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REVIEW ARTICLE

Putting vulnerability to climate change on the map: a review of approaches, benefits, and risks

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Abstract There is growing demand among stakeholders across public and private institutions for spatially-explicit information regarding vulnerability to climate change at the local scale. However, the challenges associated with mapping the geography of climate change vulnerability are non-trivial, both conceptually and technically, suggesting the need for more critical evaluation of this practice. Here, we review climate change vulnerability mapping in the context of four key questions that are fundamental to assessment design. First, what are the goals of the assessment? A review of published assessments yields a range of objective statements that emphasize problem orientation or decision-making about adaptation actions. Second, how is the assessment of vulnerability framed? Assessments vary with respect to what values are assessed (vulnerability of what) and the underlying determinants of vulnerability that are considered (vulnerability to what). The selected frame ultimately influences perceptions of the primary driving forces of vulnerability as well as preferences regarding management alternatives. Third, what are the technical methods by which an assessment is conducted? The integration of vulnerability determinants into a common map remains an emergent and subjective practice associated with a number of methodological challenges. Fourth, who participates in the assessment and how will it be used to facilitate change? Assessments are often conducted under the auspices of benefiting stakeholders, yet many lack direct engagement with stakeholders. Each of these questions is reviewed in turn by drawing on an illustrative set of 45 vulnerability mapping studies appearing in the literature. A number of pathways for placing vulnerability mapping on a more robust footing are also identified.

Keywords Vulnerability assessment · Mapping · Climate change · Adaptation

Introduction

Vulnerability assessment is a common tool for representing the potential for harm to occur within human and ecological systems of value in response to global climate change (Adger et al. 2007). The process of undertaking assessments can contribute to better understanding of community and environmental needs with respect to capacity-building and/or the identification of adaptation actions for vulnerability reduction (Adger et al. 2004). The realization of such positive outcomes is challenged, however, by the high degree of spatial and temporal heterogeneity associated with physical, socioeconomic, and cultural determinants of vulnerability, not to mention the diversity of normative societal judgments regarding what values should be protected. This complexity ultimately makes vulnerability an emergent and highly contextual property of complex

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coupled human/environmental systems (Turner et al. 2003a, 2003b). Effective communication regarding this complexity that enables improved understanding regarding how climate change interacts with other system drivers, and the prioritization of subsequent responses by societal institutions is critical to the reduction of vulnerability (Kelly and Adger 2000; Preston et al. 2009).

To this end, the mapping of climate change vulnerability is a popular analysis approach that enables the representation of local context within vulnerability assessment through the spatial rendering of geographically heterogeneous determinants of vulnerability and their interactions. The goal of such assessment approaches is to communicate the 'vulnerability of place'—the potential for harm to arise from climate change interacting with the local context (Cutter 1996; Adger and Kelly 1999; Cutter et al. 2000). The potential benefits of vulnerability mapping are twofold. First, they help support spatial planning (Clark et al. 1998; NRC 2007a). Much of urban and regional planning focuses on reconciling competing societal demands for the use and management of land (ESPACE 2007), recognizing that different activities will be perceived as more or less appropriate given a plurality of societal preferences for amenity, opportunity and risk. In a changing climate, the risk management component of spatial planning has taken on increasing importance as climate change is likely to alter the spatial and temporal distribution of climate hazards. For example, in a review of geospatial data and tools for disaster management, the National Research Council (NRC 2007a, p 2), states,

> "It is widely acknowledged that maps are essential in the earliest stages of search and rescue, that evacuation planning is important, and that overhead images provide the best early source of information on damage."

The challenges of climate change are likely to be mitigated or exacerbated by socioeconomic trajectories and stochastic phenomena that alter the distribution of people and valued assets on the landscape and their capacities to cope with change. Understanding the geography of climate change vulnerability has the potential to assist with risk and disaster management, reducing exposure of human and ecological assets, anticipating future 'hot spots' for adverse impacts, and identifying particularly vulnerable populations that may be prioritized for intervention (NRC 2007a; Preston et al. 2009).

Second, vulnerability mapping has a role to play in educating the public about climate change and the mechanisms by which it may interact with coupled human/environmental systems (Preston et al. 2009). For example, Clark et al. (1998), Sheppard (2005), and Shaw et al. (2009) all discuss the utility of realistic landscape visualizations of the effects of climate change and/or vulnerability maps for social learning and motivating policy responses. Preston et al. (2009) used vulnerability mapping in Sydney, Australia to help stakeholders visualize climate change impacts on the landscape; place those impacts in a recognizable, local context; and illustrate interactions between biophysical and socioeconomic determinants of vulnerability. In such applications, vulnerability maps become 'boundary objects' that represent common points of reference for the facilitation of communication and learning among stakeholders and researchers (Lynch et al. 2008). Visualizations can also help dispel conventional assumptions about climate change being a distant or nebulous issue, or one that is amenable to simple conceptualizations of cause-and-effect.

Despite evidence of the benefits of vulnerability mapping, there is also evidence that the power of maps has cultivated a bias regarding their inherent utility. McCall (2003), for example, notes,

> "There is an implicit, sometimes explicit, assumption that using GIS at this local level is both efficient and effective, in that it is believed to simultaneously deal with the planning content, answer the questions asked of the geo-information, and also address and satisfy the local stakeholders' underlying interests."

Such assumptions should be examined critically, as there are a number of pathways by which the processes and methods used in mapping of environmental and social systems can obfuscate an issue rather than provide clarity. Preston et al. (2009), for example, note that, in the absence of clear guidance, maps of climate change vulnerability may be interpreted in myriad ways by different audiences. Ambiguity can lead to spurious conclusions regarding vulnerability and its determinants, in which case one can question whether the power of visual information can generate more harm than good. It can also lead to over-confidence on behalf of stakeholders and premature decision-making under the belief that once a map is available, sufficient information is in hand for effective decision-making. Such determinations can be drawn only after critical examination of the map itself, the underlying data and assumptions, and the context and purpose for which it was originally developed.

Given the existence of such pitfalls, there is a need for assessment practitioners and stakeholders to be more circumspect in their pursuit of vulnerability mapping, the methods employed, and the manner results are communicated. To date, the role of maps in communicating risk and vulnerability to the public has received little critical attention in comparison to the frequency of their use for such purposes (Dransch et al. 2010). To assist in this effort, this paper reviews climate change vulnerability mapping practice by (1) identifying a suite of key questions that should be addressed in the design of a spatial vulnerability assessment, and (2) exploring the relevance of these questions and the various approaches by which they have been addressed with specific examples from the literature. This is followed by some recommendations for the more robust development of vulnerability mapping practice. Ultimately, the goal of this paper is not to discourage the practice of putting climate change vulnerability on the map. To the contrary, the goal is to highlight both the diversity of approaches to vulnerability mapping that have been applied to date in different contexts as well as common conventions. Furthermore, this review seeks to identify potential strengths and weaknesses associated with particular applications.

Approach to this review

The current study reviews two knowledge pools in its investigation of vulnerability mapping in the context of climate change. The first pool is focused on the literature associated with vulnerability assessment concepts. This includes conceptual models of vulnerability, idealized frameworks for assessment, attributes of effective assessment, and participatory approaches to assessment. The second pool represents the literature focused on vulnerability mapping practice, which includes applications of vulnerability mapping that have been conducted at various geo-political scales and for different sectors to inform understanding about the spatial distribution of vulnerability in specific contexts.

The literature on vulnerability assessment concepts reveals a number of core themes that are instrumental to operationalizing vulnerability within the context of assessment. These themes can be expressed as questions that should be posed and answered in the design and execution of an assessment:

1. What are the goals and objectives? Is there a particular utility associated with spatial analysis of vulnerability that justifies its use and, if so, what are the anticipated goals and benefits to stakeholders? Are there potential risks associated with presenting information spatially that may undermined expressed goals?
2. How is the assessment of vulnerability framed? What aspects of systems are vulnerable and what are the determinants of that vulnerability? How are spatial, temporal and multi-scale dynamics of vulnerability represented?
3. By what methods will vulnerability be assessed? What methods are used in the assessment and mapping of vulnerability and how does one cope with complexity and uncertainty?
4. Who participates and how are results translated into action? Who is responsible for designing and undertaking a spatial analysis, and which stakeholders will participate in the process? Who are the intended audience and what efforts will be made to ensure information is presented in a relevant manner and, subsequently, interpreted appropriately? What are the processes by which an assessment of vulnerability can facilitate adaptive responses?

These central questions are discussed in this review and explored on a more practical level by revisiting a set of published assessments. A convenience sample of 69 self-described climate change (and/or sea-level rise) ‘vulnerability assessments’ published in the peer-reviewed and ‘grey’ literature was identified through ISI database searches and searches through publication holdings of a range of national and international boundary organizations and government agencies (e.g., the Economy and Environment Program for Southeast Asia, the International Food Policy Research Institutes, and various climate change research institutions). In the context of this review, climate change vulnerability assessment was interpreted as exercises involving the development of representational metrics (quantitative or qualitative) of the potential for harm to occur to assets and systems of value in response to climate change and its interactions with other system drivers. Those metrics could include individual determinants of biophysical, social, economic, or cultural vulnerability and adaptive capacity as well as meta-metrics of vulnerability generated from the integration of multiple determinants. The emphasis on vulnerability assessments led specifically to the exclusion of what is clearly a large literature on climate change impact/risk assessment, which are recognized as related, but distinct, approaches to consequence analysis (Carter et al. 2007). From this sample of studies, 45 used some form of geographic visualization to represent vulnerability and/or its determinants spatially (Table 1). These 45 studies formed the basis of the current review of vulnerability mapping practice (see “Appendix”, Table 5). While all of these assessments have an emphasis on vulnerability to climate change and/or sea-level rise, many examine climate change as just one of a number of possible determinants of vulnerability (with others including, for example, globalization, trade, land use change, or measures of adaptive capacity). Studies ranged in publication date from 1997 to 2009, with over one-half published post-2006. In addition, some common characteristics of assessment relevant to the aforementioned questions were collected for each study, categorized, and recorded in a database allowing comparison and generalization across the set of assessments. The remainder of

Table 1 Representative goals articulated by a sample of 45 climate change vulnerability mapping studies

