More Than $200,000 Annually	Income	ACS	−
Per Capita Income	Income	ACS	−
Percent Speaking English as a Second Language with Limited Proficiency	Race/Ethnicity	ACS	+
Percent Female	Gender	Census	+
Percent Female-Headed Households	Gender, Family Structure	Census	+
Percent of Population Living in Nursing and Skilled-Nursing Facilities	Age, Dependency	Census	+
Percent with Less Than 12th Grade Education	Education	ACS	+
Population Density (Population per Square Mile)	Urbanization	Census	+
People per Housing Unit	Family Structure	Census	+
Percent Renters	Income, Tenancy	Census	+
Percent of Housing Units with No Car	Income, Urbanization	ACS	+

4.1.2 New York flood exposure

For New York we used two different maps: an *Evacuation Zones* map released by New York City's Office of Emergency Management (06/20013), and the *Hurricane Sandy Impact Analysis* by the Federal Emergency Management Agency (FEMA) Modeling Task Force (MOTF), which highlights the areas flooded by Sandy (Figure 3a and b).

Figure 3a shows the evacuation map as issued by FEMA. The zones determine when an area has to be evacuated, with zone 1 being the first (relatively weak flooding) and zone 6 being the last (a very strong event). We intersected this map

Table 3:
Principal components of New York's SoVI

Factor	Name	Variance explained	Principal variables	Correlation	Sign
1	Poverty	**17.4%**	*Per Capita Income*	−0.849	+
			% Earning $200,000+	−0.894	
2	Dense Urbanization	**16.3%**	*% with No Car*	0.879	+
			% Renters	0.794	
			Population Density	0.766	
3	Black and Single Parent Households	**15.8%**	*% Black*	0.838	+
			% Female-Headed Households	0.800	
			% Children in Married-Couple Families	−0.723	
4	Age	**11.9%**	*% Under Age 5 or Over Age 65*	0.891	+
			Median Age	0.753	
5	Hispanic	**11.8%**	*Percent Hispanic*	0.745	+
			Percent Native American	0.758	

Figure 2:
Weighted SoVI (left) and Averaged SoVI (right) for New York (quintiles)

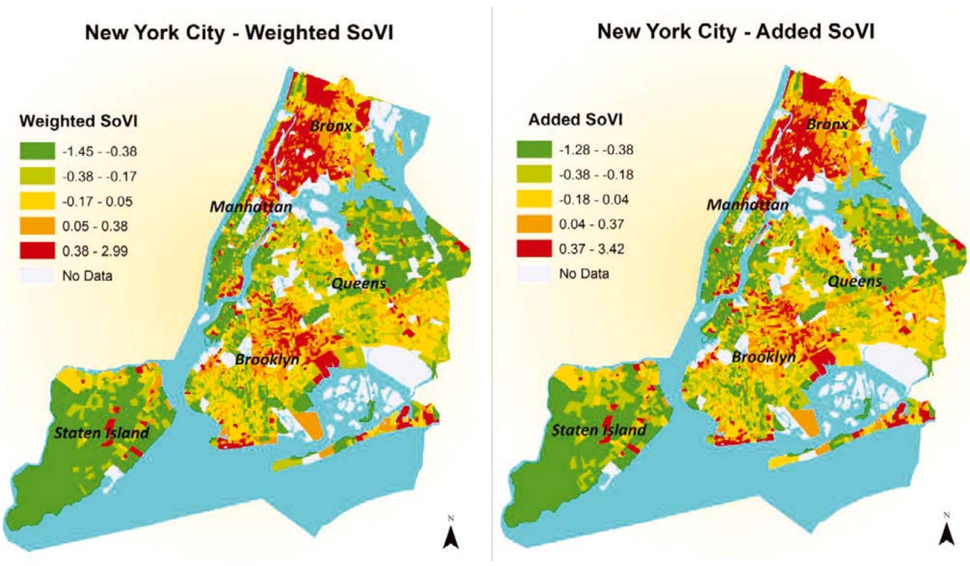
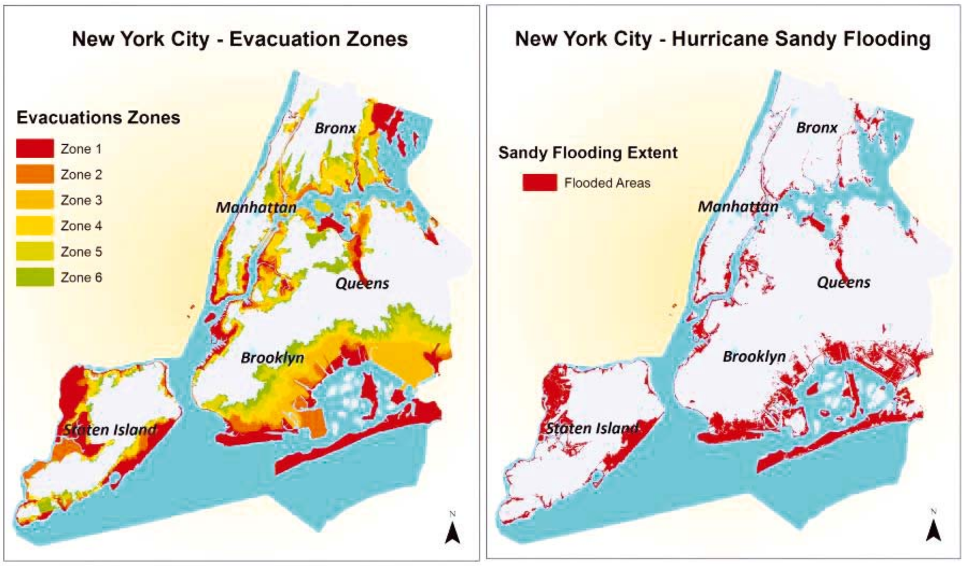


Figure 3:
(a) Evacuation zones and (b) Sandy flooding extent maps, New York



with the block group boundaries base map in order to give an 'evacuation score' to each block group. This score was assigned to the block group based on the proportion of the block group that fell in the zone (majority rule). We reclassified the evacuation zones such that each block group fell into one of the seven categories, moving from lowest to highest risk. Category A represents block groups not in any evacuation zone, and categories B-G represent those in the lowest flood risk category (zone 6) to those in the highest category (zone 1). We included the evacuation zones because Sandy was a singular event with flood impacts that were determined by the specific meteorological conditions that produced it. The evacuation zones represent a broader risk assessment for hurricanes with multiple trajectories, wind speeds, and locations of landfall.

Figure 3b represents the area covered by Hurricane Sandy flooding in NYC. Here we created a 'flooding score' for each block group, and separated them into four categories. Category A represents block groups outside of the flooding zone (77.5% of all block groups). Using quantiles (7.5% each) we divided the remaining block groups as follows: category B was 0.01–13.5% flooded, category C was 13.6–50% flooded, and category D was 50–100% flooded. We were thus able to compare the social vulnerability levels based on both a theoretical (evacuation) score and a factual exposure (flooding) score.

Table 4:
Mumbai SoVI variables

Variables	Category	Effect on the SOVI
Population Density	Urbanization	+
% Female	Gender	+
% Under Age 6	Age	+
% Scheduled Tribes or Castes	Race/Ethnicity	+
% Literacy	Education	–
% Slum Population	Income	+
% Workers Among Females	Gender	–
% Unemployment	Social Exclusion	+
% of Households Using Bank Services	Social Exclusion	–
% of Households with a TV	Income	–
% of Households with a Motorcycle	Income	–
% of Households with a Car	Income	–

4.2 Mumbai

4.2.1 Mumbai social vulnerability

Up-to-date, high-resolution census data for Mumbai were much more difficult to obtain, and matching boundary files had to be obtained from third parties. The Indian census provides relatively good-quality, recent (2011), and easy-to find data at a country, state, or city level. But it was impossible to locate more spatially resolved data for city-level analyses. Ultimately we settled on data from the 2001 census for 99 wards (average of 120,000 inhabitants/ward), and selected 12 variables that fit the factors that contribute to vulnerability, as described in the introduction to section 4 (Table 4). We believe that the 2001 data are reasonably representative of conditions at the time of the Mumbai Floods.

We performed a PCA, and obtained three components representing 76.4% of the total variance (Table 5). Again, we created an averaged and weighted (by percentage variance explained) SoVI. Figure 4 presents a map of the results.

The results show that, as expected, the wealthy Mumbai City District, located in the southern part of the city, is the least vulnerable. The highest SoVI scores are concentrated in the eastern and northwestern sections of the city. In Mumbai the central business district is relatively prosperous, while the northern parts of the city are dominated by poorer populations who either work locally or commute to the business district by train. The northern sections are also home to some of the most densely populated slums in the world.

Table 5:
Principal Mumbai components extracted by PCA

Factor	Name	Variation explained	Principal variables	Correlation	Sign
1	***Standard of life and access to information***	42.1 %	% Households Using Bank Services	**0.95**	–
			% Households with TV	**0.94**	
			% Literacy	**0.90**	
2	***Employment***	17.8 %	% Unemployment	**0.97**	+
3	***Female employment***	16.5 %	% Workers Among Females	**0.89**	–

4.2.2 Mumbai flood exposure

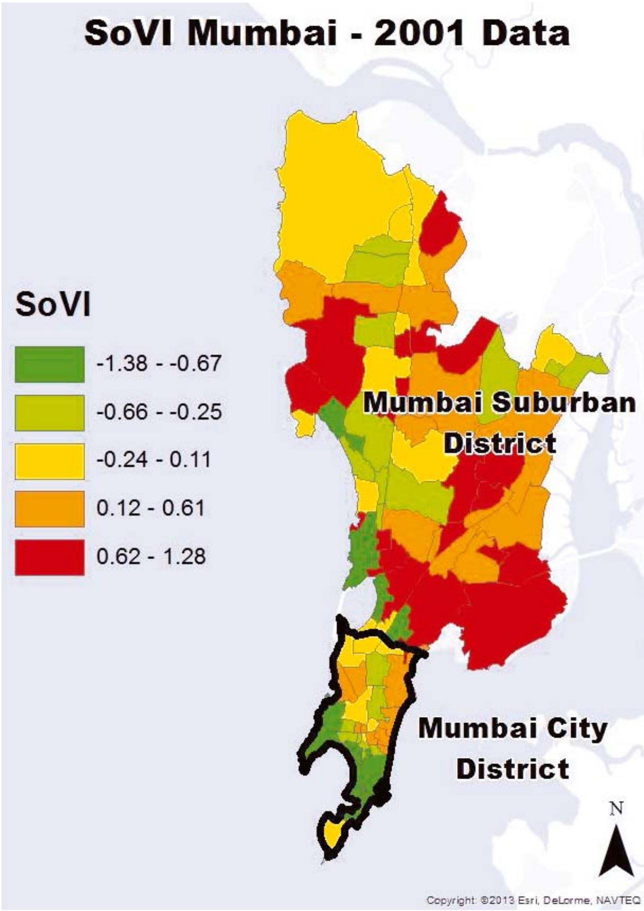
We obtained data from Ranger et al. (2011) and Hallegatte et al. (2010), in which they modeled the flood extent associated with the July 2005 flood (Figure 5). The data are derived from relatively coarse-resolution digital elevation models using NASA Shuttle Radar Topography Mission data, and once again do not match the resolution of the data that we had available for NYC.

4.2.3 Mumbai data limitations

While the SoVI maps give a sense of the overall distribution of social vulnerability levels within the city, it should be emphasized that the ward scale is not accurate enough to depict Mumbai's complex realities, as a single ward can contain both rich neighborhoods and slums. At this scale of analysis it is tempting to commit the ecological fallacy of assuming a degree of homogeneity within units that does not exist. Furthermore, there are far fewer variables available for Mumbai than for NYC, which limits the flood-relevance of the analysis. In particular, for Mumbai we lack age structure data that would permit the construction of an under-five and over-65 indicator similar to the indicator created for New York. Finally, while the census data of 2001 may reflect realities at the time of the flood event, they are clearly dated for a city that is evolving so rapidly.

On the exposure side, the exposure data were modeled based on relatively coarse-resolution elevation models, and because the flood polygons represent an extreme—i.e. a once-in-200-year event (Hallegatte et al. 2010)—they cannot be seen as representative of more typical flooding patterns.

Figure 4:
Weighted SoVI scores, 5 quintiles

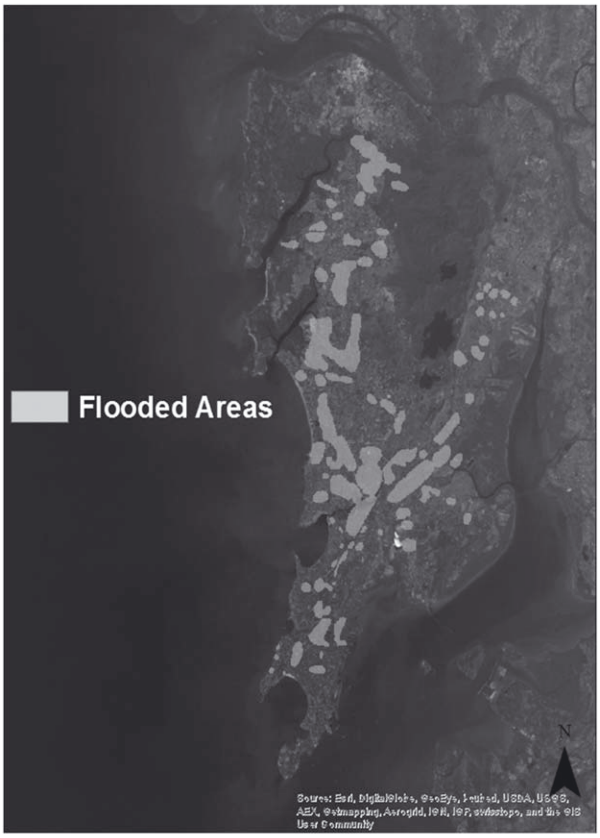


5 Results

5.1 New York City

For New York City the average SoVI scores by evacuation category are in Table 6, and the average SoVI scores by proportion of block group flooded are in Table 8. We also provide average values for the indicators that have been found to be particularly relevant to flood vulnerability assessment in Tables 7 and 9. The difference in means are all significant at the $p< 0.01$ level or higher. The fact that all but a few of the categories have above-average SoVI scores (>0) is a reflection

Figure 5:
Digitized flood extent map for the 2005 event (data courtesy Ranger et al. 2011)



of the population-weighting; densely populated block groups have higher SoVI scores.[6] A separate analysis in which the mean SoVI scores were calculated without population weighting resulted in more SoVI scores below the mean in several exposure categories.

The results provide only limited support for the differential exposure hypothesis. The SoVI scores are the same in the most flooded (category D) and the non-flooded (category A) areas. Flood category A's high scores probably reflect the high concentrations of poverty in Harlem and the Bronx, which are located farther from the coast and at higher elevations. The SoVI scores are highest in the highest risk evacuation zone, but are lowest (and nearly inverted) in the next-highest risk zone,

6 The Pearson's r between population density and SoVI scores is 0.35 ($p< .0001$).

Table 6:
NYC SoVI averages for evacuation categories

Category	Weighted SoVI	Averaged SoVI
A (no evacuation)	0.02	0.02
B (low risk)	0.02	0.01
C	0.04	0.03
D	0.05	0.04
E	0.07	0.05
F	–0.08	–0.09
G (high risk)	0.08	0.09

Table 7:
NYC averages of individual indicators for evacuation categories (high values in bold)

Category	% Population aged <5 and >65	% Population in poverty	% of Pop with less than 12th grade education	% Female headed Households	% Black
A (no evacuation)	18.6	18.5	21.6	39.4	23.9
B (Zone 6)	17.9	**19.6**	**21.9**	40.6	25.8
C (Zone 5)	18.4	18.6	21.1	41.3	31.0
D (Zone 4)	18.4	17.4	20.0	41.8	30.7
E (Zone 3)	19.2	18.2	19.2	**42.1**	**32.8**
F (Zone 2)	18.9	14.4	18.3	38.4	23.2
G (Zone 1)	**22.0**	17.4	19.4	39.6	19.5

Table 8:
NYC SoVI averages for flooding categories

Category	Weighted SoVI	Averaged SoVI
A (0% flooded)	0.03	0.03
B (0.01–13.5% flooded)	–0.08	–0.07
C (13.6–50% flooded)	–0.03	–0.02
D (50–100% flooded)	0.03	0.03

the largest spatial area of which is found in southern Brooklyn, northwestern Staten Island, and the more prosperous parts of Queens.

The age dependency variable shows relatively consistent results across all of the evacuation and flood risk categories except the highest evacuation and flood risk

Table 9:
NYC averages of individual indicators for flooding categories (high values in bold)

Category	% Population aged <5 and >65	% Population in poverty	% of Pop with less than 12th grade education	% Female headed Households	% Black
A (0% flooded)	18.4	**18.9**	**21.7**	**40.3**	**26.4**
B (0.01–13.5% flooded)	19.4	16.2	17.5	37.9	22.5
C (13.6–50% flooded)	19.0	15.9	18.6	40.0	22.6
D (50–100% flooded)	**21.5**	16.1	18.6	38.8	21.0

categories, where there is a ~ 2 percentage-point higher dependency. This finding may suggest there are greater numbers of retirees or young families living on the waterfront, although without more data this remains a hypothesis. By contrast, the other social vulnerability indicators are all highest for flood category A. Similarly, for zone 1 there is a significantly higher age dependency, but the other indicators show no discernible pattern.

We tested for the PEB, setting two thresholds: >30% and >50% block group area flooded. Our aim was to determine whether the fraction of the poor population exposed to Hurricane Sandy flooding was higher than the fraction of the total population. We found that almost exactly the same proportion of the poor population and the total population were flooded in both groups: ~ 0.08 of the total population and 0.07 of the poor population experienced >30% flooding, and 0.06 of the total population and 0.05 of the poor population experienced >50% flooding. These results do not support the differential exposure hypothesis.

5.2 Mumbai

We used the 2005 flooding extent maps to compare average SoVI scores to exposure. We created four categories: category A is made up of non-flooded wards, and categories B to D consist of wards from the least to the most flooded by proportion area; again divided into equal intervals. We then applied the difference in means analysis to obtain Table 10. As we did in presenting the NYC results, we provide average values for indicators that were found to be particularly relevant to flood vulnerability assessment in Table 11, reporting only those indicators for which the differences in means are significant at the $p < 0.10$ level or higher (two indicators, percentage population scheduled castes or tribes and percent population < 6, did not have statistically significant results).

Table 10:
Mumbai SoVI averages for flooding categories

Category	Weighted SoVI (results not significant)	Averaged SoVI
A (no flood)	0.14	0.19
B (low flood)	0.34	1.00
C (med. flood)	0.25	0.80
D (high flood)	0.29	0.95

Table 11:
Mumbai average indicator scores by flooding categories (high value in bold)

Category	% Slum population	% Households with a television
A (no flood)	21.7	70.3
B (low flood)	41.5	76.7
C (med. flood)	43.9	**79.4**
D (high flood)	**49.3**	75.6

Overall, the Averaged SoVI scores are higher for each flood category than in New York. The highest scores are for the added SoVI across all flooded areas. The Weighted SoVI gives more importance to factor 1 (access to information; 42.6% of variance explained), and generally results in lower SoVI scores across all of the flooded categories than the Averaged SoVI. Furthermore, the difference in means is not significant. In both cases, the main observation is that the wards with no flooding are always the least vulnerable for each type of SoVI. This analysis generally confirms our hypothesis that the socially vulnerable wards were more affected by the July 2005 flash floods; or at a minimum that the least-exposed wards had the lowest levels of social vulnerability. While the results are interesting, and suggest tentative support for the differential exposure hypothesis, we would require higher resolution census data and more spatially explicit flood maps to conclusively confirm the hypothesis.

We also tested for the PEB. Since 78 of 99 wards experienced at least some flooding, we set three thresholds – >10%, >30% and >50% of the ward area flooded – to determine whether the fraction of the slum population exposed to the flood was higher than the fraction of the total population. We found that almost exactly the same shares of the slum population and of the total population were found in wards that were >10% and >30% flooded (~0.72 and 0.31, respectively, for the slum and the total population), whereas marginally higher fractions of the slum population were found in the wards that were >50% flooded (0.185 of the slum population versus 0.155 of the total population). These results provide only limited evidence to support the differential exposure hypothesis.

6 Discussion and conclusion

In the case of New York, our study provides only limited support for the hypothesis that the most socially vulnerable are differentially exposed to flood hazards. For Mumbai, we find stronger support for this hypothesis, but we also acknowledge the data limitations. Our results are tentative for a number of reasons. First, while the differences in means are statistically significant, the actual differences in SoVI scores are often quite small. But there are also broader data and methodological challenges. Here we discuss the limitations of this study, which are broadly applicable to urban spatial vulnerability assessments in three areas: uncertainty, spatial resolution, and the use and limitations of aggregate indices such as the SoVI.

In the United States there are large margins of error in the ACS data at the block group level, and there are arguments for using data at the census track level (Spielman et al. 2014, Bazuin & Frazier 2013), even though there is a loss in spatial precision when units are overlaid on exposure categories.[7] Thus, the highest resolution units introduce uncertainty owing to the small household sample sizes. At the other extreme, many developing countries provide data at highly aggregated levels only, often without matching spatial boundary layers. The data for Mumbai are so highly aggregated and so infrequently updated that their use introduces other forms of uncertainty; namely, that the large units mask major sub-unit spatial variability in population characteristics, and that the infrequent updates inadequately capture changes in highly dynamic urban populations.

These issues are indicative of a general problem that arises in urban climate vulnerability assessments conducted in developing countries: there is a need for higher resolution, regularly updated spatial data for both exposure and the exposed elements (Martine and Schensul 2013). For the exposure estimates, the flood extents we used were reasonably accurate for New York, whereas for Mumbai the flooded areas were modeled based on fairly coarse-resolution satellite-derived digital elevation models. For the exposed elements, we were able to obtain for NYC census data for more than 6,198 block groups averaging $\sim 1,000$ inhabitants, but for Mumbai we were only able to obtain data for 99 wards averaging $\sim 120,000$ inhabitants. The lack of access to high-resolution census data in many developing countries obviously limits the spatial precision of vulnerability assessments. Dasymetric mapping, in which relatively coarse-resolution population inputs are redistributed based on ancillary data (e.g. information on slopes or parklands), is increasingly being employed to model population distributions at

[7] There are 4,336 census tracts in New York City, as opposed to 6,198 block groups.

higher levels of spatial resolution (Mantaay et al. 2009). Yet the process involved in this type of mapping is time consuming, and not without its own technical challenges. Moreover, it less evident how we can spatially disaggregate population characteristics (as opposed to population counts).

There are also temporal dimensions to uncertainty. Our research is retrospective and does not necessarily represent the present reality (at least in Mumbai, a dynamic city for which the only available data were from 2001) or likely future patterns, as flood and storm surge risks are intensifying as the climate changes (IPCC 2012). Forecasting flood extents may be possible using standard modeling techniques (e.g. Storch et al. 2011), but predicting future social vulnerability is much harder. Forecasting future risks and vulnerabilities for cities and communities is becoming increasingly important for the design of adaptation interventions. There are incipient efforts to use big data sources, such as mobile phone recharge rates or satellite data, to provide more real-time estimates of poverty for climate resilience, but this area of research has not yet reached a high level of maturity.

Turning to the issue of aggregate indices, we note that the SoVI itself, like all PCA-based methods, is driven by the statistical relationships between the indicators, and not by theory (Abson et al. 2012). Thus, the most important indicators from a theoretical perspective, or those used to assess susceptibility to floods (e.g. percent of population aged > 65), may influence the overall results the least, especially if there are few covariates. It is also possible that some of the variables that theoretically predict greater harm (health, economic, or mortality impacts), such as the percentage of the population who are elderly, may not correlate with actual outcomes. This might be the case, for example, if the elderly are well off and have the means to escape easily (i.e. a car or a second home). While we feel that our process for identifying variables was robust, given the low levels of mortality or other outcome measures, we could not identify which factors best predicted that outcome variable. In post-Sandy surveys, Madajewic and Coirolo (2015) found that poverty levels were rather poor predictors of losses. In the wake of Hurricane Sandy, those who suffered the greatest impacts (economic losses) were middle-income homeowners, whereas renters in lower socioeconomic brackets were able to move out of the area, avail themselves of social services, and recover rather quickly. We do not have as much evidence for Mumbai, but broadly it seems that despite the severity of the flood, mortality levels were limited owing to self-help networks such as slum dweller associations (de Sherbinin et al. 2007). In both cases, it is clear that there is a need for more targeted data collection efforts post-event to determine where the greatest vulnerabilities lie. In turn, these data can help to refine the ‘global’ models, such as the SoVI, which can cover broad areas using census-derived metrics.

In terms of policy relevance, this work contributes to the broader environmental justice literature that investigates the extent to which poorer populations are disproportionately exposed to hazards. The effect of climate extremes on exposed populations is the stuff of weekly headlines. As we noted earlier, we are not only likely to see more extreme weather events in the future (IPCC 2012), but many of today’s extreme events can be attributed to climate change (James 2015, Herring et al. 2014). Yet assessing the environmental justice aspects of climate extremes is in many ways more challenging, partly because climate change impacts are a more evenly distributed 'public bad' than, for example, toxic waste sites; and partly because there is uncertainty about the location of future impacts.

As we discussed in the introduction, there are theoretical reasons to suppose that poorer populations may be disproportionately located in flood zones if those zones are characterized by lower rents. But there are also reasons to suppose that wealthier populations may be drawn to locations along shorefronts and rivers because of the amenities these settings offer. The availability of land in flood-prone areas, such as brownfields or former docklands, may drive expansion in these areas, as exemplified by New York City Mayor Bill de Blasio's decision to place more affordable housing along highly exposed shorelines (Bagley 2015). Given the market distortions introduced by government-subsidized flood insurance in high-income countries and the laissez-faire approaches to land management and growing informal settlements in low-income countries, we can expect that many more people – both the well off and the poor – will find themselves in flood zones in the future. While we may not have provided definitive evidence in this study of differential exposure in the two cities, we maintain that understanding the social protection needs of vulnerable populations will become increasingly important in the context of climate change (Johnson et al. 2013).

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Appendix: Correlation and covariance matrices

Correlation and covariance matrices are on the following pages.

Table A.1:
New York City correlation matrix

Correlation	QBLACK	QNATAM	QASIAN	QHISP	QAGEDEP	QFAM	MEDAGE	QSSBEN	QPOVTY	QRICH2K	PERCAP	QESL	QFEMALE	QFHH	QNRRES	QED12LES	POPDENS	PPUNIT	QRENTER	QNOAUTO
QBLACK	1	.131**	-.424**	-.027*	-.127**	-.717**	-.171**	-.019	.202**	-.287**	-.305**	-.265**	.360**	.595**	.013	.135**	-.072**	.153**	.112**	.047**
QNATAM	.131**	1	-.152**	.666**	-.242**	-.462**	-.367**	-.163**	.392**	-.295**	-.352**	.325**	-.089**	.259**	-.038**	.488**	.161**	.350**	.368**	.240**
QASIAN	-.424**	-.152**	1	-.190**	-.011	.423**	.172**	.008	-.149**	-.013	-.016	.362**	-.202**	-.458**	-.015	.026*	-.046**	.111**	-.126**	-.149**
QHISP	-.027*	.666**	-.190**	1	-.262**	-.525**	-.416**	-.163**	.465**	-.359**	-.417**	.519**	-.157**	.292**	-.024	.625**	.266**	.362**	.515**	.327**
QAGEDEP	-.127**	-.242**	-.011	-.262**	1	.231**	.718**	.493**	-.108**	.132**	.160**	-.043**	.317**	-.043**	.409**	-.118**	-.079**	-.197**	-.288**	-.173**
QFAM	-.717**	-.462**	.423**	-.525**	.231**	1	.346**	.096**	-.514**	.437**	.463**	-.090**	-.320**	-.806**	.010	-.489**	-.158**	-.152**	-.526**	-.365**
MEDAGE	-.171**	-.367**	.172**	-.416**	.718**	.346**	1	.457**	-.433**	.266**	.352**	-.164**	.185**	-.161**	.281**	-.370**	-.165**	-.448**	-.500**	-.318**
QSSBEN	-.019	-.163**	.008	-.163**	.493**	.096**	.457**	1	-.173**	-.014	-.003	-.086**	.187**	-.055**	.037**	-.016	-.203**	-.072**	-.351**	-.265**
QPOVTY	.202**	.392**	-.149**	.465**	-.108**	-.514**	-.433**	-.173**	1	-.350**	-.451**	.343**	.021	.398**	.054**	.601**	.237**	.246**	.558**	.485**
QRICH2K	-.287**	-.295**	-.013	-.359**	.132**	.437**	.266**	-.014	-.350**	1	.853**	-.318**	-.003	-.187**	-.018	-.458**	.108**	-.396**	-.264**	.023
PERCAP	-.305**	-.352**	-.016	-.417**	.160**	.463**	.352**	-.003	-.451**	.853**	1	-.375**	.049**	-.129**	-.041**	-.555**	.141**	-.548**	-.258**	.061**
QESL	-.265**	.325**	.362**	.519**	-.043**	-.090**	-.164**	-.086**	.343**	-.318**	-.375**	1	-.252**	-.086**	.013	.617**	.220**	.355**	.382**	.244**
QFEMALE	.360**	-.089**	-.202**	-.157**	.317**	-.320**	.185**	.187**	.021	-.003	.049**	-.252**	1	.589**	.049**	-.099**	.126**	-.196**	.025*	.063**
QFHH	.595**	.259**	-.458**	.292**	-.043**	-.806**	-.161**	-.055**	.398**	-.187**	-.129**	-.086**	.589**	1	.006	.247**	.335**	-.231**	.530**	.520**
QNRRES	.013	-.038**	-.015	-.024	.409**	.010	.281**	.037**	.054**	-.018	-.041**	.013	.049**	.006	1	.068**	-.035**	-.045**	.006	-.009
QED12LES	.135**	.488**	.026*	.625**	-.118**	-.489**	-.370**	-.016	.601**	-.458**	-.555**	.617**	-.099**	.247**	.068**	1	.170**	.451**	.465**	.311**
POPDENS	-.072**	.161**	-.046**	.266**	-.079**	-.158**	-.165**	-.203**	.237**	.108**	.141**	.220**	.126**	.335**	-.035**	.170**	1	-.175**	.508**	.602**
PPUNIT	.153**	.350**	.111**	.362**	-.197**	-.152**	-.448**	-.072**	.246**	-.396**	-.548**	.355**	-.196**	-.231**	-.045**	.451**	-.175**	1	-.039**	-.274**
QRENTER	.112**	.368**	-.126**	.515**	-.288**	-.526**	-.500**	-.351**	.558**	-.264**	-.258**	.382**	.025*	.530**	.006	.465**	.508**	-.039**	1	.758**
QNOAUTO	.047**	.240**	-.149**	.327**	-.173**	-.365**	-.318**	-.265**	.485**	.023	.061**	.244**	.063**	.520**	-.009	.311**	.602**	-.274**	.758**	1

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Table A.2:
New York City covariance matrix

