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Climate Vulnerability Mapping: A Systematic Review and Future Prospects

WIRES Climate Change – Advanced Review

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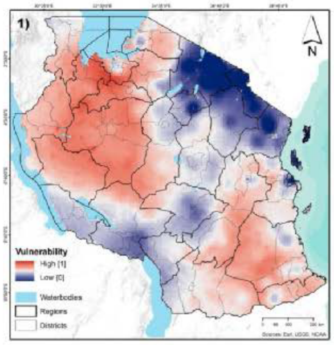
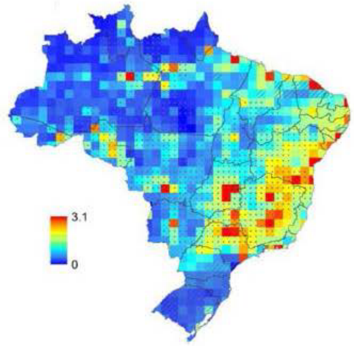
Abstract

Maps synthesizing climate, biophysical and socioeconomic data have become part of the standard tool-kit for communicating the risks of climate change to society. Vulnerability maps are used to direct attention to geographic areas where impacts on society are expected to be greatest and that may therefore require adaptation interventions. Under the Green Climate Fund and other bilateral climate adaptation funding mechanisms, donors are investing billions of dollars of adaptation funds, often with guidance from modelling results, visualized and communicated through maps and spatial decision support tools. This paper presents the results of a systematic review of 84 studies that map social vulnerability to climate impacts. These assessments are compiled by interdisciplinary teams of researchers, span many regions, range in scale from local to global, and vary in terms of frameworks, data, methods, and thematic foci. The goal is to identify common approaches to mapping, evaluate their strengths and limitations, and offer recommendations and future directions for the field. The systematic review finds some convergence around common frameworks developed by the Intergovernmental Panel on Climate Change, frequent use of linear index aggregation, and common approaches to the selection and use of climate and socioeconomic data. Further, it identifies limitations such as a lack of future climate and socioeconomic projections in many studies, insufficient characterization of uncertainty, challenges in map validation, and insufficient engagement with policy audiences for those studies that purport to be policy relevant. Finally, it provides recommendations for addressing the identified shortcomings.

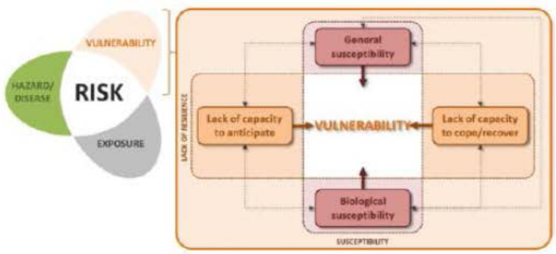
Graphical/Visual Abstract and Caption



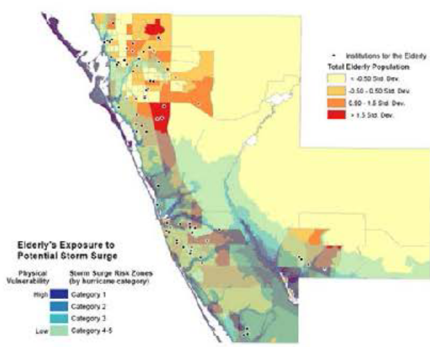
Vulnerability to Malaria in Tanzania, circa 2010 (Hagenlocher and Castro 2015)



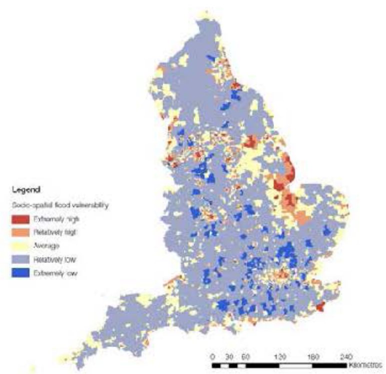
Socio-Climatic Vulnerability Index for Brazil circa 2010; hatching indicates regions where climate projection-related uncertainty is high (Filho et al. 2016)



Example vulnerability and risk framing for malaria (Hagenlocher and Castro 2015)



Physical vulnerability of the elderly to potential storm surge in Sarasota County, circa 2010 (Wang and Yarnel 2012)

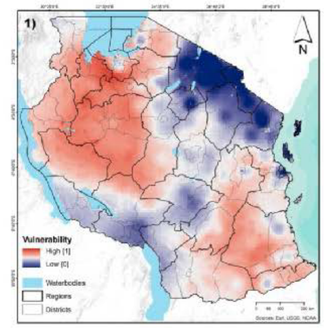


Socio-spatial flood vulnerability in England (Lindley et al. 2011)

Maps of climate vulnerability have addressed a range of issues, such as (clockwise from upper left) vulnerability to malaria, socioeconomic vulnerability to future climate risks, vulnerability to floods, and vulnerability of elderly to storm surge, with a range of framings (center).

Introduction

With the advent of the Green Climate Fund and other bilateral climate adaptation funding mechanisms, donors are directing billions of dollars of adaptation funds toward high need areas based on climate vulnerability assessments, including climate vulnerability maps (Muccione et al. 2016, Klein 2009). The United Nations Environment Programme's (UNEP) Research on Climate Change Vulnerability, Impacts and Adaptation (PROVIA), a comprehensive effort to assess the state of vulnerability assessment for adaptation planning, states explicitly that measuring and mapping vulnerability is a top research priority (PROVIA 2013). Maps have been used to identify areas of social vulnerability to climate hazards such as flood, drought, and sea level rise (Notenbaert et al. 2010, Lam et al. 2015, Islam et al. 2013) and health impacts such as malaria (Hagenlocher & Castro 2015), dengue (Dickin et al. 2013), extreme heat (Reid et al. 2009, Weber et al. 2015) and food insecurity (Kok et al. 2010, Thornton et al. 2008, van Wesenbeeck et al. 2016) (Fig. 1). End users have found the information contained in vulnerability maps useful for planning adaptation assistance (de Sherbinin et al. 2017), understanding the underlying factors contributing to vulnerability (Preston et al. 2009), emergency response and disaster planning (Blaikie et al. 1994), risk communication and informing risk-reduction decision-making (Patt et al. 2005, Edwards et al. 2007), and land use management (UNDP 2010). Given the research and policy priority given to mapping vulnerability, it is imperative to develop a better understanding of suitable approaches to vulnerability mapping across a range of scales, regions, climate hazards, and thematic foci.



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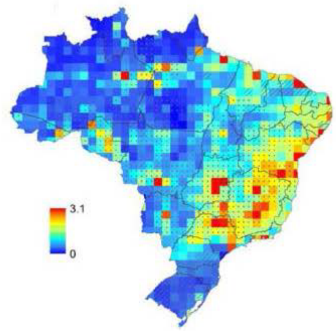

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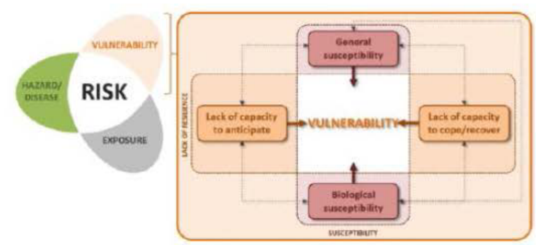

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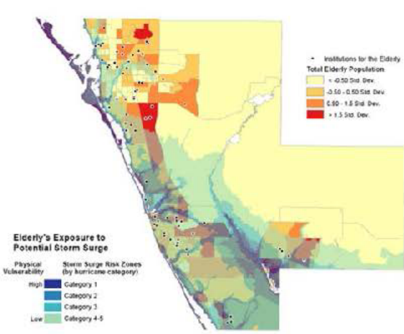

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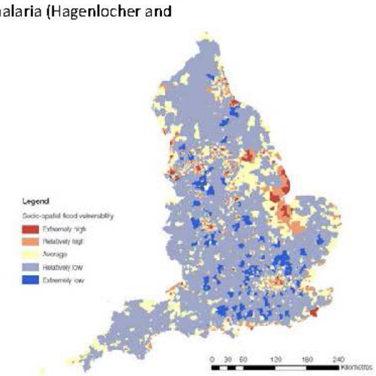

Socio-spatial flood vulnerability in England (Lindley et al. 2011)

Figure 1: Examples of vulnerability maps at different scales and for different purposes

Several literature reviews exist in allied areas. For example, Preston et al. (2011) reviewed the state of climate vulnerability mapping up until 2010 based on a sample of 45 studies that, contrary to this paper's focus on social vulnerability, included the vulnerability of economic sectors and ecosystems. de Sherbinin (2013) examined 15 global and nine regional hotspots mapping studies—including some derived purely from climate model outputs and others using process-based models to understand water or food system impacts—to identify common issues in underlying approaches and regions at risk from the most severe climate impacts. Kienberger et al. (2013) evaluated 20 mapping studies in respect to their treatment of scale, time periods covered, vulnerability and hazard focus, methods, and map products. Gall et al. (2015), based on a review of 1,006 journal articles, evaluated the degree to which disaster risk research is truly integrated across scales, stakeholders, knowledge domains, disciplines, and methods. Rufat et al. (2015) analyzed 67 flood disaster case studies with regard to measurement approaches for social vulnerability to floods. Rasanen et al. (2016) evaluated 125 climate vulnerability studies to identify interacting factors that affect vulnerability. And finally, Jurgilevich et al. (2017) reviewed 42 sub-national climate risk and vulnerability assessments to assess the degree to which changes over time (dynamics) were incorporated. While all of these studies have made valuable contributions to our understanding of vulnerability mapping and interdisciplinary research, there remains a need for a comprehensive and systematic review of the state of the art in mapping social vulnerability to climate change.