Reference	Description	Expressed goal
Assessment for identifying determinants of vulnerability		
Yohe et al. (2006); p 35	Global distribution of climate change vulnerability	"Here we explore how variation in adaptive capacity and climate impacts can be seen to influence the global distribution of vulnerability"
O'Brien et al. (2004); p 312	Livelihood vulnerability in India	"By combining regional vulnerability mapping with local-level case studies, we are able to capture factors and processes operating and interacting at different scales, and to understand how local-level decisions are shaped by factors at the national and international level"
Preston and Jones (2008); p 260	Water resources vulnerability in Australia	"…we report the first attempt to screen risk to the security of water supply and quality within Australia's 325 surface water management areas in the context of current and future biophysical and socio-economic stresses"
Assessment for method development		
Luers et al. (2003); p 255	Agricultural vulnerability in the Yaqui Valley, Mexico	"We then propose a new approach to quantifying vulnerability that integrates four essential concepts: the state of the system relative to a threshold of damage, sensitivity, exposure and adaptive capacity"
Vescovi et al. (2005); pp 76–77	Human vulnerability to extreme heat events in Quebec	"This paper demonstrates the feasibility and potential of a risk assessment approach and the development of public health risk indices for a regional impact and adaptation climate change study applied to high temperature events"
Sullivan and Meigh (2005); p 69	Nested vulnerability of water resources	"The objective of this paper is to demonstrate the potential for making vulnerability assessments using the CVI at a scale which is appropriate to targeting the vulnerability of local populations. At the same time, we demonstrate that the approach is practicable for application over large areas"
Assessment for risk identification		
Al-Jeneid et al. (2008); p 89	Coastal vulnerability of Bahrain	"The objectives of this paper are to identify and quantify the vulnerable low lying coastal area of the islands to the adverse effects of CC/SLR, categorizing these vulnerable sectors, regions and resources in response to three projected SLR scenarios: a conservative, moderate and worst rate per century"
Kienberger et al. (2009); p 767	Social vulnerability to flood hazards in Salzach catchment, Austria	"This paper discusses a spatial explicit model for assessing socio-economic vulnerability to flood hazards at the sub-national level and independent from administrative boundaries"
Yusuf and Francisco (2009); p 1	Vulnerability in Asia/Pacific nations and sub-regions	"The general objective of this study is to identify which regions in Southeast Asia are the most vulnerable to climate change"
Assessment for decision-making		
Diffenbaugh et al. (2007); p 20,195	Global socioeconomic exposure and vulnerability to climate change	"…agreement on such binding [greenhouse gas emissions] limits may well require a greater understanding of how the costs and benefits of climate change are likely to vary between nations. Variations in national climate change exposure are thus central to ongoing negotiations regarding GHG emissions reductions"
Schröter et al. (2004); p 10	Climate change vulnerability of Europe	"The underlying general objective of the vulnerability assessment was to inform the decision-making of stakeholders about options for adapting to the effects of global change and thereby to facilitate environmental management and sustainable development"
Karim and Mimura (2008); p 499	Vulnerability of coastal Bangladesh to storm surge flooding	"The outcomes of the present research would set a firm basis for policy and decision makers for future shelter planning and designing safe shelter heights"

this report discusses the insights gained from the review of the conceptual and practical literature on climate change vulnerability assessment.

What are the goals and objectives?

As with other forms of risk assessment and action planning, a critical aspect of any vulnerability assessment, irrespective of whether the results are analyzed spatially, is establishing goals and objectives (Willows and Connell 2003; Lim et al. 2005; AGO 2006). These help bound the scope of any given vulnerability mapping assessment, informing issues such as how the issue is framed, who should participate and which methods are most appropriate. Goals and objectives are also crucial, along with suitable evaluation criteria, in providing a mechanism for evaluating subsequent successes or shortcomings of an assessment. Undoubtedly, individual assessments will vary with respect to objectives. What is important is the extent to which the choice of an assessment approach is consistent with those objectives.

The conventional wisdom underlying the use of spatial analysis in vulnerability assessment is that such analyses will help build understanding about climate vulnerability and its geographic distribution and, ultimately, facilitate adaptive responses on behalf of institutions and civil society (NRC 2007a, b; Kienberger et al. 2009). One can, however, recognize two distinct processes in operation here: problem orientation and decision-support. Problem orientation refers to building understanding about the nature of the problem, including not only cause-and-effect relationships, but also the institutional and governance context in which that problem sits (Clark 2002). Clark (2002), for example, argues that institutions must first articulate the problem if robust management strategies are to be identified. Preston et al. (2009) argue that, without a shared understanding of the system of interest and the assessment process by stakeholders, assessment outputs may raise more questions than they answer, thereby clouding the decision process. This is due, in part, to the fact that vulnerability assessments are attempts to represent the structure and function of systems of great complexity (Patt et al. 2004). Meanwhile, decision-making around the management of vulnerability involves determining why one plausible management strategy is preferable to an alternative and the manner in which it should be implemented (Clark 2002). It is commonly assumed that the two processes are one and the same, in that knowledge of spatial vulnerability flows inexorably into decision-making. This is the basis of the Linear Model/Knowledge Deficit Model of science/policy interactions (Stokes 1997; Hansen et al. 2003; Wynne 1991, 2006; Godin 2006; Trench 2008). However this assumption is naïve, both in its conceptualization of policy as being a linear outcome of intelligence gathering, and in its suggestion that spatial information inherently benefits decision-making (Oreskes 2004). Hence, while both problem orientation and decision-support are worthy aspirations and justifications for undertaking vulnerability assessment, failure to distinguish between the two and align assessment methods to these objectives may detract from the intended utility of an assessment.

In examining vulnerability mapping in practice, the 45 studies were scrutinized to identify the stated objectives of the assessment. Statements of objective were recorded in a database and classified into one of four types:

1. Development and trialing of assessment methods;
2. Identification of the determinants of vulnerability;
3. Risk/vulnerability identification; and
4. Decision support

The first three of these objectives correspond with problem orientation in that they help build understanding of the nature of vulnerability and its magnitude, and/or assist in the development of methods for analyzing vulnerability. The fourth objective, however, is specific to supporting decision-making around adaptation. Of the 45 studies reviewed here, the majority (91%) represent assessments for problem orientation. Yet, it also apparent from vulnerability mapping practice that assessments vary with respect to which of the three aforementioned approaches to problem orientation they emphasize.

The most commonly cited (49%) objective for vulnerability mapping was risk identification through, for example, the generation of estimates of vulnerability for different sectors, communities, or geographic areas. Of those, 36% focused on mapping coastal vulnerability to sea-level rise and/or storm surge events (Hammar-Klose et al. 2003; Sharples et al. 2009; Al-Jeneid et al. 2008; Demirkesen et al. 2008; Pruszak and Zawadzka 2008; Alpar 2009). Beyond the coastal zone, White et al. (2003), Liu et al. (2008), Thorton et al. (2008) and Oyekale et al. (2009) map the spatial heterogeneity in the vulnerability of agricultural commodities and food security. Other applications of mapping vulnerability hotspots have included ecosystems (Bayliss et al. 1997), water resources (Alessa et al. 2008; Döll 2009), public health (Bulto et al. 2006) or human settlements (Kienberger et al. 2009). Some vulnerability maps focus more generally on human welfare rather than a specific sector (Kropp et al. 2006; Thow and de Blois 2008; Yusuf and Francisco 2009), and some studies have used spatial information to highlight multiple vulnerabilities and/or determinants across several sectors (NAST 2001; Barnett et al. 2007).

Despite risk identification being the most common objective, there is disagreement in the literature regarding the extent to which risk identification in itself is, in fact, a worthwhile goal of assessment. Hinkel (2011), for example, argues that vulnerability mapping may be appropriate at local scales to identify vulnerable people, regions or sectors. However, Smit and Wandel (2006), p 289) argue that the goal of vulnerability assessment,

> "is not to produce a score or rating of a particular community's current or future vulnerability. Rather, the aim is to attain information on the nature of vulnerability and its components and determinants."

Building understanding regarding the determinants of vulnerability and their interactions was the second most commonly cited objective for vulnerability mapping, apparent within 29% of the studies reviewed here. For example, O'Brien et al. (2004) use vulnerability maps to identify large-scale patterns of vulnerability, which was then followed by more bottom-up assessments of adaptive capacity at the local scale. In this instance, vulnerability mapping was used as a focal lens for targeting research, with the emphasis on building an understanding of the geography and determinants of vulnerability. Kleinosky et al. (2007) mapped vulnerability for Hampton Roads (VA) in the United States to examine how sea-level rise would interact with other drivers to increase future vulnerability to coastal hazards. Preston et al. (2009) emphasize the use of vulnerability mapping as a stakeholder engagement and education tool. Meanwhile, Baum et al. (2009) emphasize the importance of exploring the spatial dimensions of climate vulnerability by integrating socioeconomic factors with biophysical factors. In addition to understanding determinants of vulnerability, approximately 14% of the studies reviewed here made objective statements regarding the trialing of methods for vulnerability assessment and mapping. For example, Sullivan and Meigh (2005) report on the development of methods for nested vulnerability mapping for water resources. Hence, the assessment was viewed largely as a means of testing approaches to problem orientation rather than facilitating such orientation in itself. Similar objectives are stated by Luers et al. (2003), Vescovi et al. (2005), Torresan et al. (2008), and Alessa et al. (2008).

Just over 9% of the studies reviewed here identify the assessment objective as not simply problem orientation but decision-support. For example, Diffenbaugh et al. (2007) map the global distribution of socioeconomic exposure to climate change, suggesting such information on the potential differential distribution of climate impacts can inform ongoing negotiations regarding international greenhouse gas mitigation efforts. Yusuf and Francisco (2009) compare climate change vulnerability indices across a range of nations in the Asia/Pacific region, and argue that such indices can be used to prioritize the allocation of development assistance for adaptation. Schröter et al. (2004) suggest the vulnerability maps produced by the Advanced Terrestrial Ecosystem Assessment and Modeling (ATEAM) project for Europe were designed to be widely accessible to diverse stakeholders to support decision-making. Karim and Mimura (2008) claim their assessment of tropical cyclone vulnerability in coastal Bangladesh can be used to guide investment decisions for future shelters. Meanwhile, at more regional scales, Sietchiping (2006) argues that the analysis of the distribution of adaptive capacity among agricultural communities in Northwest Victoria (Australia) can be used to prioritize investments in capacity building. The validity of such applications is dependent upon two factors, the first of which is the capacity of vulnerability indices to serve as robust indicators of underlying socio-ecological vulnerability (Kienberger et al. 2009). Barnett et al. (2008) questions the ability of vulnerability assessments and indices to reflect such relevant context. Similarly, Hinkel (2011) argues that while vulnerability assessment may have some utility in identifying vulnerable people and places, suggesting a role for vulnerability mapping, such assessments are an inappropriate basis for policy development and decision-making.