COVARIANCE	QBLACK	QNATAM	QASIAN	QHISP	QAGEDEP	QFAM	MEDAGE	QSSBEN	QPOVTY	QRICH2K	PERCAP	QESL	QFEMALE	QFHH	QNRRES	QED12LES	POPDENS	PPUNIT	QRENTER	QNOAUTO
QBLACK	917.31	3.12	-203.61	-19.84	-24.03	-463.00	-35.65	-7.45	96.04	-82.75	-252079.44	-1.01	45.30	222.38	0.01	62.70	-106189.27	2.94	92.87	37.56
QNATAM	3.12	0.61	-1.89	12.50	-1.20	-7.73	-1.98	-1.61	4.88	-2.21	-7597.98	0.03	-0.27	2.51	0.00	5.96	6340.18	0.17	7.68	4.91
QASIAN	-203.61	-1.89	251.91	-71.92	-1.00	143.25	19.02	2.02	-37.24	-1.98	-7414.92	0.72	-13.36	-89.75	-0.01	6.60	-37565.55	1.07	-53.88	-61.86
QHISP	-19.84	12.50	-71.92	570.20	-39.68	-267.29	-68.15	-50.26	175.88	-81.57	-272857.34	1.56	-14.53	85.53	-0.02	232.02	317137.03	5.32	327.43	203.75
QAGEDEP	-24.03	-1.20	-1.00	-39.68	39.32	30.84	30.59	40.27	-11.18	8.03	27881.91	-0.04	7.25	-4.12	0.09	-11.66	-26085.08	-0.81	-50.63	-29.29
QFAM	-463.00	-7.73	143.25	-267.29	30.84	454.89	50.19	26.03	-172.15	88.63	269728.46	-0.24	-25.48	-208.55	0.01	-161.31	-168689.91	-1.97	-297.52	-202.74
MEDAGE	-35.65	-1.98	19.02	-68.15	30.59	50.19	46.35	40.21	-47.11	17.35	66206.98	-0.14	5.24	-13.51	0.06	-39.59	-56177.78	-1.90	-92.11	-57.15
QSSBEN	-7.45	-1.61	2.02	-50.26	40.27	26.03	40.21	162.47	-34.25	-1.56	79.46	-0.13	8.93	-7.36	0.02	-2.74	-128723.38	-0.50	-118.47	-88.25
QPOVTY	96.04	4.88	-37.24	175.88	-11.18	-172.15	-47.11	-34.25	246.07	-52.39	-193797.46	0.68	1.83	77.03	0.02	146.70	187609.39	2.43	235.42	197.94
QRICH2K	-82.75	-2.21	-1.98	-81.57	8.03	88.63	17.35	-1.56	-52.39	90.60	222022.29	-0.38	-0.16	-21.80	-0.01	-67.62	50809.06	-2.31	-66.63	5.70
PERCAP	-252079.44	-7597.98	-7414.92	-272857.34	27881.91	269728.46	66206.98	79.46	-193797.46	222022.29	747870451.58	-1293.21	3882.45	-45417.35	-38.54	-235639.97	189202780.59	-9392.90	-190247.74	43636.81
QESL	-1.01	0.03	0.72	1.56	-0.04	-0.24	-0.14	-0.13	0.68	-0.38	-1293.21	0.02	-0.13	-0.14	0.00	1.20	1374.44	0.03	1.27	0.80
QFEMALE	45.30	-0.27	-13.36	-14.53	7.25	-25.48	5.24	8.93	1.83	-0.16	3882.45	-0.13	12.87	26.73	0.01	-4.93	21423.71	-0.58	0.53	5.96
QFHH	222.38	2.51	-89.75	85.53	-4.12	-208.55	-13.51	-7.36	77.03	-21.80	-45417.35	-0.14	26.73	146.99	0.01	47.30	201028.51	-1.92	169.42	164.55
QNRRES	0.01	0.00	-0.01	-0.02	0.09	0.01	0.06	0.02	0.02	-0.01	-38.54	0.00	0.01	0.01	0.00	0.04	-56.68	0.00	0.01	-0.01
QED12LES	62.70	5.96	6.60	232.02	-11.66	-161.31	-39.59	-2.74	146.70	-67.62	-235639.97	1.20	-4.93	47.30	0.04	240.09	133613.52	4.37	192.92	125.74
POPDENS	-106189.27	6340.18	-37565.55	317137.03	-26085.08	-168689.91	-56177.78	-128723.38	187609.39	50809.06	189202780.59	1374.44	21423.71	201028.51	-56.68	133613.52	2484756386.50	-5618.16	672989.40	781891.35
PPUNIT	2.94	0.17	1.07	5.32	-0.81	-1.97	-1.90	-0.50	2.43	-2.31	-9392.90	0.03	-0.58	-1.92	0.00	4.37	-5618.16	0.37	-0.92	-4.40
QRENTER	92.87	7.68	-53.88	327.43	-50.63	-297.52	-92.11	-118.47	235.42	-66.63	-190247.74	1.27	0.53	169.42	0.01	192.92	672989.40	-0.92	702.73	522.91
QNOAUTO	37.56	4.91	-61.86	203.75	-29.29	-202.74	-57.15	-88.25	197.94	5.70	43636.81	0.80	5.96	164.55	-0.01	125.74	781891.35	-4.40	522.91	677.63

Table A.3:
Mumbai correlation matrix

	Pop SqMile	% Female	% 0To6 Years	% SchCasteOrTribe	% Litteracy	% Slum_Pop	% WorkersAmgFemale	% NonWorkers	% HH_AvBankServ	% HH_TV	% HH_Moto	% HH_Car
Pop SqMile	1	-.272**	-.098	-.228*	.077	-.187	-.394**	-.086	.031	.094	-.013	-.220*
% Female	-.272**	1	.063	.053	.182	-.045	.273**	.748**	.302**	.349**	.360**	.390**
% 0To6Years	-.098	.063	1	.313**	-.758**	.652**	-.240*	.410**	-.765**	-.731**	-.540**	-.515**
% SchCasteOrTribe	-.228*	.053	.313**	1	-.404**	.177	.224*	.124	-.390**	-.303**	-.383**	-.228*
% Litteracy	.077	.182	-.758**	-.404**	1	-.311**	-.109	.073	.903**	.924**	.592**	.466**
% Slum_Pop	-.187	-.045	.652**	.177	-.311**	1	-.359**	.378**	-.465**	-.426**	-.612**	-.335**
% WorkersAmgFemale	-.394**	.273**	-.240*	.224*	-.109	-.359**	1	-.351**	.072	-.038	.181	.476**
% NonWorkers	-.086	.748**	.410**	.124	.073	.378**	-.351**	1	.048	.173	.013	-.073
% HH_AvBankServ	.031	.302**	-.765**	-.390**	.903**	-.465**	.072	.048	1	.940**	.727**	.555**
% HH_TV	.094	.349**	-.731**	-.303**	.924**	-.426**	-.038	.173	.940**	1	.696**	.519**
% HH_Moto	-.013	.360**	-.540**	-.383**	.592**	-.612**	.181	.013	.727**	.696**	1	.579**
% HH_Car	-.220*	.390**	-.515**	-.228*	.466**	-.335**	.476**	-.073	.555**	.519**	.579**	1

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Table A.4:
Mumbai covariance matrix

	Pop SqMile	% Female	% 0To6Years	% SchCastOrTribe	% Litteracy	% Slum_Pop	% Workers_AmgFemale	% NonWorkers	% HH_AvBankServ	% HH_TV	% HH_Moto	% HH_Car
Pop SqMile	10,139,651,651	-107,002	-22,942	-87,284	50,654	-596,422	-209,314	-48,680	56,573	116,606	-6,320	-228,599
% Female	-107,002	15	1	1	5	-6	6	16	21	17	7	16
% 0To6Years	-22,942	1	5	3	-11	48	-3	5	-32	-21	-6	-12
% SchCastOrTribe	-87,284	1	3	14	-10	21	4	3	-27	-14	-7	-9
% Litteracy	50,654	5	-11	-10	42	-64	-4	3	105	74	18	31
% Slum_Pop	-596,422	-6	48	21	-64	1,006	-60	68	-264	-166	-91	-110
% Workers AmgFemale	-209,314	6	-3	4	-4	-60	28	-10	7	-2	4	26
% NonWorkers	-48,680	16	5	3	3	68	-10	32	5	12	0	-4
% HH_AvBankServ	56,573	21	-32	-27	105	-264	7	5	320	206	61	103
% HH_TV	116,606	17	-21	-14	74	-166	-2	12	206	151	40	66
% HH_Moto	-6,320	7	-6	-7	18	-91	4	0	61	40	22	28
% HH_Car	-228,599	16	-12	-9	31	-110	26	-4	103	66	28	107

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Who perceives what? A demographic analysis of subjective perception in rural Thailand

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Abstract

Rural households that rely on natural resources for their livelihoods are expected to face increased vulnerability due to climate variability. A number of empirical papers have assessed the impact of environmental shocks on these households, including demographic research that has investigated the impact of shocks on migration. To date, few studies have explicitly modeled how individual and household characteristics influence a household respondent's subjective perceptions of environmental or other shocks. My paper uses a unique panel dataset from rural Thailand to predict a respondent's probability of attributing a reduction in income to an environmental shock based on household composition and income, as well as on community-level effects. Preliminary results suggest that household composition influences respondents' perceptions of environmental risk, and that policies aimed at vulnerable communities should consider the life courses of the households within a given community.

1 Introduction

According to current climate models, drought and floods are likely to become more frequent and more severe in the future, and the effects of these extreme events are already being felt by residents in rural developing communities (Bernstein et al. 2007; Coe and Stern 2011; Porter et al. 2014). A substantial literature has emerged that has theorized, conceptualized, and empirically identified the most vulnerable residents in rural areas. However, this literature has largely relied on notions of vulnerability that were formulated by outside researchers and development agencies, while neglecting to examine perceptions of vulnerability among target populations (Heijmans 2001). Objective environmental conditions are defined by meteorological

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data. At the same time, however, an individual's subjective assessment of the financial health of his or her household, and the degree to which he or she perceives environmental risks as a source of environmental stress, can reveal a great deal about the household's level of exposure to environmental perturbations, as well as about the members' resilience and ability to cope in the face of environmental risks (Barrett et al. 2001). To date, few studies have explicitly modeled the determinants of the environmental risk perceptions of people living in vulnerable environments. Policymakers interested in crafting sound policies to address the social impacts of climate change must also address the issues that are most salient to and most likely to be reported by the people living in areas that are increasingly vulnerable to exogenous shocks, such as drought or flooding (Volker et al. 2011).

Previous studies on vulnerability and adaptation to climate change have made considerable progress toward providing us with an understanding of the complex relationships between human and environmental systems in an evolving climate, and toward identifying which populations are most vulnerable to environmental shocks (Cutter et al. 2009; Oliver-Smith 2009). Early research focused on the severity of potential impacts to natural systems under proposed climate scenarios, and tended to move in a linear fashion, examining the potential vulnerability as a relationship that moves in a single direction from stressor to impacts, without considering more complex feedback loops that might better encapsulate conditions on the ground (Blaikie et al. 2004; Turner et al. 2003; Eakin and Luers 2006). However, this singular focus gave way to more complex modeling of the linkages between humans and environmental systems (Fussel and Klein 2006; Turner et al. 2003). These more nuanced studies considered not only where impacts are likely to occur; they also sought to answer context-specific questions, such as how these shocks might be dampened or exacerbated by underlying societal conditions, and how the demographic characteristics of specific population groups might be associated with different levels of vulnerability to exogenous shocks like adverse climatic events (Adger 2006; Acosta-Michlik and Espaldon 2008). Although the conceptualization of vulnerability is becoming increasingly complex, few studies have attempted to model how socio-demographic and objective exposure to the environment shape the environmental perceptions of rural residents. This research gap can be explained in part by the lack of questions in household surveys that ask respondents to report the occurrence of a climatic event, and to indicate whether they experienced financial hardship as a result of such an event—despite frequent calls for these kinds of questions to be included (Billsborrow 2009; Sanchez-Pena and Fuchs 2012).

My paper explicitly explores the causes cited by surveyed household members for why the respondent's household had a bad income year, and the associated demographic characteristics across households in which the respondent reported that environmental and other economic problems represented risk factors. In particular, I investigate how the age and gender composition of a household, and access to a variety of capital assets, condition the likelihood that a household respondent attributed a bad income year to an environmental problem or to another factor. I use the 1997 to 2006 waves of the Townsend Thai Data, a unique annual economic panel dataset that collects information on self-reported risks to income, as well as household-level information on occupation and other demographic characteristics, to analyze a number of characteristics related to a household respondent's subjective assessments of livelihood risks. To test whether a household member's life course transitions influence his or her perceptions of risk, I explore the demographic characteristics of households in which a member reported having experienced an income shock due to an environmental problem, and compared them with the characteristics of respondents who reported having experienced a good income year or a bad income year due to another type of shock. Conceptually, I draw on the sustainable livelihoods framework and ideas about family life course to explore whether differential access to assets and/or the age structure of the household was significantly associated with the members' perceptions of the environment as a source of livelihood stress. I find that the odds of perceiving that the household was facing an environmental risk to income were higher among the respondents from households in which a majority of the working members were employed in agriculture. Similarly, while larger households were more likely to have reported facing an environmental risk, as the number of older working-age women (aged 25 to 59) and of elderly people in a household increased, the higher the odds were that the respondent reported that the household had experienced a bad income year due to the environment.

2 Theoretical framework and previous studies

My analysis is informed by the sustainable livelihoods framework (SLF), a concept that has been used in the past to explore determinants of poverty in the developing world. The SLF was initially used to study underlying factors that contribute to poverty in the developing world, but has since been expanded for use in research on sustainability and livelihood (Carney 1998; Eakin and Luers 2006; Scoones 1998). The strength of this framework is that it allows for the exploration of differential access to a series of assets (human, natural, social, physical, and financial)[1] and entitlements that can highlight vulnerability to environmental risk. It also shows how these assets can be used to mediate the impacts of exogenous shocks, including environmental impacts (Bunting et al. 2013; Carney 1998; Eakin and Luers 2006; Scoones 1998). To date, only a few studies have modeled the determinants of subjective risk perceptions of populations in rural areas of

[1] Human capital refers to the skills, the education, and the good health that enable people or households to support themselves. Social capital refers to the relationships or institutions (formal or informal) that people draw upon for social support in times of shocks. Natural capital refers to having access to quality natural resources (for those households that rely on natural resources for daily production). Physical capital refers to the basic infrastructure (i.e. roads) that facilitate daily activities. Finally, financial capital refers to savings or access to credit. See http://www.eldis.org/vfile/upload/1/document/0901/section2.pdf for more information.

the developing world. The results of these studies have indicated that there is heterogeneity in perceptions of livelihood threats among subpopulations within a seemingly homogenous landscape. I have organized the findings in the existing literature according to the five assets conceptualized in the framework to highlight which factors influenced whether a household respondent identified the environment as a main risk to income, and to suggest opportunities for future research.

The evidence is mixed on how human capital—which is typically measured at the level of the head of the household—influences the likelihood that a household respondent will report perceiving an environmental risk. In a study of East African pastoralists by Barrett et al. (2001), gender and economic activity were found to have strongly influenced risk perception: men were more likely than women to have reported perceiving risks to livestock, water availability, and pasture; factors that were related to men's primary agricultural activities. Similarly, in the South African context, women who were tasked with cooking were more likely to have reported perceiving environmental risks related to water quality and the impacts of wood smoke. (Hunter et al. 2010). In Botswana and Namibia, men and women both said they perceived that the decline in natural resources represented a significant risk to their livelihoods. However, men were slightly more likely to have said they perceived an environmental risk, which is again attributable to the greater participation of men than of women in economic activities that are impacted by flooding and drought (Bunting et al. 2010). However, Doss et al. (2008) found that individual-level characteristics such as age, sex, and education of the head did not significantly affect risk perceptions. The education of the head, which was included to capture the potential for participation in formal labor market, was not found to be significant in the studies that modeled this factor. In Vietnam and Thailand, individuals who were working in agriculture were significantly more likely than non-agricultural workers to have said they perceive climate as a risk (Volker et al. 2011).

Human and financial capital were shown to interact with natural capital in several studies. Respondents who said they consider drought to be a significant risk tended to have greater access to natural capital (on average, higher rainfall amounts). However, this access was found to have been muted by reduced financial and human capital among pastoralists in East Africa. Somewhat surprisingly, household members located in areas that get more rainfall on average were more likely to have reported perceiving rainfall as a main livelihood risk. These households tended to be poorer than other households in the study area, and were more likely to have been engaged in agriculture. Findings such as these further indicate that there is a need to incorporate subjective measures as well as objective data in analyses of these associations (Barrett et al. 2001). A study of villagers in Botswana and Namibia found that subsistence-based farmers were more likely than villagers in more formal labor markets to have ranked drought as a significant risk to their livelihoods. Again, these findings reflect a lack of access to a diversity of human and natural capital in these villages (Bunting et al. 2013).

Natural capital also intersects with social capital to shape how individuals form their perceptions of the environment. In particular, participation in social learning might encourage residents to share information about the impact of erratic rainfall amounts, which could in turn influence how individuals perceive rainfall as an environmental risk (Bunting et al. 2013; Lybbert et al. 2007). Doss et al. (2008) found that natural capital variables such as rainfall have significant effects on risk rankings when measured at the community level, and when household and individual-level characteristics are controlled for. Similarly, in Vietnam participation in socio-political organizations has been shown to increase the odds of climate risk perception (Volker et al. 2011).

Physical capital has also been found to influence perceptions, particularly in areas that lack the kind of infrastructure that might mediate such concerns. Hunter et al. (2010) introduced another dimension to the literature by analyzing the spatial proximity of a village to an environmental problem in a study of rural South African residents. An individual was more likely to have reported perceiving the environment as a major concern if he or she was living in a household located in a village in close proximity to an environmental problem, such as polluted water, eroded soil, or refuse.

The existing literature on determinants of risk perceptions has explored a number of key livelihoods concepts that enrich the study of subjective and objective measures of risk. In particular, these studies have highlighted a number of factors that explain the heterogeneity of risk perceptions in areas assumed to be vulnerable to environmental stress, such as access to financial and natural capital. However, the existing studies that examined the determinants of subjective perceptions in the developing world were limited by a number of factors. The first factor was a lack of temporal depth, which limited the ability of researchers to study how risk perceptions vary over time. Doss et al. (2008) analyzed the risk perceptions of a sample population over a period of 27 months, and found that people's risk perceptions varied across time and with the seasons. However, the remaining studies were cross-sectional studies that captured a single time period—an approach that does not allow for observations of temporal variation and past experience, or for analyses of how these factors combine to update or extend risk perceptions. Individual perceptions are influenced by a number of factors that can change over time, including the following: the degree of objective exposure to a risk (place-specific, such as rainfall), individual perception (which can be conditioned by previous experience), and whether a respondent can apply *ex ante* mitigation or *ex post* coping strategies (Barrett et al. 2001).

The second limitation has been the lack of robust household demographic measures that could show how household composition and structure shape perceived risks to livelihoods. While some existing risk perception studies have incorporated household demographic data, these data have been limited to information about the household head, and the results of these studies have been mixed. Because male and female East African pastoralists engage in different sectors of the economy, the risks they reported perceiving also differed (Barrett et al. 2001). In South Africa, individuals in older households (in which one-third of the members were over age 50) with fewer opportunities to diversify their livelihoods away from a dependence on natural resources were more likely than individuals in younger households (in which one-third of the members were under age 15) to have expressed great concern about water quality; however, this measure was not a consistent metric in the study, and was limited by the cross-sectional nature of the data (Hunter et al. 2010). A more refined measure of age and gender structures within a household might indicate whether household composition is highly associated with a household respondent reporting that he or she perceives that environmental problems threaten his or her livelihood. As a household's composition changes due to life course events (such as births, deaths, or household members leaving for labor market or educational opportunities), the household members' economic opportunities and perceptions of vulnerability might also change (Martine and Schensul 2013). Previous research on household composition and family life course transitions in rural China found that younger households, and younger males in particular, were more likely to have engaged in innovative labor reallocation strategies during a period of reform (Chen and Korinek 2010). In the literature on gender and climate change, women have been shown to perceive disasters differently than men, mainly as a function of gendered social structure, and because men and women have different relationships to agriculture and livestock (Hunter and David 2011; Terry 2009).

My paper addresses the limitations of previous studies that explicitly modeled the determinants of perceptions of environmental risk. First, I address the issue of temporal depth by analyzing data from the Townsend Thai Data project, a unique panel study of rural households in two provinces located in the poorer northeast region of Thailand, and in two provinces in the more prosperous central region of the country. The Townsend Thai Data project collected household-level retrospective subjective measures of perceived risks to income, including environmental threats, as well as detailed data on the age, sex, and occupation of household members. These data allow me to model the age, gender, and occupational structure of the household. The Townsend Thai Data project also collected data on income, assets, and social capital, which enable me to model access to capital assets found in the SLF. In order to measure natural capital, I have added to my analysis robust objective environmental data that coincide with the time period of the household survey.

Based on my review of previous research, I intend to test a number of hypotheses with these data. First, I explore whether objective environmental data are highly associated with environmental risk perceptions. Next, I explore whether risk perceptions are influenced by the concentration of working-age household members who were primarily employed in the agricultural sector. I then explore whether the respondents in households with relatively young age structures had risk perceptions that differed significantly from those of the respondents in households with older age structures. I also intend to explore whether respondents in households with younger or older males had different risk perceptions than respondents in households with younger or older females. Finally, I plan to explore whether social learning and previous reports of an environmental risk were associated with income risk perceptions among household members.

2.1 Thailand and climate change

Thailand is a suitable context for examining the vulnerability of rural households to climate change. In the past 50 years, the number of rainy days in Thailand has decreased, and the mean annual temperature between 1981 and 2007 rose by one degree Celsius (Dore 2005; Marks 2011). Rice, which is one of the main crops of Thailand, is particularly sensitive to the kinds of changes in the weather that are predicted in current climate change scenarios. A large number of farmers in Thailand rely on rain-fed irrigation to water their paddies (Marks 2011). The predicted changes in precipitation in both space and time have the potential to greatly change agricultural production in areas that are dependent on rainfall for irrigation. To date, only a small number empirical studies have considered the issue of vulnerability in Thailand, despite evidence that the effects of climate change are already being felt. A comparative, cross-sectional study of climate risk in Vietnam and Thailand has found that a majority of individuals in rural agricultural households reported having suffered from a variety of shocks between 2002 and 2008, including climatic, biological, socio-demographic, and economic impacts. Climatic shocks were the most common type of shock reported, and having experienced these kinds of shocks was highly associated with perceptions of future climatic risk. Moreover, being employed in agriculture was positively correlated with climatic risk perceptions (Volker et al. 2011).

From an agro-climatic perspective, rice is a crop that is sensitive to both the quantity and the timing of rainfall. Predictions of the effects of climate change on rice yields vary depending on the level of climatic change used in economic impact models. Felkner et al. (2009) estimated the impact of climate change on rice production using three possible emissions scenarios: neutral to high, neutral to low, and low to high. In addition to current environmental data, they included in their model information about farm inputs, soil quality, and household socioeconomic conditions (Felkner, et al. 2009). Their analysis indicated that, depending on the level of emissions, rice production may increase slightly in response to increased rainfall at the right stage in the growth cycle. Their overall conclusion is that while farmers will be able to adapt at lower emissions levels, they will be unable to mitigate the effects on production yields of higher emission levels. They further concluded that some farmers will be able to make adjustments to their inputs in order to preserve rice yields if the effects of climate change remain at moderate levels, but that poorer farmers (those with access to fewer resources) will not be able to respond even at lower levels of climatic impact. Prolonged drought due to climate change may further compound the negative effects on the production of rice and the livelihoods of households in the region. As rice is sensitive to drought, a delay in the start of the rainy season may cause a drop in yields. Hayano et al.

(2008) reported that when the rainy season began 20 days later than normal, rice production decreased by 20% (Hayano, et al. 2008).

In sum, there is limited but important evidence that individuals living in rural areas of Thailand who are employed in agriculture have both experienced and perceive climatic factors as representing risks to their livelihood. Climate data already indicate that rainfall patterns in the area are changing, and there is evidence that these changing patterns might affect rice, a particularly important cash crop in Thailand.

3 Data and measures

3.1 Townsend Thai data

As one of the longest running panel surveys in the developing world, the Townsend Thai Data project provides rich data on household composition, income, and assets; and collects information on the exposure of households to a number of exogenous shocks, including the environment. The project began as a cross-sectional survey in 1997 designed to measure and investigate how informal institutions such as family and social networks mediate exogenous shocks that might otherwise compromise livelihood outcomes. Following the devaluation of the baht and the subsequent Asian financial crisis, Townsend and his colleagues saw a unique opportunity to examine over time how exogenous shocks affect households, and how members of these households make use of formal and informal institutions to recover, by conducting an annual resurvey that would follow a percentage of the households from the original 1997 survey. The households in the study are located in four provinces: two provinces in the poorer northeastern region and two provinces in the more prosperous central region. Within these regions 15 households in 64 villages were randomly chosen, for a total of 960 respondent households per year.[2]

3.2 Objective environmental data – NDVI

Traditional measures of drought and flooding that rely on rainfall amounts, including gridded precipitation datasets, can be inaccurate if rainfall gauges are not evenly distributed in the area of interest (Thenkabail et al. 2004). One way to address potential inaccuracies in rainfall data is to use a vegetation index product, which is derived from satellite images and is available over a long time scale. The normalized difference vegetation index (NDVI) is a measure of plant biomass and general health obtained from satellite remote sensing imagery (Tucker et al. 1985)

[2] For more detailed information about the design of the dataset, please see: http://cier.uchicago.edu/data/data-overview.shtml.

that is increasingly being used as an alternative to measures of rainfall to assess the impact of climate environmental change on plant health (Pettorelli et al. 2005).

For my analysis, I use the Global Inventory Modelling and Mapping Studies (GIMMS) NDVI dataset, which provides global data on 24 years (1982 to 2006) of vegetation changes measured on bi-monthly basis (24 measures each year). The data were obtained via images produced by National Oceanic and Atmospheric Administration-Advanced Very High Resolution Radiometer (NOAA-AVHRR) satellites and instruments, measured in 8km x 8km pixels. While the spatial resolution of these images is coarser than the resolution of images gathered by more recent NDVI products, the strength of these data lies in their rich temporal resolution, which makes it possible to combine them with longitudinal social data. The NDVI represents a ratio of light reflectivity in the red and near-infrared bands of the electromagnetic spectrum, and thus gives an indication of how much of the photosynthetically active bands of light are being absorbed by vegetation on the ground (Tucker 1979): NDVI = (NIR−RED)/(NIR+RED).

As actively growing healthy vegetation tends to reflect less red light and more near-infrared light, a higher NDVI value can be interpreted as an indication of healthier plants. Anomalies in the NDVI, or divergences in the monthly or the annual measure from the long-term average for the same time periods, can be used to identify periods of drought or flooding (Anyamba et al. 2005).

3.3 Analysis file

To ensure that my environmental measures match the subjective measures collected in the survey data as well as possible, I restricted my analysis file to 10 years of data from the 1997 to 2006 rounds. Using these data, I constructed an analysis file consisting of household year records.

I used the following question from the Risk Response Survey module to generate my dependent variable: “Comparing this past year (e.g. June 2002-May 2003) to the year before that (e.g. June 2001–May 2002), which year was worse for household income?” The household respondents who indicated that their household income was lower in the past year than in the previous year were prompted to cite the most important reason why they believe this was the case. The survey question was identical each year, with the only change being the years referenced (year $t-1$ compared to year $t-2$). For this paper, the outcome variable is whether a respondent indicated that the household’s income had decreased due to an environmental problem or another factor, or that the household’s income had not been negatively affected. For the environmental cause, I combined the following responses: ‘not enough rainfall’, ‘flooding’, or ‘pests destroyed my crops’. The last category is considered an environmental cause because studies have shown that the hot and dry conditions that accompany drought can often favor the proliferation of insects that destroy crops (Mattson and Haack 1987). The majority of household respondents who reported having experienced a bad year because of the environment said that

Table 1:
Standardized NDVI variable

SDVI value	Corresponding z-score
0 – Average NDVI	0
1 – Below average NDVI	−1/−2
2 – Above average NDVI	1/2

‘not enough rainfall’ was the cause. All of the other responses to this question (non-environmental) were coded as ‘other’. The dependent variable was coded into three categories: (1) last year was a good income year (reference category), (2) last year was a bad income year due to an environmental problem, and (3) last year was a bad income year for some other reasons. I included the non-environmental category to determine whether the household characteristics associated with having perceived an environmental shock were also associated with having perceived another type of shock.

To account for my objective exposure data, I created an annual NDVI measure for each amphoe (district) where the households are located. Next, I calculated a period (1997 to 2006) average and then created standardized z-scores to indicate yearly anomalies in the period-average NDVI. This new variable, which I call my standardized NDVI (or sdvi) variable, takes the following form: sdvi = (Annual NDVI – Period Average NDVI)/Period Standard Deviation. Table 1 demonstrates the coding decision used to generate the variable.

Next, to model how these factors mediate a household respondent’s perceptions of risks, I constructed variables that correspond to the various forms of capital introduced in the SLF. Human capital represents the various skill sets and available labor within a household, and is based on a mix of factors related to age, education, and labor force participation. To model these factors, I included controls for age, sex, and education level of the head, as well as a variable that measures whether 50% or more of working-age household members were engaged in agriculture as their primary occupation. To capture the influence of the age and gender effects on household composition, I included a number of variables that measured the influence of younger (aged 15 to 24) and older (aged 25 to 59) working-age males and females present in the household, as well as the number of children (aged 0 to 14) and elderly people (over age 59).

To test for the influence of financial capital on a household’s response to the income question, I generated an ‘income changed’ variable, or a dummy that indicates whether a household’s current year income fell in the same quintile as the year before, or was in a higher or a lower income quintile relative to the year before. I also included a wealth index measure that provides a measure of the longer-term status of the household. In a study on the population’s vulnerability to a variety of shocks in Guatemala, Tesliuc and Lindert (2004) constructed a wealth index using PCA. The goal of this approach was to overcome the potentially spurious relationship between poverty and shocks. They found that households with higher scores on the wealth index were less likely to have reported experiencing a welfare shock.

If a household respondent indicated that the previous year was a bad income year, he or she was asked whether he or she perceived that other households in the village also had a bad year. I used the response to this question (yes/no) to proxy social capital or social learning.

Taking advantage of the longitudinal nature of these data, I analyzed the impact of past environmental problems via a cumulative measure (up to time t) of the number of times a household had attributed a bad year to an environmental problem. I used this measure to test whether some household respondents always attributed a bad income year to an environmental problem, thus increasing the odds of making the same report in year t. Conversely, I tested whether the cumulative measure indicated familiarity with environmental risks to livelihoods, which would result in a decrease in the odds of reporting an environmental concern (Meijer-Irons, 2015). Table 2 provides summary statistics for the dependent and independent variables.

3.4 Statistical model

I fitted a mixed model with random intercepts (i.e. fixed effects) and random coefficients (i.e. random effects) using GSEM in Stata 13 in order to assess the effects of household characteristics on three different categories of my dependent variable: last year's household income was good (reference category), last year's household income was bad due to an environmental problem, and last year's household income was bad due to another factor. I included village-level dummies in my model to account for potential unobserved similarities of the households in each village (not included in output). I selected a random-effects model (at the household level) in order to examine variability between (rather than within) households over time, and to model how this variability influenced the dependent variable. In the multinomial model, the log odds of reporting a bad income year of type j relative to a good income year are given by

$$\log\left(\frac{p_{jht}}{p_{Jht}}\right) = \alpha_j + \beta_j X_{ht}$$

where p_{jit} is the odds of reporting a bad income year due to type of income shock j for household h in year t. α_j is a constant, and X_{ht} is a vector of independent variables for household h in year t. β_j is a vector of parameters for the effects of the independent variables on income year type j.

I estimated two models: a base model that included household characteristics only; and a second model that included an asset index, the district-level measure of NDVI anomalies, the cumulative environmental response variable, and the

Table 2:
Means and standard deviation of variables

Dependent variable categories (0, 1)	**Mean**	**S.D.**
HH reported a good income year	0.50	0.50
HH reported a bad income year due to environment	0.20	0.40
HH reported a bad income year due to another cause	0.30	0.46
Independent variables / head of household		
Age	54.21	13.36
Sex	0.72	0.45
No education	0.13	0.33
Primary education or less	0.78	0.41
Some secondary education	0.06	0.23
Finished secondary education	0.02	0.13
Vocational or other	0.01	0.11
Household characteristics / capital assets		
Financial capital		
Household Income Quintile 1	10868.94	34196.12
Household Income Quintile 2	36189.98	9492.7
Household Income Quintile 3	62099.14	14788.2
Household Income Quintile 4	100000	24522
Household Income Quintile 5	320000	410000
Asset Index	−0.02	0.88
Human capital		
0 to 49% employed in agriculture	0.55	0.50
50% or more employed in agriculture	0.45	0.50
# of males aged 15 to 24	0.39	0.64
# of females aged 15 to 24	0.36	0.61
# of males aged 25 to 59	0.91	0.66
# of females aged 25 to 59	1.00	0.58
# of elders	0.59	0.75
# of children	1.20	1.12
Social capital		
HH indicated year was bad for others in village	0.56	0.50
Cumulative # of times HH said it was a bad income year due to the environment	0.92	1.21
District level natural capital variables		
Average NDVI	0.39	0.49
Below average NDVI	0.27	0.44
Above average NDVI	0.34	0.47

Table 3:
Results of multinomial logit models, including odds ratios and significance tests

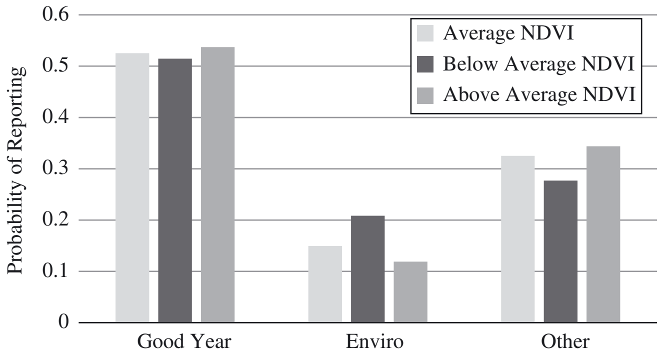
	Model 1				Model 2			
	Environmental risk		Other risk		Environmental risk		Other risk	
Independent variables/ head of household								
Sex (female referent)	1.240	**	1.144	*	1.218	*	1.134	*
Age	1.033		0.984		1.055	*	0.986	
Age squared	0.999	*	0.999		0.999	*	0.999	
Education (no education referent)								
Primary	0.865		1.067		0.746	*	0.976	
Some secondary	0.585	***	0.825		0.495	**	0.771	+
Household characteristics/ Capital assets								
Financial capital								
Income Change Indicator (referent is income quintile same both years)								
Income last year better than year before	0.777	***	0.658	***	0.780	**	0.656	***
Income last year worse than year before	2.468	***	2.450	***	2.596	***	2.482	***
Asset Index					0.927		0.964	
Human capital								
50% of employed members in agriculture	1.425	***	0.944	+	1.248	**	0.885	+
# of males aged 15 to 24	1.036		1.082		1.005		1.060	
# of females aged 15 to 24	1.054		1.021		1.040		1.026	
# of Males aged 25 to 59	1.042		0.955		1.064		0.954	
# of females aged 25 to 59	1.267	***	1.015		1.263	***	1.006	
# of elders	1.164	*	0.967		1.251	***	0.981	
# of children	1.085	*	1.083	***	1.025		1.061	*
Social capital								
HH indicated year was bad for others					12.329	***	2.674	***
in village					12.329	***	2.674	***
Cumulative environmental perception					0.766	***	0.982	
District level variables/ natural capital								
Below average NDVI	1.192	*	0.813		1.353	***	0.845	*
Above average NDVI	1.014		1.216		0.840	**	1.161	**
# of observations	8404				8404			
AIC	16451.13				15271.91			
BIC	17598.08				16461.08			

Note: $+p <= .10$, $^{*}p <= .05$, $^{**}p <= .01$, $^{***}p <= .005$.

respondent's perception of whether the year had been bad for other households in the village. The results of these two models are provided in Table 3.