To bridge this gap, we systematically assessed 84 vulnerability mapping studies with the goal of encouraging further methodological refinement and identifying outstanding examples that could help to guide future work in this area. This study has three objectives: 1) characterize current practices in climate vulnerability mapping, 2) identify best practices and limitations, and 3) provide recommendations that chart the way forward for future efforts. This paper is organized as follows. The next section reviews the methods employed. This is followed by a characterization of the studies, a review of the current state of practice, and assessment of policy relevance. The last section points to future directions for research and practice followed by brief conclusions.

2 MATERIALS, METHODS AND DATA

The systematic review of vulnerability mapping case studies presented here draws on meta-analytical and synthesis methods (Qin and Grigsby 2016, Magliocca et al. 2015, Berrang-Ford et al. 2015). This included the development of study selection criteria, a standardized vulnerability mapping evaluation protocol, and a thematic coding scheme.

We adopt a broad definition of vulnerability, which is the degree to which a system or population is likely to experience harm due to exposure to perturbations or stress (Turner et al. 2003). For our selection criteria, studies had to include both *climate hazard* (or exposure) and *differential social vulnerability*. Climate hazard could be represented by past, present, or future climate variability, extremes, and change (trends or delta), and in some instances the hazard could be a function of climate extremes in combination with other factors such as land use changes that increase susceptibility to, e.g., floods and landslides. Social vulnerability, on the other hand, had to account for socioeconomic characteristics or institutional dimensions affecting the susceptibility of certain populations to climate change impacts and related risks (i.e., differential vulnerability) (Soares et al. 2012), and not simply population exposure. Fig. 2 shows the mapping case study selection criteria applied in this project.

Mapping studies that met the aforementioned criteria were further screened for the following considerations: vulnerability assessment portrayed in cartographic form; mapping units based on subnational ecological/administrative units or grid cells; and publication after the Intergovernmental Panel on Climate Change (IPCC) fourth assessment report (AR4) public release (2007 and onwards). Because important literature in this area is in the form of reports to development agencies, we also reviewed policy reports, white papers, dissertations, and books/atlases in addition to peer-reviewed journal articles. In cases where vulnerability assessments were published in more than one format (e.g., report and peer-reviewed journal publication), all publications were treated collectively as a singular study.

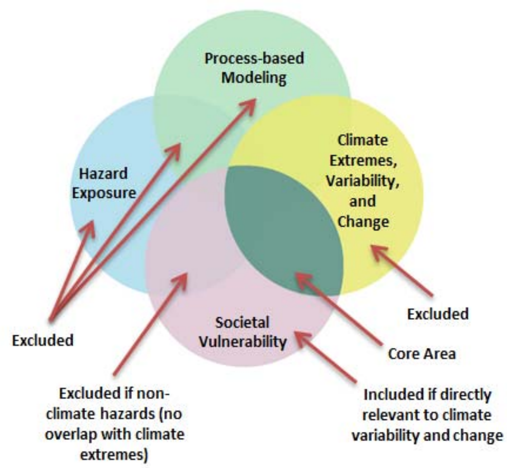

Figure 2. Studies selection criteria for the vulnerability mapping systematic review

As shown in Fig. 2, we excluded studies that considered only the aggregate exposure of populations to climate hazards or that addressed social vulnerability without reference to climate impacts. We also excluded process-based modeling efforts that used climate model outputs for crop, hydrological or other studies relating to the vulnerability of biophysical systems. We chose to limit our research to English language literature since it is the dominant language of international science. To identify candidate studies, we conducted searches on Google Scholar and the Web of Science using combinations of the keywords “vulnerability mapping”, “climate change”, and “social vulnerability” (restricting searches to studies published after January 2007).

Table 1 shows that depending on the combination of terms used, the two search engines yielded results ranging from 129 to more than 10,000 entries. Owing to our interest in including gray literature such as reports produced by or for development agencies, we chose to use Google Scholar, focusing on the union of the three search terms (Table 1, row 3). We sorted the Google Scholar search results by relevance, and then evaluated the studies individually. Only studies that fully met our criteria were retained. Our total sample included 84 studies covering a range of geographic regions, thematic areas, and spatial scales (see Supplementary Online Materials (SOM) for details on the search methods, and Table S1 for the full list). The final sample comprised 62 journal articles, 18 reports, two white papers, one book chapter, and one dissertation.

Table 1. Search results using online search engines: the Web of Science and Google Scholar (June 2016).

Search keywords	Web of Science	Google Scholar
“vulnerability mapping”	10,087	>4,000
“vulnerability mapping”, “climate change”	639	2,100
“vulnerability mapping”, “climate change”, “social vulnerability”	129	547

To develop the evaluation protocol, we collated available guidance regarding vulnerability assessment and mapping as well as the mapping of information for communication and decision-support (BMZ 2014, de Sherbinin 2014, Preston et al. 2011, Fussel 2007). The criteria included aspects such as clear identification of the external hazard and valued attributes of the socioeconomic system, a sound conceptual framework, evaluation of data layers, testing of alternative integration and aggregation schemes, proper selection and use of climatic data, sensitivity analysis, communication of study limitations and uncertainty, input data citation, and adherence to basic cartographic conventions. The authors and four additional experts (see acknowledgments) then qualitatively examined the selected vulnerability mapping studies to benchmark the state of practice. Additional fields were included for thematic coding, such as disciplines of authors, region, and spatial extent. The evaluation protocol and thematic coding scheme were developed and implemented in Google Forms (see SOM Box S1 for the full list of fields and response options). While only the 84 studies published during the decade from 2007 to 2016 formed the basis for our statistical characterization of the literature (Section 3), more recent studies are used to illustrate good vulnerability mapping practice.

Initially, at least two coders reviewed each study. The evaluation criteria ranged from objective ‘facts’ to items that required some degree of subjective interpretation by the expert coders. In order to harmonize the coding for these subjective items, the authors met at a workshop in May 2017 and individual coders resolved differences through a re-review of the case studies.

3 RESULTS

3.1 Characteristics of the Studies

Geographic coverage. Our sample covered a wide range of geographic regions (Fig. 3 and Table S1). Only five studies were global in scope. Of the non-global studies, 35% were situated in Africa, 20% each featured Asia and North America, followed by Europe (15%), Oceania (5%), and South America (3.8%). In terms of country coverage, many studies are focused on the U.S. (10), followed by Germany (5), Australia, India, and Nigeria (4 each).

Top journals. The top five publication outlets of the sampled climate vulnerability assessments were Natural Hazards (8 studies), Climatic Change (6), Applied Geography (5), Global Environmental Change (3), and Natural Hazards and Earth System Sciences (3). The studies appear in a total of 38 different journals, with a strong representation of geography, health and interdisciplinary journals focusing on climate change or natural hazards.

Level of analysis. The level of analysis varied widely, and a few studies used multiple levels. The majority of studies in our sample were focused on local areas (e.g. watersheds or municipalities) (26 studies). The remainder bounded their mapping at global (6), continental (5), regional (10), national (19), and subnational (e.g., state or provincial) (18) levels (Table S1). Whatever the level, all studies examined units within those bounding areas, either using natural/administrative units or grids (see scale of analysis below).

Study goals. Authors cited a number of purposes for undertaking vulnerability mapping, and most studies cited more than one. Hotspots identification was the primary purpose of many studies (57 total), followed by adaptation targeting (37), methodological refinement (34), disaster risk reduction (34), spatial/development planning (21), strategic planning (12), baseline assessment (11), advocacy (6), and monitoring and evaluation (2).

Valued attributes. The studies in our sample cited a variety of valued attributes (i.e., the system or thing that may be harmed or lost owing to climate impacts) with most addressing more than one. Health was pre-eminent among them (35 total; heat-stress and nutrition led the list), followed by social impacts (33 total; poverty and demographic change were most often the focus), livelihood impacts (31 total; especially agricultural livelihoods), economic impacts (20 total; especially assets), and ecosystems as they relate to human wellbeing (5).

3.2 The State of Practice

Here we assess the studies in terms of interdisciplinarity, vulnerability framing, indicators and aggregation approaches, data and projections, and treatment of uncertainty.

Interdisciplinarity. The field of vulnerability mapping is highly interdisciplinary; out of 80 studies with multi-authorship, 57 (71%) had authors from two or more fields of study. Geographers were disproportionately represented in our sample, with 45% of lead authors from that discipline (Fig. 3), followed by earth and environmental science (14%), economics (10%), agronomy and engineering (6% each), and a smattering of other disciplines. The disciplinary background of the authors appears to influence the degree to which the climatic exposure versus social vulnerability aspects were emphasized in the study. In some studies, the social vulnerability aspects were developed in great detail, but climate exposure metrics were weak (e.g., Kienberger et al. 2012, Udoh 2015, Lawal and Arokoyu 2015). In other studies, the opposite was the case (e.g., Kim et al. 2015, Piontek et al. 2013).