The second factor is the extent to which the assessment of vulnerability is linked to adaptation planning and the implementation of actions to reduce vulnerability. Of the 45 studies reviewed here, only 31% addressed adaptive responses as part of the assessment. Even those studies with decision-support stated as the primary objective addressed adaptation only half the time. This phenomenon reflects a 'knowledge-deficit' bias that exists among institutions, which assume that decision-making is hindered by a lack of information, and, conversely, facilitated with inputs of new intelligence (Hansen et al. 2003; Kellstedt et al. 2008), even if that intelligence lacks a decision context. Despite the abundance of vulnerability assessments that have been conducted for a range of geographic scales and sectors, there is limited evidence linking such assessment practice to decisions that have achieved a reduction in vulnerability. As a consequence, assumptions regarding information about climate change being a barrier to effective adaptation are increasingly being challenged (Hulme and Dessai 2008; Dessai et al. 2009). In fact, Hinkel (2011) argues that, at least at national scales, assessments of vulnerability would seem to offer little knowledge to decision-makers beyond what is already known about challenges and management options. Preston et al. (2009) suggest this might be true at the local scale as well. Instead, what often occurs is that decision-making is hindered not by a lack of knowledge, but by misaligned governance systems, conflicting values, and lack of creativity in positing possible adaptation policies and measures (Clark 2002; Hajer 2003; Adger et al. 2009a; Smith et al. 2009). Hence, the strength in vulnerability maps may lie not in their capacity to support decision-making per se, but rather in their ability to uncover sociopolitical barriers to decision-making by serving as boundary objects that facilitate discourse.

How is the assessment of vulnerability framed?

The concept of vulnerability appears across a range of disciplines, including finance, security, public health, economic development, natural hazards and, of course, climate change (Janssen et al. 2006). Meanwhile, vulnerability maintains its own colloquial, generic meaning independent of disciplinary preferences. This diversity ultimately generates problems for the development of a consistent definition and its operationalization in assessment practice (Preston and Stafford-Smith 2009; Hinkel 2011). One formal definition of the concept of vulnerability can be taken from the literature on sustainability science (White 1974): vulnerability is the degree to which a system, subsystem, or system component is likely to experience harm due to exposure to a hazard, either a perturbation of stress/stressor. This suggests vulnerability is a reflection of the potential for a system to experience harm in response to some external influence, pressure or hazard. The relevant system or process may be an individual or population; a business enterprise or an entire regional economy; a single species or an entire ecosystem. In other words, there is a diversity of values for which vulnerability can be assessed, suggesting the need for some specificity in articulating what is vulnerable in the course of an assessment. Meanwhile, that vulnerability can arise from a diversity of exogenous determinants, for which specificity is also needed. Increasingly, attention is also being given to endogenous determinants of vulnerability that influence the potential for harm, such as individual, community or institutional factors that convey resilience and/or adaptive capacity (Gallopín 2006; Smit and Wandel 2006; Adger et al. 2009a; Smith et al. 2009). The question then arises of how vulnerability mapping exercises operationalize these questions of *vulnerability of what* and *vulnerability to what*.

Given the broad implications of climate change for a range of economic sectors, human and ecological communities, and geographic areas, there is room for assessments to target a broad range of potential vulnerabilities. Accordingly, a number of authors have developed sector or region-specific guidance for assessing climate change vulnerability. Füssel (2008) and Ebi and Burton (2008) present frameworks for human health vulnerability in a changing climate, while a number of assessment frameworks are available for coastal assessment (IPCC CZMS 1992; Klein et al. 1999). Of the 45 vulnerability mapping studies considered here, one-half assessed vulnerability of either coastal systems (27%) or more generally of human well-being and livelihoods (23%). Secondary sectors of focus included agriculture, fisheries and forestry (16%) and water resources (11%). Lesser consideration was given to human settlements/communities (7%), public health (7%) or ecosystems (2%). Meanwhile, approximately 7% assessed vulnerability across multiple sectors.

While it is possible to categorize what is vulnerable along sectoral lines, one can also express vulnerability in terms of value. For example, coasts are valued for their *environmental* role as geological constructs and habitat for flora and fauna. They are also valued for their benefits to *society* in terms of amenity and the *economic* opportunities that arise from such amenity. Finally, they may be valued *culturally* by creating a sense of place, supporting traditional livelihoods or being associated with spiritual significance. Hence, there is a need for precision in problem framing if a map is to emerge from an assessment that can be readily interpreted by stakeholders. Applying the aforementioned ‘quadruple bottom-line’ typology to the 45 studies reviewed here, social (77%) and economic (55%) values were the most common incorporated into vulnerability mapping studies (although multiple values could be represented in a single assessment). This was followed relatively closely by environmental values (52%). Cultural values were in the minority (7%) and, when they were acknowledged, they were always considered in conjunction with other values (e.g., social or environmental), which may reflect a lack of attention to such values and/or difficulties in developing metrics that can represent normative cultural values over space and time.

Meanwhile, for any given vulnerability, there may be myriad driving forces, which necessitates careful consideration of to what a given asset or system is vulnerable. This involves analysis of the factors that determine the potential for harm from exogenous threats as well as the endogenous adaptive capacity of institutions, sectors, and communities. At the macro-level, two broad classes of generic determinants of vulnerability are recognized (Adger et al. 2004; Preston and Stafford-Smith 2009):

1. Biophysical determinants. The physical, biological and ecological factors that influence the potential for harm. Such factors might include climatic conditions, natural hazards, topography, land cover, or primary productivity.
2. Socioeconomic determinants. The social, economic or cultural factors that influence the potential for harm. Such factors might include demography, poverty, trade, employment, gender, or governance.

If the goal of vulnerability assessment is to provide information on the drivers of vulnerability to help inform where adaptation actions may be necessary and beneficial, then once again clarity and specificity in analysis of the determinants of vulnerability is important. This may necessitate careful consideration regarding which of the aforementioned generic determinants are relevant as well as the identification of determinants that are specific to the context of interest. The majority (64%) of the 45 studies reviewed here incorporated both biophysical and socioeconomic determinants in the mapping of vulnerability. Nevertheless, 29% and 7% of studies focused exclusively on biophysical or socioeconomic determinants, respectively. While there is value in considering individual determinants of vulnerability (Clark et al. 1998), in practice, most vulnerability mapping applications seek to develop integrated vulnerability indices for geographic visualization, despite increasing criticism of their utility and appropriateness (Hinkel 2011).

Multiple vulnerability assessment frameworks have emerged that represent different conceptual models of how different determinants interact to influence vulnerability. For example, Turner et al. (2003a); pp 8074–8075) identify two classic approaches to expressing vulnerability across different disciplines as well as a third 'expanded vulnerability' approach (see also Füssel 2007):

- Risk-hazard (RH) models that aim "to understand the impact of hazard as a function of exposure to the hazard event and the dose–response (sensitivity) of the entity exposed."
- Pressure-and-release (PAR) models in which "risk is explicitly defined as a function of the perturbation, stressor, or stress and the vulnerability of the exposed unit."
- Expanded vulnerability (EV) models that "direct attention to coupled human–environment systems, the vulnerability and sustainability of which are predicated on synergy between the human and biophysical subsystems as they are affected by processes operating at different spatiotemporal (as well as functional) scales."

RH models emphasize biophysical processes and direct risk factors that contribute to system sensitivity, but neglect the system's capacity to influence such sensitivity as well as the broader socio-political aspects of vulnerability, such as the role of institutions and adaptive capacity (Turner et al. 2003a). Meanwhile, PAR models place greater emphasis on social processes and entitlements that contribute to vulnerability, but often overlook dynamic relationships and feedbacks among biophysical processes and vulnerability processes at different scales. Turner et al.'s (2003a) EV models are a response to these perceived limitations of RH and PAR models and reflect the evolution in the conceptualization of vulnerability and risk that has occurred over the past decade (Füssel and Klein 2006; Jones and Preston 2011). In addition, another type of approach, social vulnerability/adaptive capacity (SV) models, which focuses on the vulnerability of exposed units to socioeconomic pressures (much like the PAR models), but do not integrate this with information on biophysical stressors, such as climate variability and change, is also apparent in the literature. Such differing perspectives on vulnerability and its determinants are typical of vulnerability assessment practice in general and represent alternative approaches to the critical assessment questions of 'vulnerability of what' and 'vulnerability to what'. Each of these models of vulnerability has been applied in mapping applications, a review of which helps to illustrate the diversity of frames in use among different practitioners. It should be noted, however, that these models are conceptually broad and there is little direct guidance with respect to how they should be operationalized within an assessment (Hinkel 2011).

Risk-hazard models

Available examples of applications of RH models within vulnerability mapping studies largely emphasize exposure to biophysical drivers and hazards and the sensitivity of exposed systems to those hazards, consistent with a dose–response model of effect. Relevant hazards often include sea-level rise, floods, or extreme heat events. Meanwhile, sensitivity may be represented by the relative density of exposed assets (e.g., population or development density) or physiological thresholds (e.g., population age distribution or thermal tolerances). Of the 45 studies considered here, approximately 31% were classified as RH models. The application of RH models is perhaps best represented by a number of coastal vulnerability mapping exercises that have been conducted at local, regional and national scales in Australia (Sharples et al. 2009), Bangladesh (Karim and Mimura 2008); Fiji (Gravelle and Mimura 2008), Turkey (Demirkesen et al. 2008; Alpar 2009) and the United States (Hammar-Klose et al. 2003). Such studies either develop pseudoquantiative, relativistic measures of vulnerability based upon geomorphological characteristics (erodability, subsidence, and tidal variability; e.g., Bryan et al. 2001; Hammar-Klose et al. 2003; Sharples et al. 2009; Torresan et al. 2008) or apply digital elevation models and scenarios of sea-level rise and/or storm surge to assess land areas at risk of inundation and associated exposed assets (e.g., Demirkesen et al. 2008; Gravelle and Mimura 2008; Karim and Mimura 2008; Alpar 2009; DCC 2009). RH models have also been applied to mapping the vulnerability of ecosystems (Bayliss et al. 1997), infectious disease (Bulto et al. 2006), and water resources (Döll 2009). Such studies may invest little effort in understanding the nature of the hazard itself, opting instead to concentrate on those factors that create potential for harm (i.e., sensitivity) should a hazard arise. However, Diffenbaugh et al. (2007) integrate projections of future climate from general circulation models with data for the spatial distribution of material wealth and poverty in mapping global socioeconomic exposure to climate change. While such studies have assisted in identifying susceptible landscapes, infrastructure, and populations, they have tended to neglect a broad range of characteristics and processes, particularly social, economic, political and cultural factors that act to modify both exposure and sensitivity in space and time. Hence, while described as assessments of vulnerability in the conventional sense, RH models are inconsistent with the more holistic and integrated approaches to vulnerability assessment associated with PAR and EV models (Davis 2004; Turner et al. 2003a).