Before summarizing the findings of the effects of the characteristics of the household head and of other household members on the likelihood of reporting a bad income year due to the environment or due to another factor, I present the results of

Figure 1:
Probability of a HH attributing a good income year or a bad income year to an environmental problem or another cause, controlling for environmental conditions



the objective environmental analysis.[3] The results indicate that when the objective environmental conditions in the district where a household was located were below average, the odds of a household respondent reporting having experienced a bad income year due to the environment increased by 35%, while the odds of a respondent citing another reason for a bad income year decreased by 16%. Figure 1 shows the predicted probabilities (holding all other variables at their means) of a household respondent reporting one of the three income year types across a range of environmental conditions.

Next, I present the results of the analysis of the characteristics of the household heads. In households headed by men respondents were slightly more likely than average to have cited an environmental problem as the cause of a bad income year. In addition, the odds of attributing a bad income year to the environment was 5% higher than average among older household heads, but the squared term indicates this was not a linear relationship, and that it declined as the age of the head increased.

The results of the multinomial logit reveal a number of significant relationships between household composition and the likelihood that a household respondent would attribute a bad income or a good income year to the environment or another factor. It should be noted that respondents in larger households had higher odds of attributing a bad income year to the environment, although these odds were not significantly elevated in all age categories. The odds of a respondent reporting that the household experienced a bad income year due to an environmental problem increased by 26% as the number of females aged 25 to 59 present in the household

[3] The model fit criteria (AIC and BIC) indicate that the full model (Model 2) better fits the data. I report on the results of this full model in this discussion section.

Figure 2:
Predicted probability of a respondent attributing a good income year or a bad income year to an environmental problem or another cause, by number of female household members aged 25–59

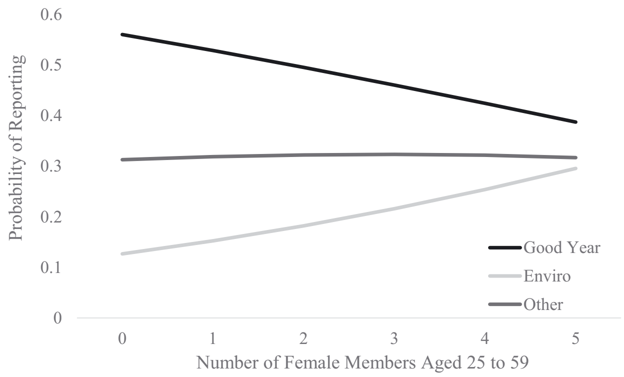
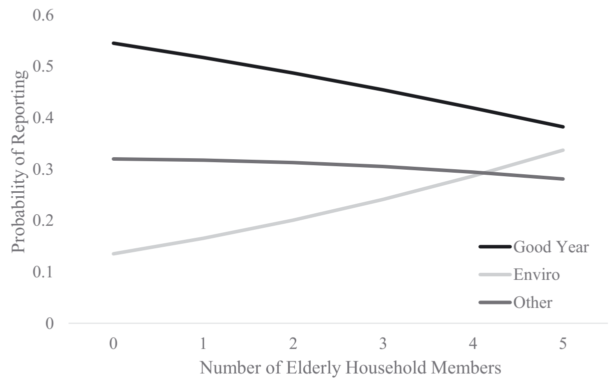


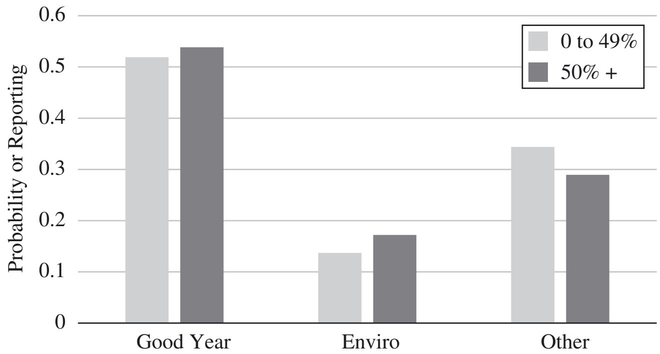
Figure 3:
Probability of a HH attributing a good income year or a bad income year to an environmental problem or another cause, by number of elderly HH members



increased. Similarly, the presence of a large number of elderly members in the household increased by 25% the odds that a respondent would attribute a bad income year to an environmental problem. Figures 2 and 3 show the predicted probabilities of a household respondent reporting having experienced a good or a bad income year due to the environment or another factor, holding all other variables at their means.

My results also show that in households in which more than 50% of the members were engaged in agriculture the odds that the respondent reported perceiving

Figure 4:
Probability of a HH attributing a good income year or a bad income year to an environmental problem or another cause, by percentage of HH members in agriculture

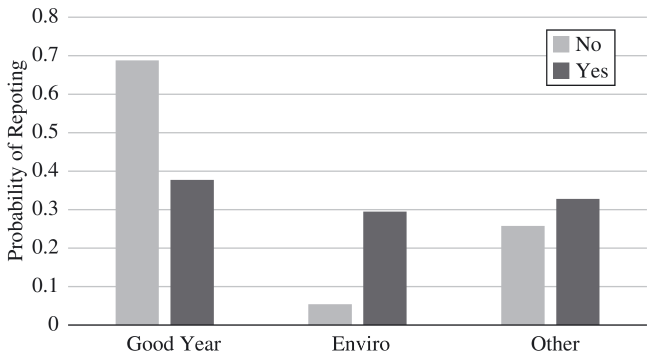


an environmental problem was 25% higher in a bad income year than a good income year. However, the odds that a respondent attributed a bad income year to another reason decreased 12% if the share of household members engaged in agriculture exceeded 50%. Figure 4 displays the predicted probabilities of a household respondent attributing a good income year or a bad income year to environmental or other factors, based on the concentration of agricultural labor in the household.

If a respondent perceived that other households in the village also had a bad income year, the odds were significantly higher that the respondent attributed the bad income year to the environment or to another factor. Figure 5 illustrates the predicted probabilities of a household respondent reporting a bad income year based on his or her perceptions that others in the village also had a bad income year. Of the household respondents who attributed a bad income year to the environment, a large share reported that others in the village also had a bad year. However, the household respondents who attributed a bad income year to another factor were split in their responses to the question about whether others in the village had also had a bad income year. While in both cases the perception that others in the village had also experienced a bad year increased the odds of a respondent reporting that his or her own household had experienced a bad income year, the differential distribution of the village-wide perception variable depending on the reported cause of a bad income year might hint at the presence of covariant and idiosyncratic shocks. Covariant shocks affect most people in a village, while idiosyncratic shocks tend to affect only a few members of a community.

The cumulative number of times a household respondent attributed a bad income year to the environment (measured up to year t) decreased the odds by 23% that

Figure 5:
Probability of a HH attributing a good income year or a bad income year to an environmental problem or another cause, by perception that others in the village had a bad year



the respondent would attribute a bad income year to an environmental problem in year *t*. This result suggests that a psychological adaptation might be at play. Prior research suggests that a household respondent's perceptions that environmental factors pose a risk to the household's income change as his or her familiarity with environmental stresses increases; or that having had earlier experiences with a hazard might decrease the likelihood that the respondent would attribute a bad year to the environment, even if the hazard remained (Casimir 2008; Loewenstein and Mather 1990).

Finally, I interacted the income change variable with the NDVI variable to determine whether there is a differential pattern of causal attribution dependent on both income and environmental condition; the results of this model are included in Table A.2 in the appendix. Figures 6 and 7 illustrate the predicted probability of a household respondent attributing a bad income year to the environment or another factor, conditional on his or her income and environmental conditions. The predicted probabilities can be found in Table A.1 of the appendix.

The interaction results from Figures 6 and 7 show that the probability of a respondent attributing a bad income year to both an environmental problem and another factor was substantially higher if the household income in the previous year was lower than it was two years ago. However, those respondents whose income in the previous year was higher than it was two years ago, when the NDVI was below average, were even more likely to have reported experiencing a bad income year due to environmental problems. Indeed, having experienced poor environmental conditions may have altered a household respondent's perception of his or her economic situation, even though the household's income did not suffer. Meanwhile, the probability of attributing a bad income year to some other cause was higher when

Figure 6:
Probability of a household respondent attributing a bad income year to an environmental problem, conditional on income and environmental conditions

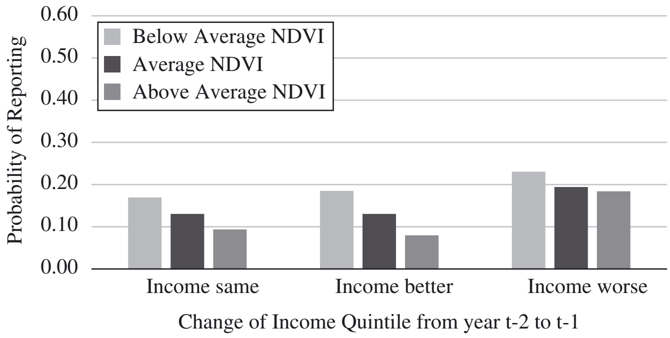
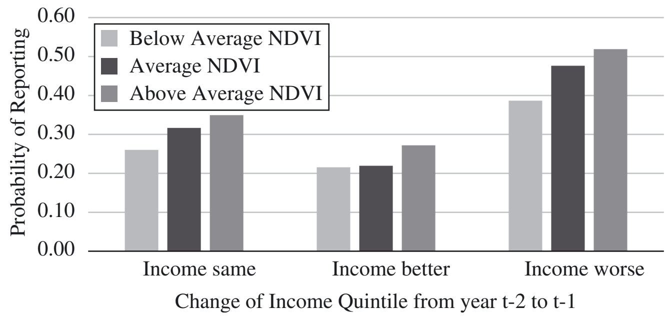


Figure 7:
Probability of a household respondent attributing a bad income year to another factor, conditional on income and environmental conditions



the NDVI was above average, regardless of the actual income change. This implies that these respondents perceived that factors unrelated to environmental conditions posed greater risks than environmental problems, but further research is needed to investigate the exact mechanisms underlying these results.

4 Discussion and future research

In my study I set out to explicitly model whether access to household assets and household composition are highly associated with the likelihood that a household respondent would attribute a decline in household income primarily to the environment. I used the sustainable livelihoods framework as a conceptual model to organize the findings of past research, and to select the appropriate variables for my analysis. The strength of this framework is that it makes it possible to parse out how differential access to capital assets influences both how vulnerable a given household is to exogenous risks, and how the household members' access to these assets might condition their perceptions of vulnerability. Indeed, past research has shown that individuals who were living in areas with similar objectively measured environmental conditions had different perceptions of the risks posed by environmental hazards to their financial well-being. These differences were related to the availability of and the household members' access to natural, financial, physical, social, and human capital. These past findings suggest that we should seek to gain a better understanding of how these factors influence risk perception, as they might influence human behavior even more than objective measures of the environment.

While this past research has added to our understanding of the individual-level and the household-level determinants that shape risk perceptions, these studies were limited in a number of key ways. First, the majority of the studies that modeled determinants of risk perceptions in the developing world were cross-sectional. These cross-sectional approaches did not allow researchers to account for how accumulated experiences with the environment, or changes in economic conditions or household composition, might shape the risk perceptions of individuals over time. Second, the data analyzed in past research did not include robust measures of household demographic data or of income and asset data. Using a unique panel dataset from Thailand, I attempted to close a number of the gaps in these previous studies.

I selected Thailand as the site for my study because previous research on vulnerability and risk perception in the country has shown that many Thais—and particularly those engaged in agriculture—already believe that climate change is affecting their livelihood. Finally, there is evidence to suggest that under future climate scenarios, rice, which is a staple crop in Thailand, will be affected by changing precipitation patterns. To test my research questions, I used the 1997 to 2006 waves of the Townsend Thai Data, a unique economic panel survey that contains data on self-reported risks to income, including environmental causes, and household composition data. To control for the effects of objective environmental conditions on risk perceptions, I added to my analysis robust objective environmental data that coincided with the time period of the social data. My dependent variable included three categories: the respondent perceived that the previous year was a good income year; the respondent perceived that the previous year was a bad income year due to an environmental problem; and the respondent perceived that the previous year was a bad income year due to another factor. I constructed my dependent variable in this way to determine whether there were significant differences in terms of household composition between the respondents who attributed a bad income year to an environmental problem or to another factor.

The results of my study showed that respondents from larger households had higher odds of reporting a bad income year, regardless of cause, than of reporting a good income year. However, the respondents who were living in a household in which the numbers of members who were elderly and older working-age (age 25 to 59) women were high had significantly greater odds of attributing a bad income year to an environmental problem. One possible explanation for this finding is that the households that are more vulnerable to environmental shocks are also those in which many of the male members work elsewhere for part of the year, leaving behind older household members and older women who remain tied to the household via agriculture (Klasen et al. 2015). However, while men and women in rural households in Thailand have different roles and expectations, there is evidence that these strict gender roles that had previously tied women to rice growing and other agricultural duties within the household are waning as non-farm economic opportunities expand. (Curran and Saguy 2001:63; Curran et al. 2005; Garip and Curran 2010). This finding requires further study to determine its possible underlying mechanisms, including additional modeling of the interactions between occupation, gender, and age.

The results also indicate that occupational diversity within a household influenced whether respondents reported risks to their livelihoods. These findings are consistent with previous research in Thailand that found that respondents employed in agricultural employment described the environmental risks to their livelihood as significant. In the Townsend Thai Data, the respondents from households in which 50% of the working-age members were primarily employed in agriculture had much higher odds than the respondents in households in which less than 50% of the working-age members were primarily employed in agriculture of reporting that a lack of rainfall, floods, or pests represented threats to their livelihood. Households in which the members were engaged in off-farm employment might have been able to maintain more stable income in years in which the environment was compromised. It thus appears that policies designed to foster these opportunities might help increase the adaptive capacity of these households.

On the other hand, the cumulative measure that counts the number of times a household respondent had previously attributed a bad income year to an environmental problem decreased the odds that he or she would attribute a bad income year to environmental shocks, but increased the odds that he or she would attribute a bad income year to another factor instead. This finding might be indicative of a form of psychological adaptation to environmental stress. Repeated exposure to environmental shocks might reset an individual's reference point regarding what constitutes normal conditions, thereby dampening the effect of an environmental shock. However, exposure does not appear to reduce the individual's feeling that his or her income is at risk; just the perceived cause (Loewenstein and Mather 1990).

Perceiving that others in the village had a bad income year increased the odds that a respondent would report a bad income year, regardless of cause; although if a respondent attributed a bad income year to the environment, she or he was also likely to have reported that others in the village were impacted as well. Identifying the reasons for these patterns will require some additional research. This pattern could indicate that when an environmental shock hits, it is likely to affect almost everyone in the village; or, at the very least, be a topic of informal conversation among villagers. The use of a mixed methods approach that includes both detailed demographic data and qualitative survey data, which allow for more in-depth analysis of these perceptual responses, would help shed light on a number of the questions analyzed in this paper.

Despite these limitations and the need for further research, I argue that the results add to our understanding of the characteristics of the household respondents who are likely to report an environmental shock, such as insufficient rainfall, which is common in the study area. The respondents from households that were less dependent on agriculture, had a younger mix of members, and had higher incomes were less likely to have reported having experienced a bad income year or attributed a bad year to the environment, even if they lived in areas with insufficient rainfall. Policy recommendations based on this research might include mechanisms to diversify occupational opportunities in order to buffer individuals and households from reduced livelihoods during times of environmental shocks. A number of studies have shown that seasonal migration and remittances can serve as adaptive responses to environmental shocks, providing needed buffers to help households supplement their non-farm income. This preliminary work also points to the need to consider a life course approach in the development of research on the responses of rural households to climate change. This approach would allow us to gain a solid understanding of the structure and composition of rural households, as well as of the roles individuals play within these households. Rather than assuming that all households experience a given shock in the same way, this more nuanced examination of the make-up of a household could help to guide policy and development work intended to assist the most vulnerable in a community.

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Appendix

Table A.1:
Predicted probability of attributing a good income year or a bad income year to an environmental problem or another cause, conditional on income and environment

	Income same	Income better	Income worse
Reports an enviro risk			
Below average NDVI	0.17	0.19	0.23
Average NDVI	0.13	0.13	0.19
Above average NDVI	0.09	0.08	0.18
Reports other risk			
Below average NDVI	0.26	0.22	0.39
Average NDVI	0.32	0.22	0.48
Above average NDVI	0.35	0.27	0.52

Table A.2:
Results of interaction of income and vegetation

	Environmental risk		Other risk	
Independent variables / head of household				
Sex (female referent)	1.221	*	1.135	
Age	1.056		0.987	
Age squared	0.999		1.000	
Education (no education referent)				
Primary	0.925	*	0.975	
Some secondary	0.500	***	0.774	
Household characteristics / capital assets				
Financial capital				
Income change Indicator (referent is income quintile same both years)				
Income last year better than year before	0.651	***	0.567	
Income last year worse than year before	2.496	***	2.524	
Asset Index	0.925		0.962	
Human capital				
50% of employed members in agriculture	1.250	**	0.889	+
# of males aged 15 to 24	1.010		1.063	
# of females aged 15 to 24	1.042		1.028	
# of males aged 25 to 59	1.072		0.958	
# of females aged 25 to 59	1.262	***	1.005	
# of elders	1.258	***	0.983	
# of children	1.028		1.062	*
Social capital				
HH indicated year was bad for others in village	12.326	***	2.683	***
Cumulative environmental perception	0.764	***	0.980	
District level variables/ natural capital				
Below average NDVI	1.258	+	0.796	*
Above average NDVI	0.713	*	1.095	
Interactions				
Income * Vegetation				
Income last year better than year before * below average NDVI	1.597	*	1.390	*
Income last year better than year before * above average NDVI	1.123		1.179	
Income last year worse than year before * below average NDVI	0.813		0.878	
Income last year worse than year before * above average NDVI	1.475	+	1.104	

$+p <= .10$, $^{*}p <= .05$, $^{**}p <= .01$, $^{***}p <= .005$

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Who is concerned about and takes action on climate change? Gender and education divides among Thais

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Abstract

Using data from Opinions about the Environment and Global Warming 2010, a nationally representative survey of 3900 adults, this study investigates demographic differentials in levels of concern about climate change and climate-relevant behaviours. The factor analysis of 11 environmentally friendly and carbon emissions reduction behaviours identifies two main factors that underlie climate-relevant behaviours: (1) efforts to save electricity and water, and (2) technical and behavioural changes. The multivariate analyses show that women and individuals with higher education are more likely than others to worry a great deal about global warming, and to make technical and behavioural changes. It may be the case that education is positively correlated with making technical and behavioural changes, but not with making efforts to save electricity or water, because the former set of actions require more effort and knowledge to pursue, while the latter set of actions are commonly undertaken for economic reasons. Having concerns about global warming and having experienced environmental problems are also associated with an increased adoption of climate-relevant behaviours.

1 Introduction

Households are major contributors to the total carbon emissions of a country. For example, the heating of homes in the United States and in most European countries accounts for as much as 30–40% of total energy consumption (Abrahamse et al.

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2005). Day-to-day activities ranging from burning gas for home heating, using electricity generated from non-renewable resources, and burning gasoline when driving all contribute to greenhouse gas (GHG) emissions. Accordingly, changes in the energy-related behaviours of the public could contribute substantially to the reduction of GHG emissions. As it is generally expected that new low-carbon energy production, energy efficiency, and carbon sequestration technologies will take decades to develop and implement, promoting individual and household behavioural changes appears to be the most feasible option for reducing emissions quickly (Pacala and Socolow 2004).

Although behavioural changes such as adopting existing household technologies or altering modes of personal transportation are fairly straightforward (Gardner and Stern 2008), prompting the public to make voluntary changes in their environmental behaviours may not have the desired result (Dietz et al. 2009). Barriers to the adoption of proactive environmental strategies range from a lack of awareness and understanding, to doubts about the efficacy of one's actions, to a lack of knowledge about how to change one's behaviour to mitigate climate change. Meanwhile, previous studies have demonstrated that informing the public of concerns about climate change can lead people to actively change their climate-relevant behaviours or take political action, as the likelihood of engaging in direct and indirect pro-environmental behaviours has been shown to be positively correlated with awareness of such concerns (Tobler et al. 2012; Wicker and Becken 2013). In particular, when climate risks or impacts are perceived as psychologically close (e.g. geographically or temporally proximate), they can motivate mitigation behaviour (Spence et al. 2012).

Nevertheless, public attitudes regarding climate change and the extent to which people approve of pro-environmental values and behaviours vary considerably by demographic and socio-economic characteristics. Existing studies predominantly carried out in Europe or the United States have found that environmentalism, environmental concerns, and belief in climate change are positively associated with being young, being female, having a left-leaning political ideology, and having relatively high levels of education and income (McCright and Dunlap 2011a; Running 2013; Whitmarsh 2011). Younger people tend to be more environmentally aware than older people, possibly because the younger cohorts are more exposed to media and school curricula that address environmental issues (Howell and Laska 1992). Likewise, the gender gap could be due to different expectations for men and women during parenthood and socialisation processes (Zelezny et al. 2000), gender roles and the division of labour within the family (Blocker and Eckberg 1997), and differences in the value formation processes of men and women (Stern et al. 1995). While boys are raised to be independent and dominant over others, girls are raised to value nature and nurturance. With respect to socio-economic characteristics, highly educated people may know more than those with less education about environmental problems, and about how individuals can change their behaviour and learn more about the environment (Liere and Dunlap 1980; Semenza et al. 2008). Meanwhile, people with relatively high incomes may have been able to fulfil their basic material needs, and are therefore looking to achieve a better quality of life and greater environmental sustainability (Inglehart 1995).

Furthermore, not all climate-relevant behaviours require the same amount of effort to implement. Behaviours that contribute to climate change mitigation can be classified as *high*- or *low*-cost behaviours. The cost of adopting a certain behaviour includes not just pecuniary costs, but opportunity costs involving time, inconvenience, or the effort needed to pursue the behaviour (Diekmann and Preisendörfer 2003). Typically, the cost of switching from driving a private car to using public transport is high, whereas the cost of recycling or buying eco-friendly products is low. Accordingly, when the cost difference is small, behavioural change is more likely.

Pro-environmental behaviours can also be categorised as *efficiency* or *curtailment* behaviours (Gardner and Stern 2002). Efficiency behaviours are one-shot behaviours that involve the purchase of energy-efficient items, such as cars and household appliances. By contrast, curtailment behaviours involve continual efforts to reduce energy consumption by, for example, keeping the thermostat settings low. It therefore appears that technical measures are more accepted than measures designed to change on-going behavioural or consumption patterns (Poortinga et al. 2003). Given the demographic differentials in preferences and opportunities, the adoption of different types of climate-relevant behaviours can vary considerably between population sub-groups.

Meanwhile, previous cross-national studies have shown that public attitudes and perceptions of the threat posed by climate change differ substantially across countries (Lorenzoni and Pidgeon 2006). Risk perception itself is specific to culture and place (Weber and Hsee 1999). Different levels of exposure to climate hazards, as well as social factors such as ethics, norms, and knowledge, may therefore explain this national variation. Likewise, public attitudes about and support for climate change policies can vary considerably between developed and less developed nations. For example, studies have shown that people in developing countries are less likely to express the willingness to pay to combat climate change (Alló and Loureiro 2014). It has been argued that because people in lower income countries are still struggling to meet their basic material needs, they have less room to consider post-materialistic values, such as quality of life, freedom, and the environment (Dunlap and York 2008; Gelissen 2007).

Nevertheless, with the rapid urbanisation and industrialisation of emerging economies, increasing demand for energy use in these countries will have significant effects on their GHG emissions (Sadorsky 2014). While developed countries have to put more effort into emissions reduction, developing countries are also central to climate action, given the substantial growth in their contributions to global carbon dioxide (CO_2) emissions: the share of global emissions generated by developing countries increased from 33% in 1990 to 53% in 2008 (Romani et al. 2012). Understanding the public's level of awareness and perceptions of climate change in these countries could therefore be useful in designing and communicating climate change policies.

However, most of the studies that focus on perceptions of climate change and pro-environmental behaviours have been carried out in high income countries, while evidence from less developed countries is scarce. Hence, this study aims to provide new empirical evidence on demographic differentials in levels of concern about climate change and in climate-relevant behaviours in Thailand using the 2010 Opinion Survey on Environment and Global Warming (OEGW). The two main research questions investigated in this study are: (1) whether levels of concern about climate change differ according to demographic characteristics; and (2) what the determinants of climate-relevant behaviour are, and whether they vary with different types of behaviours.

As the second-largest economy in Southeast Asia, Thailand is also the second-largest CO_2 emitter in the region (Shrestha and Pradhan 2010). As GDP has risen in Thailand, electricity demand has also increased. Indeed, the demand for electricity from the household sector appears to have risen steadily even after the economic slump in 2008 (APEC 2010). Under the business-as-usual scenario (BAU), Thailand's greenhouse gas emissions are projected to reach 715.2 million tonnes of carbon dioxide equivalent (MtCO2eq) in 2030 and 1398.7 MtCO2eq in 2050 (Chotichanathawewong and Thongplew 2012). The latter figure is almost equivalent to the total emissions of India in the year 2008 (IEA 2010). To move towards improving the country's energy security and reducing its GHG emissions, Thailand has adopted the 20-year Energy Efficiency Development Plan 2011–2030 (EEDP). While the plan establishes requirements for energy efficiency via regulations and standards and promotes technology development and innovation, it also includes strategies aimed at fostering public awareness of sustainable energy options and of ways individuals can change their energy consumption behaviour (EEPO 2011). Understanding public perceptions of climate change and individual environmental behaviour is thus essential for the design of effective energy and climate policies.

The remainder of the paper is organised as follows. In the next sections, we describe the survey data and the methods we used for empirical analysis. We then present our results, and discuss our findings in the discussion section. We offer concluding remarks in the final section.

2 Data

This study's findings are based on data from Opinions about the Environment and Global Warming (OEGW) 2010, a nationally representative, cross-sectional population-based survey carried out by the National Statistical Office of Thailand (NSO). In order to provide policy-makers with insight into the public's opinions on environmental and global warming-related issues, the survey asked respondents about these topics. Specifically, the survey asked members of the public about the environmental problems they have experienced, their level of concern about global warming and its effects, the activities they have undertaken to reduce global warming, and the strategies they believe are useful for combatting global warming.

Information on the basic demographic and socio-economic characteristics of the respondents was also collected in the survey.

The OEGW survey was carried out in April 2010 on a nationally representative sample of adults aged ≥15 years in all regions in Thailand. A stratified, three-stage cluster sampling design was adopted, with the strata consisting of five geographic regions: metropolitan Bangkok, north, northeast, central, and south. The primary sampling units (PSUs) were blocks in urban areas or villages in rural areas. In the first stage, the PSUs were randomly selected using selection probability proportional to size sampling, and 390 blocks/villages out of 109,966 blocks/villages in the whole country were selected. In the second stage, ten households were randomly selected from the previously chosen urban or rural PSUs using simple systematic random sampling. In the third stage, one eligible person within each selected household (i.e. a household member aged ≥15) was randomly selected for a face-to-face interview.

In total, 3900 households were sampled, and 1829 men and 2071 women were interviewed. As there was no missing information in the variables of interest, all 3900 observations were retained for statistical analysis.

While the survey we used is attractive due to its relatively large sample size and wide coverage of the research questions of interest, survey data of this kind can suffer from bias and measurement error. The first problem is social desirability bias: in this case, the respondents' reports of their levels of concern about climate change and of their engagement in mitigation actions may have been overstated. Indeed, some studies purposively designed to test the existence of social desirability bias have found that self-reported data on pro-environmental behaviour in a survey are subject to social desirability biases when tested against observational data (Gamberini et al. 2014). Nevertheless, questionnaires and interviews remain the most widely used methods in pro-environmental and energy conservation studies. Another problem is recall bias in the reporting of the activities undertaken to reduce global warming. The information on climate-relevant behaviours relies solely on self-report methods. The respondents may have recall biases in the retrospective reporting of a one-shot behaviour, such as the purchase of energy-saving light bulbs or energy-efficient appliances. If the action has taken place long ago, the bias may be especially large. Ideally, we would like to have outcome variable measures from different sources (i.e. actual observations of behaviour), but such data are scarcely available. While we acknowledge the potential problems of recall and social desirability biases, it is beyond the scope of this study to address these issues.

3 Methods

3.1 Measures and variables

3.1.1 Dependent variables

This study investigates two outcomes:

1. *Concern about global warming*
   The variable concern about global warming is derived from the following question: 'How much are you worried about the problem of global warming?' The respondents were asked to choose from four possible responses: (1) a great deal, (2) a fair amount, (3) a little, and (4) not at all. Only 4.4% and 3.2% of the respondents chose the 'a little' and the 'not at all' categories, respectively. The two categories are thus combined in our statistical analysis.
2. *Climate-relevant behaviours*
   The variable on climate-relevant behaviours is taken from a question that asked the respondents whether they had taken certain actions to minimise the problem of global warming. A list of 11 actions were provided (see Table 1). The respondents were prompted to indicate which actions they had taken and how often they had performed these actions using the following options: (1) regularly, (2) sometimes, and (3) not at all/not applicable. Note that the third category could be problematic since a particular action such as 'setting the air conditioner to 25°C' would not apply to the respondents who did not possess an air conditioner. Accordingly, in the survey those respondents would be classified as having failed to take this action to reduce global warming. This assumption could be misleading, especially when we assess the socio-demographic determinants of climate-relevant behaviours. In the final analysis, such problematic items are excluded.

3.1.2 Independent variables

In Table 1 we present a number of other explanatory and control variables added to the analysis, including demographic characteristics, perceptions regarding climate change and environmental issues, and contextual characteristics.

Demographic characteristics Our main goal is to investigate how concerns about global warming and climate-relevant behaviours vary by demographic characteristics, including age, gender, and educational attainment. *Age* is grouped into six categories: 15–19 years, 20–29 years, 30–39 years, 40–49 years, 50–59 years, and ≥60 years. Note that because the survey did not collect age information in exact years, the information on age is available in age groups only. *Gender* is a dummy variable coded one if the respondent is female, and zero otherwise. *Educational attainment* is divided into seven levels: no education, primary, lower secondary, upper secondary, vocational, diploma, and bachelor's degree and above.