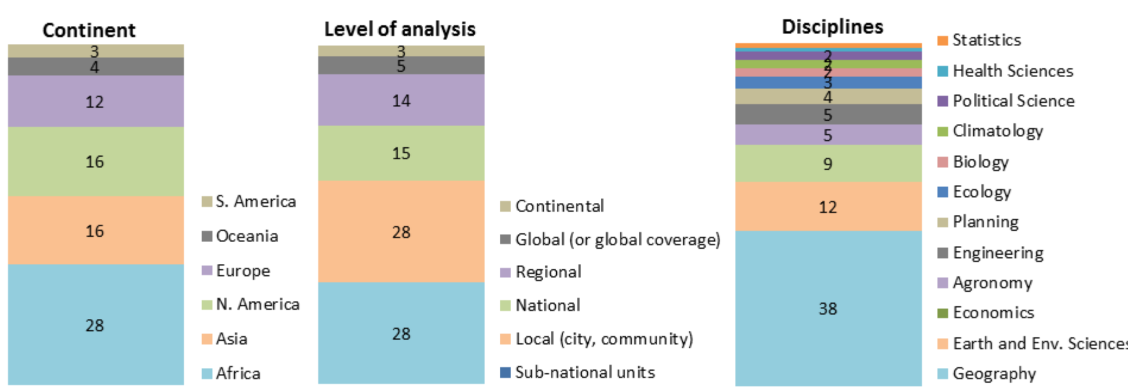

Figure 3: Studies by Continent, Level of Analysis, and Discipline

Vulnerability framing. Close to 60% of the studies draw on the framings of vulnerability and risk developed by the IPCC Working Group II across several assessment reports. The IPCC Third Assessment Report (TAR) and AR4 vulnerability frameworks (McCarthy et al. 2001 and Parry et al. 2007, respectively) identify vulnerability as a function of exposure to climate hazards, on the one hand, and the sensitivity and adaptive capacity of the system or society on the other. In 2012, the IPCC Special Report on Extremes (IPCC 2012) introduced a risk framework, also adopted by the Fifth Assessment Report (AR5) (Oppenheimer et al. 2014), which distinguished between exposure and vulnerability, the latter combining the sensitivity and adaptive capacity elements of the earlier frameworks. The "vulnerability" element in this risk framing thus represents social vulnerability or other types of vulnerability (e.g., ecosystems or infrastructure), depending on the study. Some argue that this more clearly separates out the climatological/hazard elements from the system being exposed (Cardona et al. 2012). While both risk and vulnerability framings may include social vulnerability, risk management tends to focus on the probability distributions of extreme weather events and long term trends of certain magnitudes, which is vital for disaster preparedness and infrastructure construction, whereas vulnerability assessments tend to emphasize underlying factors that put people and infrastructure at risk (de Sherbinin 2014).

Of the studies in our sample, one-third used the IPCC AR4 vulnerability framework (Parry et al. 2007), 17% utilized the very similar IPCC Third Assessment Report (TAR) vulnerability framework (McCarthy et al. 2001), and 10% utilized different risk frameworks, including the AR5 risk framework. The only studies in our sample that explicitly adapted the SREX framework were Kienberger and Hagenlocher (2014), Hagenlocher and Castro (2015), and de Sherbinin et al. (2014a). A number of studies mapped risk more broadly (Carrao et al. 2016, Aubrecht & Özceylan 2013, Poompavai and Ramalingam 2013, Scheuer et al. 2011, Johnson et al 2009). Another 3.5% used livelihood frameworks (Carney et al. 1998), and 36.5% used a variety of custom or derivative framings. For example, some studies (e.g., Behanzin et al. 2016, Papathoma-Koehle et al. 2007) developed their own vulnerability framing, or adapted frameworks developed by others (e.g., Wang & Yarnal 2012, Fekete 2009).

Whatever the choice of framework, it needs to be "fit for purpose" in terms of illuminating the features of interest in the complex coupled human-environment system. At a minimum, any quantitative vulnerability assessment requires definition of the system of analysis (what is vulnerable?), the valued attributes of concern (why are they important?) (Fig. 4), the external hazard (to what is the system vulnerable?), and a temporal reference (when?) (Füssel 2007). Preston et al. (2009) also note that when vulnerability mappers engage with stakeholders, including decision-makers, the framing must take into account their needs and desired outcomes. Participation of end users can ensure that the choice of framework and subsequent assessment process meets users' needs and increases the usability of map products.

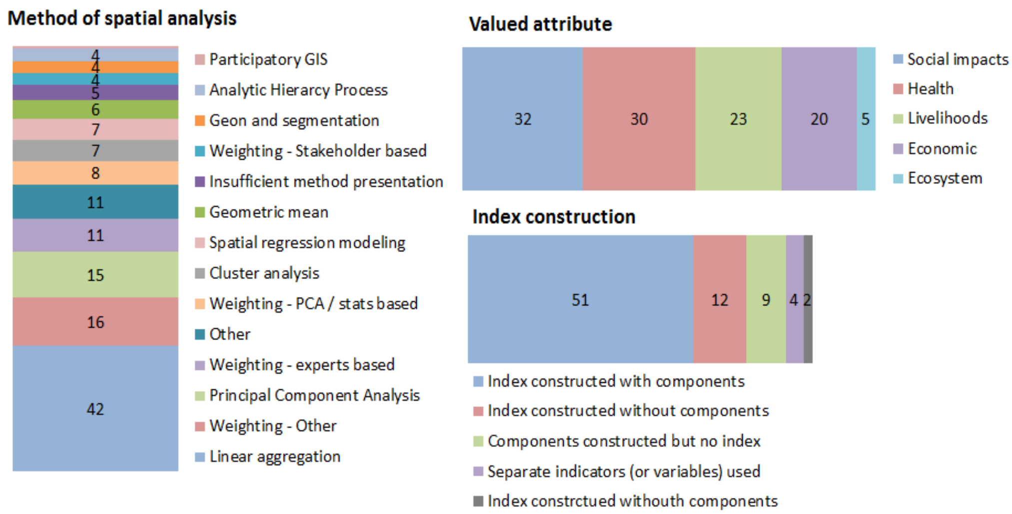

Figure 4. Summary of the studies in terms of (a) method of spatial analysis, (b) valued attribute, and (c) aggregation method

Non-Climate Indicators. In general, authors relied upon census or survey data for socioeconomic indicators as proxies for sensitivity and adaptive capacity (Hinkel 2011), and only rarely collected data (e.g., Kienberger 2012). Common proxies for social vulnerability included age, race, income, and education, which are readily available parameters. Rarely were outcome measures such as malnutrition, body mass index, or morbidity employed (e.g., van Wesenbeeck et al 2016, de Sherbinin et al. 2014b). Furthermore, papers varied in their consideration of past literature to identify relevant drivers of vulnerability; for example, Tapia et al. (2017) conducted an exhaustive literature review of 150 studies to identify climate impact chains in Europe cities and to select indicators of vulnerability across multiple exposure types. Non-climate biophysical indicators included land use and land cover (50% of studies), geographic proximity to physical features (e.g., coasts, rivers, roads) (38%), or vegetation types (26%), soil (19%), and topography (12%) (Fig. 5). With the exception of Rasanen et al. (2016), no studies considered exposure to non-climatic stressors, such as economic downturn or health crises, in addition to climatic stressors.

Fekete (2012) notes common problems of socioeconomic data include measurement errors, biased samples, geographic gaps, missing values, infrequency of updates, data decay and appropriate normalization. To obtain more frequently updated socioeconomic parameters, there are growing efforts to use remotely-sensed proxies for poverty, such as housing structure in slums (Ebert et al. 2009) or "nightlights poverty" (Davies et al. 2010), as well as for other parameters (de Sherbinin et al. 2015). None of the studies in our sample used other non-traditional data sources such as cell-phone call detail records and recharge rates or geo-located social media, though these data sources are showing increasing promise for mapping daily mobility patterns related to hazard exposure as well as vulnerability (Yu et al. 2018).

Climate-related parameters and projections. The climatic variables and climate-related processes and phenomena of greatest interest included temperature and precipitation (48% of studies each), flood (44%), drought (21%), sea level rise (13%), cyclones (12%), storm surge (10%), heatwaves (7%), coastal or riparian erosion (6%), bushfires (6%), and landslides (6%) (Fig. 5). Among 31 papers that incorporated climate data, 35% incorporated long-term climatic averages, followed by daily data (32%), monthly and annual data (13% each), and seasonal parameters (6%).

Most vulnerability mapping studies focused on the present-day climate or recent past (Jurgilevich et al. 2017). Thirty-one studies (36%) included future projections, and of these 70% used climate projections but no socio-economic projections; 17% included both climate and socio-economic projections; 6.5% employed socioeconomic projections only; and 6.5% used scenarios of sea level rise. For those that did utilize future climate projections, 38% had ensemble scenarios (multi-model, multi-scenario) based on the mean values (e.g. Filho et al. 2016, Torres et al. 2012, Thorton et al. 2008), whereas the remainder used one model, a practice generally discouraged by the climate science community (Knutti et al. 2010). For example, the European Spatial Planning Observation Network (ESPON) Climate report used only one model and one scenario: the COSMO Climate Limited-area Modelling (CCLM) and the special report on emissions scenarios (SRES) A1B (ESPON 2013). Several other studies also used only the SRES A1B scenario (Holsten and Kropp 2010, Lissner et al. 2012, Busby et al. 2014, Corobov et al. 2013). The use of single models with one scenario makes it difficult to characterize uncertainty (see below). In our sample, only Liu et al. (2008), Müller et al. (2014), and de Sherbinin et al. (2014b) used multiple scenarios with confidence intervals bounding the results. A more recent study (Mani et al. 2018) used 11 GCMs, selected on their ability to reproduce past climate, to project climate changes over South Asia, and a few other studies in our sample (e.g., Busby et al. 2014, Torres et al. 2012, Preston et al. 2008) approach best practices by employing state-of-the-art modeling of future climate.