Social vulnerability models

The antithesis of RH vulnerability assessments are social vulnerability (SV) models that focus specifically on characterizing the geography of socio-political determinants of vulnerability that influence how human and natural systems cope with or respond to stress. This concept is often expressed in the climate change literature as adaptive capacity. Such models of vulnerability were evident in just 7% of the studies reviewed here. Such studies emphasize the fact that physical environmental drivers and hazards are one component of vulnerability, but the ultimate outcomes associated with such physical processes are quite often dependent upon the socioeconomic context in which these processes occur (Hilhorst and Bankoff 2004). The spatial distribution of people and other assets of human value on the landscape determines the level of human exposure to climate variability and climate change. Yet, characteristics of different populations, settlement types, risk management practices, or cultural behaviors may mitigate or enhance the risk of adverse outcomes during a hazard. A number of SV indices have been developed at a range of geographic scales in the context of climate change vulnerability. Vincent (2004) mapped social vulnerability to climate change at the national scale for Africa. Kienberger et al. (2009) examined socioeconomic vulnerability in the Salzach catchment of Australia, based upon indicators of sensitivity as well as adaptive capacity. Sietchiping (2006) mapped socio-cultural, economic, and institutional/infrastructure metrics of adaptive capacity for communities in the wheat belt of Victoria, Australia.

The current examples of SV assessments have contributed to a significant expansion of the boundaries commonly used by practitioners, and have introduced new forms of relevant knowledge into climate change assessment activities. Such knowledge is often argued to provide spatial context regarding social vulnerability and disadvantage that can help avoid 'one size fits all' management interventions (Cutter et al. 2003). The principle advantage of such methods is that they often use data based upon a common sampling frame and thus enable robust multivariate statistical treatment of vulnerability indicators factor analysis and principal component analysis (Baum et al. 2009). However, such approaches often develop spatial context from a top-down perspective, relying upon large spatial data sets of population and housing as proxies for complex social and cultural phenomena at the local scale (Vincent 2004; Baum et al. 2009; Kienberger et al. 2009). Significant questions arise as to whether the context generated by such methods is relevant to vulnerability processes or simply an artificial construct based upon a priori assumptions. Commonly used data do not provide information regarding human perceptions of risk, behavioral responses, or the robustness of political institutions. The generic nature of such metrics also means they lack specific information regarding to what communities are vulnerable, assuming that different stressors are effectively fungible. From a problem orientation perspective, the use of top-down data can still broker understanding regarding the importance of socioeconomic drivers of change, but without more bottom-up understanding of vulnerability processes and consideration for a broader range of decision criteria, such knowledge regarding vulnerability may be adequate to guide robust and legitimate decision processes (Barnett et al. 2008; Hinkel 2011).

Pressures-and-release models

While RH and SV models of vulnerability collectively capture multiple components of biophysical and social vulnerability including hazard, exposure, sensitivity and adaptive capacity, the fact that each model neglects elements of the other means both they are incomplete. For example, Clark et al. (1998) note that social vulnerability significantly modulates community physical vulnerability to flood events. Diffenbaugh et al. (2007) find a substantial degree of geographic coincidence between physical changes in the climate system and societal exposure to those changes. On the other hand, Gbetibouo and Ringler (2009) note that those agricultural communities and regions associated with low adaptive capacity may be geographically distinct from those with the greatest exposure to climate change. Therefore, without an integrated view of climate vulnerability and social vulnerability/adaptive capacity within a defined context, one is likely to draw erroneous conclusions regarding the spatial distribution of vulnerability (Barnett et al. 2008; Preston et al. 2009).

More holistic approaches to vulnerability assessment, which draw upon PAR models of assessment in pursuance of more systemic understanding of human/environment interactions, are being used increasingly. Of the 45 studies reviewed here, 51% could be categorized as PAR assessments. Such integrated assessments reflect the fact that conditions of social vulnerability may exist independent of a climate hazard, but the implications of that vulnerability may become acutely apparent when exposure to such a hazard occurs. In fact, those locations at greatest risk of climate variability and change are those that face the dual challenges of climatic extremes and acute social vulnerability and low adaptive capacity. Both societal impacts of the European heat wave of 2003 and Hurricane Katrina in 2005 are oft-cited demonstrations of this phenomenon (Stott et al. 2004; Poumadere et al. 2005; Vandentorren et al. 2006; Green et al. 2007; Laska and Morrow 2007; Finch et al. 2010)—situations where hazard, exposure, sensitivity, cultural norms, and institutional weaknesses conspired to exacerbate harm. The biophysical component of PAR vulnerability models can be based upon physical indicators or process-based physical models (Schröter et al. 2004). Meanwhile, the socioeconomic indicators are often based upon secondary data sources such as census data or other routinized data collection, although primary data may be collected for highly focused assessments (Adger and Kelly 1999; O'Brien et al. 2004; Hahn et al. 2009). While the methodological challenges of integrating such disparate information are significant (see "By what methods will vulnerability be assessed?"), one can also question whether such integration is in fact conceptually legitimate. Despite the inherent coupling of human and environmental systems, their integration without first defining the relationships between the two may simply lead to arbitrary conclusions regarding their relative contributions to vulnerability.

Nevertheless, as indicated by the literature, a number of studies have braved such concerns to produce integrated spatial assessments of vulnerability to climate variability and change. At a global scale, Yohe et al. (2006) and Thow and de Blois (2008) integrate climate change projections with metrics of education, wealth, resource access and population to map interactions between biophysical and socio-political aspects of vulnerability. Yusuf and Francisco (2009) applied similar approaches to map climate change vulnerability of different nations and sub-national regions in the Asia/Pacific region. The ATEAM project integrated output from a quantitative biophysical model of the continent's ecosystems and natural resources with an adaptive capacity index (Schröter et al. 2004; Berry et al. 2006). Sharma and Patwardhan (2008) estimate vulnerability to tropical cyclones among different districts in India while Preston and Jones (2008) combine biophysical, socioeconomic, and natural resources management indicators to map catchment vulnerability in Australia. The majority of such applications, however, have been undertaken at the municipal or local level. For example, Wu et al. (2002) and Kleinosky et al. (2007) base their maps of the vulnerability of coastal communities on indicators of poverty, gender, race and ethnicity, age, and disabilities that were integrated with scenarios of sea-level rise and storm surge flooding. Hebb and Mortsch (2007) take a similar approach examining flood vulnerability in the Upper Thames watershed. Similarly, Vescovi et al. (2005) and Baum et al. (2009) focus on urban environments, but examine vulnerability of human health to extreme heat events specifically. Preston et al. (2009) use metrics of exposure, sensitivity and adaptive capacity to map the vulnerability of coastal local government areas in Sydney Australia to a range of climate change hazards (Fig. 1).

Expanded vulnerability models

Expanded vulnerability (EV) models are rare within vulnerability mapping, with characteristics of EV models apparent within just 9% of reviewed studies. This may be linked to the challenges of representing complex interactions among vulnerability determinants spatially. Maps are often developed for a fixed geography and a fixed resolution and provide limited consideration for processes external to the region of interest. This is due perhaps in part to the limitations placed on assessment by data availability, the complexity of human/environment interactions, and the desire of researchers and stakeholders to focus on a limited set of questions, over limited temporal and spatial scales. In so doing, however, assessments fall short of representing the interactive and dynamic nature of vulnerability (Patt et al. 2004; Turner et al. 2003a, 2003b), which propagates over multiple spatial and temporal scales. Many assessments consider a limited suite of exogenous pressures, such as climate change (although there are a number of examples of climate change being examined in the context of other global changes). In addition, many vulnerability mapping exercises are limited with respect to examination of the role of integration among institutions, entitlements, and agency in determining vulnerability and adaptive capacity. Such issues and gaps in assessment may simply be an act of convenience rather than necessity. O'Brien et al. (2004) examine both climate stressors as well as the pressures of globalization, demonstrating that multiple drivers and multi-scaled processes can in fact be incorporated in a vulnerability assessment. Furthermore, both O'Brien et al. (2004) as well as Preston et al. (2009) integrate top-down regional-scale assessments of vulnerability with bottom-up assessments at the local scale. Similarly, Luers et al. (2003) and Acosta-Michlik and Espaldon

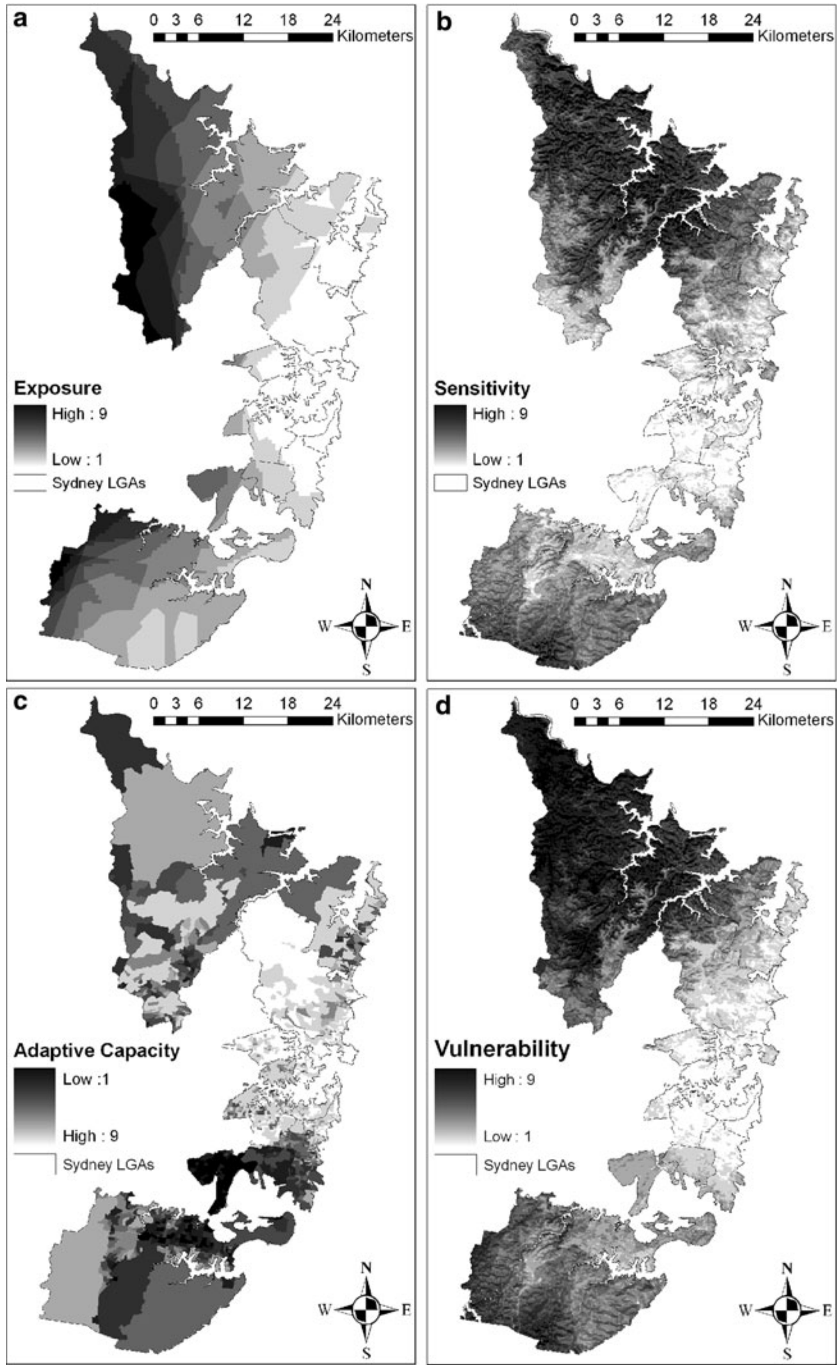

Fig. 1 Examples of a pressure-and-release (PAR) model of vulnerability from the Sydney, Australia region (Preston et al. 2009). **a–c** Three components of vulnerability to bushfire: exposure (**a**), sensitivity (**b**), and adaptive capacity (**c**). **d** Integration of these components into net vulnerability