Empirical support for gender and educational differences in levels of concern about climate change or the environment has been rather consistent. Because of gender differences in socialisation, political orientation, and risk perception, women are generally more likely to believe in global warming and to engage in behaviours that contribute to global warming mitigation (Egan and Mullin 2012; Hamilton and Stampone 2013; Joireman and Liu 2014). The gender socialisation perspective holds

Table 1:
Overview and descriptive statistics of variables

Variable	Scale	% of respondents
Concern about global warming	ordinal	
a great deal		52.7
a fair amount		39.9
little/not at all		7.4
Climate relevant behaviours		
Use cloth bags instead of plastic bags	ordinal	
regularly		11.8
sometimes		54.5
never		33.7
Plant trees and conserve forests	ordinal	
regularly		20.0
sometimes		62.9
never		17.0
Use energy-saving light bulbs	ordinal	
regularly		36.7
sometimes		38.6
never		24.7
Unplug electrical devices when not in use	ordinal	
regularly		70.3
sometimes		28.0
never		1.7
Turn off unused lights	ordinal	
regularly		80.7
sometimes		18.5
never		0.8
Use energy-efficient appliances	ordinal	
regularly		52.6
sometimes		37.3
never		10.1
Set air conditioner to 25°C	ordinal	
regularly		15.5
sometimes		11.1
never		73.3
Use public transportation rather than a private vehicle	ordinal	
regularly		20.0
sometimes		54.1
never		25.9
Turn off the tap while brushing teeth/taking shower	ordinal	
regularly		66.2
sometimes		26.8
never		7.0

Continued

Table 1: Continued

Variable	Scale	% of respondents
Fill a container when washing rather than running tap water	ordinal	
regularly		58.7
sometimes		32.3
never		9.0
Reduce the use of styrofoam containers	ordinal	
regularly		19.7
sometimes		56.6
never		23.7
Individual characteristics		
female	dummy	52.7
Age groups	ordinal	
aged 15–19 years		7.4
aged 20–29 years		14.5
aged 30–39 years		22.9
aged 40–49 years		22.8
aged 50–59 years		20.6
aged 60 years and over		11.8
Highest level of education	ordinal	
no education		1.9
primary education		46.7
lower secondary		15.9
upper secondary		12.4
vocational		4.9
diploma		6.1
bachelor's and above		12.1
average monthly wage	continuous	10264 (109)[a]
Climate change perceptions		
Had environmental problems in the community	dummy	70.4
Believed that the climate had changed over the past year	dummy	96.6
Heard about global warming/climate change	dummy	95.7
Region of residence	nominal	
Bangkok		11.4
central region		24.0
northern region		19.0
north-eastern region		33.0
southern region		12.7

Note: [a] Means and standard errors in parentheses. Sample weight applied for the percentages presented.

that while boys are socialised to be competitive, independent, and unemotional; girls are socialised to be compassionate, co-operative, and empathetic—characteristics that are associated with caring about nature, including about environmental and climate change concerns (McCright 2010). Furthermore, men tend to feel less vulnerable to risk thanks to their dominant position in the social structure, and are thus more likely than women to seek to manage, control, and benefit from risks. Women, by contrast, are more likely than men to feel vulnerable to risk and to perceive the world as dangerous, as they have less power and control over resources. These gender disparities in perceptions of technological risks also apply to perceptions of climate change risks. With respect to education, we expect to find that education is positively correlated with expressing concerns about global warming and taking climate-relevant actions. Education improves an individual's cognitive ability to evaluate scientific evidence (Egan and Mullin 2012), and increases his or her knowledge of and familiarity with a range of issues, including environmental problems and global warming (Tjernström and Tietenberg 2008). Thus, having more education tends to be associated with increased concern about climate change.

On the other hand, evidence on the effects of age on the level of concern about global warming has been less consistent. Some studies have reported a negative correlation between age and being concerned about global warming (Kellstedt et al. 2008; Malka et al. 2009). With fewer years of remaining life expectancy, older people may believe that global warming is unlikely to affect them personally, and may therefore be less inclined to change their behaviour. However, other studies have found no significant association between age and perceptions of global warming (Wood and Vedlitz 2007).

We also control for income (average monthly wage), as education may capture income differences, and some individuals may be more able than others to afford to engage in certain behaviours. In particular, conserving electricity and water could be motivated by financial incentives, and is directly related to income. However, there is no information on income in the OEGW survey. We therefore impute the income variable by matching each OEGW respondent's reported occupation, sex, and region to the average monthly wage by occupation, sex, and region provided by the quarterly Labour Force Survey (LFS) in 2010 and the Socioeconomic Survey (SES) in 2011. The summary statistics of the average monthly wage, adjusted for the sample weights, is reported in Table 1.

Climate change and environmental perceptions The extent to which a person is concerned about climate change is influenced by his or her perceptions of climate change, which can in turn affect his or her motivation to act (Swim et al. 2009). Furthermore, levels of concern about climate change and climate-relevant behaviours are associated with people's experiences of environmental problems/natural disasters and knowledge of global warming. A number of studies have found that people often conflate climate change with other environmental problems (Reynolds et al. 2010). It is therefore possible that experiencing environmental problems increases an individual's willingness to adopt mitigation activities. Similarly, a person's perceptions of having experienced warming or changes in the usual weather patterns have been found to be positively correlated with believing in and being concerned about climate change (Li et al. 2011; Taylor et al. 2014). Here we include two dummy variables indicating whether the respondents (1) *have experienced an environmental problem in their community*, and (2) *believe that the weather has changed over the past year*.

Region of residence In addition, we control for *region of residence,* a variable that is divided into five regions: metropolitan Bangkok, central, north, northeast, and south. These five regions differ substantially in terms of social, economic, and geographical characteristics. Bangkok, the capital city, is the largest urban centre in the country. Bangkok's rapid economic development has been accompanied by negative side effects, such as air pollution from intensive traffic, industry, power plants, and incinerators. Moreover, because Bangkok is built on land close to the ocean that is flat, marshy, and unstable, the city is vulnerable to flooding. Meanwhile, the central plain is the most fertile region of the country, but monoculture farming coupled with mismanagement of water irrigation has resulted in land degradation. Low-lying central Thailand is prone to flooding during the rainy season, when rivers tend to swell and overflow. In the mountainous region of northern Thailand, intensive farming with chemicals has led to land degradation. The region has also suffered from deforestation due to illegal logging and improper land use. The northeast has the highest incidence of poverty and the greatest number of poor residents. As this region consists primarily of a semi-arid plateau with sandy infertile soil, its main agricultural products are rainfed rice and low-return dryland field crops such as cassava. Poor soil conditions coupled with an uneven distribution of rainfall and limited irrigation facilities make the northeast particularly prone to drought. The south, on the other hand, is one of the wealthiest regions thanks to its rubber plantations and fruit production, as well as the fishing and international tourism industries in its coastal areas (McGregor 2008). However, growth in tourism, fisheries, port development, and shrimp farming in the region have led to mangrove destruction, salinisation, and coastal erosion. Climate change is likely to exacerbate these existing environmental challenges, and these regional differences may influence the respondents' climate change attitudes and behaviours accordingly.

3.1.3 Statistical analysis

The data analysis consists of three main steps. First, in order to address the first research question on demographic differentials in concerns about climate change, the variable that measures the level of 'worry about the problem of global warming' was recoded into three categories in a sequential order: (1) little/not at all, (2) a fair amount, and (3) a great deal. Because the outcome variable was not normally distributed, ordinary least squares (OLS) regression could not be used, as the normality assumption would be violated. Thus, ordered logistic regression, as outlined below, is employed to estimate the association between concern about climate change and demographic characteristics given the ordinal response variable like ours.

$$\begin{aligned} y_i^* &= \beta_0 + \beta_1 female_i + \beta_2 age_i + \beta_3 education_i + \beta_4 \boldsymbol{x}_i + \varepsilon_i, \\ y_i &= 1 \quad \textit{if } y_i^* \leq \gamma_1 \\ y_i &= 2 \quad \textit{if } \gamma_1 < y_i^* \leq \gamma_2 \\ y_i &= 3 \quad \textit{if } y_i^* > \gamma_2, \end{aligned}$$

where y_i^* is the underlying latent concern about climate change of an individual i, which is modelled as a function of demographic variables $female_i$, age_i, $education_i$, and other controlled characteristics $\boldsymbol{x}_i$ such as environmental perceptions and region of residence. If y_i^* is smaller than or equal to the unknown parameter γ_1, the individual i will report that he or she is a little or not at all concerned about the problem of global warming. If $\gamma_1 < y_i^* \leq \gamma_2$, the individual i will report that he or she has a fair amount of concern. If $y_i^* > \gamma_2$, the individual i will report that he or she has a great deal of concern. Both γ_1 and γ_2 are estimated jointly with β_i in the model.

In addition, the likelihood-ratio test was performed to test the proportional odds assumption, and the results confirmed that the assumption was not violated (Wolfe and Gould 1998). Hence, the use of ordered logistic estimation is justified.

Second, exploratory factor analysis was performed to identify the number of behavioural dimensions and to cluster the items that measured the same climate-relevant behaviours. The 11 items of the behaviours listed in Table 1 were subjected to a principal components analysis. The item 'set air conditioner to 25°C' has a rather high uniqueness value of 0.52; i.e. 52% of the common variance of the variable not associated with the factors. Thus, the item is excluded from the final factor analysis. In addition, since a response to the item 'use public transportation rather than private vehicle' depends considerably on whether the respondent possesses a private vehicle, this item was also excluded. Factor analysis was then performed on nine items.

The factor analysis for the items that capture climate-relevant behaviours resulted in a two-factor solution, as presented in Table 2. For both of the factors retained, all of the items have factor loadings of > .40, except for 'planting trees and forest conservation', which has factor loadings of .37. The first factor labelled '*electricity and water saving*' explained 55.3% of the variance, and consisted of four items: two actions that contribute to saving electricity (i.e. unplugging electrical devices when not in use and turning off unused lights), and two actions that contribute to saving water (i.e. turning off the tap while brushing teeth/taking a shower and filling a container when washing rather than running tap water). The index of electricity and water saving was constructed based on these four items (Cronbach's $\alpha = 0.64$). The second factor labelled '*technical and behavioural change*' explained 44.7% of the

Table 2:
Factor loading and item-scale correlations for each item of climate-relevant behaviour scales

Scale	Items	Factor loading	Item-total correlation
Electricity and water saving	Unplug electrical devices when not in use	0.63	0.67
Eigenvalue = 2.62	Turn off unused lights	0.69	0.65
Explained variance = 55.3%	Turn off the tap while brushing teeth/taking shower	0.45	0.73
Cronbach's α = 0.64	Fill a container when washing rather than running tap water	0.42	0.73
Technical and behavioural change	Use energy-saving light bulbs	0.55	0.61
Eigenvalue = 1.31	Use energy-efficient appliances	0.42	0.70
Explained variance = 44.7%	Use cloth bags instead of plastic bags	0.49	0.61
Cronbach's α = 0.60	Plant trees and conserve forests	0.37	0.55
	Reduce the use of styrofoam containers	0.45	0.62

variance, and consisted of five items: two items that represent *efficiency* behaviours (i.e. using energy-saving light bulbs and using energy-efficient electrical devices), and three items that represent *curtailment* behaviours involving repetitive efforts to reduce GHG emissions (i.e. using a cloth bag instead of a plastic bag, planting trees and conserving forests, and reducing the use of styrofoam containers). The index of technical and behavioural change was constructed based on these five items (Cronbach's $\alpha = 0.60$).

Third, to answer the second research question on the determinants of climate-relevant behaviours and how these determinants vary with different behaviours, OLS regressions on the two behaviour indices (i.e. *electricity and water saving* and *technical and behaviour changes*) created from factor analysis were performed. OLS regression is an appropriate method since the two indices are normally distributed. Each index has a maximum score of three. The higher the score, the more engaged the respondent is in climate-friendly behaviours.

4 Results

4.1 Demographic differentials in concern about global warming

Table 3 presents a series of ordered logit models that estimate the level of concern about global warming, while taking into account demographic characteristics and other relevant factors. The first model considers demographic characteristics only, while the second model controls for perceptions about climate change and the environment. The last model includes a control for region of residence, as location may influence the level of concern about global warming.

Across the three models, we observe significant gender and educational differentials in levels of concern about global warming. The odds of having a great deal of concern about global warming are 1.2 times ($e^{0.148}$) higher for women than for men. The association between educational attainment and the level of concern about global warming is rather linear. Compared to those with no education, the respondents with an upper secondary level of education or higher were significantly more likely to report that they are worried about global warming. In particular, respondents with a bachelor's degree were 2.9 times ($e^{1.076}$) more likely to say they are concerned about global warming. No significant relationship is observed between age or income, as estimated by log(monthly wage), and level of concern about global warming. Individuals who reported living in a community with environmental problems expressed higher levels of concern about global warming. Meanwhile, respondents who said they believe the weather had changed over the past year were 2.3 times ($e^{0.831}$) more likely to express concern about global warming. Compared to the central region, respondents living in the south expressed significantly lower levels of concern.

Table 3:
Ordered logit estimates of concern about global warming

	Model 1		**Model 2**		**Model 3**	
	Demographic characteristics		**Climate change perceptions**		**Other characteristics**	
	β	*s.e.*	*β*	*s.e.*	*β*	*s.e.*
Demographic characteristics						
female	0.129*	(0.065)	0.148*	(0.067)	0.148*	(0.067)
aged 15–19 years	ref		ref		ref	
aged 20–29 years	0.066	(0.176)	0.055	(0.175)	0.054	(0.176)
aged 30–39 years	0.001	(0.160)	0.008	(0.159)	0.000	(0.160)
aged 40–49 years	0.077	(0.160)	0.079	(0.155)	0.070	(0.156)
aged 50–59 years	−0.064	(0.182)	−0.063	(0.177)	−0.073	(0.178)
aged 60 years and over	0.109	(0.203)	0.151	(0.199)	0.145	(0.198)
no education	ref		ref		ref	
primary education	0.412	(0.270)	0.402	(0.274)	0.381	(0.271)
lower secondary	0.480	(0.295)	0.501+	(0.294)	0.482+	(0.291)
upper secondary	0.811**	(0.300)	0.830**	(0.297)	0.816**	(0.296)
vocational	0.595*	(0.290)	0.686*	(0.287)	0.657*	(0.287)
diploma	0.921**	(0.284)	0.974***	(0.283)	0.962***	(0.281)
bachelor and above	1.047***	(0.291)	1.085***	(0.287)	1.076***	(0.287)
log(wage)	0.000	(0.007)	0.002	(0.007)	0.001	(0.007)
Climate change perceptions						
Had environmental problems in the community			0.624***	(0.128)	0.632***	(0.129)
Believed that the climate had changed over the past year			0.838***	(0.207)	0.831***	(0.194)
Region of residence						
central region					ref	
Bangkok					−0.148	(0.183)
northern region					−0.151	(0.170)
north-eastern region					−0.149	(0.202)
southern region					−0.364*	(0.167)
Little versus a fair amount/great deal	−1.878***	(0.328)	−0.636+	(0.344)	−0.809*	(0.353)
Little/a fair amount versus great deal	0.568+	(0.313)	1.861***	(0.329)	1.692***	(0.333)
Observations	3,900		3,900		3,900	
Population size	779.999		779.999		779.999	
Number of strata	5		5		5	
Number of PSUs	193		193		193	

Note: Standard errors in parentheses. Sample weight applied for the analysis presented.
$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, $+p < 0.1$.

Table 4:
Percentages distribution of climate-relevant behaviours by gender

	Male	Female	All
*Use cloth bags instead of plastic bags****			
regularly	8.6	14.7	11.8
sometimes	52.6	56.3	54.5
never/NA	38.8	29.1	33.7
*Plant trees and conserve forests**			
regularly	21.6	18.6	20.0
sometimes	62.9	62.9	62.9
never/NA	15.4	18.5	17.0
*Use energy-saving light bulbs**			
regularly	36.0	37.3	36.7
sometimes	40.9	36.5	38.6
never/NA	23.1	26.1	24.7
*Unplug electrical devices when not in use****			
regularly	68.4	72.0	70.3
sometimes	30.3	25.9	28.0
never/NA	1.3	2.1	1.7
Turn off unused lights			
regularly	80.0	81.4	80.7
sometimes	19.1	17.8	18.5
never/NA	0.9	0.8	0.8
*Use energy-efficient appliances**			
regularly	50.5	54.6	52.6
sometimes	39.1	35.6	37.3
never/NA	10.4	9.8	10.1
Set air conditioner to 25°C			
regularly	14.6	16.3	15.5
sometimes	11.8	10.5	11.1
never	73.5	73.2	73.3
*Use public transportation****			
regularly	16.6	23.0	20.0
sometimes	55.0	53.3	54.1
never/NA	28.4	23.7	25.9
*Turn off the tap while brushing teeth/taking shower***			
regularly	63.7	68.5	66.2
sometimes	29.1	24.6	26.8
never/NA	7.2	6.9	7.0

Continued

Table 4: Continued

	Male	Female	All
Fill a container when washing rather than running tap water			
regularly	57.6	59.7	58.7
sometimes	32.6	32.1	32.3
never/NA	9.8	8.2	9.0
*Reduce the use of styrofoam containers**			
regularly	18.6	20.7	19.7
sometimes	55.9	57.3	56.6
never/NA	25.6	21.9	23.7

Note: $^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$
Sample weight applied for the percentages presented. P-value is obtained from a chi-square test of association between gender and each behaviour.

4.2 Demographic differentials in climate relevant behaviours

Table 4 presents the distribution of 11 items related to climate-relevant behaviours by gender. Chi-square tests were performed to test the relationship between gender and each climate action. For most actions, the proportion of individuals who regularly engaged in environmentally friendly behaviours was significantly greater for women than for men. The four actions that were most commonly carried out regularly by both men and women were related to electricity and water conservation: i.e. turning off unused lights (80.7%), unplugging electrical devices when not in use (70.3%), turning off the tap while brushing teeth/taking a shower (66.2%), and filling a container rather than running tap water (58.7%). The majority of the respondents reported using energy-efficient appliances (52.6%), while about one-third said they use energy-saving light bulbs. Only about one-fifth of the respondents said they had taken actions that involve consistent efforts to change their behaviours and are associated with some degree of inconvenience, such as using public transportation, planting trees, and setting the air conditioner to 25°C.

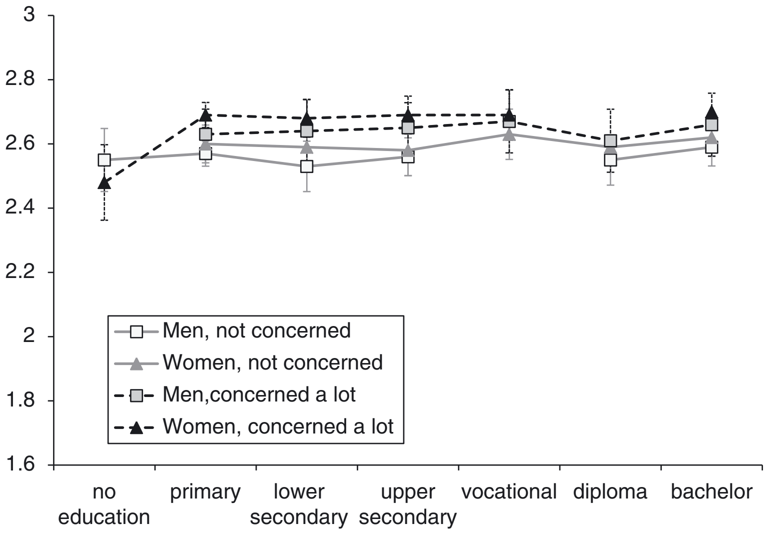
The factor analysis (see Table 2) reveals that climate-relevant behaviours can be grouped into two types of actions: (1) electricity and water saving measures; and (2) technical and behavioural changes. Table 5 displays OLS regression estimates for the two climate-relevant behaviours based on demographic and contextual characteristics and on climate change and environmental perceptions.

Women were more engaged in both climate-relevant behaviours than men. With respect to age, the older age groups were significantly more engaged in electricity and water saving actions than the respondents aged 15–19. However, we observe no age gradient in the likelihood of undertaking technical and behavioural changes. While education was not significantly associated with electricity and water saving, it had a positive relationship with technical and behavioural changes.

Table 5:
OLS regression analysis for climate-relevant behaviours

	Electric and water saving		**Technical and behavioural change**	
	β	***s.e.***	***β***	***s.e.***
Demographic characteristics				
female	0.036**	(0.011)	0.040***	(0.012)
aged 15–19 years	ref		ref	
aged 20–29 years	0.032	(0.030)	−0.047	(0.029)
aged 30–39 years	0.103**	(0.031)	−0.023	(0.030)
aged 40–49 years	0.097**	(0.032)	0.033	(0.030)
aged 50–59 years	0.131***	(0.034)	0.022	(0.030)
aged 60 years and over	0.117**	(0.039)	0.004	(0.039)
no education	ref		ref	
primary education	0.058	(0.057)	0.156***	(0.045)
lower secondary	0.058	(0.060)	0.234***	(0.050)
upper secondary	0.061	(0.064)	0.302***	(0.048)
vocational	0.095	(0.070)	0.317***	(0.051)
diploma	0.040	(0.068)	0.353***	(0.055)
bachelor and above	0.077	(0.065)	0.430***	(0.051)
log(wage)	−0.001	(0.001)	−0.001	(0.001)
Climate change perceptions				
Worry a little/not at all about global warming	ref		ref	
Worry a fair amount about global warming	0.023	(0.046)	0.104**	(0.036)
Worry a great deal about global warming	0.095*	(0.045)	0.175***	(0.037)
Had environmental problems in the community	0.053	(0.032)	0.073**	(0.027)
Believed that the climate had changed over the past year	0.040	(0.048)	0.051	(0.051)
Region of residence				
central region	ref		ref	
Bangkok	−0.023	(0.038)	0.011	(0.036)
northern region	−0.012	(0.046)	−0.029	(0.042)
north-eastern region	−0.003	(0.043)	−0.158 * **	(0.036)
southern region	−0.040	(0.044)	−0.008	(0.036)
constant	2.356***	(0.097)	1.632***	(0.076)
Observations	3,900		3,900	
Population size	779.999		779.999	
Number of strata	5		5	
Number of PSUs	193		193	
R-squared	0.030		0.122	

Figure 1:
Predicted score with 95% confidence interval of adopting electricity and water saving behaviour for a person aged 40–49 years living in the south



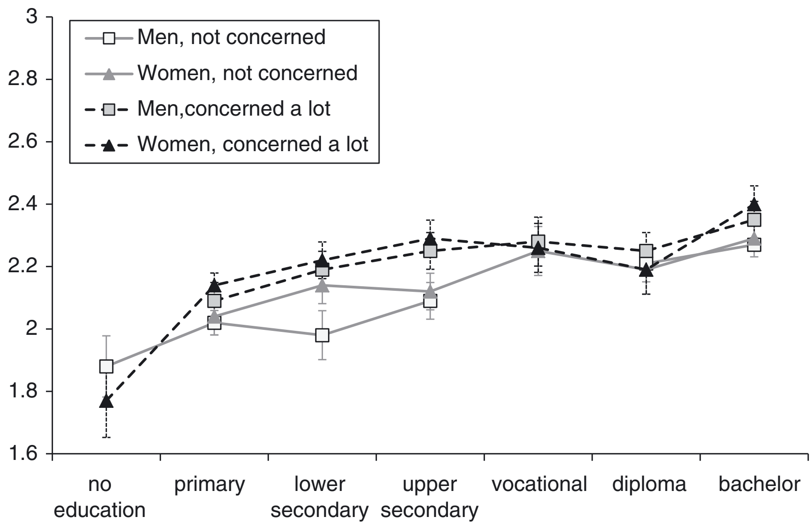
Income had no significant relationship with either group of behaviours. Concern about global warming was positively related with engagement in climate-relevant behaviours, especially technical and behavioural changes. In addition, respondents who were living in the northeast were less likely to report engaging in technical and behavioural changes than those who were living in the central region.

In order to visualise the relationship between education and the uptake of climate-relevant behaviours, we calculated the predicted scores of climate-relevant behaviours for a hypothetical person aged 40–49 who was living in the south, based on the OLS estimates in Table 5. Figures 1 and 2 illustrate the likelihood of adopting electricity and water saving behaviours and of undertaking technical and behavioural changes by gender, education, and level of concern about global warming. Figure 1 shows that the likelihood of adopting electricity and water saving behaviours varies little by gender, education, or level of concern about global warming. On the other hand, Figure 2 shows that the likelihood of adopting technical and behavioural changes varies considerably by education and level of concern about global warming.

5 Discussion

Based on a nationally representative survey of 3900 adults, the Opinions about the Environment and Global Warming 2010 survey, we found that the key demographic

Figure 2:
Predicted score with 95% confidence interval of undertaking technical and behaviour change for a person aged 40–49 years living in the south



characteristics that explain the level of concern about climate change and the likelihood of adopting behaviours that help to reduce GHG emissions are gender and education. The level of concern about global warming and the likelihood of engaging in mitigation behaviours is thus shown to be greater among women than among men. This finding is consistent with those of previous studies in industrialised countries, such as the United States (McCright and Dunlap 2011a) and Australia (Tranter 2011). After empirically testing different hypotheses regarding the gender differences in levels of climate change concern, McCright (2010) found evidence in support of the gender socialisation argument, which claims that the emphasis on nurture, empathy, and care attached to feminine identity translates into a higher degree of concern about the environment and climate change. Despite their active participation in the economy, the public sector, businesses, and professional occupations, women in Thailand have also been socialised to serve and care for family members and the community (Vichit-Vadakan 2008). Thus, gender socialisation may explain our finding that there are gender differences in levels of concern about climate change and climate-relevant behaviours.

We also found that the level of concern about climate change is greater among individuals with higher levels of education, even when we control for other variables, such as income, that are potentially related to education. More highly educated individuals generally have a better understanding of science and more familiarity with a range of issues than those with less education. Since having greater knowledge about climate change has been shown to be positively correlated with concern about climate change (Milfont 2012), it is hardly surprising that we observed a positive relationship between educational attainment and the level of climate change concern. Interestingly, we found no differences by education in the likelihood of taking electricity and water saving actions, but a positive association between education and engaging in actions involving technical and behavioural changes. It is possible that people are more likely to conserve water and electricity because they want to save on the cost of utilities, while they are less likely to make behavioural changes—such as using cloth bags instead of plastic bags, or reducing their use of styrofoam containers—because doing so involves additional effort or decreased comfort. Individuals with higher education, who are generally more concerned about the environment and climate change, may be more willing to perform these actions (Diamantopoulos et al. 2003; Ortega-Egea et al. 2014). Likewise, engaging in technical behaviours such as using energy-saving light bulbs or energy-efficient appliances, requires the individual to have the capacity and desire to accept new information and knowledge (Karytsas and Theodoropoulou 2014; Welsch and Kühling 2010). Our findings therefore suggest that education increases both the level of concern about climate change and the capacity to carry out climate-friendly actions.

The existing literature has found that having a higher income is associated with a greater likelihood of engaging in pro-environmental behaviours, most likely because having a higher income means that an individual's basic material needs have been met, and that he or she can therefore focus on achieving better environmental conditions and a better quality of life (Inglehart 1995). However, we did not find a significant association between income and the level of concern about global warming or pro-environmental behaviours.

The evidence in the literature on the relationship between age and climate change-related attitudes and behaviours is not conclusive (Frederiks et al. 2015). While some previous studies have reported a negative correlation between age and the level of climate change concern (Hamilton 2011; McCright and Dunlap 2011b), and others have found lower levels of concern among the younger and older age groups (Adelekan and Gbadegesin 2005; Agho et al. 2010), we found no significant relationships between these two factors in our Thai sample. Some scholars have argued that the association between the level of environmental concern and demographic characteristics such as age, sex, and race has declined due to the spread of ecological concerns across social groups (Jones and Dunlap 1992). On the other hand, our failure to find an association between age and the level of climate change concern could be attributable to low levels of environmental awareness across age groups in Thailand. Regarding climate-relevant behaviours, it appears that older people are more likely try to conserve electricity and water, but are less likely to engage in technical and behavioural changes. This finding is consistent with the results of a recent study in European countries, which showed that older people are more likely than younger people to be engaged in some form of climate change-motivated activity (Ortega-Egea et al. 2014; Wicker and Becken

2013). In particular, energy saving behaviour is reported to be positively associated with age (Martinsson et al. 2011; Whitmarsh 2009). Energy consumption is closely related to the life-cycle: i.e. older people tend to consume and travel less than young people. Indeed, for certain climate-relevant behaviours, such as conserving heat and hot water, environmental attitudes play a less important role than socio-demographic factors (Martinsson et al. 2011). Similarly, we find that saving electricity and water is weakly associated with the level of concern about climate change, but is strongly correlated with age. In this case, saving money may be the main incentive, as a previous study found that among households with a high share of elderly members, the most frequently cited reason for conserving energy was financial (Mills and Schleich 2012).

Our finding that people who have experienced environmental problems in their community tend to be more concerned about global warming and more likely to adopt climate-relevant behaviours is in line with the results of previous studies that looked at the impact of having experienced a flood (Spence et al. 2011; Whitmarsh 2008). Experience of natural disasters is easily linked to climate change perception since the likelihood of a risk can be readily imagined. Meanwhile, people who have experienced environmental problems are more likely to report that they are worried about climate change, possibly because they conflate the risks associated with climate change with other environmental risks (Read et al. 1994; Reynolds et al. 2010). Even in European countries, where climate change issues are given more media attention than in less developed countries (Schmidt et al. 2013), people often fail to distinguish between environmental and climate change issues (Fischer et al. 2012). While the conflation of climate change with other environmental problems may hinder the adoption of appropriate behavioural changes and mitigation and adaptation actions (Weber and Stern 2011), in the case of Thailand we found that people who had experienced environmental problems were also more likely to engage in technical and behavioural changes. Promoting accurate knowledge about climate change nevertheless remains crucial, since a lack of knowledge is one of the key barriers to behavioural changes.

Other factors, such as hazard exposure and geographical risk, can also influence an individual's risk perception, and thus his or her level of concern about climate change. Indeed, we found that people who were living in the southern region were less likely to express concern about climate change than those who were living in the central region. In particular, the people who were living in the south were less likely to say they are worried about climate change than those were living in the north, the northeast, or the central regions, where droughts and floods are more frequent (Garbero and Muttarak 2013). While we found no substantial regional differences in the likelihood of conserving electricity and water, people who were living in the northeast were significantly less likely than those living in other parts of the country to report that they had adopted technical and behavioural changes. In the northeast, which is the poorest region in Thailand (Jitsuchon and Richter 2007), there may be contextual factors that constrain pro-environmental behaviour; e.g. a lack of access to a market supply of goods. The northeast also has the lowest average level of education in the country, which may hinder the diffusion of knowledge and the acquisition of the skills needed to adopt technical and behaviour changes.

In addition, our analysis clearly shows that engaging in electricity and water saving actions and carrying out technical and behavioural changes are different types of behaviours. The vast majority of the respondents reported that they regularly made efforts to conserve electricity and water. While this behaviour was found to be weakly correlated with concern about global warming, it appears to be mainly motivated by a desire to save money (Whitmarsh 2009). On the other hand, the actions needed to make technical and behavioural changes involve sacrificing comfort and acquiring new appliances. Accordingly, we find that the level of education matters much more for this type of behaviour than for electricity and water conservation actions. While most people pay attention to electricity and water consumption because doing so translates into cheaper electricity and water bills, technical and behavioural change may require certain levels of knowledge and awareness about climate change, and the ability to afford new equipment – attributes that highly educated individuals are more likely to have.

Note that the present study has three main limitations. First, because we were using secondary survey data (i.e. the Opinions about the Environment and Global Warming (OEGW) 2010 data), we relied on how the questions were framed in the survey. In cases in which the respondents had not carried out a particular climate-relevant action, they were given the option of indicating in the same response category either that they had (1) not performed the particular action, or that (2) the question did not apply to them. This could lead to an underestimation of climate-relevant behaviours, since the respondents might have reported that they had not performed a particular action, such as setting an air conditioner to 25°C, simply because they did not own an air conditioner. To avoid underestimation, we excluded from the statistical analysis these kinds of potentially problematic actions; i.e. setting an air conditioner to 25°C and using public transportation.

Second, this study relies on self-reported climate-relevant actions. The respondents may have overstated their levels of concern about climate change and of engagement in mitigation actions due to social desirability biases. If certain demographic groups have a greater tendency to give socially desirable responses instead of choosing responses that represent their true feelings or beliefs, the levels of climate change concern and engagement in mitigation actions estimated will be biased upwards for such groups. It is possible that individuals with higher levels of education tend to over-report their levels of concern about climate change and of engagement in mitigation actions, as has been shown to occur in surveys of voter turnout (Karp and Brockington 2005) or of reading to children (Hofferth 1999). Nevertheless, as our data include non-student samples and the climate-relevant behaviours measured were performed in the past or the present (instead of reflecting future intentions), our measures of climate concern and mitigation actions are unlikely to be affected by social desirability biases (Frick et al. 2004).

Third, our findings may be influenced by the wording of the questions in the survey. Studies in the United States on the extent to which people are concerned about climate change have shown that responses varied depending on whether the term ‘global warming’ or ‘climate change’ was used (Jang and Hart 2015; Schuldt et al. 2011, 2015). For example, Republican respondents were more likely to have expressed scepticism that global climate change is a real phenomenon when the term ‘global warming’ rather than ‘climate change’ was used. However, a survey of 31 countries in Europe revealed that European respondents perceived ‘global warming’ and ‘climate changed’ to be equally serious problems (Villar and Krosnick 2010). To our knowledge, there is no such comparative survey for Thailand. It is possible that our finding that 53% of respondents claim to worry a great deal about global warming is underestimated if Thai citizens follow the US pattern of being more sceptical when the term ‘global warming’ is used instead of the term ‘climate change’. However, we cannot test this possibility with the available data.