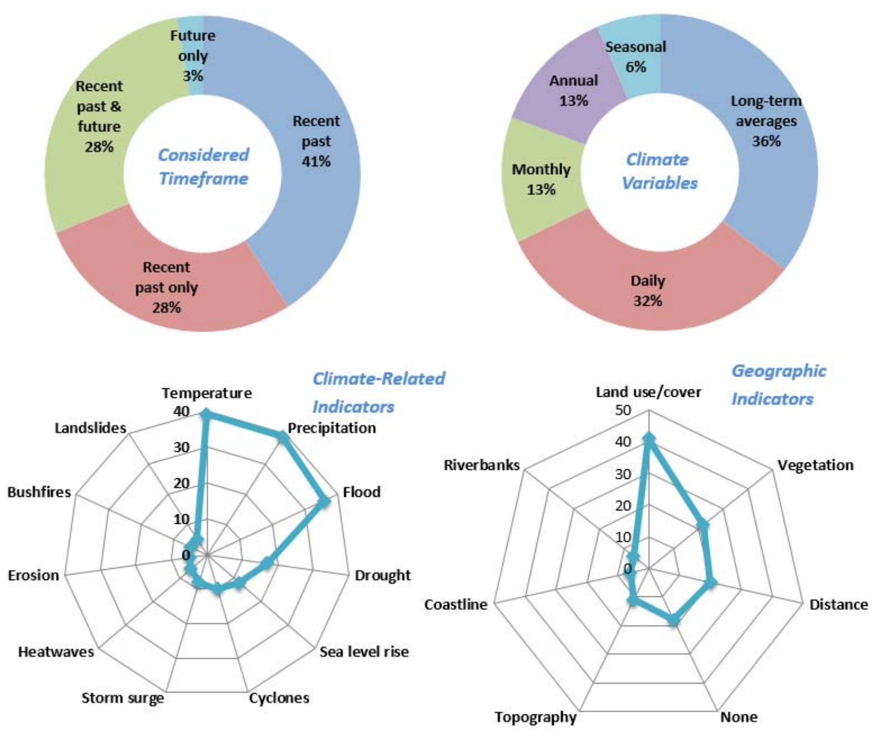

Figure 5: Summary of the studies, clockwise from upper left, in terms of (a) timeframes of analysis (%), (b) temporal nature of the climate parameters considered (%), (c) spatial data layers or parameters considered (no.), and (d) climate-related phenomena or parameters considered (no.)

In terms of downscaling, 11% of the studies used coarse spatial resolution (0.5 to 1 degree) global climate models (GCMs), 7% used downscaling -- dynamical (1) or statistical (5) -- and 6% used regional climate models (RCMs) at moderate to fine spatial resolution. The appropriateness of GCMs for local-level assessments is a matter of debate; for broader continental-scale studies these may be sufficient, but for any smaller regions or areas with significant topography, it is generally desirable to use downscaled climate projections or RCMs (Trzaska and Schnarr 2014). While GCMs may not adequately represent local climatic conditions, the uncertainty introduced by different downscaling methods need to be taken into consideration (Barsugli et al. 2013).

Aggregation methods. The sample of case studies presented a variety of methods for data analysis and aggregation, with index construction being the most common. Sixty-one percent of the studies produced a vulnerability index with sub-components (i.e., hierarchical models), whereas 14% developed indices without components, 11% produced components but no overall index, and 5% featured separate indicators (or variables) without indices. An index was calculated for 2% of studies but without presentation of the components. Only 7% had no index or indicator construction (Fig. 4), being based on overlay, cluster or regression analysis.

Fifty percent of studies relied on linear aggregation for index construction, 62% of which used weighting based on expert input or judgment of the researchers on the relative importance of indicators. Data reduction strategies appeared in 21% of studies, generally using principal components analysis (PCA) and subsequent linear aggregation. Other, less common, aggregation schemes included cluster analysis (3.5%), spatial regression modeling (7%), geometric mean (7%), and geon or spatial segmentation (5%). Five studies had insufficient methods description to determine the approach used, a major shortcoming. In some cases (e.g. Baum et al. 2009), PCA was used for the construction of a social vulnerability index, after which linear aggregation was used with the remaining indicators.

The statistics of index construction and the many alternative ways of constructing indices is the subject of a growing literature (Greco et al. 2018, Reckien 2018, Becker et al. 2017, Tate 2012, Rufat et al. 2015, Nardo et al. 2005), and issues at each stage of construction—the choice of indicators, analysis scale, measurement errors, transformation, normalization, factor retention (in PCA), and weighting—all influence results (Tate 2012). Much of the work in our case studies sample simply adapted methods or approaches from prior vulnerability mapping work, resulting in derivative approaches applied to new regions. Statistical best practices, such as uncertainty analysis/sensitivity analysis or validation (below), are underutilized. Exceptions included Mainali & Pricope (2017) and de Sherbinin et al. (2014b), both of which compared results from linear aggregation and PCA and conducted sensitivity analyses. Lastly, many of the studies displayed scant awareness of the statistical implications of their index construction methods (e.g., issues of compensability or co-linearity in linear aggregation), a general failing across many studies of social vulnerability (Tate 2012).

Scale of Analysis. The choice of bounding box (level of analysis) and spatial unit of analysis are important, and have ramifications for the approach to data integration (given multiple formats and scales of data inputs) and the statistical properties of the inputs and outputs. A more complete review of scale issues in data integration are found in Fekete et al. (2010), Kienberger et al. (2013), and de Sherbinin (2014 and 2016). Fifty-five percent of our studies used administrative units, followed by grid cells (40%), and geons (2%). One study each used natural units or parcel/property.

Ideally, the choice of spatial unit would be determined by the scale of action (Cao and Lam 1997), that is, the scale at which variation in vulnerability is best observed or at which decisions need to be made. All too often the choice of common scale for data integration is pragmatically dictated by the measurement scale of available and accessible data – which could be the coarsest or finest resolution data set – rather than the operational scale. While coarser resolution data sets can be resampled, that does not change the underlying or nominal scale. For example, climate projections may have grid cell sizes of 0.5 to 1 degree, and may be resampled at higher resolution to integrate with higher resolution data, but the result is blocks of rasters with the same values. Few studies addressed the implications of their level or unit of analysis on their results; one that did, Abson et al. (2012), found that results depended heavily on how the bounding box was drawn.

Treatment of uncertainty. It is widely accepted that uncertainty levels are high in studies of climate vulnerability, especially at the science-policy interface (Kunreuther et al. 2014). This is partly a function of the diverse data streams from social and natural sciences that are used to construct vulnerability maps, and the uncertainties that are contained in each type, and partly due to the emergent nature of vulnerability arising out of complex coupled systems (Holling 2001, Soares et al. 2012) which forces developers to use indicators as proxies (indirect measures) of the phenomenon (e.g., likely or potential harm from impacts) of interest (Hinkel 2011). Uncertainties are compounded when projections are used. Uncertainty results from lack of precision or accuracy in the measurement of the climatic, natural or socioeconomic variables that contribute to vulnerability, which in turn may be due to a host of factors such as poor instrumentation, systematic biases (sampling or model biases), and spatial interpolation of data between measurement points, all of which contribute to both systematic and random error. Fig. 6 presents examples of spatial, temporal and attribute uncertainties that may be present in different types of geospatial data.

Category	Components		
	Space	Time	Attributes
Accuracy/ error	coordinates., buildings	+/- 1 day	counts, magnitudes
Precision	1 degree	once per day	nearest 1000
Lineage	geographic sources/transforms	time sources/transforms	attribute sources/transforms
Consistency	from / for a place	5 say Mon; 2 say Tues	multiple classifiers
Currency/ timing	age of maps	C = Tpresent - Tinfo	census data
Credibility	knowledge of place	reliability of model	U.S. analyst vs. informant

Figure 6. Categories and components of uncertainty in geospatial data (after MacEachren et al. 2005). Accuracy/error: difference between observation and reality; Precision: exactness of measurement; Lineage: conduit or processes through which information has passed; Consistency: extent to which information components agree; Currency/timing: time span from occurrence through information collection to use; Credibility: reliability of information source.

Uncertainty can be affected by data processing decisions made throughout the vulnerability mapping process, such as inclusion/exclusion of datasets, imputation of missing values (or lack thereof), spatial interpolation of data (to fill gaps), data normalization or scaling and the choice of weighting and aggregation schemes (Nardo et al. 2005). Only 40% of studies addressed uncertainty, with 20% providing textual discussion only, 18% providing additional quantitative assessment, and 2% presenting maps to support quantification (de Sherbinin et al. 2014b and Ludeke et al. 2014). Many studies do not address uncertainty at all. Those that do most often lack any quantification of uncertainty, or discuss the implications of the uncertainty for decision makers. Even fewer studies (11%) quantify the individual source of uncertainty introduced by analytical decisions, data sources, etc. with regard to the output/model variance (so-called sensitivity analysis) (Saisana et al. 2005). The paucity in uncertainty and/or sensitivity analysis is most prevalent with regard to socioeconomic models or the combination of biophysical and socioeconomic data.

Uncertainty estimates are especially important when variables at differing scales are collected and overlaid for interpretation. The issue of error induced with the introduction of each variable can quickly render an analysis little more than "guesswork" if error is not mapped or in some other way accounted for, yet only 18% of studies discussed here provided any quantitative assessment of error and only 2% mapped error. Even when systematic measurement of uncertainty is not possible, authors would do well to acknowledge data issues that contribute to uncertainty, including spatial variation in uncertainty, owing to factors such as the density of measurement points (or input unit size), sampling errors in demographic data, and data quality issues across jurisdictions (de Sherbinin and Bardy 2016). Preston et al. (2011) summarized the issue well when they stated that the failure to address uncertainty "often results in questions regarding the validity, accuracy and precision of vulnerability maps, or, in other words, whether maps themselves represent sufficiently robust visions of vulnerability to guide stakeholders regarding the potential for harm."

Data citation. Vulnerability mapping is data-intensive. Disclosure of all data inputs, data processing, as well as assessment of data deficiencies, is important for the validity of results, understanding uncertainties and replication by others (Parsons et al. 2010). Fifty-five percent of studies provided only partial information on data inputs (e.g., through acronyms in a table of data inputs), and 8% omitted references entirely. All other studies followed best practice by providing full citations with URLs wherever possible or, better yet, full metadata on layers used.

The Map. Given the centrality of "the map" in vulnerability mapping, there is much room for improvement in map design and adherence to cartographic conventions. In the reviewed studies, maps are often too small, or suffer from common cartographic pitfalls such as poor color schemes and inadequate attention to color-blind readers (Brewer 1994), overcrowding, and lack of spatial reference information (major rivers, roads or settlements). Some of the cartographic limitations may stem from restrictions on figure sizes imposed by journals. Still, given the amount of analysis required to get to the point of producing maps, lack of attention to barriers that arise from poor cartography and risk communication means that many studies that desire to influence policy may fall short of their goal.