(2008) map agricultural vulnerability at the local scale, based on local biophysical conditions and behaviors as well as national markets and globalization. Yet even these applications seem to fall short of the idealized EV approach to vulnerability assessment, suggesting the challenges associated with dynamic, multi-scale assessment have yet to be adequately overcome (Cash and Moser 2000). In fact, vulnerability maps alone may be inadequate for representing such complexity and are perhaps better employed as one of a portfolio of mutually supporting assessment tools.

By what methods will vulnerability be assessed?

The 45 mapping studies reviewed here reveal that, even when using the same conceptual model or framework for vulnerability, individual studies may differ significantly with respect to the specific methods and processes used in the assessment. In the application of particular methods, practitioners encounter a range of technical challenges, some of which are common to geographers and some which arise from the complexity of climate change and the conceptualization of vulnerability. While a full discussion of methods used in individual studies is beyond the scope of this review, some key cross-cutting issues relevant to mapping methods can be readily identified.

Absence of 'best practice'

One of the over-arching challenges in vulnerability mapping is the lack of a standardized methodology. Of the various vulnerability models discussed in "How is the assessment of vulnerability framed?", for example, there is little if any guidance available for one to decipher why one model is better or worse for a particular assessment than another. Hence, assessment practice has suffered from a parallel challenge of what methods to pursue in undertaking assessments (Simpson and Human 2008; Preston and Kay 2010). Australia has recently experienced a rapid expansion of climate change risk assessments at the local government (LGA) scale, many of which have been funded through a Commonwealth grant program that requires assessments to be completed in accordance with a risk management framework (AGO 2006; Preston and Kay 2010). Nevertheless, even within this framework, assessments have employed a diverse array of methods, limiting comparisons across LGAs with respect to climate risk (Preston and Kay 2010). Similarly, Hinkel (2011) argues that existing conceptual models of vulnerability (e.g., Turner et al. 2003a) provide only rough guidance that does little to constrain the choice of methods for developing vulnerability metrics. This is perhaps representative of the relatively recent emergence of vulnerability as a unifying theme for sustainability (Turner et al. 2003a), as well as the diverse disciplines that are currently engaged in climate change assessment (Preston and Stafford-Smith 2009). However, it has also been argued that the perceived benefits and arguments in favor of vulnerability assessment have not been adequately critiqued and it may, in fact, be inappropriate for a range of intended applications (Hinkel 2011). In the absence of greater guidance regarding how to undertake an assessment as well as which methods and tools are useful in which contexts, assessments will likely continue to be dominated by arbitrary methods, which may, in some instances, inhibit effective learning and outcomes.

Scales of assessment

In mapping vulnerability, consideration must also be given to the issue of scale, which can be interpreted in a variety of ways depending on normative views of what aspects of scale are important (Wilbanks and Kates 1999). Quite often, scale is interpreted in a geographic context, such as the geographic boundaries of a study area and, as in the case of a spatial assessment, the resolution of geographic units over which an assessment will be conducted. However, assessments also have temporal scales, particularly in climate change applications, where both historical information about climate trends and scenarios of climate futures may be incorporated into the analysis. Alternatively, one can address scale associated with the hierarchy of social systems, such as levels of governance (local vs federal government) or the individual versus the community. To add yet another perspective, the literature also distinguishes between 'top down' and 'bottom up' approaches to assessment (O'Brien et al. 2004; Jones and Preston 2011). The former tend to be technocratically driven based upon the integration of 'objective' data and an emphasis on exogenous determinants of vulnerability. Meanwhile, the latter tend to focus on the perceptions, values and behaviors of individual agents, and thus emphasize endogenous determinants of vulnerability such as worldviews and institutional structures and processes.

With respect to spatial scale, two considerations are particularly relevant to assessment design. The first is the geographic bounds of the system of interest. Quite often, geographic bounds are determined by the availability and accessibility of relevant data (Adger and Vincent 2005), rather than the dynamics of the system. To examine the issue of geographic scale in vulnerability assessment practice, the scales associated with the vulnerable system (vulnerability of what) and the determinants of vulnerability (vulnerability to what) were recorded for the 45 assessments considered in the current study. Five arbitrary scales were selected:

- *Local* Geographic area, process or behavior associated with an individual local government area or municipality
- *Regional* Geographic area, process or behavior associated with a collection of local government areas or catchments, or an individual state or province
- *National* Geographic area, process or behavior associated with an individual country or national scale process
- *Continental* Geographic area, process or behavior associated with an individual continent or agglomeration of nations (e.g., Asia–Pacific region)
- *Global* Geographic area, process or behavior corresponding with the global extent

For any given study, the question of what is vulnerable and, particularly, to what it is vulnerable can span multiple scales. To account for this, for each of the 45 studies

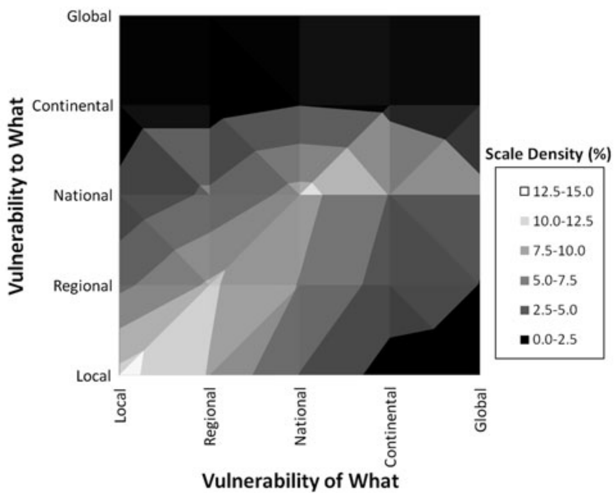

Fig. 2 Density plot of spatial scales addressed across the 45 climate change vulnerability mapping studies reviewed here. For each study, the scales addressed with respect to vulnerability of what were plotted against the scales addressed with respect to vulnerability of what, resulting in a matrix. For a given study, a value of 1 was entered in a matrix cell if the study included the associated scale. Cell values were summed across all 45 studies and expressed as a percentage. Cells with higher values indicate those scales that are most commonly captured within vulnerability mapping studies. The bias on the vulnerability of what axis to higher spatial scales is due to the tendency for analyses to aggregate measures of vulnerability to higher geographic scales. For example, national measures of vulnerability may be based upon the aggregation of local measures derived from local determinants

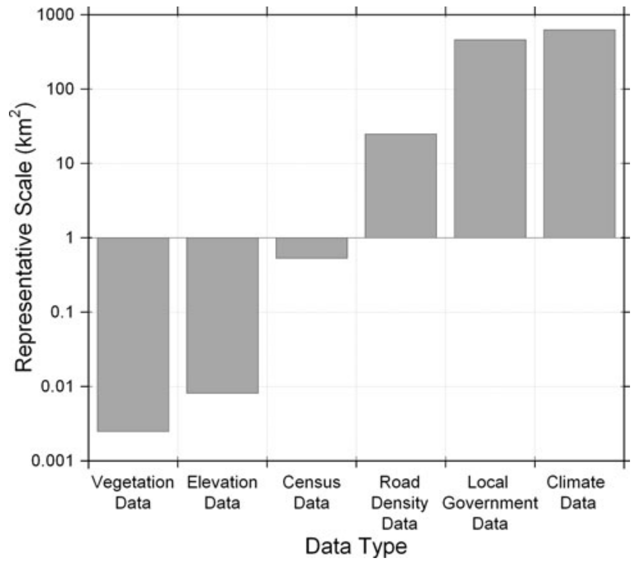

Fig. 3 Spatial scale differences among different data sources used commonly in vulnerability mapping. Representative scales represent the average area associated with different raster and vector data sets for different types of data (based on data used in Preston et al. 2009)

reviewed, the entire geographic range of both vulnerability of what and vulnerability to what was recorded and this information was aggregated to yield an overall view of preferences in the bounding of vulnerability mapping studies (Fig. 2). In so doing, it becomes clear that vulnerability mapping practice reflects a strong local orientation, consistent with the emphasis in the vulnerability literature on the importance of understanding the ‘vulnerability of place’ that emerges from local context. However, a number of studies, particularly those targeting the developing world (e.g., Africa and the Asia/Pacific region; Vincent 2004; Yusuf and Francisco 2009) favor assessment at the national-scale and/or international comparisons, likely due to a lack of data on determinants of vulnerability at local and regional scales. Nevertheless, the majority of studies (73%) spanned multiple scales. For example, some studies, such as that of O’Brien et al. (2004), examine vulnerability at the district/regional scale in India, followed by village/local assessments. Similarly, Preston et al. (2009) undertook a vulnerability mapping exercise for 15 local governments in the metropolitan Sydney, Australia region. Yet this was followed by in-depth interviews within a subset of local governments to build understanding regarding location-specific institutional dimensions of vulnerability.

The other consideration related to spatial scale is the resolution of the assessment. This is perceived as particularly critical for those interested in spatial planning at the local scale. High-resolution insights regarding future changes in the climate system and its consequences have long been challenged by the computational demands of climate modeling (Giorgi 2008). Global climate model simulations have historically been available only at very coarse resolution (e.g., 300 × 300 km grid cells). The expansion of down-scaling techniques has greatly enhanced the potential to project future climatic conditions at more localized scales. Yet, even with such tools, a single grid cell may span a dozen or more square kilometers. Perhaps more importantly, making the most of down-scaled climate information is challenged by scale mismatch with respect to other forms of data that may be used in vulnerability assessment, such as census and/or property data or other characteristics of the physical, social or ecological environment. Furthermore, as scale differences among different data may span multiple orders of magnitude (Fig. 3), any attempt to integrate biophysical and socioeconomic information requires some degree of aggregation and data reconciliation. However, interpolation of data or area averaging and aggregation can introduce errors and spatial bias in statistical relationships due to the modifiable areal unit problem (Openshaw 1984; Green and Flowerdew 1996; Cao and Lam 1997).