6 Conclusion

Despite having ratified the Kyoto Protocol in 2002, Thailand continues to experience increasing GHG emissions due to rising energy consumption: in line with the country’s rate of economic growth, energy consumption in Thailand has been rising at a rate of 4–5% per year (APEC 2010). While the power generation, transportation, and manufacturing industrial sectors are major CO_2 emitters, household electricity and energy demand has also been rising due to both population growth and economic expansion. It is estimated that if residential consumers switched to high efficiency lighting devices and electrical appliances, as much as 6.53 million tonnes of CO_2 emissions could be mitigated in 2020 (Chaosuangaroen and Limmeechokchai 2008). To move towards this goal, the government has implemented several plans and measures designed to promote energy conservation and the use of alternative fuels. Over the past few years, public awareness campaigns have been promoting energy saving and waste reduction measures, such as using fewer plastic bags.

Our study has pointed to the importance of considering demographic differentials in perceptions of climate change and in the accompanying behaviours. As different demographic groups (i.e. men and women, older people and younger people, and the highly educated and the less educated) vary in their life-styles, values, and attitudes; they also differ in their levels of concern and willingness to take action to mitigate climate change. Moreover, there are substantial regional differences in climate-related attitudes and behaviours. Consequently, the psychological, technical, and economic barriers to behavioural change specific to each population sub-group should be considered in GHG emission reduction efforts.

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Future differential vulnerability to natural disasters by level of education

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Abstract

The present paper looks at the implications of anticipated changes in population size and composition for the projected number of deaths from natural disasters Building on empirical evidence from cross-country time series of factors associated with natural disaster fatalities since 1970 in 174 countries, the paper first highlights the major role of education in enabling people to cope with weather extremes in the past. Using the five demographic scenarios implied by the Shared Socioeconomic Pathways (SSPs), which include trajectories for the future of educational expansion, this evidence is translated in the second part of the paper into projections of the number of deaths from climate-related extreme natural events for six major world regions. Assuming constant hazard, we demonstrate the importance of including in assessments of future vulnerability not only the projected population size but the full population heterogeneity by age, sex and level of education.

1 Introduction

Following a widespread definition, environmental risk can be described as a function of hazard and vulnerability (Brooks et al. 2005). Hazard is usually a necessary precondition for natural disasters, but it typically also requires a vulnerable population who are exposed to the hazard. While hazard is largely geographically determined, or is a matter of 'where' you are; vulnerability is strongly linked to social factors, or is a matter of 'who' you are. In searching for ways of reducing future risks associated with natural catastrophes, we thus need to look more closely at the determinants of vulnerability. Given that changing climatic conditions are

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expected to lead to both more frequent and more catastrophic extreme weather events, levels of future vulnerability to natural disasters will be closely related to societies' adaptive capacities.

As an important source of premature mortality, vulnerability to natural disasters is of significant demographic interest, even in the absence of climate change. One important characteristic of vulnerability that has been studied extensively is age. Vulnerability to natural disasters affects people at all stages of their life course. While there is some evidence that people at the very beginning and at the very end of their life cycle are more vulnerable because they directly depend on the help of others, other factors tend to dominate differences in the risks faced by non-elderly adults (KC, Lutz, et al. 2014). These factors range from household characteristics associated with economic standing (such as the construction and stability of the house) to the ecological setting of the house, to individual behavioural variables.

Less attention has been paid in risk studies to the important role of another individual characteristic: namely, the level of educational attainment. This gap in the research has recently been filled in part by a series of studies published as a special issue of *Ecology & Society*, which clearly demonstrated the decisive role of education in risk reduction (Butz et al. 2014). But in general, the future adaptive capacities of societies and the differential vulnerabilities of their members continue to be among the least studied aspects of the important question of how dangerous climate change is likely to be for future human well-being.

To study more thoroughly the interactions of socioeconomic developments and societies' levels of resilience to climate change, and also to provide a scenario 'thread' through the different climate research communities (van Vuuren et al. 2012), the global integrated-assessment modelling community has recently joined forces with the impacts, adaptation, and vulnerability community to launch a new scenario development effort (Kriegler et al. 2012), which has resulted in the creation of a set of scenarios known as the Shared Socioeconomic Pathways (SSPs). The SSPs are representative narratives of how the world might develop over the course of the 21st century that follow a widely negotiated and sufficiently broad range of possible alternative trajectories, particularly with regard to future societies' capacities for mitigation and adaptation to climate change (O'Neill et al. 2013). Using these narratives, researchers can integrate their findings and make them comparable across a range of different fields, thereby broadening the scope of our knowledge about the likely implications of climate change.

The original narratives underlying the SSPs have been translated into the language of demographic change by KC and Lutz (2014). By uncovering the 'human core of the SSPs', the authors have provided comprehensive assumptions regarding the future of fertility, mortality, migration, and education for all countries in the world. They emphasised that after age and sex, education is the third most important source of observable population heterogeneity, and thus demanded the default inclusion of education in population projections. In light of its strong influence on the determinants of population development, education is one of the key variables in the SSPs. As good quality data on years of schooling are hard to come by, education in the SSPs is measured by attainment; i.e. by the specified educational level. The six categories of educational attainment are no education, incomplete primary, completed primary, lower secondary, upper secondary, and post-secondary education. The methodological difficulties that had to be overcome in order to produce the most comprehensive dataset on global educational attainment to date are described in full detail in KC, Potančoková et al. (2014).

As has been pointed out by Hunter and O'Neill (2014), the SSPs can be used to project the effects of demographic trends into the future. Some examples of such translation attempts include the use of the SSPs for projecting future GDP per capita (Crespo Cuaresma 2015), assessing the urbanisation impacts from different scenarios (Jiang and O'Neill 2015), estimating the damage and adaptation costs resulting from future sea level rise (Hinkel et al. 2014), and estimating the likelihood of future armed conflict (Hegre et al. 2016).

In this paper, we attempt to provide a similar and innovative translation of the SSPs to address the issue of future vulnerability to extreme natural events for six world regions. We explicitly incorporate information from the SSPs about changes in countries' population sizes and educational structures. With strong support from the results presented in *Ecology & Society* (Muttarak and Lutz 2014), our central hypothesis is that education can play an important role in reducing the negative impacts of climate change on future disaster-related mortality. Building on updated empirical evidence from cross-country time series of factors associated with past natural disaster fatalities since 1970 in 174 countries (Striessnig et al. 2013), we first quantify the central role of education in reducing fatalities due to natural disasters. We also introduce the concept and the narratives of the SSPs, and show what the different development paths would mean for future total population sizes for each world region. In the second part, we translate the model results into projections of numbers of deaths due to climate-related extreme natural events, while making use of the five demographic scenarios as defined by the SSPs. The results are presented in the form of the predicted number of deaths for each major world region,[1] and illustrate the effect education is expected to have on future fatalities through changes in the total size and the educational composition of each population.

2 Data and model specification

Our main source of data for studying the differential impact of natural catastrophes in different parts of the world is the Emergency Events Data Base (EM-DAT 2010) maintained by the Centre for the Research of the Epidemiology of Disasters. The EM-DAT provides information on different disaster outcome measures such as total financial damage and number of deaths, as well as an approximate estimate of the number of people affected by a wide range of different types of natural disasters

[1] For a complete list of all countries by region, see Table A.1 in the appendix.

since 1900. Of these three measures, we decided to use the number of deaths per million of population as our dependent variable, as it is more reliable and measurable than the other two.

It is important to note that deaths may be undercounted in the EM-DAT. In a recent comparison with WHO death registration data, Zagheni et al. (in this issue) showed that the EM-DAT figures appear to underrepresent deaths from small disasters that did not qualify as natural catastrophes under the EM-DAT criterion of having caused at least 10 casualties.[2] Yet in assessing the impact of natural disasters it is still preferable to use the number of deaths rather than financial damage figures. Because financial damage estimates are mainly driven by a country's wealth, they tend to overstate damage in rich nations, while making it difficult to determine the number of people affected. Moreover, because they are often made in the turbulent aftermath of natural disasters, estimates of financial damage tend to be vague and unreliable.

It is also important to point out that before the advent of modern communication technologies and mass media, the likelihood that disasters would be detected varied across the globe. We therefore restrict ourselves to the period 1970–2010, and aggregate our data by 10-year intervals to limit the influence of extreme outlier years and events. Since we are primarily interested in those events that can be expected to increase as a function of climate change, we further limit our analysis to six different types of hydro-meteorological disasters.[3]

On the explanatory side of the equation, we account for the disaster hazard by controlling for the number of disasters a country experienced within a given decade, again using data from the EM-DAT. Exposure is controlled for first by assessing the number of deaths on a per million population basis. In addition, we include the land mass of a country that is actually inhabited. The proxy used here is arable land as reported by the World Bank's development indicators (2012). Since our main hypothesis is that people are affected differently depending on a country's average level of educational attainment, we also control for the share of women aged 20–39 with at least secondary education. Previous research that considered not just the total population, but the distribution of the population by age, sex, and level of educational attainment, has shown that this variable is highly relevant in studying topics as diverse as economic growth or the transition to a free democracy (Lutz et al. 2008; Lutz et al. 2010). According to these earlier findings, the share of women aged 20–39 with at least secondary education is the indicator that best reflects

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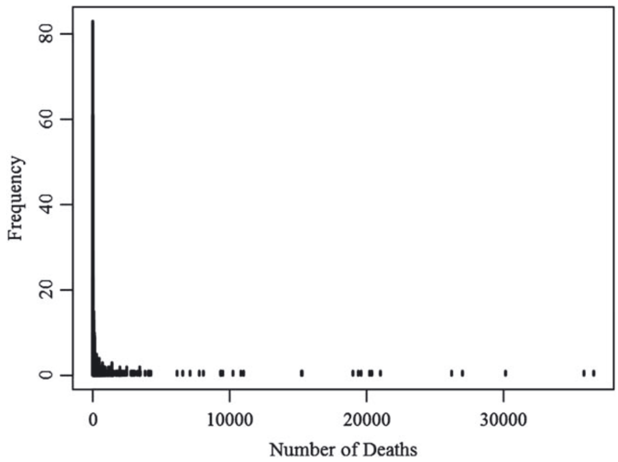
2 The three remaining criteria used by the EM-DAT include (1) 100 or more people affected, (2) a declaration of a state of emergency, and (3) a call for international rescue help. If any one of these four criteria is met, an event is counted as a disaster in the EM-DAT database. As not all disasters meet these criteria, we can assume that the number of disasters is underestimated.

3 These are droughts, floods, storms, extreme temperature events, wildfires, and landslides. Note that our results are not sensitive to the exclusion of deaths from geophysical events and other less catastrophic types of disasters.

Figure 1:
Frequency distribution of number of deaths due to natural disasters, 1970 to 2010



Source: EM-DAT.

inequality, and that has the greatest discriminatory power. Because women aged 20–39 play central roles in family matters ranging from childbearing to family health to changes in the labour force participation of household members, they seem to be of particular importance for social as well as economic development. The data are obtained from the latest reconstruction of population by age, sex, and educational attainment by the Wittgenstein Centre for Demography and Global Human Capital in Vienna (Lutz et al. 2014). Additional controls include population growth rates and infant mortality rates from the United Nation's *World Population Prospects* (2013), as well as time-fixed effects and 26 world regions comprised of countries from the same geographical region with the same most frequent disaster type among the six disaster types included.

2.1 Estimation method

Figure 1 presents the distribution of the number of deaths due to natural disasters observed in the EM-DAT over the period 1970–2010, which is our outcome of interest. As can be seen in Figure 1, there are many country-year combinations in our sample that report zero casualties from natural catastrophes.[4] At the same time, the variable we are trying to explain appears to be severely over-dispersed. In 83 out of

[4] In these cases, an event was counted as a disaster in the EM-DAT database because one of the other three criteria—other than the criterion of having caused at least 10 deaths—is applied.

554 observations, the proportion of zeroes is rather high compared to the distribution of the positive count outcomes; and while the majority of all disasters caused fewer than 1000 casualties, seven disasters in the observational period were responsible for more than 40,000 deaths each. To avoid distortions in our predictions due to the extreme magnitudes of these outliers, we exclude them from our analysis.[5]

This distribution of the number of deaths due to natural disasters suggests that the application of a zero-inflated negative binominal or a hurdle model would be appropriate, as both models can deal with the presence of excess zeroes and over-dispersion (Atkins et al. 2013). The difference between the two models lies in the assumptions made about the origin of zeroes. In the hurdle model all zeroes are assumed to originate from the same process (sampling zeroes), whereas the zero-inflated models are built on the assumption that there are two kinds of zeroes: sampling zeroes and structural zeroes (Frome et al. 2012). Since there is no reason to assume that there are structural zeroes in our dependent variable—i.e. there is no reason to believe that in any country a natural disaster would not be able to cause any death per se—we apply a hurdle model. We estimate the model using the *pscl*-package in R (Zeileis et al. 2007). Hurdle models are two-part models in which a model that explicitly models zero- vs. non-zero outcomes is combined with a model that only handles non-zero outcomes (Atkins et al. 2013). In our analysis, outcomes of non-zero disaster deaths are modelled as a negative binomial regression with a log link function (count model), whereas observations with zero deaths are dealt with in a binomial regression with a logit link function (zero model). This combination can be described more formally as

$$f_{\text{hurdle}}(y; x, z, \beta, \gamma) = \begin{cases} f_{\text{zero}}(0; z, \gamma) & \text{if } y = 0 \\ (1 - f_{\text{zero}}(0; z, \gamma)) * \dfrac{f_{\text{count}}(y; x, \beta)}{1 - f_{\text{count}}(0; x, \beta)} & \text{if } y > 0 \end{cases}$$

where the model parameters β and γ are estimated by maximum-likelihood (Zeileis et al. 2007).

2.2 Results from hurdle negative binomial regression models

Earlier results by Striessnig et al. (2013) suggested that education, especially for women, plays a significant role in reducing disaster fatalities after controlling for other key determinants of socioeconomic development and exposure to risk. These results are confirmed when using a larger number of countries and the refined estimation strategy just described (Table 1). Our approach generates separate estimation results for observations in which a natural disaster led to at least one death (count model, prob (Y > 0)) or to no deaths (zero model, prob (Y = 0)).

[5] The excluded disasters were in Bangladesh (1970), Ethiopia (1978 and 1984), Mozambique and Sudan (1985), Bangladesh (1991), and Myanmar (2008).

Table 1:
Determinants of national deaths from natural disasters per million of population. Hurdle regression for 174 countries over 10-year intervals between 1970 and 2010

Variables	**Prob(Y > 0)**	**Prob(Y = 0)**
Constant	−3.073***	11.735
	(0.72)	(8115.58)
Log (#Disasters)	0.796***	4.027***
	(0.13)	(0.52)
Log (Arable Land in km^2)	−1.083***	
	(0.14)	
Logged IMR	0.331**	
	(0.14)	
Logit (Share Fem 20–39 Sec + Edu)	−0.451***	−0.889**
	(0.16)	(0.37)
Pop Growth Rate	0.700***	
	(0.09)	
Log (Theta)	−0.554***	
	(0.07)	
Dummies for 26 World Regions	YES	YES
Dummies for Decadal Periods	YES	YES
Log-likelihood	−3157	
AIC	6449	
BIC	6743	
N	554	

Note: Theta is the dispersion parameter. For a comparison of the model fit with two alternative model specifications using GDP per capita instead of education, see Table A.1 of the appendix. Significance codes: 0.01 = ***; 0.05 = **; 0.1 = *.

We first ran the model using all of the explanatory variables in both models, and then ran it again while excluding the variables that were insignificant in the first run. As shown in Tables A.2 and A.3 in the appendix, including the insignificant variables has only minor effects on our results.

In the part of the model that explains the occurrence of ‘zero’ casualties, apart from the obviously important logged number of disasters, only the education variable turns out to have a significant effect pointing in the expected direction: whereas a greater number of disasters increases the likelihood that a country will experience one or more deaths, having a higher share of the population with secondary education decreases the probability that an event will clear the hurdle and have a positive casualty count. In the count part of the model we found that in addition to the variables already included in the zero model, a country's arable land mass, population growth rate, and lagged infant mortality rate are significant predictors of disaster impact. In line with the definition of risk given above, our results show that countries with vast, thinly populated areas used primarily for agricultural purposes experience lower deaths per million of population. Conversely, population pressure, as measured by the population growth rate, tends to put pressure on infrastructures that may not be capable of dealing with intensified environmental conditions. In addition, as rapid population growth often does not allow for adequate planning of settlement projects, countries with fast-growing populations may have large numbers of highly vulnerable informal settlements. Not surprisingly, the infant mortality rate, which can be seen as a proxy for the capacities of a country's health care system, can reveal weaknesses in national coping strategies. As has been shown by Pamuk et al. (2011), there is a strong case that investments in education can help countries reduce their infant mortality rates.

2.3 The SSP scenario framework

The SSPs were designed to include both a qualitative narrative and a quantitative component that numerically describes the development of certain socioeconomic drivers of climate change (Arnell et al. 2011). The 'human core' of the SSPs consists of detailed population projections by age, sex, and level of education produced by the Wittgenstein Centre for Demography and Global Human Capital in Vienna (Lutz et al. 2014). The decision to include the education variable is based on the recognition that education plays an important role in both mitigation of and adaptation to future climate change (Lutz and Striessnig 2015). While the five different SSPs cannot depict all possible futures, they nevertheless span a broad range of scenarios that illustrate the main challenges associated with mitigation and adaptation, as described in detail by O'Neill et al. (2013).

In what is probably the most optimistic scenario, SSP1, the challenges in terms of both mitigation and adaptation are assumed to be small, and the world makes very substantial progress towards sustainability. This advancement is achieved by a high rate of technological progress and subsequent co-operation between the development leaders and followers. As a consequence, income levels rise steadily, poverty is further alleviated, and global inequality is reduced. On the demographic side, SSP1 corresponds to a rapid demographic transition driven by a rapid expansion of educational systems. Low levels of fertility in today's high-fertility countries eventually lead to a comparatively low overall population levels.

SSP2 is referred to as the 'middle of the road' scenario because it assumes that the challenges associated with mitigation and adaptation to climate change will be at an intermediate level of severity. In this scenario, we experience the continuation of current trends with regard to development, democratisation, and shifts in the global energy mix towards more sustainable sources. Educational expansion occurs, but not as rapidly as in SSP1. In line with medium assumptions for both fertility and mortality, population growth does not decelerate to the same extent as in SSP1.

SSP3 describes a world of extreme fragmentation and polarisation. While some highly industrialised countries pull ahead, large fractions of the world population, particularly in the global south, are left behind, leading to staggeringly high levels of inequality across countries. The consequence of this trend is a stalled transition towards the establishment of knowledge-based societies. As education does not expand nearly as much as in the previous two scenarios, levels of fertility are high and population growth is unevenly distributed. Moreover, since international co-operation is reduced to a minimum, migration between the newly developing regional blocks of countries does not play a strong role in this scenario's population dynamics. Not surprisingly, the challenges associated with both mitigation and adaptation appear to be insurmountable in this scenario.

SSP4 is different from SSP3 mainly because in this scenario the challenges associated with mitigation are lower. Yet in SSP4, the adaptive capacities of societies are rather limited because of high levels of both within- and between-country inequality. On the one hand, large proportions of people do not make substantial contributions to global climate change, as they are simply not rich enough to adopt consumerist Western lifestyles. On the other hand, climate change becomes a particularly acute threat for the very large numbers of disadvantaged people who find it difficult to adapt. Demographically, this scenario corresponds to a high degree of inequality in the distribution of education. Fertility in the medium-income developing countries is lower under SSP4 than under SSP3, while fertility in high-income countries is low under both SSP3 and SSP4. The recent increase in fertility in many rich low-fertility OECD countries (Myrskylä et al. 2009) is halted because the social transformations that facilitate this trend do not reach far enough.

Finally, SSP5 corresponds to conventional development: i.e. the idea that 'more of the same', or unrestricted economic growth, is going to solve all economic and social problems. While the environmental consequences of this emphasis on robust economic growth lead to major mitigation challenges, the adaptation challenges are rather small because of economic growth. Educational levels are assumed to be high throughout the world, but the fertility trends are more complex. While fertility is comparatively high in the countries that are currently rich and have low fertility, combining work and family becomes increasingly difficult everywhere else in the world. The overall effect on the world population is mixed.

Figure 2 shows the specific demographic implications of SSP1 to SSP5 in terms of total population by six major world regions. Although world population growth is driven primarily by developments in Asia and Africa, the SSPs also show very different pathways for the smaller regions. While SSP1 and SSP5 lead to rapid demographic transitions, and thus to lower overall population levels in the three regions at the bottom of the figure, the three more developed regions in the top part of the figure experience a reversal in their current fertility trajectories in these two scenarios. As population continues to increase in the more affluent parts of the world in particular, mitigation challenges for the planet as a whole are especially

Figure 2:
Total population according to the five SSPs, six major world regions, 2010–2100

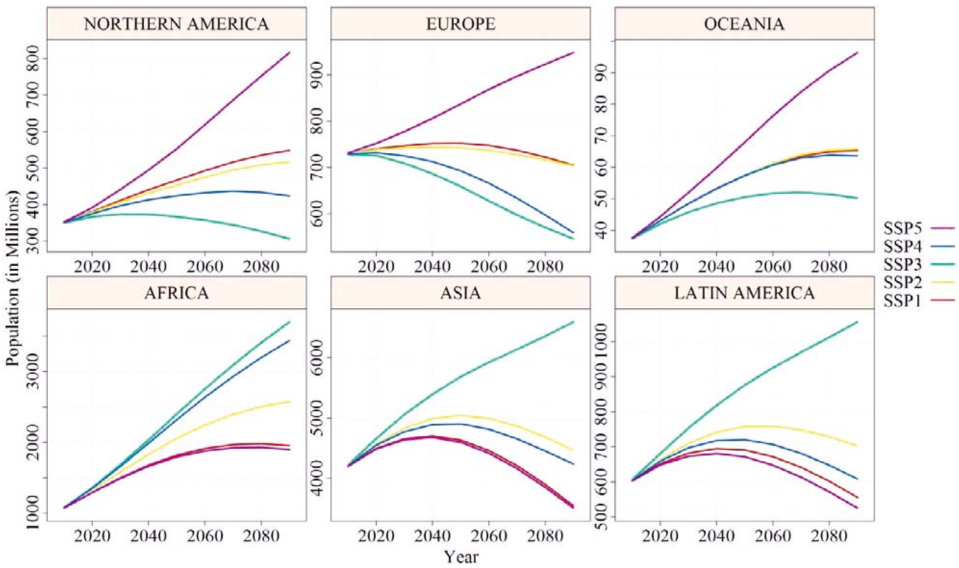
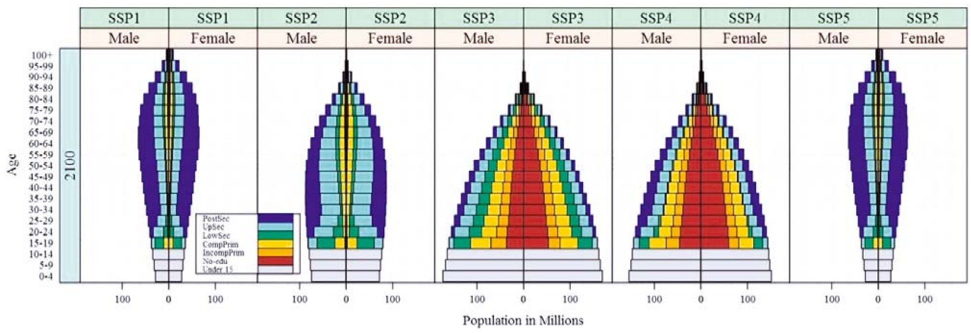


Figure 3:
Population by age, sex, and educational attainment according to the five SSPs, Africa, 2100



large under SSP5. The opposite effect can be observed in SSP3: while populations in the global north continue to age, fertility transitions in the south are stalled, and population reaches its maximum level across all of the five SSPs.

The SSPs differ not only in terms of overall population levels, but also in terms of the population distributions by age, sex, and educational attainment. This diversity of outcomes is illustrated by the case of Africa in 2100 in Figure 3. Interestingly, we can see that both SSP1 and SSP5 lead to very high levels of education and low levels of overall population. Yet the development pathways leading to these results are very different: in SSP1 the pathways are sustainability and low levels of emissions, while in SSP5 the pathways are conventional GDP-focused development and the highest emissions levels.

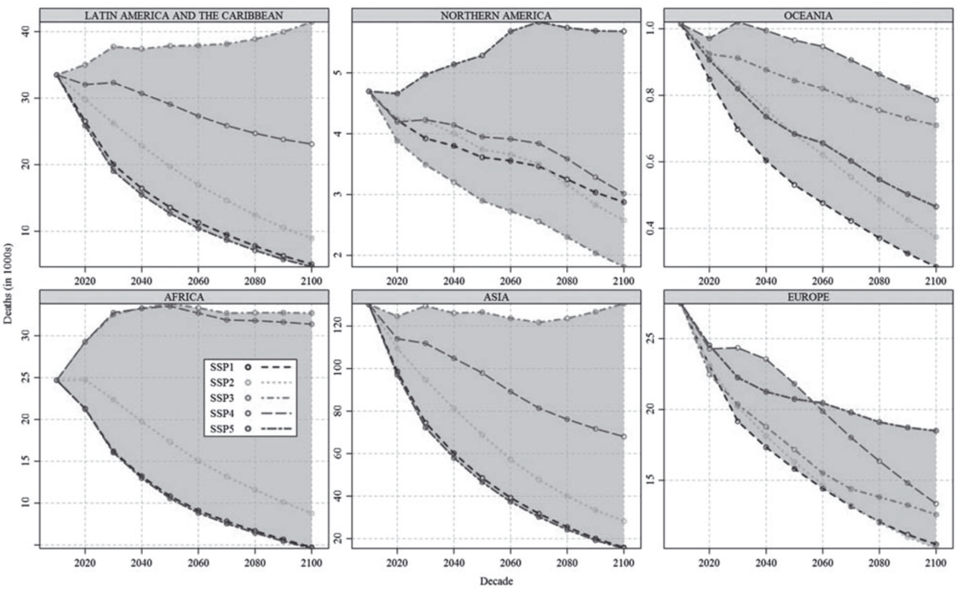
3 Predicted disaster deaths under the SSPs

We show the results for decadal projections of future disaster deaths in six major world regions (a complete list of the countries within each respective region can be found in Table A.1 in the appendix) by applying the regression estimates from Table 1 to the demographic scenarios underlying the SSPs. We assume unchanged hazard levels; i.e. we keep the number of disasters that enter the predictions constant. While these results are of course highly stylised, the primary focus of this exercise is to demonstrate the effects of different futures with regard to education, as well as population heterogeneity on the total number of deaths related to natural disasters. The trajectories presented in Figure 4 are shaped by both reduced vulnerability due to increases in educational attainment and increased vulnerability due to population growth. Since different sub-regions are projected to shift from having positive to having negative population growth in different decades, the regional aggregates of decadal deaths are not simply monotonic, but represent upward and downward trends. In addition, the SSPs do not contain explicit assumptions regarding the future hazard, future land use, or infant mortality. In our baseline calculations, we therefore assume that these indicators will remain at their respective values from the base period of our predictions throughout the entire 21st century. The population growth rate and the share of women aged 20–39 with at least secondary education enter the projections with their respective country- and decade-specific values.

Figure 4 clearly shows that due to their sheer size relative to the other three regions, the bulk of disaster mortality in the 21st century is expected to occur in Asia, Latin America and the Caribbean, and Africa. However, the ultimate trajectory depends on the specific population scenario. While under conditions of fragmentation (SSP3) all three regions experience strong increases in the number of deaths, under conditions of high levels of inequality (SSP4) Africa experiences worse effects than Asia and Latin America, as SSP4 is associated with significantly lower fertility levels than SSP3, and a smaller population is therefore at risk. In addition, inequality in the expansion of education is greater in SSP4 than in SSP3. Because the starting distributions of educational attainment are very different in the three regions, this trend has stronger effects in Asia and Latin America than in Africa. In the remaining scenarios casualty figures go down in all three regions.

However, our interpretation of these findings changes after we relate the projected number of deaths to the actual population in the respective SSP scenario (cf. Figure 2), as we do in Figure 5. We then see that the downward trend in the number

Figure 4:
Predicted number of decadal deaths in 1000s, assuming constant hazard for six world regions, 2010–2100

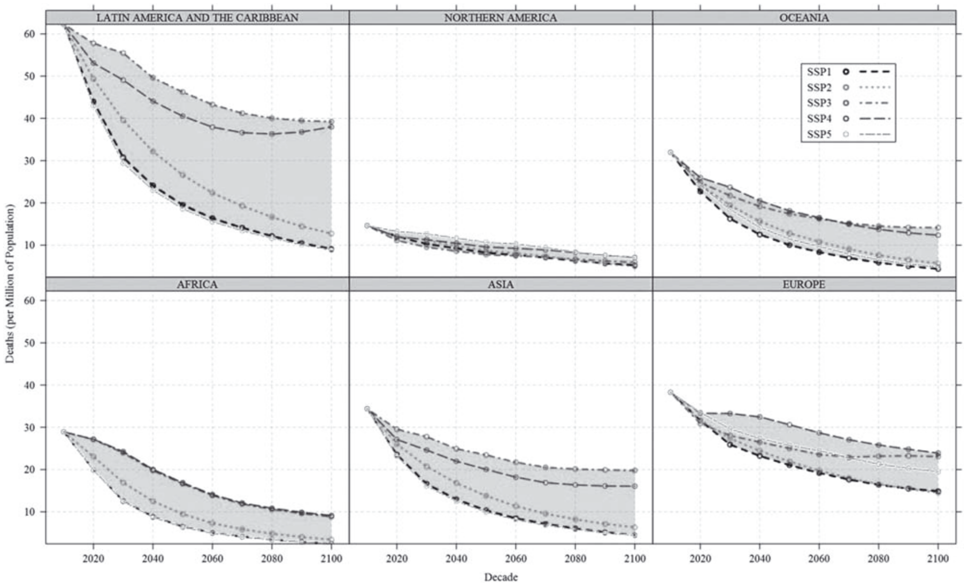


of deaths from extreme natural events experienced in the past will continue in all regions and SSPs, albeit at different levels. Another difference that becomes more pronounced when we look at deaths relative to total population size is that between Europe and North America. This gap is primarily attributable to the excess mortality associated with the 2003 summer heat wave, which according to EM-DAT figures caused roughly 20,000 deaths in Italy, 19,000 deaths in France, 15,000 deaths in Spain, and 9,000 deaths in Germany. In comparison, Hurricane Katrina, the largest individual disaster experienced by the US in the base period of our projections, caused ‘only’ 1,800 deaths. Based on these figures, the projected number of deaths is significantly larger in Europe.

4 Discussion

Our study has shown that different levels of investment in the educational attainment of populations around the world—captured in the individual definition of each SSP scenario—can result in dramatic differences in the predicted number of fatalities due to natural disasters related to climate change. The prediction of a decline in the number of decadal deaths in each of the six regions can be attributed to both higher

Figure 5:
Predicted number of decadal deaths per million of population, assuming constant hazard for six world regions, 2010–2100



levels of education among populations and the accompanying effect of smaller populations at risk. Our analysis has shown these effects for the first time at the level of large world regions. Still, much more context-specific analysis of differential vulnerabilities and the role of demographic factors, including education, is needed in order to arrive at robust country-specific projections and policy recommendations. In general, however, our results support the claim that universal basic education of the entire population, including basic literacy and numeracy, is a key factor in enhancing the adaptive capacity and reducing the vulnerability of populations.

There are many uncertainties when examining the likely implications of the different SSPs on future disaster mortality, even without considering climate change. First, the demographic scenarios underlying the SSPs are not available in a probabilistic format. Thus, we are not able to assign probabilities to specific prediction outcomes. Instead, the SSPs are intended to span a reasonable range of possible futures, and our primary goal here was to translate this range in terms of future numbers of disaster deaths to complement assessments of the future vulnerability of people in different parts of the world.

Another uncertainty is related to the extent to which climate change is going to affect the number of extreme events in those different scenarios. As there is to date no comparable translation of the SSPs into future numbers of natural disasters for different geographic areas, we are forced to make some rather general assumptions about the frequency of all types of hydro-meteorological extreme events. Hence, we are unable—as Kriegler et al. (2012) put it—to 'close the loop', and to study how climate outcomes respond to differences in the SSPs. Certainly, low radiative forcing levels will be harder to achieve at very high population levels (i.e. SSP3 and SSP4), and attempts to mitigate the consequences of climate change, which are more likely to succeed under conditions of sustainable development than under conditions of conventional development, will affect the challenges associated with adaptation.

Another point to keep in mind is the possibility of a spatial redistribution of populations as an adaptation strategy, which is not considered in our model. In addition, due to emergency preparedness plans that have been implemented in response to previous natural disasters (for example, many European cities implemented such plans in reaction to the high number of excess deaths during the 2003 heat wave, and these plans appear to have greatly reduced casualty numbers during subsequent heat waves; see Cadot et al. 2007), it is less likely that similar events will lead to similar numbers of casualties in the future. Studying these extremely important dynamics is left to future analyses.