3.3 Policy Relevance

Most studies claimed to be policy relevant and emphasized the importance of vulnerability mapping to adaptation planning, but very few studies provided specific policy recommendations or engaged with policy makers and other stakeholders to frame the primary research questions or to assess outcomes. Such engagement requires working relationships and demands additional forms of inquiry such as interviews with stakeholders or follow-up research investigating the utility of the maps. Given the claims of policy relevance by many studies, it is worthwhile exploring the uptake of study results to gauge the transfer of research to practice as well as the efficacy of climate vulnerability maps.

While many studies were academic in nature, and thus not geared toward policy makers, those that claimed policy relevance often fell short of best practice. For example, several studies lacked specificity regarding the valued attribute or the climate hazard of focus (e.g., Acosta et al. 2013, Chakraborty and Joshi 2013, Hutton et al. 2011). Depending on the decision-maker and the intended usage, vaguely defined maps of "vulnerable populations" are unlikely to lead to concrete policy or implementation responses. Similarly, researchers often chose a multi-hazard approach to social vulnerability index development (e.g., Busby et al. 2014, Chakraborty and Joshi 2013, Yusuf and Francisco 2009). When it comes to implementation decisions, multi-hazard approaches with overly broad definitions of social vulnerability provide limited guidance compared to more hazard-specific vulnerability maps (e.g., vulnerability to flood, drought, heat stress, or cyclones), though they can be effective for resource prioritization or risk communication to broader audiences.

Similarly, the chosen spatial scale of maps should match that of the decisions for which they are likely relevant or useful. For example, in addition to providing gridded maps showing spatial variation in vulnerability, policy makers may be interested in results aggregated to and/or ranked by administrative units (e.g. rank position of average index scores), but this is rarely done (exceptions include de Sherbinin et al. 2017, Fig. S1). In addition, many studies – particularly those covering large spatial extents – did not contextualize the results by elaborating on climate impacts on sectors, systems or groups. While such maps can be useful for general risk communication, their utility for decision making is limited. Without context or stakeholder engagement, maps may become an end in themselves, rather than an entry point for discussion or "boundary object" for discussion among stakeholders (de Sherbinin et al. 2017, Preston et al. 2011).

Only a few studies directly worked with decision makers (e.g., McCusker et al. 2016, Roy and Blasche 2015, Weber et al. 2015, de Sherbinin et al. 2014b, Collins et al. 2013, Kienberger 2012, Lindley et al. 2011, Preston et al. 2009). These studies generally found that the co-production of knowledge was important to the success of the project. The majority of studies were academic exercises driven by intellectual curiosity or methodological development. While this may be a function of research objectives or funding source requirements, lack of engagement with stakeholders may also stem from the fact that the co-production of knowledge takes time and a commitment to process (Meadow et al. 2015). This includes listening to concerns, joint problem identification and design of the analytical framework, choice of weighting schemes, interpretation of the map products, communication of uncertainty, and design of adaptation interventions. Praxis related activities often require a different skill set than the geospatial data integration and statistical skills possessed by most vulnerability mappers, but they can be learned (Stuart and Hovland 2004).

4 RECOMMENDATIONS AND FUTURE DIRECTIONS

During the workshop, expert participants were asked to present and defend their choice of their top two mapping studies (see SOM Table S2), and time was set aside to discuss lessons from the identified studies that could inform mapping practice. The following is a distillation of recommendations and future directions for vulnerability mapping.

Improved cartography and decision support tools. As mentioned above, mapping conventions were not uniformly followed in the studies. Vulnerability mappers would do well to interact with decision makers to ensure that their map results can be easily understood by non-technical audiences (Ishikawa et al. 2005, de Sherbinin et al. 2017), as well as data scientists, visualization experts and cognitive scientists to evaluate different ways of mapping and visualizing vulnerability information (Padilla et al. 2017, Dasgupta et al. 2015). At a minimum, the field would benefit from the use of sequential color schemes in which a limited number of hues are used and the range is illustrated with a change in saturation. Only in cases where there is a clear mid-point in the data (e.g., z-scores or values that run both positive and negative) is it appropriate to use diverging color schemes with two hues (Brewer 1994). Similarly if the data are categorical, using more than one color is appropriate. In addition, well designed diagrams such as those included in Kienberger et al. (2016) (Fig. 7) or Kienberger and Hagenlocher (2014) are particularly helpful in communicating the relationships among the elements of the framework.

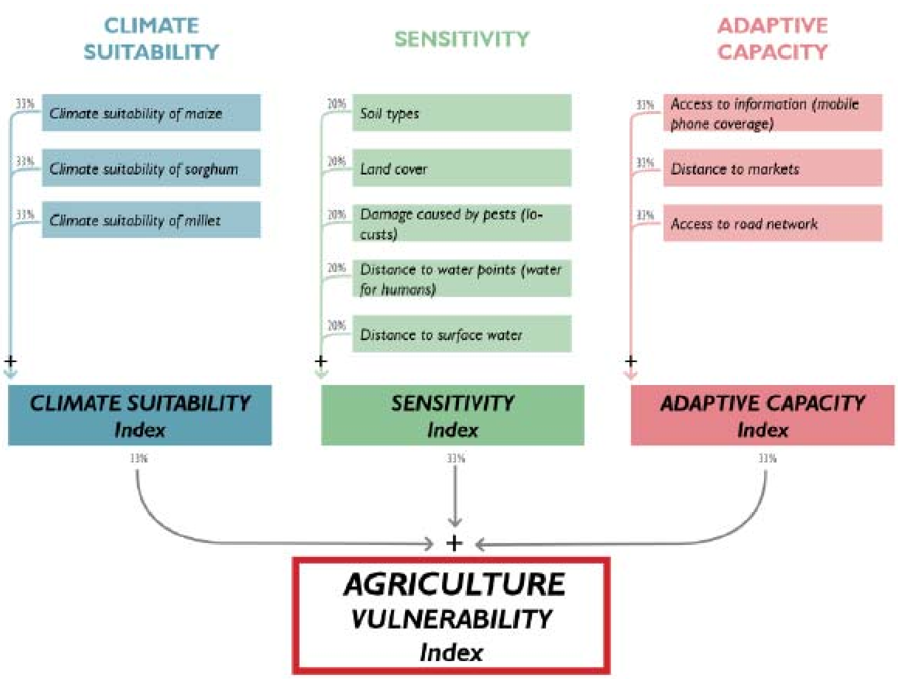

Figure 7. Diagram from Kienberger et al. 2016 illustrating the elements contributing to an agricultural vulnerability index, including weighting of the variables and components

Maps should communicate uncertainty in the data and analysis. Retchless and Brewer (2016) suggest that including uncertainty information on the map is more effective than including it in an adjacent map, and that this inclusion does not interfere with map reading if done correctly. There are a number of common methods for cartographic communication of uncertainty: One is to cross hatch areas or increase the color saturation in areas where results are more certain, such as where multiple climate model scenarios agree (Kaye et al. 2012). Another is to create fuzzy boundaries (Kienberger 2012) or to run a low-pass filter (spatial averaging) over results. By interacting with the end users, map developers can identify the best way to portray uncertainty.

As maps become more interactive and web-based, practitioners may find advantages in decision support tools (DSTs). DSTs move beyond the presentation and representation of findings to help formulate or test hypotheses, identify unknowns, and support decisions under a variety of scenarios. Indeed geovisual analytics, as a field within GIScience, has identified the benefits of interactive decision support maps (Andrienko et al. 2007), however there is a need for more research in this domain that is focused on climate vulnerability mapping.

Beyond the map. Advanced data sources and statistical methods are moving beyond the mapping of hotspots to help elicit the drivers of vulnerability and, by extension, what interventions are possible (e.g., McCusker et al. 2016, van Weesenbeek et al. 2016). These approaches often use relatively recent survey data (e.g., Demographic and Health Surveys or Living Standards Measurement Surveys), tied to specific locations through the centroids of sample locations and interpolated using spatial kriging, to tease out the factors contributing to vulnerability, along with advanced statistics and geospatial analysis to target development interventions (e.g., Runfola et al. 2015).

As an example, livelihood-informed vulnerability analysis involves data analysis of large household surveys on shocks and shock responses to determine factors that correlate with resilience and vulnerability. McCusker et al. (2016) use three models -- logistic regression, spatial filter logistic regression, and geographically weighted regression -- to tease out the drivers behind self-reported household shocks. Self-reported shocks were regressed with demographics and the socioeconomic characteristics of the households across the country, and results were mapped if significant in all the three models. This form of vulnerability mapping has the advantage of creating detailed maps, statistics and graphics of the distribution of selected variables and regression results over space.

Single index aggregation reduces the richness of information provided by the suites of individual vulnerability indicators on which the maps are based, and can produce similar scores in two locations where vulnerability is driven by very different processes. To gain a more holistic insight requires an understanding of how multiple factors that exacerbate or mitigate vulnerability to exogenous livelihood shocks vary in relation to each other (Abson et al. 2012). With additional understanding of the local context, researchers are able to understand the shocks (e.g., weather, food prices, financial, or health) that are most important to households, and determine appropriate responses (McCusker et al. 2016). This underscores an important point: a map can serve to point out differential vulnerability in a given area, but deeper field research is almost always required to develop appropriate adaptation responses.

Mapping the future. Combining socioeconomic and climate scenarios will be increasingly important for understanding the relative contributions of both changes in human factors (demography, economic development, urbanization) and climatic factors in generating future impacts. A key element for future work will be the inclusion of socioeconomic scenarios such as those developed using the Shared Socioeconomic Pathways (SSPs) or similar approaches (O'Neill et al. 2014).