These scale discrepancies persist into the temporal realm. Given that coupled human/environment systems are undergoing change simultaneously, assessments that neglect such temporal dynamics miss an important component of climate risk (Nicholls et al. 2008). The logical starting point for vulnerability mapping studies is the consideration of current vulnerability, which provides a baseline against which future changes in vulnerability can be compared. Tools for projecting future climatic conditions are readily available, and thus the biophysical component of vulnerability assessment often benefits from quantitative understanding regarding future changes in, for example, temperature, rainfall or sea-level rise. These may be used subsequently to perturb physical or biological models of natural resources such as water, ecosystem structure and function, or agriculture and forestry. Nevertheless, only approximately two-thirds of vulnerability mapping studies reviewed here made use of such biophysical scenarios in the assessment, suggesting that building understanding about current vulnerability is often viewed as a useful starting point in and of itself. Meanwhile, capturing the temporal dynamics associated with social vulnerability and adaptive capacity is, perhaps, more challenging (Schröter et al. 2004; Nicholls et al. 2008). Only approximately one-third of studies reviewed here used scenarios of future social or economic change in the mapping of vulnerability. Rather, more often than not, understanding of future biophysical changes is superimposed on the current demographic and socioeconomic state of affairs (e.g., Vescovi et al. 2005; Hebb and Mortsch 2007; Karim and Mimura 2008; Preston et al. 2009; Yusuf and Francisco 2009). The ATEAM project (Schröter et al. 2004), however, developed a consistent suite of scenarios that were applied to both biophysical modeling and adaptive capacity to enable the forecasting of integrated vulnerability. Similarly, Nicholls et al. (2008) highlight the limited use of scenarios in coastal vulnerability assessments while illustrating how this can be resolved through the development of internally consistent biophysical and socioeconomic scenarios.

Many of these distinctions regarding scale are arbitrary, if not artificial. There are no fundamental rules for bounding systems, other than the selection of bounds should be determined by the goals of the assessment and the interests of stakeholders the assessment intends to serve. Yet quite often, assessment bounds are determined by the availability and accessibility of relevant data (Adger and Vincent 2005). Adger et al. (2009b) and Eakin et al. (2009) argue that vulnerabilities of seemingly disparate communities, sectors and regions are linked through teleconnections associated with processes of trade, communication, migration, and international policy. Vulnerabilities at the local scale can be mobilized in a global economy to have implications elsewhere (a phenomenon known in physics as ‘action at a distance’). Therefore, vulnerability is ultimately ‘nested’ in overlapping scales of determinants. This conceptualization of nested and teleconnected vulnerability is consistent with EV assessment models, which also emphasize interactions across scales and feedbacks among determinants of vulnerability. Effectively mapping vulnerability in a manner that reflects such complexity can be challenging, and, again, one can question whether current mapping approaches are too static in their treatment of scales. Nevertheless, for practical purposes, assessments must be bounded in some manner to make the problem tractable to researchers and stakeholders alike. Hence, there are often rational justifications for the bounding of potentially vulnerable systems, but those reasons should be made explicit.

Management of uncertainty

While addressing uncertainty is commonplace among mathematical and process-based models, the often qualitative, or at least semi-quantitative, nature of many vulnerability assessments as well as the normative judgments they entail make determining the appropriate mechanisms for managing uncertainty difficult. This is exacerbated in climate change applications by the attempt to develop insights regarding future states that are associated with significant aleatory and epistemic uncertainty (Patt et al. 2004). Unfortunately, the tendency within vulnerability assessments is to neglect the issue of uncertainty almost entirely—an occurrence that is likely to undermine the uptake of vulnerability assessments in decision support.

One of the most common analytical approaches to vulnerability assessment is through the construction of vulnerability indices, based upon the interrogation of a wide range of data sources. Often, principal component analysis or other factor reduction methods are used to reduce large numbers of putative vulnerability indicators to those that reflect the dominant variance in the available data. Such approaches represent statistically robust means of analyzing large data sets, but Adger and Vincent (2005) note a number of limitations including the constraints placed on the index by data availability and the reliance upon a priori benchmark indicators of vulnerability. For example, none of the vulnerability mapping studies reviewed here utilized primary data to represent biophysical determinants of vulnerability, and only 9% collected some form of primary data regarding socioeconomic determinants. This reliance upon data developed for purposes other than vulnerability assessment raises doubts as to the relevance of those data. Adger and Vincent (2005), for example, argue that vulnerability indicators should first be selected based upon theoretical linkages between different drivers of vulnerability and socioeconomic phenomenon, and apply this approach in developing indices of adaptive capacity for African nations. Similarly, Preston et al. (2009) first developed conceptual models of the relationship between

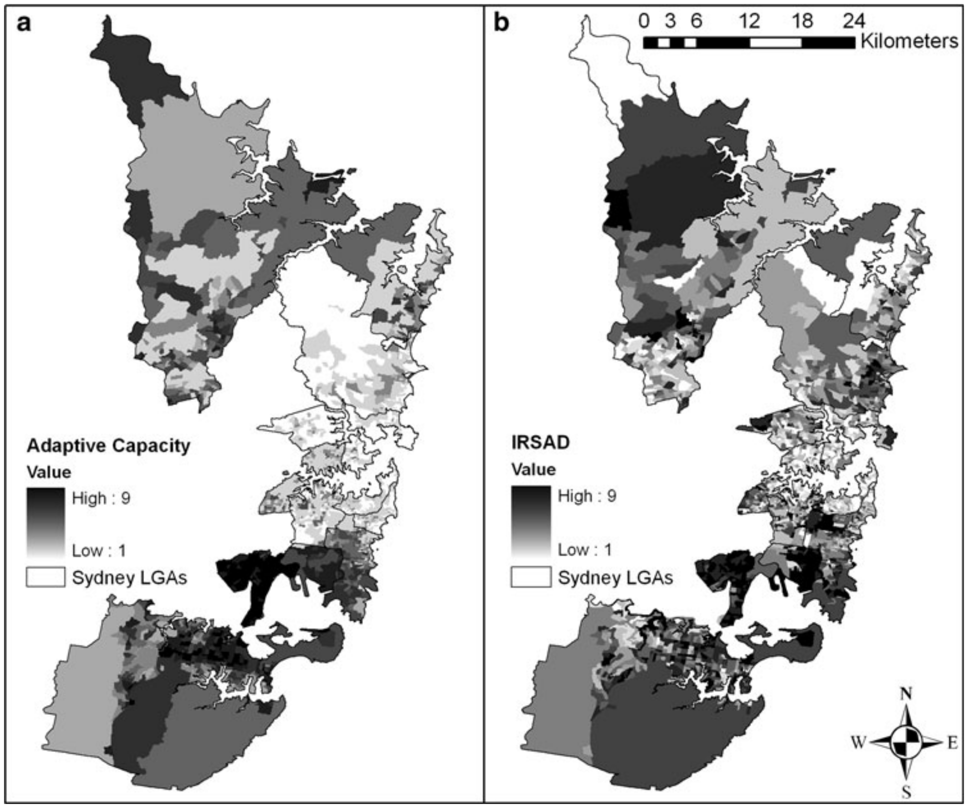

Fig. 4 Uncertainty in social vulnerability/adaptive capacity in the Sydney, Australia region arising from different framings. **a** Metrics of adaptive capacity based upon household indicators of income, education and access to technology as well as local government performance metrics such as per capita expenditures on community, health and environmental services (as in Fig. 1; Preston et al. 2009). **b** Index of Social Advantage/Disadvantage (IRSAD) based solely upon household indicators, normalized to a nine-point scale as in **a** (Adhikari 2006). Comparison of the two maps reveals areas of both significant convergence and divergence

climate, natural hazards, adaptive capacity and social and ecological outcomes and then used these to select relevant vulnerability indicators. Nevertheless, as different methods of constructing indices can yield highly divergent maps of vulnerability (Fig. 4), some assessment of the sensitivity of the distribution of vulnerability to methods is warranted. For example, Preston and Jones (2008) examined five indicators of climatic and non-climatic vulnerability of water resources in Australian catchments, and used the standard deviation in ranked indicators to identify those catchments where indicators were in agreement and those where indicators were more divergent in their response. In practice, however, such sensitivity analyses are rarely undertaken for vulnerability metrics. Furthermore, once diverse determinants of vulnerability are collapsed into a single index, it may be difficult to subsequently diagnose the drivers of vulnerability at different geographic locations without deconstructing the index into its constituent components (Clark et al. 1998).

Another approach to managing uncertainty in vulnerability mapping is through the use of multiple alternative scenarios of socioeconomic and biophysical states to explore the sensitivity of vulnerability to input assumptions. For example, Nicholls et al. (2008) present multiple global scenarios for coastal vulnerability assessment, based upon the IPCC's SRES scenarios (Nakicenovic et al. 2000). Döll (2009) also uses IPCC scenarios to assess global groundwater vulnerability in response to future climate change, population growth, and development. Liu et al. (2008) applied similar methods to assessing food insecurity in Sub-Saharan Africa. Schröter et al. (2004) developed different internally consistent and spatially explicit scenarios of climate change, socioeconomic change, ecosystem response and adaptive capacity as part of the ATEAM project (see also Berry et al. 2006). Generic socioeconomic scenarios have been developed for the UK at national and regional levels (e.g., UKCIP 2000; OST 2002; Dahlstrom and Salmons 2005) and subsequently used in vulnerability mapping exercises to provide a set of internally consistent social, economic and demographic changes. While such approaches enable the exploration of alternative futures, they do not necessarily address the challenges of determining the likelihood of those alternatives. Furthermore, as mentioned previously, scenarios of future states are used inconsistently in vulnerability mapping, particularly with respect to scenarios of socioeconomic change.