Since the general assumption behind the results shown is that hazard levels will remain constant at base period levels, the finding that casualty figures are almost universally going down is of course somewhat optimistic. Indeed, most climate scientists would view this as a rather unlikely scenario. Since the assessment of the future frequency of natural disasters around the world depends on a myriad of factors, such as geography and societies' capacities to prevent extreme natural events from turning into disasters, the IPCC is rather careful in quantifying the effect of climate change on the number of extreme natural events. There seems to be a general consensus, however, that almost all types of disasters are becoming more frequent as a consequence of sea level rise and higher global mean temperatures (IPCC 2014). Hence, the projected numbers of deaths are conservative, and are thus probably too low.

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Appendix

Table A.1:
Countries by world region

Asia	Europe	Africa	Latin America and The Caribbean	Oceania	Northern America
Afghanistan	Albania	Algeria	Argentina	Australia	Canada
Armenia	Austria	Angola	Bahamas	Fiji	United States of America
Azerbaijan	Belarus	Benin	Barbados	French Polynesia	
Bangladesh	Belgium	Botswana	Belize	Guam	
Bhutan	Bosnia and Herzegovina	Burkina Faso	Bolivia	Micronesia (Fed. States of)	
Brunei Darussalam	Bulgaria	Burundi	Brazil	New Caledonia	
Cambodia	Croatia	Cameroon	Chile	New Zealand	
China	Czech Republic	Cape Verde	Colombia	Papua New Guinea	
Cyprus	Denmark	Central African Republic	Costa Rica	Samoa	
Dem. People's Republic of Korea	Estonia	Chad	Cuba	Solomon Islands	
Georgia	Finland	Comoros	Dominican Republic	Tonga	
India	France	Congo	Ecuador	Vanuatu	
Indonesia	Germany	Cote d'Ivoire	El Salvador		
Iran (Islamic Republic of)	Greece	Democratic Republic of the Congo	Grenada		
Iraq	Hungary	Djibouti	Guatemala		
Israel	Iceland	Egypt	Guyana		
Japan	Ireland	Eritrea	Haiti		
Jordan	Italy	Ethiopia	Honduras		
Kazakhstan	Latvia	Gabon	Jamaica		
Kuwait	Lithuania	Gambia	Mexico		
Kyrgyzstan	Luxembourg	Ghana	Nicaragua		
Lao People's Democratic Republic	Netherlands	Guinea	Panama		
Lebanon	Norway	Guinea Bissau	Paraguay		
Malaysia	Poland	Kenya	Peru		
Maldives	Portugal	Lesotho	Puerto Rico		
Mongolia	Republic of Moldova	Liberia	Saint Lucia		
Myanmar	Romania	Libyan Arab Jamahiriya	Saint Vincent and the Grenadines		
Nepal	Russian Federation	Madagascar	Suriname		
Oman	Slovakia	Malawi	Trinidad and Tobago		
Pakistan	Slovenia	Mali	Uruguay		
Philippines	Spain	Mauritania	Venezuela (Bolivarian Republic of)		

Continued

Table A.1: Continued

Asia	Europe	Africa	Latin America and The Caribbean	Oceania	Northern America
Republic of Korea	Sweden	Mauritius			
Saudi Arabia	Switzerland	Morocco			
Sri Lanka	TFYR Macedonia	Mozambique			
Syrian Arab Republic	Ukraine	Namibia			
Tajikistan	United Kingdom	Niger			
Thailand		Nigeria			
Timor Teste		Rwanda			
Turkey		Sao Tome and Principe			
Uzbekistan		Senegal			
Viet Nam		Sierra Leone			
Yemen		Somalia			
		South Africa			
		Sudan			
		Swaziland			
		Togo			
		Tunisia			
		Uganda			
		United Republic of Tanzania			
		Zambia			
		Zimbabwe			

Table A.2:
Determinants of national deaths from natural disasters per million of population

	Education		Income		Education and Income	
	Prob(Y > 0)	**Prob(Y = 0)**	**Prob(Y > 0)**	**Prob(Y = 0)**	**Prob(Y > 0)**	**Prob(Y = 0)**
Constant	-2.990^{***}	11.933	-2.744^{***}	13.227	-2.969^{***}	12.085
	(0.720)	(8111.828)	(0.722)	(8101.958)	(0.722)	(8108.840)
Log (Number of Disasters)	0.821^{****}	3.969^{***}	0.892^{***}	3.861^{****}	0.821^{***}	4.021^{***}
	(0.140)	(0.516)	(0.139)	(0.505)	(0.140)	(0.526)
Log (Arable Land in km^2)	-1.079^{***}		-1.144^{***}		-1.075^{***}	
	(0.134)		(0.135)		(0.135)	
Lagged Infant Mortality Rate	0.317^{**}		0.426^{***}		0.344^{**}	
	(0.141)		(0.162)		(0.164)	
Pop Growth Rate	0.735^{***}		0.782^{***}		0.730^{***}	
	(0.093)		(0.093)		(0.094)	
Logit (Share of Women Aged 20–39	-0.404^{**}	-0.881^{**}			-0.414^{**}	-0.946^{**}
with at least Secondary Education)	(0.163)	(0.368)			(0.165)	(0.383)
Log (GDP per Capita)			−0.035	−0.019	0.062	0.229
			(0.194)	(0.344)	(0.195)	(0.365)
Log (Theta)	-0.557^{***}		-0.570^{***}		0.557^{***}	
	(0.075)		(0.076)		(0.075)	
Log-likelihood	−3077		−3083		−3077	
AIC	6290		6301		6293	
BIC	6581		6593		6593	
N	537		537		537	

Note: Using the variable income reduces the number of observations from 554 to 537, since a few countries do not report income data. For comparison reasons we run the model called 'Education' with the reduced number of observations that are also present in the other two models. 'Income' replaces the education variable by GDP per capita, as available from the Penn World Tables. 'Education and Income' controls for both education and income per capita. Note that the 'Education' model is chosen based on log-likelihood and both information criteria, and that the log of GDP per capita is insignificant in both specifications. The independent variables not reported in both the count (Prob($Y > 0$)) and the zero (Prob($Y = 0$)) components of the hurdle models are three decadal dummy variables and 26 dummy variables for world regions. Theta is the dispersion parameter. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

Table A.3:
Determinants of national deaths from natural disasters per million of population

	Policy		Openness		All combined	
	Prob(Y > 0)	Prob(Y = 0)	Prob(Y > 0)	Prob(Y = 0)	Prob(Y > 0)	Prob(Y = 0)
Constant	−3.145***	13.441	−3.193***	12.985	−3.198***	13.046
	(0.709)	(13345.429)	(0.712)	(13526.859)	(0.712)	(13452.230)
Log (#Disasters)	0.729***	4.007***	0.706***	3.988***	0.713***	3.955***
	(0.152)	(0.604)	(0.149)	(0.600)	(0.153)	(0.605)
Log (Arable Land in km^2)	−0.703***		−0.720***		−0.720***	
	(0.123)		(0.125)		(0.126)	
Lagged Infant Mortality Rate	0.497***		0.475***		0.468***	
	(0.173)		(0.175)		(0.178)	
Population Growth Rate	0.764***		0.787***		0.787***	
	(0.095)		(0.101)		(0.101)	
Logit (Share Women 20–39 with at least Secondary Education)	−0.339*	−0.934**	−0.327*	−0.760*	−0.323*	−0.904*
	(0.176)	(0.468)	(0.176)	(0.457)	(0.178)	(0.473)
Log (GDP per Capita)	0.105	0.112	0.092	0.275	0.091	0.241
	(0.204)	(0.458)	(0.205)	(0.470)	(0.205)	(0.472)
Polity Score	−0.018	0.409	−0.021	0.406		
	(0.111)	(0.326)		(0.111)	(0.326)	
Log (Openness)			−0.058	−0.311	−0.059	−0.310
			(0.093)	(0.295)	(0.093)	(0.296)
Log (theta)		−0.500***	−0.499***		−0.499***	
	(0.076)		(0.076)		(0.076)	
Dummies for 26 World Regions	YES	YES	YES	YES	YES	YES
Dummies for Decadal Periods	YES	YES	YES	YES	YES	YES
Log-likelihood	−2890		−2890		−2889	
AIC	5921		5921		5923	
BIC	6213		6213		6224	
N	483		483		483	

Note: Adding the log of openness, available from the Penn World Tables (Heston et al. 2012), as well as a country's polity score, available from the Polity IV Project (Marshall and Jaggers 2005), reduces the number of observations from 554 to 483, since these are not available for all countries and all years. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

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The demography of human development and climate change vulnerability: A projection exercise

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Abstract

We propose a methodological framework aimed at obtaining projections of the Human Development Index (HDI) that can be used to assess the degree of vulnerability of future societies to extreme climatic events. By combining recent developments in the modeling and projection of population by age, sex, and educational attainment, our modeling set-up ensures that the different components of the HDI are projected using a self-contained, consistent modeling effort. We develop scenarios that correspond to the Shared Socioeconomic Pathways (SSPs) developed in the context of the Intergovernmental Panel on Climate Change (IPCC), and thus present a projection framework that can be used to expand the evaluation of the potential mitigation and adaptation challenges associated with climate change in general, and with vulnerability to natural disasters in particular.

1 Introduction

To estimate the degree to which future societies will be vulnerable to climate change, we must assess several dimensions of human development, and construct quantitative scenarios that include potential changes in income, education, and health at the global level over the coming decades. The development of socioeconomic scenarios plays a central role in research dealing with the quantification of climate change impacts, as well as in the design of policy

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responses in the framework of the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report on climate change (see for example Kriegler et al. 2012). Investigating the human dimension of resilience associated with future climate extremes and the corresponding higher risks of (climatic) natural disasters complements the study of the physical dimension of such risks.

In its approaches to dealing with climate change, the international community has been gradually moving away from an almost exclusive focus on mitigation, and toward the recognition of the need to prepare for adapting to changes in the climate that are already unavoidable (see, for example, IPCC 2014). In making this shift, policy-makers and scholars are also increasingly acknowledging that when trying to determine which populations are most vulnerable to climate change, we need to take into account not just where people are, but also who they are in terms of their demographic characteristics and capabilities. A recent international scientific panel on Population and Sustainable Development highlighted this issue in its published action points: “(i) Recognize that the numbers, characteristics, and behaviors of people are at the heart of sustainable development challenges and of their solutions. (ii) Identify subpopulations that contribute most to environmental degradation and those that are most vulnerable to its consequences. In poor countries especially, these subpopulations are readily identifiable according to age, gender, level of education, place of residence, and standard of living.” (Lutz et al. 2014).

This focus on relative vulnerability is rather recent among researchers who deal with natural disasters and adaptation, as their primary focus has traditionally been on location. The importance of demographic factors—and particularly of the changing educational composition of the population—in human survival and well-being as the climate changes has recently been investigated in great detail (see Butz et al. 2014). Education has been shown to be a way for individuals to acquire knowledge, skills, and competencies that can directly or indirectly influence their adaptive capacity; and thus reduce risk. There have been several recent studies on this topic, including an individual-level study of disaster preparedness during the 2012 Indian Ocean earthquakes among households located along the Andaman coast in the Phang Nga province. The study found that formal education—measured at the individual, household, and community levels—increased the likelihood that households had taken preparedness actions (Muttarak and Pothisiri 2013). While having been affected by the 2004 tsunami was clearly associated with increased emergency preparedness, education was also a factor in determining whether households anticipated the risk and took preparedness actions, even among those who lacked disaster experience.

In another study, Frankenberg et al. (2013) used longitudinal survey data collected in two provinces on the island of Sumatra, Indonesia, before and after the 2004 Indian Ocean tsunami to examine the extent to which education confers protection against natural disaster at the individual level. They found that education clearly affected the ability of individuals to cope with the disaster over the longer term, as the better educated individuals were in better psycho-social health five years after the tsunami. These individuals were less likely than others to have been living under precarious conditions, and appear to have been more adept at compensating for the loss of income following the tsunami.

Similar evidence on the association between education and vulnerability has been reported at the community level. Using comprehensive village-level data in Nepal, KC (2013) found strong effects of education on the extent to which villages hit by floods and landslides lost human and animal lives and suffered other forms of household damage. After comparing the effect of education with those of income and wealth, the author concluded that education had a stronger and more consistent effect on the level of damage due to floods and landslides in Nepal. Likewise, Pichler and Striessnig (2013) used data from qualitative interviews conducted in Cuba and the Dominican Republic to compare the disaster vulnerability of these two island states. Even though the two countries are fairly similar in terms of the extent of their exposure to extreme natural events, their disaster outcomes differ greatly. The Cuban population is one of the most educated in the developing world, and their responses to disaster tend to be highly effective. By contrast, the interviews strongly confirmed that the lack of education and of literacy in the Dominican Republic makes the population more vulnerable, as many people have difficulties even understanding warnings about upcoming danger.

Using national-level time series of disaster fatalities around the world, a study by Striessnig et al. (2013) found significant evidence that education plays a role in reducing disaster fatalities. However, they found no evidence confirming the widespread assumption that income per capita is associated with reduced vulnerability after controlling for other key determinants of socioeconomic development, as well as for exposure to risk. They also studied disaster deaths using the Human Development Index (HDI) and its three constituent components. While the aggregate HDI was shown to be strongly correlated with the disaster vulnerability of each country, education was found to be the most significant of the individual components. The results presented in Patt et al. (2010) reinforce the view that the information contained in the HDI is well suited to serve as a disaster vulnerability indicator. In their work, Patt et al. (2010) found that countries that have a relatively high ranking on the HDI, and have thus made improvements in human development that have been captured in the HDI, tend to be less vulnerable to climatic risks. Life expectancy (as a proxy for health) and educational attainment levels have often been proposed as important determinants of vulnerability and adaptive capacity (see Brooks et al. 2005). Income, as a determinant of social vulnerability, has been found to ameliorate the impacts of extreme climate events (see, for instance, Adger 1999). The existing studies that have addressed the importance of the three components of the HDI as predictors of vulnerability have tended to emphasize the need to approach this issue in a comprehensive manner.

The insights provided by such robust results imply that examining the dynamics of income, education attainment, and life expectancy can provide us with very valuable information about the extent to which specific populations are vulnerable to future natural disasters. In particular, linking the projections of the HDI to the climate change scenarios used for the assessment of climatic disaster risks should generate a powerful source of information for policy-makers. In this contribution, we combine a set of recent methodologies that are capable of doing precisely that. The framework utilizes recent developments in population and income projection methods (see KC and Lutz 2015 and Crespo Cuaresma 2015, respectively) in order to obtain projected paths for the *Life Expectancy Index*, the *Education Index* and the *Income Index* that compose the HDI; and, thus, for the HDI itself.

The studies reviewed above have explicitly investigated differential vulnerability to recently observed natural disasters, which is not the same as vulnerability to future climate change. However, there are reasons to assume that disaster vulnerability is generally isomorphic to the vulnerability that will result from certain aspects of future climate change, and particularly from the projected higher incidence of extreme events (see IPCC, 2013). It therefore seems highly relevant to project the HDI and its three components into the future using a range of scenarios. Such a projection can provide us with a quantitative handle for assessing future differential vulnerability to climate change. Following KC and Lutz (2015), we use methods of multi-dimensional population dynamics to obtain projections of human capital for all countries of the world. We measure human capital by examining the characteristics of the population, including age, sex, and educational attainment. The importance of human capital as a fundamental driver of changes in income per capita has been stressed in the theoretical and the empirical economic growth literature. Starting with the effects of education on labor productivity, which is a robust empirical stylized fact at the microeconomic level, several recent contributions have recognized the role played by the stock of human capital (in addition to the rate of accumulation) as a catalyst of technological innovation and of foreign technology adoption (see Nelson and Phelps 1966 and Benhabib and Spiegel 1994). The availability of new global data on populations by age, sex, and educational attainment (see Lutz et al. 2007) has enabled researchers to investigate the effect on economic growth of the distribution of education across age groups. The results in Lutz et al. (2008) and Crespo Cuaresma and Mishra (2011) show that differences in the growth of income across countries and over time can be better predicted if the age dimension of human capital is incorporated into the modeling framework.

In the spirit of such modeling strategies, we complement the life expectancy and educational attainment projections that constitute the input to the *Life Expectancy Index* and the *Education Index* with income projections obtained using econometric models for per capita income growth in the spirit of Crespo Cuaresma (2015). Such econometric specifications account for the dual role of improvements in human capital as a determinant of labor productivity and of the ability of countries to make new technological advancements and to adopt foreign technologies. Projections of income per capita can be obtained by combining specifications that are estimated using a panel dataset of historical data with calibrations of the underlying parameters. This approach allows us to place the underlying storylines corresponding to the different scenarios in the context of global convergence trends and overall total factor productivity growth. This modeling set-up ensures that the different components of the HDI are projected using an internally consistent modeling structure. Our method further ensures that the components are comparable with the storylines that frame the scenarios put forward by Kriegler et al. (2012), and that are used as Shared Socioeconomic Pathways in the IPCC's 5th Assessment Report. Thus, we are able to tie the discussion on the human dimension of vulnerability to catastrophic risks to standardized climate change scenarios.

The set of HDI projections presented in the paper represents a unique, self-contained, and coherent modeling exercise, which combines a set of specifications that deliver internally consistent predictions of the different components of the index. The modeling framework builds upon a series of modern contributions to the literature of demographic projections aimed at informing climate change research (see KC and Lutz 2015).

The paper is structured as follows. The methods used to obtain the HDI projections are presented in Section 2. In Section 3 the characteristics of the HDI projections up to the year 2075 are described, and the different scenarios corresponding to the IPCC's storylines are compared. Section 4 concludes.

2 A methodological framework for human development index projections

2.1 The human development index

Following the changes introduced in the United Nations Development Programme (2013), the HDI has been computed as the geometric mean of three indicators designed to capture the income, health, and education dimensions of human development.[1] The income index is a function of gross national income (GNI) per capita; the health index is based on life expectancy at birth; and the education index is a geometric average of actual and expected educational attainment, as measured by years of schooling. Analytically, the HDI for year t in a given country is thus given by

$$HDI_t = \sqrt[3]{I_{Y,t} I_{LE,t} I_{ED,t}}, \tag{1}$$

where $I_{Y,t}$, $I_{LE,t}$ and $I_{ED,t}$ denote the indices for income, life expectancy, and education, respectively. The index for income is given by

$$I_{Y,t} = \frac{\ln Y_t - \ln Y_{MIN}}{\ln Y_{MAX} - \ln Y_{MIN}}, \tag{2}$$

where Y_t is GNI per capita, while Y_{MAX} and Y_{MIN} are predetermined maximum and minimum historical values for income. The HDI 2010 uses \$108,211 and \$163 (at 2005 PPP-adjusted prices) for Y_{MAX} and Y_{MIN}, respectively.

[1] See Klugman et al. (2011) for a detailed account of the construction of the 2010 version of the HDI, as well as its limitations.

The life expectancy index, $I_{LE,t}$ takes a form similar to that of $I_{Y,t}$, albeit without a logarithmic transformation of the underlying variable,

$$I_{LE,t} = \frac{LE_t - LE_{MIN}}{LE_{MAX} - LE_{MIN}}, \tag{3}$$

where LE, t denotes life expectancy at birth and the maximum and minimum values ($LE_{MAX} - LE_{MIN}$) are set to 83.2 and 20, respectively, following UNDP (2010).

The education dimension of the human development index is in turn constructed as the arithmetic mean of two indicators: mean years of schooling (divided by a measure of maximum years of schooling) and expected years of schooling (divided by a measure of maximum expected years of schooling),

$$I_{ED,t} = \frac{1}{2} I_{MYS,t} + \frac{1}{2} I_{EYS,t} = \frac{1}{2} \frac{MYS_t}{MYS_{MAX}} + \frac{1}{2} \frac{EYS_t}{EYS_{MAX}}. \tag{4}$$

In the expression given by equation (4), MYS_t stands for the mean years of schooling of an individual aged 25 or older, while EYS_t measures the years of schooling a child is expected to attain given current enrolment rates. Based on historical data obtained from UNDP (2010), MYS_{MAX} and EYS_{MAX} are set to 13.2 and 20.6 years, respectively.

The way the HDI combines the indices that measure the progress made on these three dimensions of human development has not been free of criticism. Klugman et al. (2011) presented some of the controversies related to the aggregation of the three components, while Ravallion (2010) and Ravallion (2011) highlighted some problems related to the existing trade-offs between the dimensions that compose the HDI. A potential solution to the deficiencies described by Ravallion (2010), Ravallion (2011) and Chakravarty (2011) is the aggregation of the individual income, life expectancy, and education indices using the generalized HDI in Chakravarty (2003).[2] Since the projection framework presented in our contribution is based on extrapolating the dynamics of each of the components of the HDI individually, different aggregation methods can be used within this framework. While we acknowledge the theoretical controversies surrounding the aggregation methods used in the HDI, we present projections based on the current HDI aggregation methodology in order to ensure comparability with existing studies.

2.2 Projecting life expectancy

A model used to project life expectancy in all countries of the world has recently been applied in the new Wittgenstein Centre scenarios for population and human capital in the 21st century. This model, which has been extensively documented in Lutz et al. (2014), is based on the broad assumption of long-term global convergence.

2 Some of these criticisms are assessed by Klugman et al. (2011).

There are two main concepts of convergence in the literature. The first, beta-convergence, occurs when the growth rate of the variable of interest (normally the growth rate in GDP) depends negatively on its prior value. Controlling for the influence of other factors, this produces conditional convergence, whereby the level of convergence depends on those other factors. The second concept is sigma-convergence, which occurs when the dispersion of the indicator decreases. Using the concept of sigma-convergence in absolute terms, the model produces female life expectancy forecasts for all countries. Exceptions are made for countries affected by HIV-AIDS. Due to the specific dynamics of HIV-AIDS-related mortality, the UN Medium Variant assumptions based on a model by UNAIDS are used for those countries until 2050, after which the models and the rules of convergence are applied (see KC et al. 2014). In general, this convergence approach is based on the claim that "national mortality trends should be viewed in a larger international context rather than being analysed and projected individually" (Lee, 2003). The model also follows the argument made by Torri and Vaupel (2012) that life expectancy in different countries tends to be positively correlated, and that the life expectancies of particular countries can be projected by forecasting the best-practice level, and then the gap between the national performance and the best-practice level.

In the model used for the projections (Garbero and Sanderson 2014), Japan is identified as the current global forerunner in female life expectancy. Under the medium scenario, the life expectancy at birth of a Japanese woman is assumed to grow two years per decade, from 86.1 years in 2005–2010 to 104.2 in 2095–2100. Next, we identify the regional forerunners (22 regions) for which female life expectancy is projected to converge with that of Japan, and is thus expected to grow two years per decade. After the life expectancies for the regional forerunners are projected using the estimates of a dynamic panel data model, a similar specification is applied to the countries within each region that are assumed to follow their regional forerunners. The advantage of this convergence model is that it is based on empirical data. In addition, it takes into account the heterogeneous country-specific historical experiences, as well as the differences in the gains made by forerunners and laggards over time and across regions. Thus, the model takes into account the structural as well as the stochastic components that contribute to life expectancy trends over time, and is therefore able to generate unbiased parameters upon which the new forecasts can be based. These model-based results are then blended with the country-specific expert assessments, as detailed in Garbero and Pamuk (2014).

Once the medium overall life expectancy at birth trajectories for five-year periods for 2010–2100 have been defined for women in 196 countries, the life expectancy trajectories for males can be derived by applying the difference between the female and the overall life expectancy in the UN medium variant (United Nations, 2011). Next, gender-specific education differentials in mortality are introduced as differences in life expectancy at age 15. Based on current empirical data, the life expectancy gap at age 15 between the populations with no education and with tertiary education is assumed to be six years for men and four years for women. This is operationalized by assuming two years' difference between 'completed primary' and 'completed lower secondary', and one year for the remaining levels of attainment. Finally, for children up to age 15 the differential mortality is introduced through the mother's education. Here the differentials in terms of the relative ratio of mortality rates for individuals in the completed upper secondary category are 1.8, 1.7, 1.6, 1.4, 1.0, and 0.8; in ascending order of educational attainment. These values are based on the averages of under-five mortality rates in the countries included in the Demographic and Health Survey (DHS) program.[3]

These procedures result in a full set of age-, sex-, and education-specific mortality trajectories for all of the countries for the medium scenario. The high and low scenarios follow the same logic, with the main difference being that the life expectancy gains experienced by the global forerunner (Japan) are assumed to be three years per decade in the high scenario, and one year per decade in the low scenario. Some more specific assumptions are made for the nearer term in some high mortality countries, as detailed in KC et al. (2014).

2.3 Projecting educational attainment

The education projections used here are identical to those used in the recent contribution by Lutz et al. (2014). Unlike other existing population projection exercises, they explicitly account for the systematic differences in fertility, mortality, and migration by educational attainment level. They start with empirical data on educational attainment distributions for seven educational categories by age and sex for all countries around 2010. This empirical database is described in detail in KC et al. (2014). The medium education scenario is the so-called Global Education Trend (GET) scenario. It is based on a Bayesian model that estimates the most likely future trajectory in education-specific progression rates to higher levels using the cumulative experience of all countries over the past 40 years.

More specifically, the proportional distribution by six levels of educational attainment in the age group 30–34 is first extracted from the Bayesian model as a median trajectory of thousands of iterations (Barakat and Durham, 2014). It represents the final education distribution of a particular cohort, which, apart from changes due to education differentials in mortality and migration, may be expected to remain unchanged over the cohort's remaining life span. In order to calculate the education distribution under age 30, the education-specific proportions in the age group 30–34 are back-casted to ages 15–19, 20–24, and 25–29; such that attainment in the younger age groups follows the country-specific experience in the past. We impose convergence in cases in which attainment progressions in certain education groups are occurring at later ages. For example, we expect that primary education, which typically lasts four years, will be completed by age 15. These sets

3 See http://dhsprogram.com/where-we-work/country-list.cfm.

of education distributions are prepared for each sex separately, and for all periods from 2010 to 2100.

In addition to the medium GET scenario, three alternative scenarios are defined. These scenarios are used to explore the sensitivity of the population projections to our education assumption. The results suggest that altering education can result in differences in the projected population of almost one billion by 2060. The three scenarios are defined as follows:

- Fast Benchmark or Fast Track (FT). In this scenario, the most rapid country-specific expansion parameters are applied to all countries throughout the projection period. In other words, all countries follow the educational development paths taken in the past by the frontrunners in east and southeast Asia.
- Constant Enrolment Rates (CER). For this scenario, the attainment shares at age 30–34 of future cohorts are fixed at the levels observed in the base year (but are adjusted if younger age groups in the base year are already exhibiting attainment levels that are higher than predicted).
- Constant Enrolment Numbers (CEN). This scenario differs from CER, as country-specific attainment by age (under 35) and sex is kept constant at the absolute levels observed in the base year. While CER is a pessimistic low scenario, CEN could be either lower than CER for countries with larger younger cohorts, or higher than CER in countries with smaller younger cohorts. This scenario is of particular interest when considering the consequences of keeping levels of investment in schools and universities constant in the coming decades.

The frequently used indicator of mean years of schooling (MYS) has the advantage of expressing the entire distribution of educational attainment in a single number. It is therefore often used in cross-country comparisons as well as in models (e.g. economic and environmental models) as the unique indicator of educational attainment and human capital stock. The computation of mean years of schooling from a given educational attainment distribution is complex for two main reasons. First, the standard duration of different levels of schooling can vary from country to country; and within countries school levels can vary in length depending on the particular course of study (e.g. general secondary or vocational secondary). Second, the calculation is biased by the share of students who do not complete the full course of any level, which can be substantial in some countries. To address these difficulties, the methodology used here computes mean years of schooling as the weighted mean of six educational levels (and zero for no education). This procedure, as described in KC et al. (2014), takes into account country-specific educational systems, as well as changes in these systems over time. Information on the duration of schooling for each completed ISCED level is taken from the UNESCO Institute for Statistics

(UNESCO UIS) database[4] For the cohorts who attended school prior to 1970, the last year for which UIS provides information, we assume durations identical to those from the last year of observation. For the projected periods, we use the constant durations given for 2010.

For the countries and the cohorts with nearly universal primary education, we find that incomplete primary has a longer duration among the fraction of individuals who dropped out of primary school. This relationship holds for both genders and across broad world regions, with the exception of south Asia. For the regions where the data needed for such models were not available—like Europe, North America, Australia, and Oceania, as well as the former Soviet republics in central Asia—we assume the same relationship as in Latin America. Thus, we assume that the duration of schooling is long for those individuals with an incomplete primary education, since these regions generally have high levels of educational attainment. In these regions the fraction of individuals in the incomplete primary education category is negligible overall, even among older cohorts.

2.4 Projecting income per capita

The modeling context by Crespo Cuaresma (2015) provides an internally consistent framework to obtain GDP projections using human capital trajectory scenarios. Starting with an aggregate production function with heterogeneous labor input defined by age and educational attainment groups, Crespo Cuaresma (2015) proposes the integration of population projections (by age and educational attainment) to obtain projected income paths that can be used for the assessment of climate change impacts.

In addition to taking into account the labor productivity effects of education, in the spirit of Benhabib and Spiegel (1994) the aggregate production includes the impact of educational improvements on technological progress, in the form of both innovation and technology adoption. These effects are specified by including the interaction of income per capita and educational attainment (by age groups) as determinants of GDP growth. This specification is then estimated to obtain elasticities for the projection exercise. The starting point of the income projection exercise is thus given by the aggregate production function

$$Y_{it} = A_{it} K_{it}^{\alpha} \prod_{j=0}^{3} \prod_{k=1}^{2} L_{i,jkt}^{\beta_{jk}} \tag{5}$$

where Y_{it} is total GDP in country i at time t, A_{it} is total factor productivity (TFP), K_{it} is the capital stock, and $L_{i,jkt}$ corresponds to the labor input in age group k ($k = 1, 2$ denoting the younger and older age group) with educational attainment j

4 See http://www.uis.unesco.org/datacentre/.

(from $j = 0$ – no education – to $j = 3$ – some tertiary education level attained). In logs and taking first differences, such a production function can be written as

$$\Delta \log Y_{it} = \Delta \log A_{it} + \alpha \Delta \log K_{it} + \sum_{j=0}^{3} \sum_{k=1}^{2} \beta_{jk} \Delta \log L_{i,jkt}. \qquad (6)$$

Assuming that the growth rate of TFP is affected by the stock of human capital, both directly and through its interaction with income per capita, results in the following specification

$$\Delta \log Y_{it} = \alpha \Delta \log K_{it} + \sum_{j=0}^{3} \sum_{k=1}^{2} \beta_{jk} \Delta \log L_{i,jkt} + \delta \log \frac{Y_{it}}{L_{it}} + \\ + \sum_{j=1}^{3} \theta_j \sum_{k=1}^{2} \frac{L_{i,jkt}}{L_{it}} + \sum_{j=1}^{3} \phi_j \log \frac{Y_{it}}{L_{it}} \sum_{k=1}^{2} \frac{L_{i,jkt}}{L_{it}}. \qquad (7)$$

This is the model that is actually used to estimate the parameters for the projection model based on a global dataset for the period 1970–2005 (at five-year non-overlapping intervals) (see Crespo Cuaresma (2015)). The panel structure of the dataset allows for the estimation of fixed effects models, and thus accounts for unobservable differences in income growth across countries that have remained constant in the sample period; as well as for common GDP growth shocks that affect all countries. Using projections of population by age and education, together with assumptions about the accumulation path of physical capital, global income convergence patterns, and technology growth; paths of income per capita that are consistent with the narratives used in the assessment of the impacts of climate change are obtained for 154 countries.

3 HDI projections: Shared socioeconomic pathways and climate change vulnerability

The Intergovernmental Panel on Climate Change (IPCC) has recently finalized its Fifth Assessment Report (AR5). In this context, members of the global community who model the Integrated Assessment (IA) and Vulnerability, Risk, and Adaptation (VRA) have agreed to refer to a new common set of Shared Socioeconomic Pathways (SSPs) that describe a range of future scenarios, with a focus on the social and economic mitigation and adaptation challenges. Unlike the previous generation of SRES scenarios (Nakicenovic et al. 2000), which considered total population size and total GDP to be the only relevant socioeconomic factors, and which essentially reduced population to a scaling factor for the denominator of different variables; this new set of scenarios provides much richer socioeconomic content, including a range of population scenarios by age, sex, and six levels of educational attainment for all countries in the world. The main reason for moving to much more detailed characterizations of the socioeconomic aspects of global change is that the SSPs are no longer primarily designed to describe the factors contributing to CO_2 emissions (the challenges for mitigation), but rather to explore the extent to which societies are vulnerable to or are able to adapt to climate change. Demographic dimensions—such as age, sex, level of education, and urbanization—are considered key factors that should be explicitly included in the scenarios.

The SSPs were designed in a lengthy process involving most of the leading global change modeling teams. The process was guided by the goal of providing a comprehensive description of the socioeconomic challenges that may be expected to arise in conjunction with climate change mitigation and adaptation in the future. In addition to analyzing trends in population, education, and urbanization; the scenarios also covered several dimensions of the economy, particularly energy consumption and the carbon intensity of alternative technologies that might be developed in the future. A summary of the five SSP scenarios is provided in Table 1, and the characteristics of each scenario are presented below.