While decades of climate research have led to a improved understanding of changes in the climate system, albeit with limitations regarding climate sensitivity and extremes, very little has been achieved so far to comprehend the future dynamics of human systems and its influence on future vulnerability (Lutz and Muttarak 2017). Although projecting spatial socioeconomic characteristics of populations into the future is difficult (O'Neill and Gettleman 2018), a number of methods have already been developed (Rohat 2018) and the use of scenarios enables accounting for uncertainties in future socioeconomic development trends. Strader et al. (2017) provide a rare example of vulnerability mapping incorporating future scenarios. As such, the SSPs (O'Neill et al. 2014) offer an unprecedented opportunity to integrate socioeconomic projections—and their uncertainties under varying level of socioeconomic development—within assessments of future climate change vulnerability (Wilbanks and Ebi 2014). The world is far more dynamic than most vulnerability mapping efforts portray. Mapping efforts need to consider incorporating stochastic elements, such as extreme climate events, conflict, or other shocks to the system. Mapping will also need to acknowledge the dynamic connections between indicators, as well as linkages across scales (Jurgilevich et al. 2017).

Validation. Many authors have noted the importance of validating vulnerability maps and the lack of attention that such validation has received in studies to date (Preston et al. 2011, Hinkel 2011, Tate 2012, de Sherbinin 2013, Tellman et al. 2017). This is attributable to a number of factors: First, theoretical constructs of vulnerability are proxies for complex socio-ecological processes that are difficult to measure and, therefore, validate (Vincent 2004). Second, vulnerability maps often represent vulnerability in a generic sense – in the absence of the specific articulation of who or what is vulnerable and to what, it is not clear what the associated outcomes should be. Third, vulnerability maps attempt to represent an inherently uncertain future, for which there is no observable information or data to validate maps against.

Given these challenges, a key question in vulnerability mapping is to what extent is validation necessary? This is largely a function of the objective of the mapping exercise and how the map(s) will subsequently be used. For maps generated as part of a research activity that is disconnected from adaptation practice or decision-making, there may be little incentive to pursue validation. Developing new methods or metrics for vulnerability analysis, for example, may not have a practical application that merits validation. Vulnerability maps can be used to open a dialogue around vulnerability, its meaning, and its causes (Preston et al. 2009). So, if the objective is to help stakeholders conceptualize rather than predict vulnerability, validation may be unnecessary.

Often, vulnerability maps are intended as tools to support decision-making regarding the prioritization and targeting of adaptation interventions and/or investments (Preston et al. 2011, de Sherbinin 2014). This creates potential incentives for stakeholders to manipulate the assessment of vulnerability in order to justify a priori policy objectives. In such situations, demonstrating that indices are robust to both data inputs and outcomes of interest, including the characterization of their uncertainties and limitations, is important (Saisana et al. 2005, Hinkel 2011, Tate 2012, Weeks et al. 2013). Vulnerability metrics that do not accurately reflect the underlying outcomes or processes of interest or that generate insights not reflected in other metrics significantly increase the risk of type I and II errors (false positives and false negatives, respectively) that could waste resources or prove maladaptive.

Specific methods for validation generally follow one of two approaches (Esnard et al. 2011, Tate 2012). The most common is external validation, where vulnerability metrics are validated against independent outcomes of interest such as past health outcomes or economic losses from extreme weather events (Patt et al. 2005, Preston et al. 2009, Preston et al. 2011, Tate 2012, Tellman et al. 2017). However, metrics that are validated against one type of outcome may not work for others. For example, a metric capable of predicting historical disaster losses may not perform well in predicting future health impacts or population displacement. There may also be biases in the economic loss data used to validate the metrics, and there are issues with the fact that while a hazard may impact all areas (e.g., floods or drought), the intensity of that hazard is likely to vary spatially such that there is not equal treatment across all units in order to understand the dose-response function. Finally, in many parts of the developing world, the data necessary for external validation simply does not exist, nor is it likely to in the near future. Applications of external validation must be cognizant of these limitations.

Alternatively, some researchers have opted to use internal validation—statistical tests and sensitivity analysis—to assess the effects of metric construction on results (Tate 2012, Carrão et al. 2016, Heß 2017). Neither approach, however, overcomes the challenge of validating estimates of future vulnerability. This constraint should be acknowledged in the use of vulnerability metrics and consideration must be given to the relevance of vulnerability metrics to understanding the future implications of climate change.

Notwithstanding the difficulties of validation, it is important to continue to test methods of validation, and for policy-oriented vulnerability mapping efforts to seek to validate indices wherever possible, or the enterprise risks being discredited owing to claims that vulnerability maps are unable to predict future harm.

Value of information. There are a number of ways to assess the likely uptake or impact of vulnerability mapping for decision making, and we recommend that the community of researchers involved in vulnerability mapping more rigorously test and evaluate the value of the information provided. One approach, mentioned above, is to work directly with decision makers, data visualization experts, and cognitive scientists to understand how decision makers read maps and assimilate information. A number of promising future research directions include (a) semi-structured individual or focus group interviews; (b) work observation; (c) think aloud protocols (whereby subjects will verbally express what they are thinking about as they explore maps); (d) online focus group or Delphi exercises (MacEachren et al. 2006); and (e) task analysis (de Sherbinin et al. 2017). The aim would be to gauge policy-maker comprehension of the information presented in maps, their preferences in map design (Retchless and Brewer 2015), their comfort level with the uncertainty in map products, and, ultimately, how and why the information presented in maps influenced their decisions.

In the field of economics, value of information research is demonstrating the societal benefit of information for decision making by examining the economic costs associated with decision making that was made prior to the introduction of new information, and measuring the economic benefits (net of the cost of the new information sources) of improved decisions. Economic costs could be measured in terms of lives lost, hospital visits, or economic damages. Recent work on the value of satellite remote sensing information (Bernknopf and Brookshire 2018, Cooke et al. 2014) provide examples of rigorous economic analyses that could be performed for vulnerability mapping.

Conclusion

Vulnerability mapping is growing field, and one that is likely to increase in importance given the magnitude of expected temperature increases and associated impacts (World Bank and PIK 2012). Such mapping acknowledges that the effects of climate change on society are not solely a function of exposure to temperature and precipitation changes or increases in the frequency or magnitude of extreme events, but that the sensitivity and adaptive capacity of societies to these changes will play a crucial role in influencing outcomes. Mapping also acknowledges that all the factors that contribute to vulnerability—e.g., exposure to extremes, land use and land cover, population density, relative wealth and poverty, and institutional effectiveness—vary spatially, and that there relative contributions to overall vulnerability are different from place to place (e.g., Nayak et al. 2017, Kienberger and Hagenlocher 2014). Thus, mapping can make significant contributions to enabling society to effectively adapt, or to signal where adaptation may face sufficiently high barriers that communities may be forced to migrate (Rigaud et al. 2018).

We find that vulnerability mapping as a field is maturing, but a number of issues remain that need to be addressed for the field to advance, including increasing the degree of collaboration with end users, greater attention to map communication, moving beyond the map as the final product, work on validation, and greater justification for mapping based on value of information research. This is all the more important as decision makers look to invest large sums of money in adaptation assistance, and to justify their choices based on scientific tools such as vulnerability maps.

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Supporting Information for

Climate Vulnerability Mapping: A Systematic Review and Future Prospects

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Contents

S1 Introduction

This supplementary material provides additional information on the literature search and selected case studies (Table S1), the meta-analysis evaluation criteria and coding scheme (Box S1), the authors' top study picks and what they found to be compelling about the selected studies (Table S2), and a complete reference list for the 84 studies.

S2 The Literature Search

The search terms "vulnerability mapping", "climate change", and "social vulnerability" were used together to identify relevant literature. We started with a collection of studies that met these terms based on authors' prior knowledge, and added to those studies using Google Scholar, with results sorted by relevance. Even though the search results were broadly relevant, they did not necessarily produce results that were entirely consistent with our criteria for inclusion. Thus, studies identified using the search terms were evaluated individually. If multiple journal articles or reports were discovered for a study, they were evaluated as a study rather than individually. Only studies that fully met our criteria were retained. We found that results diminished in relevance, thus we stopped after evaluating 500 results.[1] The total in our systematic review is 84 studies covering a range of geographic regions, thematic areas, and spatial scales (Table S1).

Table S1: List of Studies and Basic Characteristics, Grouped by Scale

Scale	Nested Region / Country / Province	Topic	Citation(s)
Global	Global	Drought vulnerability	Carrão et al. (2016)
	Global	General vulnerability, global environmental change	Lüdeke et al. (2014)
	Global	Political stability, climate change and conflict	Scheffran & Battaglini (2011)
	Global, Developing World	General vulnerability, humanitarian risk	Thow & De Blois (2008); CARE (2008)
	Global, Drylands	Food security, global environmental change, vulnerability of smallholder farmers	Kok et al. (2010)
	Global, Tropics	Food security, agricultural production, social vulnerability	Ericksen et al. (2011)
Continental	Africa	Political stability, security vulnerability	Busby et al. (2012; 2014a/b)
	Africa	General vulnerability, biosphere properties	Müller et al. (2014)
	Africa, Sub-Saharan Africa	Food security, climate change and crop yields, social vulnerability	Liu et al. (2008)
	Africa, Sub-Saharan Africa	Precipitation and population change, demographic pressures	Lopez-Carr et al. (2014)
	Africa, Sub-Saharan Africa	Food security, agriculture, vulnerability of resource-poor croppers	Thornton et al. (2008)
Regional	Africa, East Africa	Health, malaria risk, social vulnerability	Kienberger & Hagenlocher (2014)
	Africa, East Africa, Central Africa	Climate hazards, social vulnerability	Notenbaert et al. (2010)
	Africa, East Africa, West Africa	Food security, security and health, vulnerability	van Wesenbeeck et al. (2016)
	Africa, Southern Africa	General vulnerability, ecosystems, social vulnerability	Abson et al. (2012)

[1] The searches were conducted during three windows: The first search was from 18-20 July 2016 and covered search results on pages 1-15; the second search was from 25 July to 1 August 2016 covering pages 16-41; the third search was on 3 October 2016 covering pages 41-50.