This 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. McCall (2003) and O'Brien et al. (2004) warn that maps can convey a false sense of precision and legitimacy to stakeholders. Meanwhile, Preston et al. (2009) argue that stakeholder preoccupation with maps and their validity can potentially derail other assessment and engagement activities. Ideally, vulnerability assessments should be validated against observed data regarding relevant adverse outcomes. However, attempts to validate measures of vulnerability against such databases have proved challenging (Adger et al. 2004; Adger and Vincent 2005). Adger et al. (2004) note that correlations between climate change vulnerability indicators and mortality outcomes in natural disasters often are poor. On the other hand, Preston et al. (2009) found a high degree of spatial correlation between their maps of bushfire vulnerability based on vulnerability indicators and the distribution of observed bushfire events. More troubling, however, is the fact that, quite often, outcome data that can be used for validation purposes are simply not available (Patt et al. 2004). The absence of validation indicates that while vulnerability assessment may be useful for describing and diagnosing potential determinants of vulnerability on landscapes, their use in predictive applications may be significantly limited.

Who participates and how are results used to facilitate change?

Vulnerability maps are constructs that emerge from those individuals and institutions that participate in the assessment process. Participants influence assessment objectives; problem framing; the selection and application of frameworks, methods and tools; and, perhaps most importantly, they are instrumental to the translation of assessment results into action. Clark and Majone (1985) present a typology of roles in assessments such as technical experts (e.g., scientists), policy makers (e.g., governments), or interest groups (e.g., community groups or advocacy organizations). The actors or stakeholders that play these various roles contribute their own suite of inputs and processes to an assessment and seek to satisfy one or more individual or societal goals. Missing stakeholders and key assessment roles create the potential for gaps in the assessment and/or the preferential focus of an assessment on a limited set of determinants or scales. Hence, robust assessment, including mapping, is dependent upon the recruitment of stakeholders into the process that represent a comprehensive and effective balance of roles (McCall 2003; Corbett 2009).

Participatory approaches to vulnerability mapping can help facilitate problem orientation among stakeholders (Shaw et al. 2009). Participatory assessments enable practitioners to draw upon stakeholder knowledge and values to aid in defining the system of interest and overcoming the common challenges that arise in assessment design and implementation (Shaw et al. 2009). Brown (2005), for example, distinguishes between five different knowledge domains that contribute to decision-making: individual, community, specialized, strategic, and holistic. Unfortunately, scientific assessment generally (Cash et al. 2002), and climate change vulnerability assessment specifically, rely preferentially upon specialized, academic knowledge. Chambers (2006) notes that the expansion of geospatial tools is promising, yet can also lead to the marginalization of stakeholders due to the necessary training, resources and expertise needed to apply complex geospatial tools. Of the 45 studies reviewed here, for example, evidence of stakeholder engagement was apparent in only 40% of the studies. This is particularly problematic if, as some clearly intend, vulnerability maps are to be used to prioritize policy decisions such as investments in adaptation (McCall 2003; Fraser et al. 2006). For example, when one examines just those studies where decision support was stated as the leading objective, the percentage with stakeholder involvement increases only to 50%. This also explains the limited consideration of adaptation responses within vulnerability mapping studies. If those participants who might be in a position to use assessment outputs to facilitate adaptive responses are not involved in the assessment, then there are limited pathways by which that facilitation can occur. The lack of stakeholder participation also raises questions regarding procedural justice in assessment processes (Quan et al. 2001; McCall 2003; Chambers 2006; Corbett 2009) and, therefore, the salience and legitimacy of resulting vulnerability maps (McCall 2003; Corbett 2009). There is no reason why stakeholders should not be included in, for example, the delineation of geographic boundaries for the assessment, the scale at which it should be conducted, the relevant metrics for assessment as well as the relative weights individual metrics (both quantitative and qualitative, positive and normative) should receive (Sietchiping 2006). Furthermore, over the past decade, the value of citizen science has been increasingly recognized and applied to support environmental management (Bäckstrand 2003; Lee et al. 2006; Goodchild 2007). Other non-traditional forms of science, such as the use of anecdotal and experiential knowledge held by individuals or recorded in informal archives, are also penetrating into the climate change and sustainability arena (Reidlinger and Berkes 2001; Robertson and McGee 2003; Duerden 2004; Peppler 2009). Careful consideration should therefore be given to potential trade-offs between technical rigor, scientific credibility, and the use of 'state-of-the-art' methods versus assessment legitimacy, stakeholder education, and stakeholder uptake of assessment findings.

Enhancing capacity for vulnerability mapping

The proliferation of spatial planning, adaptation planning, and 'evidence-based' decision-making indicates that demand for climate change vulnerability mapping, in its various incarnations, is likely to continue to increase in the future. What is not clear, however, is which approaches and methods are most appropriate in different systemic contexts (Næss et al. 2006), nor is it clear how practitioners can overcome the various challenges associated with problem framing, methods and communication. As a starting point, practitioners can benefit from closer scrutiny of other areas of geography, vulnerability mapping, and visual communication where there is already established practice (Table 2). For example, many of the attempts to map vulnerability to climate change have been influenced by analogous (and often earlier) work mapping social and biophysical vulnerability to natural hazards in the context of disaster management (e.g., Cutter et al. 2003). In some instances, methods have been co-opted and the results have simply been reinterpreted in the context of climate change (Clark et al. 1998; Baum et al. 2009; Kienberger et al. 2009; Yusuf and Francisco 2009). In others, methods have been expanded to incorporate information about climate change and/or future socioeconomic states (Schröter et al., 2004; Kleinosky et al. 2007; Preston et al. 2009). In addition to learning from other disciplines, a range of specific activities that may assist in further developing the practice of climate change vulnerability mapping for supporting social learning and vulnerability reduction are outlined below.

Table 2 Knowledge domains that can inform climate change vulnerability mapping

Knowledge domain	Representative studies
Ecological vulnerability	Wickham et al. (2000)
	SOPAC (2005)
	Halpern et al. (2008, 2009)
	Eigenbrod et al. (2010)
	Tran et al. (2010)
Natural hazards and disaster management	Zerger and Smith (2003)
	Cutter et al. (2003)
	Bankoff et al. (2004)
	UCD (2004)
	Peduzzi et al. (2005)
Geographic medicine and epidemiology	Glass (2000)
	Kistemann et al. (2002)
	Elliot and Wartenberg (2004)
	Parrott et al. (2007)
	Reid et al. (2009)
Risk perception and communication	Weinstein and Sandman (1993)
	Lipkus and Hollands (1999)
	Brown et al. (2006)
	Bostram et al. (2008)
	Dransch et al. (2010)
Participatory mapping	McCall (2003)
	Corbett (2009)
	Patiño and Gauthier (2009)
	Frazier et al. (2010)
	Gaillard et al. (2010)

Boundary critique

Perhaps the most fundamental challenge in undertaking spatial assessments of climate variability is the ongoing maintenance of 'boundary critique'—the critical analysis of the manner in which assessments are bounded including assessment goals, the processes by which assessments will be conducted, the geographic extent, the relevant stakeholders and institutions and the assumptions incorporated within the assessment (Midgley and Reynolds 2004). In short, boundary critique is the process of continually asking the four core questions presented in "Approach to this review" throughout the process of assessment. For example, the failure for many assessments to consider interactions across scales or, alternatively, to embrace the use of diverse types of knowledge within an assessment reflect decisions about system boundaries. Systems must be bounded, and thus such decisions must invariably be made if the scope of an assessment is to be managed, but those decisions should be reasoned and explicit rather than arbitrary. Ideally, system boundaries should be aligned with the management context for which possible policy interventions are planned. This principle has emerged from natural resources management where management practice has shifted over time from bounding systems based upon arbitrary or geopolitical boundaries to bounding systems based upon ecosystem structure and function (Slocombe 1993; Grumbine 1994; Wrona and Cash 1996).

Surveillance systems for vulnerability

The growing availability of geospatial information and tools has enabled significant inroads into understanding the geography of vulnerability. Nevertheless, there is still a need for integrated observing systems for global change that span physical, ecological and social dimensions, as most of the key questions facing economic development and human and environmental welfare span these dimensions. Such systems need to collect information on both drivers of change as well as outcomes that can contribute to understanding of the functional relationships between the two over both space and time. For example, disaster databases such as the international Emergency Disasters Database (EM-DAT) and the Spatial Hazard Events and Losses Database, US (SHELDUS) contain spatial information on the adverse consequences of natural disasters (Cutter and Emrich 2005; Peduzzi et al. 2005; CRED 2009; HVRI 2009). However, such databases are affected by significant spatial and temporal reporting biases (Gall et al. 2009), and they often provide very little information regarding underlying drivers of vulnerability that contribute to such outcomes. Meanwhile, the limited capacity of developing nations to make use of current geospatial technologies is well-documented (McCall 2003; Corbett 2009). Preston et al. (2009) note that disparities with respect to access to digital data for community attributes and personnel skilled in their use can be found within the developed world as well. Hence, investments in the long-term improvement of outcome databases, both with respect to spatial extent and resolution as well as the type of data collected, may lead to significant expansion of investigations into the determinants of vulnerability. Such data acquisition must occur in tandem with vulnerability data management systems that facilitate access to and sharing of data as well as the underlying metadata needed to assess data quality and enable reproduction of vulnerability indicators, indices, and maps.

Scenarios for the future

If the goal of vulnerability assessment is to elucidate the drivers of future vulnerability to climate change and, subsequently, assist in making decisions regarding where investments should be made to reduce current and future vulnerability, then assessments must attempt to reflect future states. This invariably leads one to the development of future scenarios to represent plausible, yet uncertain future trajectories in relevant determinants of vulnerability. The work of Schröter et al. (2004) and Nicholls et al. (2008) demonstrate the capacity and utility of such scenarios for assessments, yet comparable applications are quite limited. This is particularly the case for assessments at the regional or local scale, where spatially explicit information regarding future population growth, urban development, technology deployment and management interventions are in short supply and challenging to develop. Where confidence in spatial realizations of the future is low, multiple scenarios may be used to represent alternative plausible futures and/or to frame different 'if…then' questions. Yet, Nicholls et al. (2008, p 89) stress the importance of scenarios remaining "explicit, transparent and open to scientific debate concerning their realism and likelihood."

Expanding the toolkit of assessment methods

The ever-increasing number of methods and tools for undertaking climate change vulnerability assessments, including spatial assessments, creates challenges to assessment practice in and of itself. How should institutions proceed with developing an approach to assessment, given the range of case studies and guidance currently available? While much of the existing guidance suggests that assessments should be 'built-for-purpose' (Preston and Stafford-Smith 2009), in truth, most assessments are likely to pursue multiple objectives (although not all objectives may be made explicit), and those objectives may increase with the number and diversity of stakeholders. There is unlikely to be one 'optimal' methodological approach to assessment, and, in fact, agreement around the implications of scientific inquiry for decision-making is more likely to emerge when multiple assessments are undertaken from different perspectives (Clark and Majone 1985). As such, greater focus should be placed on expanding the range of approaches for mapping vulnerability as well as subsidizing vulnerability mapping with multi-method approaches to assessment. Some examples of assessment approaches that appear in the literature, but have yet to become mainstream in the context of climate change vulnerability mapping, are summarized in Table 3. Approaches such as agent-based modeling, nested analyses, cluster analysis, and Bayesian networks can be used directly in the mapping of vulnerability. Other techniques can also be pursued within broader assessment frameworks that incorporate iterative analyses or combine top down and bottom up methods in recognition of the fact that a map is just one of many potential forms of knowledge that might inform vulnerability and adaptation.