- SSP1 (Sustainability – Rapid social development): This scenario assumes a future in which the world is moving toward a more sustainable path with a relatively low global population, as educational and health investments accelerate the demographic transition. There are major improvements in human capital, while the fertility rate in the OECD countries is moderately high.
- SSP2 (Continuation – Medium Social Development): This is the middle-of-the-road scenario in which trends typical of recent decades continue, with slow progress being made toward achieving development goals, reducing resource and energy intensity, and decreasing fossil fuel dependency. In demographic terms, this scenario is identical to the medium scenario in the new global human capital projections produced by the Wittgenstein Centre for Demography and Global Human Capital (Lutz et al. 2014).
- SSP3 (Fragmentation – Stalled Social Development): In this scenario the world is separated into regions characterized by extreme poverty and pockets of moderate wealth, and large numbers of countries are struggling to maintain living standards for rapidly growing populations. The demographic transition is stalled in countries that still have high fertility, as educational levels in these countries remain low.
- In addition, SSP4 (Inequality) and SSP5 (Conventional Development) describe pathways in which large segments of the population remain vulnerable (high adaptation and low mitigation challenges), and are stuck in a pattern of carbon-intensive conventional economic growth (high mitigation and low adaptation challenges).

Using the methods described in the previous section, we obtain projection paths for each of the indices that compose the HDI, and aggregate them to create projections of the HDI. This is done for 154 countries for which data

Table 1:
Shared socio economic pathways: Assumptions

	Country groupings	Fertility	Mortality	Migration	Education
SSP1	HiFert	Low	Low	Medium	High (FT-GET)
	LoFert	Low	Low	Medium	High (FT-GET)
	Rich-OECD	Medium	Low	Medium	High (FT-GET)
SSP2	HiFert	Medium	Medium	Medium	Medium (GET)
	LoFert	Medium	Medium	Medium	Medium (GET)
	Rich-OECD	Medium	Medium	Medium	Medium (GET)
SSP3	HiFert	High	High	Low	Low (CER)
	LoFert	High	High	Low	Low (CER)
	Rich-OECD	Low	High	Low	Low (CER)
SSP4	HiFert	High	High	Medium	CER-10%/GET
	LoFert	Low	Medium	Medium	CER-10%/GET
	Rich-OECD	Low	Medium	Medium	CER/CER-20%
SSP5	HiFert	Low	Low	High	High (FT-GET)
	LoFert	Low	Low	High	High (FT-GET)
	Rich-OECD	High	Low	High	High (FT-GET)

are available (see the appendix). We accommodate the changes in the maximum value of life expectancy, income, and years of schooling over the projection period by substituting Y_{MAX}, LE_{MAX}, MYS_{MAX} and EYS_{MAX} with the corresponding maximum value across economies, projection years, and scenarios. Breaking with the standard practice for computing the HDI, we define the maximum reference point over the full projection period instead of redefining it by year. Using this approach, we are able to create a set of projections that are comparable across countries and scenarios, although we lose comparability with past values of the HDI. It should be noted, however, that other standardization methods could have been used. As projections of income per capita, years of schooling, and life expectancy are available, new human development indicators that may be relevant for policy could be created.

Figure 1 presents the distribution of the HDI and its components across countries for the five SSP scenarios over the period 2010–2075.[5] In a world in which development is polarized, as projected in SSP3 and SSP4, the HDI values are highly dispersed over the whole projection horizon, for both the aggregate index and the income, life expectancy, and education sub-indices. In SSP1 and SSP5, by contrast, the HDI levels converge at high levels, with a small degree of dispersion occurring at the end of the projection horizon. These patterns of convergence can be observed in

[5] The projected HDI series can be found at http://www.iiasa.ac.at/web/home/research/researchPrograms/WorldPopulation/.

Figure 1:
Boxplots of projected paths of HDI and its components across countries, by SSP

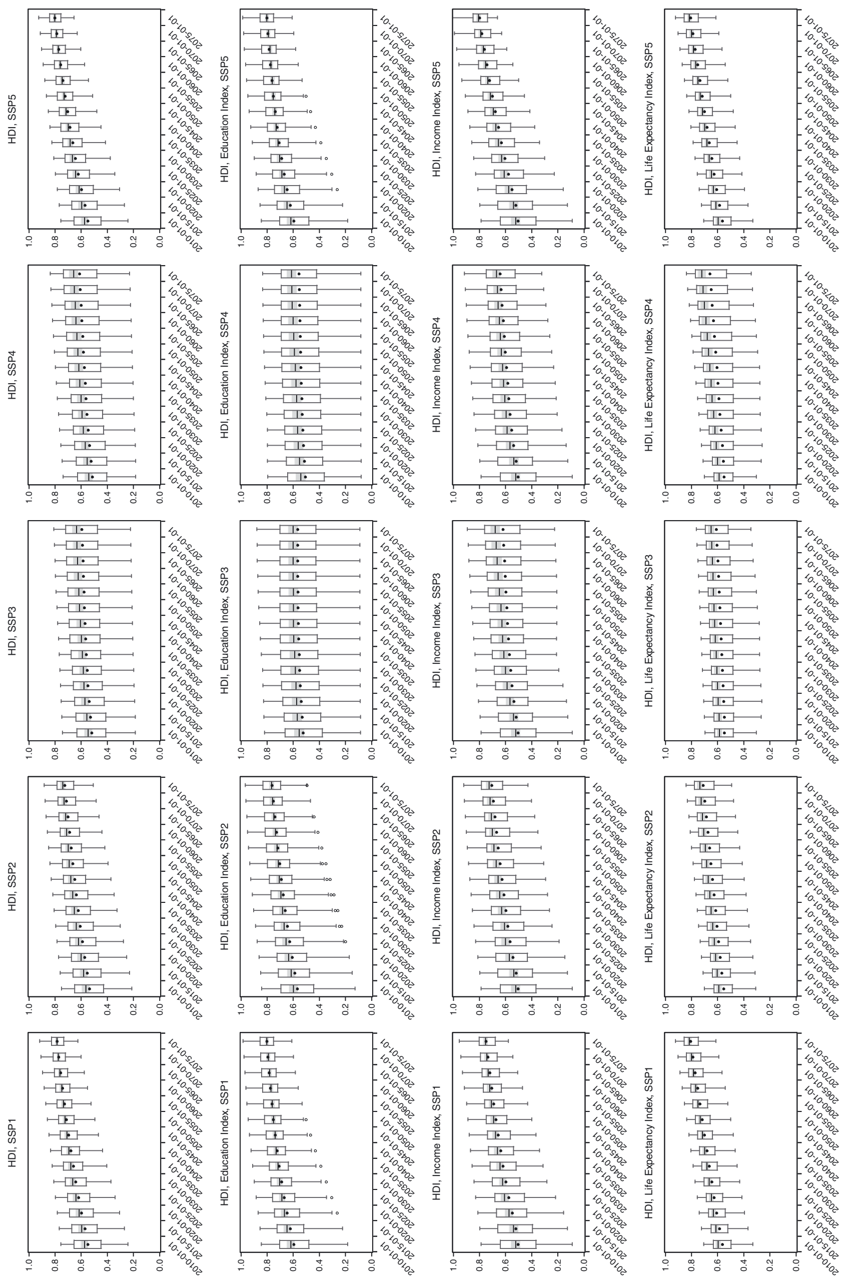
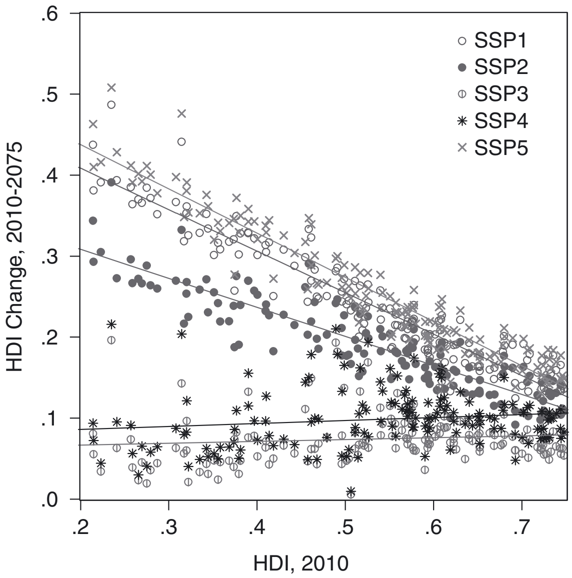


Figure 2:
HDI in 2010 against projected change between 2010 and 2075, by SSP



each of the sub-indices that compose the HDI. As expected, the pattern of cross-country dispersion in the SSP2 scenario can be seen as being between the two patterns described: in SSP2 convergence occurs across economies, but there is a higher level of dispersion in the HDI than there is in SSP1 or SSP5.

The different convergence patterns in HDI projections can be better understood by plotting the HDI level in 2010 against the change in the level by country in the projection period 2010–2075. The scatterplot shown in Figure 2 reveals the different speeds of convergence across SSP scenarios. While in SSP1, SSP2, and SSP5 lower HDI values in 2010 tend to be strongly related to larger increases of the index in the period 2010–2075; in SSP3 and SSP4 no significant relationship is discernible between the initial HDI and the subsequent change over the projection period.

To illustrate the numerical results of these HDI projections exercise, Table 2 shows the trends under the five different scenarios for Ethiopia and Pakistan, two countries that are currently at the crossroads of either experiencing rapid development, or remaining stuck at a stalled level of development associated with low female education and high fertility (and thus high population growth). Both countries are currently classified as having low levels of human development, and rank 173 and 146, respectively, in the 2013 Human Development Report (United Nations Development Programme 2013). Since life expectancy is projected in five-year periods, the values for 2010 refer to the years 2010–2014, and already vary slightly by scenario. In each period of time, we base our measure of expected years of schooling on the mean years of schooling projected in 20 years for the age group 25–29. The differences in educational attainment dynamics across projection

Table 2:
HDI projections by SSP: Ethiopia and Pakistan

Ethiopia					
Year	**SSP1**	**SSP2**	**SSP3**	**SSP4**	**SSP5**
2010	0.33	0.31	0.29	0.28	0.33
2015	0.37	0.34	0.30	0.29	0.37
2020	0.41	0.37	0.32	0.31	0.41
2025	0.44	0.39	0.32	0.31	0.44
2030	0.47	0.41	0.33	0.32	0.47
2035	0.50	0.42	0.33	0.32	0.50
2040	0.52	0.44	0.33	0.33	0.54
2045	0.55	0.46	0.34	0.34	0.57
2050	0.58	0.48	0.34	0.34	0.60
2055	0.60	0.50	0.34	0.35	0.63
2060	0.63	0.52	0.34	0.35	0.65
2065	0.65	0.54	0.35	0.36	0.68
2070	0.67	0.56	0.35	0.36	0.70
2075	0.70	0.58	0.35	0.37	0.73
Pakistan					
Year	**SSP1**	**SSP2**	**SSP3**	**SSP4**	**SSP5**
2010	0.42	0.40	0.37	0.36	0.42
2015	0.45	0.42	0.37	0.37	0.45
2020	0.47	0.44	0.38	0.37	0.48
2025	0.50	0.46	0.38	0.38	0.50
2030	0.53	0.48	0.39	0.38	0.53
2035	0.55	0.50	0.39	0.39	0.56
2040	0.58	0.52	0.39	0.39	0.59
2045	0.61	0.54	0.40	0.40	0.62
2050	0.63	0.56	0.40	0.41	0.64
2055	0.65	0.58	0.41	0.41	0.67
2060	0.67	0.60	0.41	0.42	0.69
2065	0.69	0.62	0.41	0.42	0.71
2070	0.71	0.64	0.42	0.43	0.73
2075	0.73	0.65	0.42	0.43	0.75

scenarios imply that this definition of expected years of schooling creates small differences in our HDI for the year 2010 as well. However, this strategy contributes to the internal consistency and the comparability of the projections across scenarios.

Viewed over time, the trends directly mirror the different narratives of the five SSPs. SSP1 assumes rapid progress over the coming decades. Under this scenario, Ethiopia would quickly catch up, and would even improve more rapidly than Pakistan (which starts from a somewhat higher level) under the same scenario.

These trends can be attributed to the fact that Ethiopia has recently made considerable progress in expanding education (from a very low level) among the younger cohorts, whereas in Pakistan (which is at a somewhat higher level) less progress has been made. Thus, even under isomorphic assumptions, the future trends reflect current levels of momentum. On the other hand, under the stalled development scenario of SSP3 Ethiopia would see only very minor improvements in its development over the next 50 years. Over this period, the country would not even be able to catch up with Pakistan (Ethiopia would have an index of 0.35 in 2075, whereas Pakistan would have an index of 0.37 in 2010 under the same scenario).

The implications of such scenarios in terms of vulnerability to natural disasters related to climate change can be grasped by comparing the projected trajectories with the results presented in Patt et al. (2010). The analysis in Patt et al. (2010) suggests that climatic disaster risk (as measured by the number of persons affected by a climate disaster) is highest in the countries with HDI levels of around 0.5, after controlling for other determinants of vulnerability. The number of affected individuals starts to decline only after countries reach this level of development. Using the elasticities obtained by Patt et al. (2010), we can compute the relative differences in the degree of vulnerability to climate disasters implied by each of our scenarios, keeping other determinants of vulnerability constant. The levels of development implied by SSP1 and SSP5 in 2075 imply that the ratio of individuals killed by climatic disasters to the total population will, on average, be approximately 90% and 118% higher, respectively, than in SSP2. Our projections for SSP3 and SSP4, on the other hand, indicate that the same variable will increase 150% to 175%, respectively, relative to SSP2. As expected, the biggest reductions in vulnerability to climatic disasters will be made through improvements in human development (or, conversely, the largest increases in vulnerability will be associated with increases in cross-country inequality), which tend to be concentrated in the countries of Sub-Saharan Africa. These large differences in levels of vulnerability to natural disasters clearly show that development will play an important role in determining the impact of climate change on human populations.

4 Conclusions

To study the impact of climate change, we need to construct projection models in which the quantitative assessment of different socioeconomic paths at the global level plays a central role. As human development has been systematically found to be a key determinant of vulnerability to natural disasters, the construction of reliable projection models for education, health, and income indicators that span long time horizons is a key component of climate change assessment models.

We propose an internally consistent methodology for obtaining projections of the HDI and its components that can be used to address questions related to the future vulnerability of societies to climate change. The methodological framework rests on the combination of projections of population by age, sex, and educational attainment with a production function approach in which human capital dynamics (that is, the change in the composition of a population by age and educational attainment) is the main driving force of income changes over time.

Using the proposed methodology, we present HDI projections corresponding to the narratives of the five SSPs developed in the IPCC's Fifth Assessment Report. We show that the projection method is able to replicate the main global characteristics of these scenarios, and provides a new and useful quantitative instrument for climate change research. Furthermore, because this approach is self-contained, the methodology put forward in this study is useful for other applications that involve addressing the interactions between population, development, and the environment. Thus, the method complements existing quantitative approaches that assess the risks associated with climate change (see, for instance, Birkmann et al. 2013). Like all of the other global long-term projection methods, our approach is limited by the assumption that information about historical relationships can be used to help us understand the future dynamics of socioeconomic variables. But because structural breaks in these relationships could occur in the future, the particular assumptions underlying the different scenarios presented in this contribution need to be considered when using the projected paths of the HDI and its components.

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Appendix: Countries in the projection exercise

Algeria
Argentina
Armenia
Australia
Austria
Azerbaijan
Bahamas
Bahrain
Bangladesh
Belarus
Belgium
Belize
Benin
Bhutan
Bolivia
Bosnia and Herzegovina
Brazil
Bulgaria
Burkina Faso
Burundi
Cambodia
Cameroon
Canada
Cape Verde
Central African Republic
Chad
Chile
China
Colombia
Comoros
Congo
Costa Rica
Cote d'Ivoire
Croatia
Cuba
Cyprus
Czech Republic
Democratic Republic of the Congo
Denmark
Dominican Republic
Ecuador
Egypt
El Salvador
Equatorial Guinea
Estonia
Ethiopia
Finland
France
Gabon
Gambia
Georgia
Germany
Ghana
Greece
Guatemala
Guinea
Guinea-Bissau
Guyana
Haiti
Honduras
Hong Kong
Hungary
Iceland
India
Indonesia
Iran
Iraq
Ireland
Israel
Italy
Jamaica
Japan
Jordan
Kazakhstan
Kenya
Kuwait
Kyrgyzstan
Lao
Latvia
Lebanon
Lesotho
Liberia
Lithuania
Luxembourg
Madagascar
Malawi
Malaysia
Maldives
Mali
Malta
Mauritius
Mexico
Moldova
Mongolia
Morocco
Mozambique
Namibia
Nepal
Netherlands
New Zealand
Nicaragua
Niger
Nigeria
Norway
Pakistan
Panama
Paraguay
Peru
Philippines
Poland
Portugal
Republic of Korea
Romania
Russian Federation
Rwanda
Saint Lucia
Saint Vincent and the Grenadines
Samoa
Sao Tome and Principe
Saudi Arabia
Senegal
Serbia
Sierra Leone
Singapore
Slovakia
Slovenia
South Africa
Spain
Sudan
Suriname
Swaziland
Sweden
Switzerland
Syria
Tajikistan
Tanzania
TFYR Macedonia
Thailand
Timor-Leste
Tonga
Trinidad and Tobago
Tunisia
Turkey
Turkmenistan
Uganda
Ukraine
United Kingdom
United States of America
Uruguay
Vanuatu
Venezuela
Viet Nam
Zambia
Zimbabwe

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A four-dimensional population module for the analysis of future adaptive capacity in the Phang Nga province of Thailand

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Abstract

In this paper we describe an innovative aspect of the population module in the context of an ongoing comprehensive modelling effort to assess future population-environment interactions through specific case studies. A particular focus of our study is the vulnerability of coastal populations to environmental factors and their future adaptive capacity. Based on the four-dimensional cross-classification of populations by age, sex, level of education, and labour force participation, our approach builds on a recent body of research that has critically assessed the role of demographic differentials as determinants of differential vulnerability and adaptive capacity. We use Phang Nga, a province in the south of Thailand that was severely affected by the tsunami in 2004, to describe current levels of educational attainment and investigate past trends, which in turn serve as input for detailed education projections. These education projections, in combination with projections of economic activity and household survey results about disaster preparedness, feed into further analysis of future adaptive capacity. Given our specifications and assumptions, we find that the educational composition of the province's labour force will shift towards higher levels, and that the population of Phang Nga will be better prepared for future disasters.

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1 Introduction

In this paper we describe one innovative aspect of an ongoing comprehensive modelling effort to assess future population-environment interactions, and in particular the vulnerability of coastal populations to environmental factors and their future adaptive capacity in a number of specific case studies. For our analysis we developed interactive systems models, in which changes in a population module interact with changes in economic and environmental models. This approach follows the research tradition of population-development-environment (PDE) systems studies developed at the International Institute for Applied Systems Analysis (IIASA), such as the studies on Mauritius, Namibia, Botswana, and Mozambique that are summarised in Lutz et al. (2002).

In this paper, we introduce a new PDE analysis for the southern Thai province of Phang Nga (located north of Phuket), which was chosen because it was affected by the 2004 Indian Ocean tsunami, and because it remains highly vulnerable to sea-level rise and storm surge. Applying the new population module, we aim to describe how the future population outlook translates into future adaptive capacity in a disaster-prone area like Phang Nga. The population module has several new features, including a systematic set of four-dimensional (4-D) population scenarios. This set of scenarios assesses population changes in the four-dimensional space, as defined by age, sex, level of education, and labour force participation. By factoring in education and labour force participation, the 4-D model departs from conventional population projections, which makes the development, estimation, and calibration of this population module rather innovative.

This paper also builds on a recent body of research that has critically assessed the role of demographic differentials as determinants of vulnerability and adaptive capacity. These studies have systematically assessed in different specific settings and at the global level the relative importance of age, sex, level of education, and, to a lesser extent, the role of labour force participation. Eleven of these studies were published in a special issue of *Ecology & Society* under the title ‘Education and Differential Vulnerability to Natural Disasters’ (Butz et al. 2014). A comprehensive summary of these papers can be found in Muttarak and Lutz (2014). A specific focus of these studies was the assessment of the effects of educational attainment relative to the effects of other, more frequently investigated determinants of vulnerability, such as income levels and demographic, geographic, cultural, and institutional factors. These studies found consistently that in all contexts and for both men and women educational attainment was at least as important as—and was in many cases much more important than—income in reducing vulnerability to natural disasters, as measured by responses, impacts, and coping ability. In addition, based on these consistent findings, analyses of times series of mortality from natural disasters between 1970 and 2010 across 156 countries by Lutz et al. (2014) further confirmed that the universal expansion of secondary education can reduce excess deaths from extreme climatic events.

The evidence showing that compared to less educated populations, groups with higher levels of education are less adversely affected by natural disasters, and have better responses and coping abilities when disaster hits, raises the question of the causality of the effects of education in reducing disaster vulnerability. Indeed, causality was established beyond any reasonable doubt in the sense of 'functional causality', as discussed by Lutz and Skirbekk (2014). Following a clearly specified set of criteria, this implies that it is safe to assume that there is a continuation of this strong empirical association for the time horizon of the projections. In short, it appears that high educational attainment has direct and indirect effects that tend to reduce people's vulnerability to natural disasters (Muttarak and Lutz 2014). The direct effects of education include having enhanced cognitive skills for processing risks and risk information, better problem-solving skills, better knowledge acquisition and usage, and increased risk awareness. The indirect effects of education include having a higher income that can be used for disaster preparedness, better access to information related to disasters, and a higher level of social capital.

Given that there is already a large body of literature that shows that education plays an important role in reducing disaster vulnerability, the issue of causality will not be further elaborated in this paper. Instead, we will focus on the definition and the calibration of consistent scenarios for the four-dimensional population module in the specific context of Phang Nga province in Thailand. However, this analysis can also be viewed as a prototype of isomorphic population models of systems studies that can be applied in other settings.

A new feature of this population module is the systematic cross-classification of the population stratified by age, sex, and level of education with labour force participation. Why is this important? When it comes to the association between education and economic activity, many factors contribute to the commonly observed picture that higher levels of educational attainment are associated with higher levels of labour force participation. For example, higher levels of human capital generally entail higher returns (Gunderson and Oreopoulos 2010; Patrinos and Psacharopoulos 2010), which increases the opportunity cost of not being economically active. In addition, having a higher education provides workers with access to jobs that are considered more desirable, because, for example, they offer more attractive working conditions. Moreover, there is often a higher demand for workers with a certain degree of education than there is for workers with no or little education (OECD 2011). For the economy itself, the educational attainment structure of the workforce plays a crucial role for labour productivity and economic output (Lutz et al. 2008). Hence, for any study of the impacts of future changes in the population on the structure of the economy or on economic performance in general, the explicit modelling of changes in economic activity by age, sex, and level of education is an important refinement that makes the output of the population module more relevant to other aspects of socio-economic and environmental changes.

Phang Nga was chosen as the case study for the new 4-D population module because it has become globally known as the Thai province that was hardest hit by the tsunami on 26 December 2004, in terms of both the number of lives lost and the negative economic impact.[1] In Phang Nga alone, 5880 people died or went missing, and 5597 people were injured. Of the people who died, one-half were identified as foreigners, one-third were identified as Thai, while the nationalities of the remaining victims were unknown. About 80% of the people who were injured or missing were Thai nationals (Jayasuriya and McCawley 2010). Economically, the tourism and the fishery sectors were the most affected. These experiences were among the reasons why we chose Phang Nga as the site of our in-depth PDE study. A considerable amount of data has been collected on the province's residents and on the specific experiences of the tsunami of all residents who lived there for more than 10 years. The availability of these data allows us to focus on the question of the extent to which the residents have learned from their experiences, and have drawn upon these lessons in preparing for the future.

Our focus in this paper is on a discussion of the elements of the innovative population model in its own right. We start by analysing the composition of the population of Phang Nga along four demographic dimensions (4-D): namely, age, sex, highest level of educational attainment, and labour force participation. In the next step, we combine the educational attainment projections with (1) results from a 2013 survey of the province's households on disaster preparedness, and (2) results from a previous global study on the association between education and disaster deaths. This information allows us to make some inferences about how the people of the region are likely to fare if another disaster strikes in the future compared to today, and compared to people in other world regions.

2 Methods and data

2.1 Methods

The education projections are the results of age-, sex-, and education-specific population projections – representing three out of the four core dimensions – using a multi-state cohort-component population projection model. Thus, unlike in traditional cohort-component projections, the input parameters of mortality, fertility, and migration are broken down by educational level, as well as by age and sex. This approach allows us to project the development of educational attainment along cohort lines. The fourth core dimension, labour force participation, enters the model in a subsequent stage, as described below.

In addition to being a popular tourist destination, Phang Nga attracts large numbers of migrant workers, mainly from Myanmar. These migrants are employed primarily in the agricultural sector, but also in the fishery and construction industries, and as domestic workers (Jitthai et al. 2010). Because migrants make up a

[1] Phang Nga is the province in which the beach resort of Khao Lak is located.

significant share of the population, in our education projection model we distinguish individuals by country of birth. The cross-classification of educational attainment and country of birth clearly shows that this distinction is beneficial (cf. data section below). However, country of birth is not one of our core dimensions, but is rather an auxiliary dimension based on the specifics of the population structure of Phang Nga.

Our decision to include highest level of educational attainment is based on two considerations. First, on methodological grounds, our aim is to improve the quality of the projection by selecting a dimension that captures differences in fertility, mortality, and migration. We incorporate education differences into all three parameters. Second, on theoretical grounds, we believe the additional dimension is intrinsically interesting, and worthy of further analysis. In our case, we consider educational attainment information to be highly relevant for explaining labour market activity and disaster preparedness.

Details of the method are described in KC et al. (2010). The performed projection steps are:

- Distribution of the baseline population for the year 2010 by age, sex, highest level of educational attainment, and country of birth is estimated.
- Age-, sex-, and education-specific survival rates are applied.
- Transition rates between the educational categories are applied (by age, sex, and country of birth).
- Age- and education-specific fertility rates are applied to the female population aged 15 to 49. Applying a sex ratio of 1.05, total births are divided by males and females, and compose the 0-4-year age group of the subsequent period.
- Net migrants are added or subtracted according to age, sex, educational attainment, and country of birth.

These steps are repeated for each period. The resulting population of each cycle is the new starting population for the next cycle. The projection period starts in 2010 and runs until 2060. The projections intervals are five years.

Next, we generate labour force projections in two stages. First, we calculate labour force participation rates by age, sex, and education for 2010, and design scenarios of future participation up to 2060. Second, we combine these future participation rates with the previously generated education projections in order to calculate the absolute numbers and the educational attainment structure of the future labour force.

The calculation of future vulnerability involves two separate approaches. First, we combine the results from the education-specific population projections with the results of the 2013 survey of Phang Nga households on disaster preparedness to produce an estimate of the vulnerability of the province's population to future disasters. Second, we place Phang Nga in the framework of analysis of Pichler and Striessnig (2013), who focused on the role of formal education, particularly of women, in reducing vulnerability to extreme natural events.

2.2 Data and projection assumptions

The data for the baseline population come from the Thai census 2010, and are broken down by:

- age (five-year age groups),
- sex,
- economic activity (i.e. in the labour force or not in the labour force), and
- five categories of highest completed level of educational attainment (e1: no education/less than primary education; e2: primary education; e3: lower secondary education; e4: upper secondary education; e5: diploma/bachelor's degree and above)

Basic schooling in Thailand lasts for 12 years, and is free. Pupils spend six years in primary education, three years in lower secondary education, and three years in upper secondary education. Only nine years of schooling are compulsory. Upper secondary education is split into a vocational and an academic branch. The academic branch is designed to prepare students for university. But before they can enter university, students need to pass certain entrance exams (Trakulphadetkrai 2011).

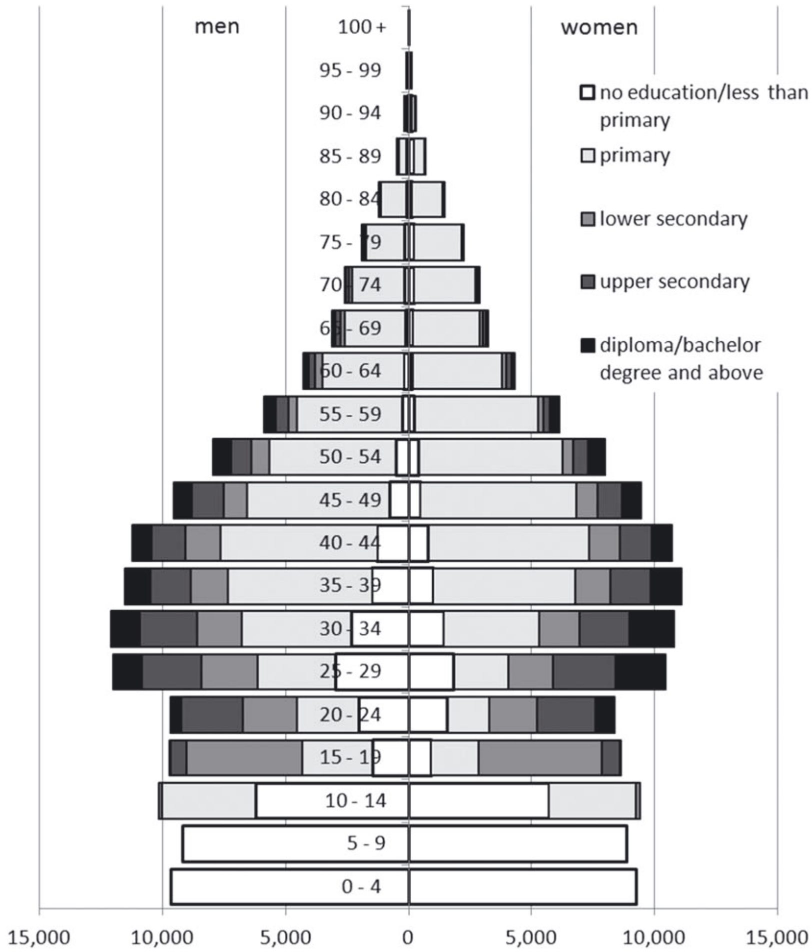
The age composition of the population in Phang Nga is very similar to the overall distribution of Thailand: in 2010, 36% of the population were under age 25 and only 8% of the population were aged 65 and older; the respective values for Thailand were 34% and 9%. The current population are profiting from a past reduction in fertility levels, which means that a large share of the population are of working age.

Figure 1 depicts the population structure in Phang Nga in 2010. Even though the age composition of Phang Nga is similar to that of Thailand as a whole, the educational attainment structures of the province and the country differ: compared to the national population, smaller shares of Phang Nga's population have higher secondary or post-secondary education, and larger shares have less than primary education. Of the 20–64 age group, 11% in Phang Nga and 4% in Thailand as a whole have less than primary education, and 26% in Phang Nga and 33% in the country overall have at least higher secondary education.

This picture changes significantly once the data are further disaggregated by country of birth: if we look only at the population born in Thailand while excluding the population born outside of Thailand, the differences in educational attainment between Phang Nga and the whole of Thailand become much smaller. The residents of Phang Nga who were born outside of Thailand had much lower levels of educational attainment than their Thai-born counterparts (Table 1): almost 100% of the adult population of Phang Nga who were born in Thailand had at least completed primary education, compared to one-third of the foreign-born population.

In 2010, the share of the population born outside of Thailand was 12% in Phang Nga and only 3% in Thailand. Within Phang Nga, the age composition of those who were born outside of Thailand was much younger than of those who were born in Thailand (Table 2). This is not surprising, considering that most migrants living in Phang Nga are labour migrants.

Figure 1:
Population pyramid by age, sex, and highest level of educational attainment, Phang Nga, 2010



Source: Census 2010, data obtained from the National Statistical Office of Thailand, own calculations.

Given these differences in the age and the education structure by country of birth, as well as the relatively high share of the population born outside of Thailand, we decided to break down the education-specific population projections by country of birth, in addition to age, sex, and education.

Table 1:
Population (ages 20–64) by country of birth and highest level of educational attainment, Phang Nga, 2010

Country of of birth	No education/less than primary	Primary	Lower secondary	Upper secondary	Diploma/bachelor degree and above
Thailand	2%	54%	15%	18%	11%
Outside of Thailand	67%	30%	1%	2%	1%

Source: Census 2010, data obtained from the National Statistical Office of Thailand, own calculations.

Table 2:
Population by country of birth and broad age group, Phang Nga, 2010

Country of birth	Age 0–19	Age 20–64	Age 65+
Thailand	30%	61%	9%
Outside of Thailand	18%	81%	0%

Source: Census 2010, data obtained from the National Statistical Office of Thailand, own calculations.