	Africa, Southern Africa	General vulnerability	Davies et al. (2010); Midgley et al. (2011)
	Africa, West Africa	Sea level rise, social vulnerability, coastal economic exposure	de Sherbinin et al. (2014b)
	Asia, Southeast Asia	General vulnerability	Yusuf & Francisco (2009)
	Latin America, Central America, Caribbean	Cyclone hazards, costal vulnerability	Lam et al. (2015)
	Western Europe	General vulnerability, adaptive capacity	Acosta et al. (2013)
	Western Europe	Climate change, vulnerability of local economies	ESPON (2013)
National	Africa, East Africa, Malawi	Climate hazards vulnerability	Malcomb et al. (2014)
	Africa, East Africa, Tanzania	Health, malaria risk in relation to climate change	Hagenlocher & Castro (2015)
	Africa, Southern Africa, South Africa	Food security, farming sector vulnerability	Gbetibouo & Ringler (2009)
	Africa, Southern Africa, Malawi	Vulnerability to climate hazards	DoDMA (2015)
	Africa, West Africa, Ghana	Food security, agricultural and social vulnerability	Antwi-Agyei et al. (2012)
	Africa, West Africa, Mali	General vulnerability	de Sherbinin et al. (2014a)
	Africa, West Africa, Niger	Social vulnerability to climate shocks	Essam et al. (2015)
	Asia, Central Asia, Tajikistan	General vulnerability	Heltberg & Bonch-Osmolovskiy (2011)
	Asia, East Asia, Korea	Drought vulnerability	Kim et al. (2015)
	Asia, South Asia, Bangladesh	Climate hazards vulnerability	Islam et al. (2013)
	Asia, South Asia, India	Vulnerability to climate hazards and other natural disasters	Chakraborty & Joshi (2013)
	Asia, South Asia, Pakistan	Climate hazards vulnerability	Khan & Salman (2012)
	Asia, Southeast Asia, Malaysia	Health, climate change and dengue	Dickin et al. (2013)
	Europe, Germany	Flood, social vulnerability	Fekete (2009)
	Europe, UK, England	Flood and heat stress, social vulnerability	Lindley et al. (2011)

	Latin America, Caribbean, Grenada	Cyclone hazards, flood, coastal vulnerability	Weis et al. (2016)
	Latin America, South America, Brazil	General vulnerability	Filho et al. (2016)
	Latin America, South America, Brazil	General vulnerability	Torres et al. (2012)
	North America, USA	Heat stress, social vulnerability	Reid et al. (2009)
Sub-national	Africa, Malawi, southern Malawi	General vulnerability	Coulibaly et al. (2015)
	Africa, Nigeria, southwestern Nigeria	Social vulnerability, underlying climatic hazards	Lawal & Arokoyu (2015)
	Africa, Southern Africa, South Africa, Limpopo Province	Flood, social vulnerability, participatory GIS	Nethengwe (2007)
	Africa, West Africa, Mauritania, southern Mauritania	Climate change, vulnerability of rural livelihood systems	Kienberger et al. (2016)
	Africa, West Africa, Nigeria, Akwa Ibom State	Climate hazards vulnerability	Udoh (2015)
	Asia, East Asia, China, Inner Mongolia	Drought vulnerability	Liu et al. (2013)
	Asia, East Asia, Taiwan, Tachia River basin	Climate hazards vulnerability, stakeholders engagement	Hung & Chen (2013)
	Asia, East Asia, Taiwan, Hualien and Taitung Area	Cross-boundary general vulnerability	Lee et al. (2016)
	Asia, East Asia, Vietnam, Mekong Delta	Sea level rise, coastal vulnerability	Nguyen & Woodroffe (2016)
	Asia, South Asia, Bangladesh, southwestern Bangladesh	Flooding, coastal vulnerability	Roy & Blaschke (2015)
	Asia, South Asia, India, Assam	Cyclone risk, social vulnerability, infrastructure vulnerability	Mazumdar & Paul (2016)
	Asia, South Asia, India, Brahmaputra River	Flood and riverbank erosion vulnerability	Sharma et al. (2010)
	Asia, South Asia, India, Tamil Nadu	Cyclone hazards, coastal vulnerability	Poompavai & Ramalingam (2013)
	Europe, Eastern Europe, Moldova, Dniester River Basin	General vulnerability	Corobov et al. (2013)

	Europe, Germany, North Rhine-Westphalia	General vulnerability, multisectoral	Holsten & Kropp (2012)
	Europe, Germany, North Rhine Westphalia	Heat stress, social vulnerability	Lissner et al. (2012)
	Multiple (river basins in Austria, India, Bhutan and Tibet)	Climate hazards, flood vulnerability	Hutton et al. (2011)
	Oceania, Australia, Queensland	Climate hazards, extreme heat and rainfall, vulnerability	Crick et al. (2012)
Local	Africa, East Africa, Mozambique, Buzi District	Flood, social vulnerability	Kienberger (2012)
	Africa, West Africa, Benin, Niger River Valley	Flood vulnerability	Behanzin et al. (2016)
	Africa, West Africa, Nigeria, Ado Ekiti	Flood vulnerability	Odeyemi et al. (2016)
	Africa, West Africa, Nigeria, Port Harcourt	Flood vulnerability	Akukwe & Ogbodo (2015)
	Asia, East Asia, China, Beijing	Flood vulnerability	Liu et al. (2016)
	Europe, Austria, Salzach catchment	Flood, social vulnerability	Kienberger et al. (2009)
	Europe, Germany, Leipzig	Flood vulnerability	Scheuer et al. (2011)
	Europe, Germany, Lichtenstein (Swabian Alb)	Climate hazards, landslide vulnerability	Papathoma-Köhle et al. (2007)
	Europe, UK, London	Flood, social vulnerability	Hebb & Mortsch (2007)
	Europe, UK, London	Heat, urban heat stress, social vulnerability	Wolf & McGregor (2013)
	Latin America, Central America, Honduras, Tegucigalpa	Climate hazards, social vulnerability	Ebert et al. (2008)
	Latin America, South America, Bolivia, Amboro-Madidi Corridor	General vulnerability	Surkin et al. (2010)
	North America, Canada, Toronto	Heat stress, social vulnerability	Rinner et al. (2010)
	North America, Mexico, Mexico City	Flood and water scarcity, vulnerability	Eakin et al. (2016)

	North America, USA (El Paso), Mexico (Ciudad Juarez)	Climate hazards vulnerability	Collins et al. (2013)
	North America, USA, Alaska, Seward Peninsula	Water, climate change and social vulnerability	Alessa et al. (2008)
	North America, USA, Arizona, Phoenix	Heat, urban heat stress, social vulnerability	Chuang & Gober (2015)
	North America, USA, Florida, Sarasota	Hurricane hazards, storm surge, vulnerability of the elderly	Wang & Yarnal (2012)
	North America, USA, Houston	Heat, urban heat stress, social vulnerability	Heaton et al. (2014)
	North America, USA, Pennsylvania, Philadelphia	Heat, urban heat stress, social vulnerability	Johnson et al. (2009)
	North America, USA, Pennsylvania, Philadelphia	Heat, urban heat stress, social vulnerability	Weber et al. (2015)
	North America, USA, Virginia, Hampton-Rhodes	Storm surge, social vulnerability in coastal areas	Kleinosky et al. (2007)
	North America, USA, Washington DC	Heat, urban heat stress, social vulnerability	Aubrecht & Özceylan (2013)
	Oceania, Australia, Gold Coast	Heat stress, extreme heat, social vulnerability	Baum et al. (2009)
	Oceania, Australia, Sydney Coastal Councils	Bush fires, social vulnerability	Preston et al. (2009)
	Oceania, Australia, Sydney Coastal Councils	General vulnerability, stakeholders engagement	Preston et al. (2008)

Box S1. Meta-Analysis Protocol

1. Study code: <numeric code>
2. Short citation (e.g., Roberts 2014): <open>
3. Type:
   - Journal article
   - Academic white paper
   - Report
   - Policy report (glossy, intended for policy makers)
   - Thesis/dissertation
   - Other: <open>
4. Journal name: <open>
5. Discipline(s) of principle authors (pick all that apply): <pulldown pick list>
6. Who is the audience:
   - Unclear / not stated
   - Academic
   - Decision makers (politicians to agency staff, donors)
   - Practitioners (consulting companies, NGOs, planners)
   - General public
   - Media and communicators
   - Private sector (insurance companies, corporations)
7. Methodological contribution/originality score (10 is high originality): <1-10>
8. Theoretical contribution/originality score (10 is high originality): <1-10>
9. If the mapping is based on established methodology(ies), provide citations: <open>
10. Scale of analysis:
    - Global
    - Continental
    - Regional
    - National
    - Sub-national units
    - Local (city, community)
11. Continent(s) (*list only if not global*): <freetext>
12. Region (*list only if not continental*) (e.g., West Africa, South Asia, Central America): <freetext>
13. Country (*list only if only one or two countries are the focus*): <freetext>
14. Country ISO3 code(s) (see https://en.wikipedia.org/wiki/ISO_3166-1_alpha-3): <freetext>
15. Subnational region or locality (*list only if study has a subnational focus*) (e.g., US Eastern Seaboard, northern Senegal): <open>
16. If ecosystem focused (check all that apply):
    - Coastal
    - Wetland
    - Mangrove
    - Forest
    - Mountain
    - Savannah
    - Grasslands / rangelands
    - Drylands
    - Polar / sub-arctic
    - Island

- Inland waters (lakes, rivers)
- Cultivated
- Olson biomes
  - Not relevant
  - Montane Grasslands & Shrublands
  - Deserts & Xeric Shrublands
  - Mangroves
  - Tropical & Subtropical Moist Broadleaf Forests
  - Tropical & Subtropical Dry Broadleaf Forests
  - Tropical & Subtropical Grasslands, Savannas & Shrub
  - Mediterranean Forests, Woodlands & Scrub
  - Temperate Broadleaf & Mixed Forests
  - Temperate Conifer Forests
  - Temperate Grasslands, Savannas & Shrublands
  - Boreal Forests/Taiga
  - Flooded Grasslands & Savannas
  - Tundra
- Other: <open>