Assessment evaluation

Finally, frameworks for the evaluation of vulnerability assessment and mapping activities are needed. For example, Corbett (2009, p 36) argues that any participatory mapping exercise should be evaluated for the "quality, completeness, accuracy and relevance of the mapped data." Meanwhile, the European Union's European Spatial Planning: Adapting to Climate Events (ESPACE 2007, p 8) program recommends that "spatial plans and adaptation measures must be reviewed and revised regularly if they are to be effective over the longer term." Nevertheless, the pursuit of assessment evaluation in practice is inconsistent, if not rare, or at least the findings of such evaluations are not well-communicated. This results in lost opportunities for determining which approaches and engagement strategies for vulnerability assessment and mapping prove most effective in a given context.

Table 3 Approaches for expanding the toolkit for climate change vulnerability mapping

Approach	Description	Examples
Iterative studies	Sequential, hierarchical assessments where each iteration expands upon regions or determinants of vulnerability prioritized in the prior iteration	Brooke and Kinrade (2006) Kinrade et al. (2008a, b)
Top-down and bottom-up approaches	The combination of top-down, indicator-based spatial assessments of vulnerability with bottom-up, ethnographic studies	O'Brien et al. (2004) Preston et al. (2009) Mastrandrea et al. (2010)
Nested studies	Assessment where analysis conducted at one-scale is either 'up-scaled' or 'down-scaled', to examine multi-scale processes and determinants of vulnerability	Eakin and Luers (2006) Adger et al. (2009b) Cutter et al. (2003) Adger et al. (2009b) Sullivan and Meigh (2005)
Cluster analysis	Development of spatial typologies of vulnerability across multiple geographic units based upon biophysical and/or socioeconomic determinants	Kropp et al. (2006) Acosta-Michlik and Espaldon (2008) Buddemeier et al. (2008) Sharma and Patwardhan (2008) Tran et al. (2010)
Agent-based methods	Use of agent-based modeling tools to simulate behavioral responses of agents across a landscape in response to climate and other internal or external driving forces	Asseng et al. (2010) Acosta-Michlik and Espaldon (2008) Bouden et al. (2008)
Bayesian methods	Use of Bayesian networks and statistics in conjunction with GIS to integrate qualitative and quantitative information (such as biophysical, socioeconomic and values-based knowledge) and its uncertainties across a range of disciplines and stakeholders	Krivoruchko and Crawford (2003) Wooldrige and Done (2004) Tighe et al. (2007)

Establishing goals and objectives for an assessment, for example, are of limited utility in the absence of evaluation criteria to determine whether objectives have in fact been met. Such review and evaluation is particularly critical given evidence that scientific environmental assessments often fail to fulfill the objectives that were anticipated at the outset (Herrick and Sarewitz 2000; Kaiser 2000; Cash and Clark 2001; NRC 2007b). Herrick and Sarewitz (2000) question the entire paradigm of using scientific assessment to guide climate policy, due to the irreducible uncertainties embodied in climate change assessments. Rather, they argue for the use of assessment as a policy evaluation tool, with the goal of determining whether or not a particular adaptation response is effective. Hinkel (2011) is critical of vulnerability assessment, specifically, as a means of informing decisions regarding climate policy. Ultimately, those attempting to map vulnerability to enhance society's capacity to respond to climate change will ultimately be called upon to demonstrate effectiveness of such approaches (Moser 2009; see also Keogh et al. 2004). Hence, approaches and methods for doing so need to become a routine component of assessment.

Conclusions

Rapid expansion of the power and accessibility of geospatial tools and data in recent years has enhanced the potential for mapping vulnerability to climate change. Such expansions in capability are associated with a commensurate increase in demand for spatial information regarding climate change, natural hazards and social vulnerability to facilitate spatial planning in anticipation of future environmental and social change (NRC 2007b). These trends are largely positive in that they reflect societal and institutional efforts to apply knowledge to address issues of societal concern. Furthermore, the rapid expansion of vulnerability mapping is indicative of the conceptual 'down-scaling' of global climate change to the local level where the consequences of climate change are experienced and the active pursuit of effective tools for conveying information about vulnerability and adaptation responses to stakeholders.

Nevertheless, the diversity of disciplines and stakeholders engaging in vulnerability mapping, when combined with the inherent complexity of climate change and

Table 4 Key challenges associated with climate change vulnerability mapping applications

Goals and objectives	Assessment framing	Methodological approaches	Participation and communication
Ambiguity regarding the intent of an assessment and anticipated uses/users of the information	Frequent analysis of biophysical determinants of vulnerability in the absence of socioeconomic determinants and vice versa	Lack of 'best practice' in vulnerability mapping	Frequent lack of stakeholder participation (or poorly screened stakeholders) may undermine assessment salience and legitimacy
Questionable assumptions regarding the utility of information for decision-making	Lack of specificity regarding what systems or system components are vulnerable and to what	Lack of robust data at the scale relevant to vulnerability processes. Lack of homogeneity among diverse data sources used to inform vulnerability	Stakeholders may fail to understand spatial representations of vulnerability, the manner in which they were created and their interpretation
Poor recognition of the potential risks of mapping vulnerability to broader assessment goals	Limited consideration of multi-scale processes and determinants of vulnerability	Limited attempts to manage uncertainty in assessment process and validate individual metrics or vulnerability indices	Stakeholders may be sensitive to the spatially explicit identification of vulnerability resulting in attempts to suppress assessment results
Lack of assessment evaluation that indicates to what extent original goals have been achieved	Bias toward 'top down' data driven conceptualizations of vulnerability and its assessment over 'bottom up' qualitative studies	Paucity of spatially explicit and internally consistent scenarios of both biophysical and socioeconomic change	Vulnerability maps are infrequently linked to adaptation planning resulting in disconnects between mapping processes and the pursuit of adaptive responses

coupled human/environmental systems, challenges attempts to develop a robust practice for climate change applications (see Table 4 for a summary of challenges). This is evident among the existing examples of vulnerability mapping discussed here, which demonstrate significant diversity with respect to the manner in which the concept of vulnerability is framed, the values that are considered vulnerable and the determinants of that vulnerability. The lack of consensus regarding the appropriate frames and methods for mapping vulnerability in different contexts results in the selection of methods out of convenience or familiarity as opposed to efficacy, which largely precludes inter-study comparison. The inconsistent manner with which uncertainty is treated in vulnerability mapping can contribute to perceptions of false precision regarding current and future estimates of vulnerability, which has subsequent implications for the effective use of such information. The aggregation of diverse types of information into a vulnerability map can cloud the issues of what exactly is vulnerable, what are the key determinants of that vulnerability, and how they interact to affect the likelihood of adverse outcomes. Meanwhile, the apparent disconnect between the mapping of vulnerability itself and the pursuance of adaptive responses that may address such vulnerability suggests significant opportunities for risk communication, learning, and deliberation over appropriate actions are being missed. Addressing this gap will require the development of criteria for evaluating the relative success of different frameworks and methods for vulnerability mapping with respect to achieving intended outcomes.

Despite these challenges, this review also identifies a range of positives in vulnerability mapping practice. For example, the clear emphasis on local context and the development of integrated perspectives on vulnerability points to vulnerability mapping as a useful tool for building understanding regarding complexity in coupled human/environmental systems at a scale that is practical for subsequent discussions around adaptation. Given that the availability and power of geospatial tools as well as the inherent appeal of geographic visualization will continue to drive vulnerability mapping applications, the future of the practice is likely to be affected by two over-arching tensions. The first is the tension between diagnostic (i.e., understanding vulnerability determinants) versus predictive approaches to assessment. In other words, to what extent is vulnerability mapping an attempt to predict where future adverse consequences will occur versus an attempt to diagnose key drivers of vulnerability that provide stakeholders with improved understanding of the system and its dynamics. The second tension is between attempts to build geographic visualizations of complex environmental and social processes of change in a holistic manner (e.g., PAR or EV models) versus more reductionist representations of a small number of determinants (e.g., RH models).

Reconciling these tensions is dependent upon the goals and objectives of the assessment and its participants. Nevertheless, there seems little question that robust problem orientation is a prerequisite for the effective management of vulnerability through capacity building and/or vulnerability reduction. Hence, capitalizing on the power of maps to assist in engaging stakeholders around the issue of climate change and the underlying drivers of vulnerability that determine consequences and outcomes may be an effective starting point for facilitating adaptation processes. To this end, the four critical design questions identified in this review provide a foundation for such problem orientation. This may subsequently inform which aspects of the system and its vulnerability merit further investigation, which may lead to more reductionist analytic methods and decision analysis. This, however, requires better integration of vulnerability mapping with participatory processes and recognition that if one is intent on facilitating social change, the technical exercise of assembling a climate change vulnerability map may be less important than the deliberative processes through which it is designed, communicated, and used.

Appendix

See Table 5.

Table 5 Spatial climate change vulnerability assessments reviewed in the current study

Bayliss et al. (1997)
Zeidler (1997)
Clark et al. (1998)
Vörösmarty et al. (2000)
Bryan et al. (2001)
US National Assessment (2001)
Wu et al. (2002)
Hammar-Klose et al. (2003)
Luers et al. (2003)
White et al. (2003)
O'Brien et al. (2004)
Schröter et al. (2004)
Vincent (2004)
Sullivan and Meigh (2005)
Vescovi et al. (2005)
Berry et al. (2006)
Bulto et al. (2006)
Kropp et al. (2006)
Sietchiping (2006)
Yohe et al. (2006)
Barnett et al. (2007)
Diffenbaugh et al. (2007)
Hebb and Mortsch (2007)
Kleinosky et al. (2007)
Acosta-Michlik and Espaldon (2008)
Alessa et al. (2008)
Al-Jeneid et al. (2008)
Demirkesen et al. (2008)
Gravelle and Mimura (2008)
Karim and Mimura (2008)
Liu et al. (2008)
Preston and Jones (2008)
Pruszak and Zawadzka (2008)
Thorton et al. (2008)
Thow and de Blois (2008)
Torresan et al. (2008)
Alpar (2009)
Baum et al. (2009)
Döll (2009)
Gbetibouo and Ringler (2009)
Kienberger et al. (2009)
Oyekale et al. (2009)
Preston et al. (2009)
Sharples et al. (2009)

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