2.2.1 Educational attainment

In order to design scenarios of future educational attainment, we performed several descriptive analyses to detect past trends in the development of educational attainment. The analysis of educational attainment progression ratios (EAPR) provides insight into past developments in educational attainment, and allows us to make inferences about future developments. EAPRs describe what share of the population in a given age group progress from each level of education to the next higher level: i.e. from no education to primary education, from primary to lower secondary education, from lower to upper secondary education, and from upper secondary education to a diploma/bachelor's degree and above (Lutz et al. 2007). As there are marked differences between the Thai-born and the non-Thai-born population in terms of education structure, the EAPRs were analysed separately for the two groups. The EAPRs for both the male and the female Thai-born population show that there has been a stalemate in the progression from lower secondary to upper secondary education (e3-e4) or from upper secondary to post-secondary education (e4-e5), but that there has been an increase in the shares who progressed from primary to lower secondary education (e2-e3). For men and women born outside of Thailand, the EAPR profiles were rather flat; i.e. no educational progress was detected. As we lack information about how old the migrants were when they entered the country, it is impossible to know whether this result reflects inequalities of opportunity between the migrant and the Thai-born population.

The scenarios of educational attainment that we apply to 15–34-year-olds are as follows:

1. **Constant scenario**. The future educational attainment progression ratios of the Thai-born and the foreign-born population are kept constant at the levels observed in 2010.
2. **Universal lower secondary education by 2030**. This scenario assumes a continuation of the trend towards increasing EAPRs from primary to lower secondary education.
3. **80% have at least upper secondary education by 2030**.[2] This scenario is based on a more rapid increase in education levels than current trends suggest. As in the second scenario, it is assumed that lower secondary education will be universal. But compared to the previous two scenarios, it is anticipated that larger shares of the population will progress from lower to upper secondary education and from upper secondary to post-secondary education.

2.2.2 Fertility

There are no data for the total fertility rate (TFR) for Phang Nga specifically, so we base our main assumption on the overall TFR observed for southern Thailand, and keep this figure constant for all three scenarios of educational attainment. The average TFR for the 2000–2010 period is 1.9, and the education differentials in fertility are obtained from the Multiple Indicator Cluster Survey (MICS) 2005/06. The fertility differentials, defined as the ratio between the education-specific TFR and the total TFR, is 1.2 for women with secondary education or less and 0.65 for women with more than secondary education. The age-specific fertility schedule (ASFR) is taken from the distribution for Thailand in 2010. For sensitivity, we also run projections in which we assume an increase in overall TFR to 2.1 and a decrease to 1.5 by 2020, respectively.

2.2.3 Mortality

Life expectancy in the 2010–15 period is estimated at 72 years for men and at 79.4 years for women. As there are no data at the province level, these estimates are based on data for the southern region of Thailand (NESDB 2013). In terms of the future development of life expectancy, we follow the assumptions made in the same publication, and extend the projection horizon of 2030 by linear interpolation to 2060. This leads to a life expectancy in 2060 of 81.0 for men and of 87.6 for women. Because we lack empirical data for Phang Nga or the southern region, the education differentials in life expectancy are the same as those assumed in KC et al.

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[2] Scenarios 2 and 3 are only applied to the population born in Thailand. It did not seem reasonable to assume that those who came to Phang Nga from abroad, most of whom were unskilled labour migrants, received further education after arriving in Phang Nga. Even though migrant children are entitled to attend school in Thailand, irrespective of their legal migration status, "the majority of migrant children still remain outside the education system" (Jampaklay 2011: 97).

Table 3:
Total migrant stock and composition by country of origin, mid-year, 1990 to 2013

Country	1990	2000	2010	2013
Myanmar	43.4%	58.4%	51.1%	50.8%
Laos	31.2%	23.0%	25.7%	24.9%
Cambodia	14.0%	12.2%	19.0%	20.2%
Others	11.4%	6.4%	4.2%	4.1%
Total	528,693	1,257,821	3,224,131	3,721,735

Source: United Nations, 2013b.

(2010); i.e. compared to their counterparts with secondary education, people with incomplete primary education have an average life expectancy at age 15 that is three years lower, and people with completed primary education have an average life expectancy that is two years lower. Thus, having more than secondary education translates into a two-year increase in life expectancy.

In order to obtain education-specific life table information, it is necessary to combine information about differences in life expectancy by education with life table data. For the population under age 35, the same life table is assumed for each education category; i.e. there are no differences in survival probabilities. For the population over age 35, life tables that include the previously mentioned education-specific differentials in life expectancy are calculated using the Brass-Gompertz relations model. The standard life table is the table for Thailand, as provided by the United Nations (2013a). This procedure is repeated for each projection interval.

2.2.4 Migration

The number of migrants living in Thailand more than sextupled between 1990 and 2013, from a good half million to more than 3.7 million (Table 3), with the bulk of the increase happening after 2000. However, the composition of migrants by country of origin changed little over this period: the majority of migrants still came from Myanmar, followed by Laos and Cambodia. These three countries alone account for over 95% of all migrants living in Thailand. This pattern can be explained by the active recruitment of unskilled workers by the Thai government since 1992, initially only from Myanmar, and later also from Laos and Cambodia (Huguet et al. 2012).

Internal migration The southern region of Thailand, which is made up of 14 provinces, experienced a net loss of internal migrants between 1965 and 1990. However, the region had more internal in-migrants than out-migrants between 1995 and 2000 (Huguet et al. 2011), and the most recent census figures for 2010 suggest that the numbers of internal in- and out-migrants were roughly equal; i.e. that there was no net gain or loss due to internal migration (NESDB 2013; NSO Thailand, 2014b). The province of Phang Nga had positive internal net migration of 1,570 persons between 2005 and 2010 (NESDB 2013). An analysis of the census data for 1970, 1980, 1990, and 2000 revealed that internal net migration in Phang Nga reached a recent peak in 2000, and declined thereafter (Figure 2). Unfortunately, we have no valid information about the characteristics of internal migrants (i.e. about their composition by age, country of birth, or educational attainment), since the sample sizes in the available census micro-data are too small to allow for any reliable breakdown into sub-populations. Hence, we split the total sample of internal migrants into men and women and apply a standard age-migration profile in which migration peaks during young adult ages.

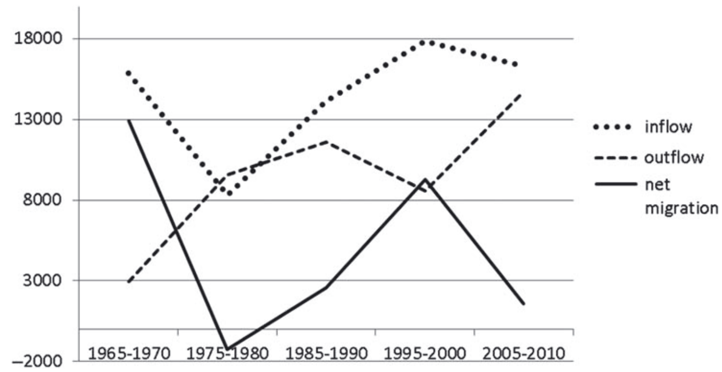
International migration An examination of the census data since 1970 to determine levels of international migration into Phang Nga indicated that zero immigrants from abroad entered Phang Nga before 1990. As it seems highly unlikely that there were no immigrants entering the province during that time, we assume that the numbers were simply very low, and that the immigrants were not picked up or included in the census. Looking at data from the 2000 census, we found that international in-migration into Phang Nga had been positive between 1995 and 2000, with 4900 persons entering (NSO Thailand 2014c). We have no direct information about either the inflow or the outflow of the number of international migrants for any later point in time. Using an indirect approach in which we compare the population size between 2000 and 2010 and take deaths, births, and internal migration during this period into account, we estimate that international net migration comprised about 4000 persons during this period.

As we mentioned above, in 2010 12% of the population of Phang Nga, or 32,174 persons, were not born in Thailand. Based on the composition of the non-Thai population – who had much lower education levels than the Thai population, and who were concentrated in the 15–49 age group (cf. Table 2) – and on the information about migrants to Thailand overall (cf. Table 3), we assume that the majority of these individuals were labour migrants from Myanmar, Laos, and Cambodia. As irregular migrants were only counted in the latest census taken in 2010, we are unable to make any useful comparisons with previous census years about the composition of the population by country of birth.

Based on the data we have on migration, we designed three migration scenarios regarding migration volume:

1. **Constant migration scenario**. Based on the most recent experiences, internal net migration is set at 1500 persons and international net migration at 2000 person for every five-year period. Thus, in this scenario internal and international migration combined comprise a net gain of 3500 migrants.
2. **Low migration scenario**. In this scenario, both internal and international net migration are gradually reduced to zero by 2020, and are kept constant at that level until 2060. This assumption can still imply a small turnover of migrants. For sensitivity purposes, we also run a scenario in which we only reduce net

Figure 2:
Internal migration: inflow into Phang Nga from the rest of Thailand and outflow from Phang Nga to other Thai provinces, 1970 to 2010. Based on the census question that asked where the respondent lived five years before the census



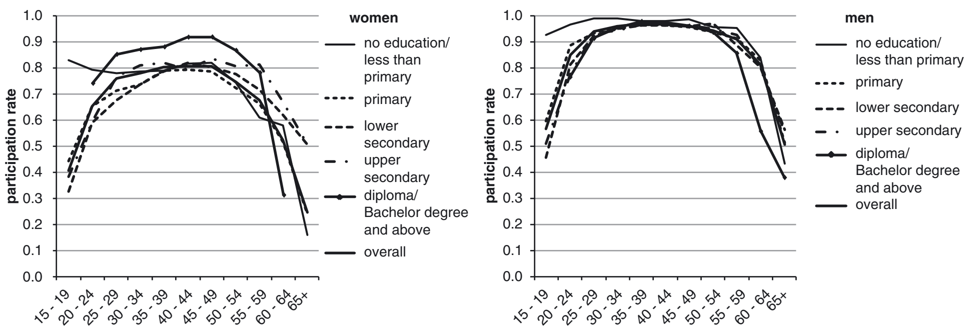
Source: Census micro-data for 1970, 1980, 1990, 2000 from IPUMS (2014), own calculations. Data for 2010 from NESDB (2013).

international migration to zero and keep internal migrations at the current level.

3. **High migration scenario**. Internal net migration is kept constant at 1500/five-year period and international net migration is doubled and set at 4000/five-year period starting in 2010.

We assume that internal migration involves only individuals born in Thailand, and that international migration involves only individuals born outside of Thailand. If the data situation had permitted, we would have avoided working with net migrants, and would have instead modelled separately the inflows and the outflows of both internal and international migrants (Rees et al. 2011; Rees et al. 2012). Internal net migrants are assigned the educational attainment distribution of the population in the respective age and sex group already residing in Phang Nga. In terms of the education structure, net international migrants in each five-year period are assigned the average of the projected education structure of the populations in Myanmar, Laos, and Cambodia, as assumed under the Global Education (GET) scenario (Lutz et al. 2014). This education scenario assigns country-specific future educational attainment based on global education trends during the last 40 years, and is considered to be the most likely education scenario. This leads to a dynamic increase in the educational attainment level of international migrants between now and 2060.

Figure 3:
Labour force participation rates by age, sex, and highest level of educational attainment, Phang Nga, 2010



Source: Census 2010, data obtained from the National Statistical Office of Thailand, own calculations.

2.2.5 Labour force participation

The age-, sex-, and education-specific profiles of labour force participation, defined according to the ILO definitions of economic activity, show several of the characteristics typical of developing countries. Participation levels are high for both men and women (Figure 3). The differences in participation levels by education are larger for women than for men, and the differences observed for women are smaller than the differences commonly observed in developed countries. The pronounced positive correlation between educational level and participation rate among women holds for all age groups; the stark decline for the highest education group after age 60 is based on very few observations.

The two scenarios of labour force participation are:

1. **Constant scenario**. Future labour force participation rates are kept constant at the levels observed in 2010.
2. **Female participation levels reach male levels in 2060**. Currently, female participation is lower than male participation. This scenario assumes that participation rates are equal in 2060. This implies no change in participation for males.

We use the profiles for men and women and do not differentiate by country of birth, since (1) we only have data for one point in time, (2) the great majority of the population are Thai, and (3) we did not want to introduce more uncertainty about future developments.

3 Results

To quantify the effects of changing levels of fertility and migration, we start by presenting a range of possible future trajectories of total population size in which we modify levels of fertility and the volume of migration. For this analysis, we employ the educational attainment assumptions of the universal lower secondary scenario. While it is impossible to assign a probability of occurrence to any of the three education scenarios, the universal lower secondary education scenario is the most likely outcome of our three scenarios, as it is based on a continuation of past attainment trends.

Next, we fix our assumptions for fertility and migration at the current level; i.e. age- and education-specific fertility rates and internal and international net migration volumes are kept constant. Applying the three educational attainment scenarios means that any change in the population size and age structure are driven by changes in the education composition of the population: for example, more women with post-secondary education will mean fewer births due to the observed education differentials in fertility (cf. section 2.2.2), which lowers the average TFR.

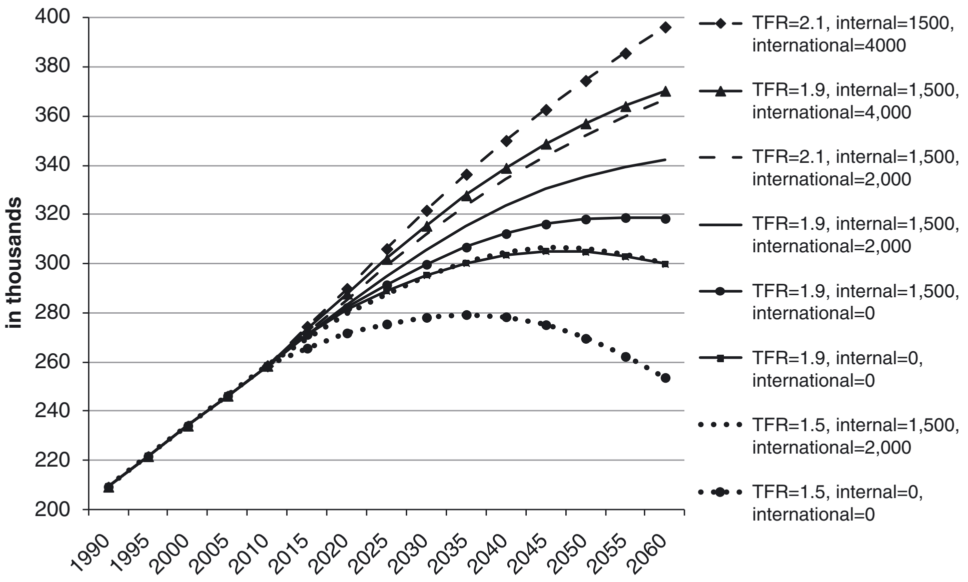
Finally, for the estimation of future labour force developments and vulnerability to natural disasters, we use the results from the three education scenarios and combine them with the respective prevalences for economic activity and disaster preparedness.

3.1 Population projections

The population in Phang Nga increased from 209,400 in 1990, to 234,200 in 2000, and to 258,500 in 2010; thus, the population increased by around 10% during each 10-year period (NSO Thailand 2014a). This implies that the Indian Ocean tsunami in 2004 did not significantly affect the total population size in the province, especially because foreign tourists accounted for almost half the death toll. To define a possible outcome range for the future population size, we calculated various combinations of assumptions about future fertility and migration, with the TFR set at 1.5, 1.9, and 2.1. The volume of internal net migration is set at zero and 1500; and the volume for international net migrations at zero, 2000, and 4000, as specified by the three migration scenarios. The underlying education scenario is the universal secondary education scenario. For the eight combination scenarios presented, the projected total population in 2060 lies between just over 250,000 and just below 400,000 (Figure 4). Only the combination of zero internal and international net migration and TFR = 1.5 leads to a smaller population size in 2060 than in 2010. All of the other scenarios lead to a projected increase. A TFR of 1.5 in combination with constant net migration numbers, as well as a TFR of 1.9 in combination with zero net migration, lead to a population peak before the end of the projection period.

For all of the following results only one scenario for fertility and migration is used: the present values for age- and education-specific fertility rates are kept

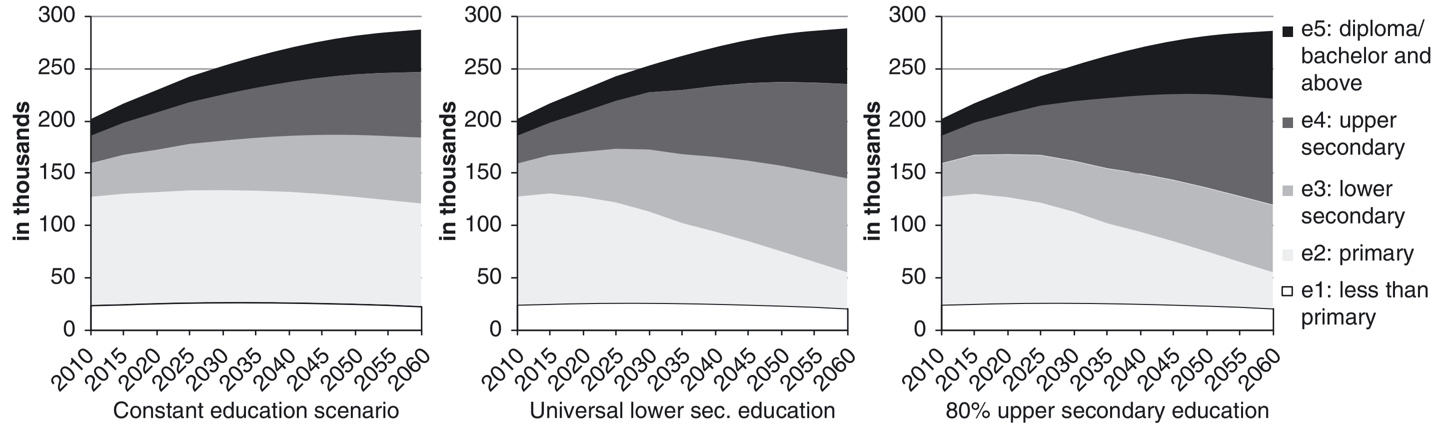
Figure 4:
Total population of Phang Nga, based on eight combinations of fertility (TFR), internal and international net migration



Source: 1990 to 2010: observed values (NSO Thailand). 2015 to 2060: own calculations.

constant, and internal and international net migration are set at a level of 1500 and 2000, respectively, for the whole projection period. In terms of the projected total population, the three education scenarios do not differ much: they vary between 335.7 and 340.6 thousand persons in 2060. This means that the differences between the education groups in terms of fertility and mortality patterns do not have the potential to significantly influence the development of Phang Nga's population in terms of its size. The development of the overall TFR and the volume of migration have much larger effects on future population size. However, as we can see in Figure 5, the educational composition of Phang Nga's future population varies significantly depending on the education scenario: the constant scenario still leads to an increase in the share of the population with at least lower secondary education as younger, better educated cohorts replace older cohorts. The increase in the share of adults with at least lower secondary education is much smaller though—from 37% in 2010 to 58% by 2060—than it is in the two cases in which universal lower secondary education is achieved (81%).

Figure 5:
Educational composition of the population ages 15+, Phang Nga, by education scenario, 2010 to 2060



Source: Own calculations.

Table 4:
Composition of the labour force ages 15+, by three education scenarios, 2030 and 2060, in combination with the constant labour force participation scenario

	Education scenario	At most primary education	Secondary education	Post-secondary education
2010	–	63%	28%	9%
2030	Constant education scenario	51%	38%	11%
	Universal lower sec. education	41%	48%	11%
	80% upper secondary education	41%	44%	15%
2060	Constant education scenario	40%	47%	13%
	Universal lower sec. education	13%	68%	19%
	80% upper secondary education	13%	64%	23%

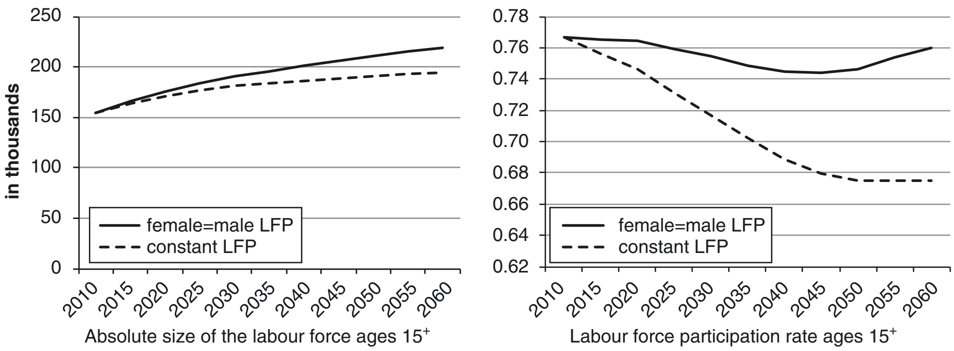
Source: Own calculations.

3.2 Labour force projections

In order to see the effect of the three different education scenarios on the composition of the labour force in Phang Nga, labour force participation is initially kept constant at the age-, sex-, and education-specific rates observed in 2010 (cf. Figure 3). For each education scenario, the labour force is likely to be composed of workers with higher levels of educational attainment than is currently the case, in which 63% of workers have primary education or less, 28% have lower or upper secondary education, and only 9% have a post-secondary degree (Table 4). Presumably, these changes in the education structure of the labour force will lead to increases in productivity. Even though we do not attempt to quantify these increases in the population module, the large projected decrease in the share of the labour force with primary education or less will very likely be beneficial for economic output.

In order to see the effect of changing labour force participation rates, the second education scenario (universal lower education) is combined with the two scenarios of labour force participation. Since the differentials in education-specific participation rates do not vary much between men and women (cf. Figure 3), we see no significant difference in the educational composition of the labour force when we compare the two participation scenarios. However, as expected, the absolute size of the labour force changes in the different scenarios (Figure 6). If participation rates stayed at current levels, the labour force would be significantly smaller in the years to come than if female participation levels reached male levels by 2060. The aggregate labour force participation rates on the right illustrates this even better, as they also include information on the development of the total population over age 15. In the constant case, overall participation would decline from 0.77 to 0.68 in the coming decades; whereas in the case of an equalisation of participation rates, overall participation would almost return to current levels after an initial decline.

Figure 6:
Size of the labour force and aggregate labour force participation rate of the population ages 15+, by two labour force participation scenarios, 2010 to 2060, in combination with the universal lower secondary education scenario



Source: Own calculations.

There is of course uncertainty about how labour force participation will evolve, particularly since our study area is rather small and only comprises about 260,000 persons. Still, irrespective of how future participation rates develop, the educational attainment structure of the population will very likely shift towards higher levels. Thus, we can assume that in the future the labour force will be composed of workers with higher human capital than today's workers have. The assumption that men and women will participate equally represents an extreme scenario; since this scenario has not materialised in even the most egalitarian societies, it is highly unlikely that it will apply to Phang Nga. In addition, the participation rates of the population ages 65+ are currently higher than they are in more advanced economies, and might decline in the future. An indication of this trend is the decline in the share of the population working in the agricultural sector. The share of the employed population who work in this sector in Phang Nga decreased between 1990 and 2000, from 65.3% (1990) to 55.4% (2000) (NSO Thailand 2014a). Changes in the sectoral composition of the elderly labour force (i.e. away from agriculture, in which informal employment is particularly common in Thailand (ILO 2013)) and in retirement provision (i.e. away from the traditional system based primarily on family support and towards a system of pension benefits) would very likely lead to lower participation levels among older people than we currently observe. Given these considerations about the economic activity trends among women and older workers, the equalisation scenario is clearly a maximum scenario. Even the constant scenario in which participation levels remain the same may not accurately reflect future developments. Still, since any assumptions about a decline in participation levels would be pure speculation, we abstain from showing any labour force scenario with reduced participation.

Table 5:
Disaster preparedness by sex and highest level of education attainment, survey population ages 25–54

	% No	% Yes	N
Male			
Lower secondary education or less	91.8	**8.2**	61
Upper secondary education and above	64.0	**36.0**	25
Female			
Lower secondary education or less	82.6	**17.4**	46
Upper secondary education and above	67.6	**32.4**	37

Note: The question in the survey was: 'Does your household have any preparation in case a disaster strikes?' The answers are only those of respondents without previous disaster experience (n = 169).

Source: Provincial survey 2013, please see text for details, own calculations.

3.3 Examples for an application to project disaster vulnerability

In our first attempt to quantify the province's future vulnerability to disaster, we combine the results from the education-specific population projections with findings from the 2013 survey of a provincial representative sample of 467 households in Phang Nga on disaster preparedness (for details about the survey, see Basten et al. 2014). Of the many factors that contribute to Phang Nga's vulnerability to natural disasters, education turned out to play a prominent role: Muttarak and Pothisiri (2013) investigated how well the coastal population was prepared for earthquakes and tsunamis, and found that the disaster preparedness of individuals increased with the level of formal educational attainment. Making use of the figures in the table below, which are based on data from the 2013 survey of households in Phang Nga on disaster preparedness, we calculated the share of the 25–54-year-old population in Phang Nga who said they had prepared for disasters, based on the sub-sample of those who did not experience the 2004 tsunami (Table 5). There is a clear education gradient: 36% of the males and 32.4% of the females with at least upper secondary education said their household had undertaken some kind of disaster preparation, whereas the respective numbers for those who had at most lower secondary education were 8.2% and 17.4%.

The distribution is based only on the sub-sample without disaster experience. If we had included the whole sample, the fact that the share of the population in the sample who had already experienced the tsunami in 2004 would have changed over time could have biased our outcome: their share would not have been constant, and their numbers would have diminished as younger cohorts replaced older cohorts. Assuming there is no natural disaster between now and 2040, no one in the specified age group will have previously experienced a disaster if there is a disaster at any point after 2040.

Table 6:
Disaster preparedness, population ages 25–54, by education scenario and sex, 2010 and 2040 to 2060

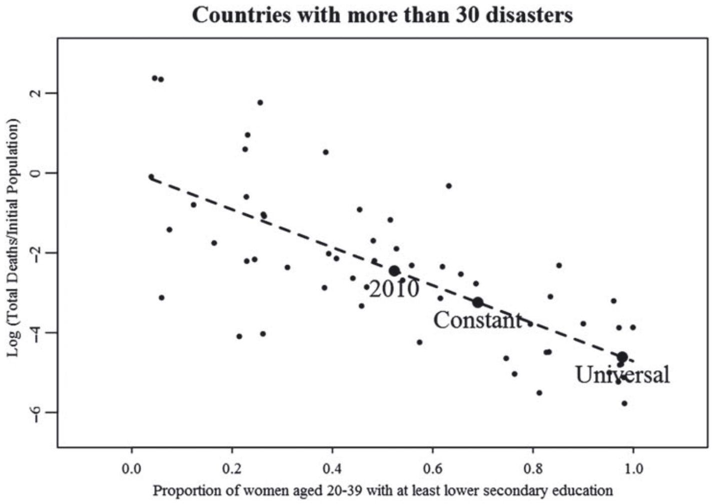
Scenario 1: constant enrolment rates			
Year	**% total**	**% male**	**% female**
2010	18.1%	14.9%	21.5%
2040	20.7%	18.1%	23.5%
2050	21.2%	18.7%	23.8%
2060	21.4%	18.9%	23.9%
Scenario 2: universal lower secondary education			
Year	**% total**	**% male**	**% female**
2010	18.1%	14.9%	21.5%
2040	23.8%	22.0%	25.6%
2050	25.5%	24.3%	26.8%
2060	26.2%	25.2%	27.2%
Scenario 3: 80% have at least upper secondary education			
Year	**% total**	**% male**	**% female**
2010	18.1%	14.9%	21.5%
2040	26.0%	25.3%	26.8%
2050	28.2%	28.2%	28.2%
2060	28.7%	28.9%	28.5%

Source: Own calculations.

Due to the projected changes in the education level of the population, combining the survey results with the education projections leads to an increase over time in the share of 25–54-year-olds who are disaster-prepared, as shown in Table 6 (column 2). Not surprisingly, the increases are particularly pronounced for the two scenarios with significant increases in completed lower secondary education. Columns 3 and 4 give the results additionally by sex, pointing out the gender differences in disaster preparedness and educational attainment.

In another attempt to quantify the expected positive effect of higher educational attainment levels on the region's vulnerability to natural disasters, we positioned Phang Nga in a global overview that shows the relationship between the proportion of women aged 20–39 with at least secondary education and the log number of deaths from climatic natural disasters (Figure 7). This graph is part of the analysis by Pichler and Striessnig (2013), which confirmed previous findings about the correlation between women's educational attainment and the number of deaths due to natural disasters (Striessnig et al. 2013). Locating Phang Nga according to its share of women aged 20–39 with at least lower secondary education in 2010, and

Figure 7:
Relationship between disaster deaths and female education



Source: Reproduction of Figure 2 in Pichler and Striessnig (2013), p. 86: relationship between the log of deaths from climatic natural disasters including floods, droughts, and storms per 1000 of the 1980 population (CRED 2004) and female education, proportional to secondary and higher education among women aged 20–39 (Lutz et al. 2007), for 56 countries with one or more disasters on average per year. Modification: addition of the position of Phang Nga (1) 2010 (2) under the constant education scenario in 2060 (3) under the universal lower secondary education scenario in 2060.

under the constant and the universal lower secondary education scenario in 2060 on the regression line in Figure 7, we would expect that if Phang Nga were to be hit by another natural disaster, the number of deaths would be lower in the future than it would be today.

4 Conclusion

In this paper we introduced the innovative four-dimensional structure, and presented the first results of the population module designed for an inter-disciplinary systems model of population-environment interactions and the assessment of likely future vulnerabilities to natural disasters in the specific case of the Phang Nga province in Thailand. Combining alternative scenarios of future education distributions and labour force participation by age and sex, we illustrated the scenario space in the population module that should be considered in the fuller model of population-development-environment interactions, which is still under development. This is to our knowledge the first such comprehensive four-dimensional population projection cross-classifying education and labour force participation by age and sex, apart from an earlier application developed for Austria (Loichinger and Lutz 2014).

In terms of demographic outcomes, we showed how the future development of the absolute size of the population of Phang Nga depends on internal and international migration and the levels of fertility, although the likely range of future fertility is rather narrow because the current levels are already low. Changes in the volume of migration have the potential to significantly influence overall population development. This is an area in which the population module will be significantly influenced by the economic development module, which is not yet operational, but will be added in future research. Based on expected changes in the educational composition of future cohorts, increases in the educational level of Phang Nga's population are very likely. But here again, there may be feed-backs from other parts of the model to these education trends. Future research linking the four-dimensional population module with economic and development modules will provide better insight into Phang Nga's future adaptive capacities.

This exploratory work on scenarios for the population module of a broader model for the province of Phang Nga showed that, if past trends continue, Phang Nga will most likely have a population and a labour force with higher levels of human capital than in the past. The functional causality between the level of education and the reduction in disaster vulnerability has been established elsewhere, and was discussed in the introduction. This link between the disaster preparedness levels of individuals and their levels of education will likely mean that the future population of Phang Nga will be less vulnerable than the current population to natural disasters or extreme events such as tropical storms resulting from climate change. These results are, however, tentative, and the whole systems model will undergo extensive sensitivity analyses and testing that will include likely feed-backs from other modules of the model, as well as further assessments of the validity of the assumption of functional causality.

Internal as well as international migration has the potential to quickly change the population size and the age, sex, and education composition of a small area like Phang Nga. Unfortunately, of all the data used for this article, the data for migration have the most limitations. Irregular migrants from outside of Thailand may not be adequately represented in the census data, even though the latest census in 2010 was supposed to cover them. Similarly, we have no information about the education levels of internal or international migrants. However, as most of the international migrants in the province are labour migrants from Myanmar, Cambodia, and Laos (United Nations 2013b), assigning them the education profile of the populations in these respective countries seems justifiable. At the same time, we are aware that migrant selectivity could affect the accuracy of our projections: for example, if the labour migrants who come to Phang Nga continue to be mainly unskilled, our assumption about the education profiles of international migrants will be biased towards higher levels of education than will actually be observed.

In general, the size and the composition of the future in- and outflow of internal migrants will depend in part on the development of labour demand and supply in both Phang Nga and the rest of Thailand. Aspects of this issue will be covered in the upcoming economic development module. International in- and out-migration may also be influenced by changes in migration regulations and policies.

Another limitation of our study is that we had to use data for the southern region when specific provincial information for Phang Nga was not available; e.g. for the overall TFP level and education differentials in fertility. We also made the simplifying assumption in the absence of any further information that all of the internal migrants were born in Thailand, and that all of the international migrants were born outside of Thailand. This assumption is clearly not accurate, but should not introduce a large bias, not least because the net migration numbers that went into the projections are quite low.

The novel 4-D population module presented in this paper allows us to project future populations by age, sex, level of education, and labour force participation. The application of this approach to the population of Phang Nga showed that in the coming five decades the province can expect to have a population and a labour force who are better educated than they are today. This trend may be expected to translate into a greater adaptive capacity for future environmental challenges, as it has been previously shown that better educated societies and communities are less negatively affected by natural disasters, and are better able to cope with their consequences.

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