17. Framework utilized
    - IPCC AR5
    - IPCC AR4
    - IPCC AR3
    - Extended vulnerability framework (e.g. Turner et al. or other)
    - Other: <open>
18. Stated purpose of the study (multiple pick list)
    - Unclear (not explicitly stated)
    - Hotspots identification
    - Adaptation targeting
    - Spatial / development planning
    - Strategic planning
    - Methods refinement
    - Baseline assessment
    - Monitoring and evaluation
    - Disaster risk reduction (e.g. hazard mitigation)
    - Advocacy
    - Education
    - Other <open>
19. Valued attribute
    - None listed
    - Social impacts
      - Migration / displacement
      - Demographic change
      - Conflict
      - Poverty
    - Health
      - Heat stress
      - Vector borne disease
      - Infectious and parasitic disease
      - Environmental (e.g., air or water pollutants)
      - Nutrition
      - Morbidity / mortality
    - Livelihoods

        - Agriculture
        - Fisheries
        - Pastoralism
        - Non-timber forest products
    - Formal employment
        - Service
        - Manufacturing
        - Public sector
    - Economic assets (homes, farms, infrastructure, etc.)
    - Ecosystem services
    - Economic sectors
20. Time frames (check all that apply)
    - Recent past
    - Current
    - Future
    - Climate variables:
        - Monthly
        - Annual
        - Daily
        - Seasonal
        - Number of years used to compute long-term averages: <number>
21. Index construction
    - Not relevant: <check box>
    - Number of indicators: <number>
    - Number of index components (if appropriate): <number>
    - List components: <open>
    - Comments: <open>
22. Climate-related parameters included
    - Number of parameters: <number>
    - Temperature
    - List Temp parameters: <open>
    - Precipitation
    - List Precip parameters: <open>
    - Flood
    - Erosion
    - Drought
    - Bushfires
    - Sea level rise
    - Storm surge
    - Cyclones
    - Heatwaves
    - Landslides
    - Other: <open>
23. Socioeconomic parameters
    - SoVI, HDI or equivalent index
    - Limited suite (5 max) of pop characteristics
    - Other: <open>
24. Geographic / biophysical parameters
    - None
    - Distance
    - Topography
    - Land use / cover

- Vegetation
- Other: <open>

25. Future scenario usage
    - None
    - Climate
        - Original data input
            - GCM
            - RCM
            - Downscaled projection
        - Ensemble scenarios (multi-model multi-scenario)
            - Mean used
            - Range used (i.e., high, med, low)
        - One model / scenario
        - One model / multiple scenarios
    - Extremes
        - Future PDFs
        - Other: <open>
    - Socioeconomic
        - Population
        - Land use
        - Economic
        - Other: <open>
26. Identify outputs spatial units
    - grid cells
    - If grid cell, size in meters: <open>
    - Admin units
    - Natural units
        - Biomes
        - Watersheds
        - Coastal zone
    - Parcel / property
    - Other ___<open>
27. Methods of index construction and spatial analysis (choose all that apply)
    - Insufficient methods presentation
    - Linear aggregation (additive)
    - Geometric mean
    - PCA
    - Spatial regression modeling
    - Cluster analysis
    - Geon and segmentation
    - Self-organizing
    - Weighting
        - Expert based
        - PCA / statically based
        - Stakeholder based
        - Other: <open>
    - Participatory GIS
    - Other: <open>
28. Uncertainty assessment
    - None
    - Textual discussion of uncertainty
    - Quantitative assessment of uncertainty

- If quantitative assessment of uncertainty, method used: <open>
- Mapping of uncertainty

29. Documentation of input data
    - None
    - Metadata on data layers used
    - Supplementary online material
    - Other: <open>
30. Policy relevance
    - Do the authors state that the research is policy relevant? Y/N
    - Do the authors make recommendations for policy? Y/N
    - Has the work been used by policy makers? Y/N
        - In what way? <open>
31. Map outputs
    - On a scale of 1-10 does the map adhere to basic cartographic conventions (see list)? <number>
    - Comment: <open>
    - On a scale of 1-10 do the map products clearly convey the concepts of vulnerability (vulnerability of what to what and time dimension)? <number>
    - Comment: <open>
    - On a scale of 1-10 rate the fitness of the map(s) given the stated objective of the map and the outlet (policy report vs journal) <number>
    - Comment: <open>

Table S2: Authors' Top Studies and Valued Characteristics

Study	Valued Characteristics
Abson et al. (2012). "Using Principal Component Analysis for information-rich socio-ecological vulnerability mapping in Southern Africa", *Applied Geography*	Good use of PCA and discussion of the method for PCA for use in vulnerability mapping, and demonstration of dependency of results on different bounding boxes
Chakraborty & Joshi (2013), "Mapping disaster vulnerability in India using analytical hierarchy process", *Geomatics, Natural Hazards, and Risk*	Uses Analytic Hierarchy Process (AHP) for multi-criteria decision-mapping to assess the vulnerability of the whole country at the sub-national level; employs district-level scale to increase the policy relevance; exposure considers both natural and climate-induced hazards; provides sufficient detail on methodological approach that makes it reproducible and transferable to other locations
de Sherbinin et al. (2014a). "Mali Climate Vulnerability Mapping," USAID report	Consistent application of IPCC AR4 framework; robust methodology and spatially explicit; scenario component; strong policy recommendation; use of uncertainty maps; documentation on methods (discussion), detailed metadata and mapping standards
Dickin et al. (2013). "Water-Associated Disease Index for Denge in Malaysia", *PLOSone*	Aims to integrate bio-physical and social variables in the health domain; relatively simple aggregation approach (arithmetic), but aims at sub-national level as well as other admin levels; maps seasonal changes
Filho et al. (2016). "Socio-climatic hotspots in Brazil", *Climatic Change*	Aims to assess the influence of social reforms on the decrease of vulnerability in Brazil; compares two vulnerability assessments with a 10-year gap; explore the influence of changes in climatic conditions *vs* changes in socioeconomic conditions; comparison maps and statistics
Hagenlocher and Castro (2015). "Mapping malaria risk and vulnerability in the United Republic of Tanzania: a spatial explicit model", *Pop Health Metrics*	Appropriate use of AR5 framework; logistic regression for variable selection and weight to construct index; relative distribution of risk factors by region and by component; sensitivity analysis using different weights

Holsten and Kropp (2012). "An integrated and transferable climate change vulnerability assessment for regional application", *Natural Hazards*	Chosen by two reviewers; multi-sectoral (physical, social, environmental, economic); novel use of municipal data; sensitivity and exposure indicators produced the impacts dimension which was visually overlaid on the adaptive capacity dimension; textual discussion/mapping of uncertainty; includes multiple different climate models; methods: linear aggregation, geometric mean, weighting
Johnson et al. (2009). "Socioeconomic indicators of heat-related health risk supplemented with remotely sensed data", *Intl J of Health Geographics*	Integration of remote sensing of the physical environment with socioeconomic indicators; sensitivity analysis of alternative vulnerability models; validation of models against observed outcomes
Kienberger and Hagenlocher (2014). "Spatial-explicit modeling of social vulnerability to malaria in East Africa", *Intl J of Health Geographics*	Chosen by two reviewers; excellent conceptual framework for modeling social vulnerability to vector-borne diseases; leveraged multiple (including non-traditional) spatial data; expert-based weighting exercise; uses geons to aggregate and visualize results (with pie charts showing relative contribution); local sensitivity analysis
Lindley et al. (2011), "Climate change, Justice and Vulnerability to Floods in UK", report of the Joseph Roundtree Foundation	Step-by-step guidance for country implementation; list of hazard-specific indicators, i.e. flood, heat; local stakeholder involvement
Ludeke et al. (2014). "Understanding Change in Patterns of Vulnerability", PIK report	Use of a climate model and an integrated assessment model to generate scenarios of future climatic and socioeconomic conditions; use of cluster analysis to generate spatial typologies of change; analysis of the implications of alternative policy interventions
Malcolm et al. (2014). "Vulnerability Modeling: An Operationalized Approach in Malawi", *Applied Geog.*	Vulnerability modeling that attempts to better integrate a wider range of socio-economic factors
Scheffren and Battaglini (2011). "Climate and conflicts: the security risks of global warming", *Reg Envtal Change*	Emphasis on actors, social context, and institutions as determinants of vulnerability; readily interpretable map of vulnerability hotspots; focus on security and instability rather than generic vulnerability

van Wesenbeek et al (2016). "Localization and characterization of pops vulnerable to CC" *Applied Geography*	Uses the Food and Nutrition Security Conceptual Framework; good use of DHS* and MICS** data; creates a household-level index based on female BMI, child malnutrition, and morbidity; then characterizes households based on vulnerability explanatory variables like age & gender of HH head, dependency ratio, assets, education, and adaptive capacity explanatory variables like remittance income, food aid, integration into the community; variables jointly improves the specificity of target groups and identification of focal areas for interventions
Wang & Yarnal (2012). "The vulnerability of the elderly to hurricane hazards in Sarasota, Florida", *Natural Hazards*	Highly customized to assess the vulnerability of older adults on the county/local level for improved policy relevance; measures social vulnerability of older residents at four different stages of disaster using Principal Component Analysis (PCA); exposure includes storm surge (SLOSH model) and flood risk (FEMA); identifies social vulnerability hotspots
Yusuf and Francisco (2009). "Climate Change Vulnerability Mapping for Southeast Asia", IDRC, CIDA, and SIDA report	Creates a composite climate hazards index (exposure) using a simple weighted linear aggregation approach; uses 'expert opinion polling' to weight indicators (adaptive capacity); map outputs adhere to best practices

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