Climate change hotspots mapping: what have we learned?

Alex de Sherbinin

Abstract In the past 5 years there has been a proliferation of efforts to map climate change "hotspots" — regions that are particularly vulnerable to current or future climate impacts, and where human security may be at risk. While some are academic exercises, many are produced with the goal of drawing policy maker attention to regions that are particularly susceptible to climate impacts, either to mitigate the risk of humanitarian crises or conflicts or to target adaptation assistance. Hotspots mapping efforts address a range of issues and sectors such as vulnerable populations, humanitarian crises, conflict, agriculture and food security, and water resources. This paper offers a timely assessment of the strengths and weaknesses of current hotspots mapping approaches with the goal of improving future efforts. It also highlights regions that are anticipated, based on combinations of high exposure, high sensitivity and low adaptive capacity, to suffer significant impacts from climate change.

1 Introduction

Maps depicting climate change "hotspots" have been issued with increasing regularity in recent years by researchers, advocacy groups, and NGOs. By identifying likely climate change impacts and conveying them in a map format with strong visual elements, hotspots maps can help to communicate issues in a manner that may be easier to interpret than text. Hotspots maps are developed with a number of goals in mind. Academic researchers are generally seeking to vet data and methodologies, applied researchers may be interested in guiding institutional strategies, and NGOs are often communicating climate impacts. In addition, building on early roots in biodiversity hotspots mapping (Myers 1990) where hotspots were developed to target conservation efforts, hotspots maps are often explicitly developed to help aid organizations in priority setting and strategic planning with regards to climate adaptation projects (Kok et al. 2010; Midgley et al. 2011; Yusuf and Francisco 2009). At a time of increasing pressure on donors and development organizations to show that scarce public resources are being used in a responsible manner, spatial indicators and hotspots maps hold the promise of transparent, "scientific", and defensible priority setting (Barnett et al. 2008). Although hotspots mapping

A. de Sherbinin (✉)
CIESIN, Columbia University, PO Box 1000, Palisades, NY 10964, USA
e-mail: adesherbinin@ciesin.columbia.edu

holds great promise for informing policy, there are a number of risks as well, which are reviewed in the discussion section. This paper offers a timely assessment of the strengths and weaknesses of current hotspots mapping approaches with the goal of improving future efforts. It also highlights regions that are anticipated, based on combinations of high exposure, high sensitivity and low adaptive capacity, to suffer significant impacts from climate change.

This review focuses on global data-driven GIS or modeling approaches to hotspots identification. Unlike national level hotspots mapping, these efforts capture subnational variation in vulnerability by combining spatial data layers, generally by converting each layer to a unitless scale and aggregating the layers to reveal vulnerability levels. In this approach, hotspots emerge from the spatial analysis, being revealed through the integration of spatial layers. In the Supplementary Online Material I also review several regional GIS-based and global expert-based hotspots mapping efforts.

I exclude from this review hotpots mapping efforts that use countries as the units of analysis, since these are essentially repackaging of country level indicators (e.g., Birkmann et al. 2011; Yohe et al. 2006), with all the limitations inherent in those approaches (Barnett et al. 2008). I also limit this review to mapping efforts whose primary goal is explicitly to identify hotspots or geographic areas where impacts will be greatest (even if not labeled per se as hotspots), rather than maps describing impacts that are incidental to a publication or report.

Papers meeting these criteria were identified through Google Scholar searches on "climate change hotspots" and "hot spots", announcements, and bibliographies of other spatial vulnerability assessment reviews. This paper identifies some common conceptual, data and methodological issues (Section 2); and then moves to a review of hotspots mapping efforts (Section 3). It then proceeds to discussion (Section 4) and conclusions (Section 5).

2 Common conceptual, data and methodological issues

Hotspots mapping efforts can be divided into three broad categories: those based solely on climate parameters, those that portray patterns of societal vulnerability to climate change impacts, and those that seek to portray impacts on particular systems, such as agriculture or water. Of the three, vulnerability mapping is the most common, and also the most conceptually challenging owing to the proliferation of frameworks and definitions (Eakin and Luers 2006; Adger 2006). O'Brien et al. (2007) describe two broad categories of vulnerability definitions, one that identifies contextual vulnerability or the intrinsic characteristics of a system, which is rooted in political economy, and another, outcome vulnerability, which combines information on potential climate impacts and on the capacity of society to cope and adapt. Vulnerability hotspots mapping efforts generally adopt the latter, which is closer to the IPCC definition of vulnerability as a function of exposure, sensitivity, and coping capacity (Parry et al. 2007). While there is no one correct way to characterize vulnerability, there are certainly wrong ways to do so. Füssel (2007) argues that quantitative vulnerability assessment requires definition of the *system* of analysis (what is vulnerable?), the *valued attributes* of concern (why is it important?), the *external hazard* (to what is the system vulnerable?), and a *temporal reference* (when?).

Beyond conceptual definitions and frameworks, there are significant measurement challenges (Birkmann and Wisner 2006). The exposure aspect of vulnerability generally presents fewer problems, since biophysical data sets are reasonably well advanced, and the uncertainties in the data are, for the most part, quantifiable. However, owing to data gaps, the socioeconomic aspects are often measured through the use of proxies. Thus for sensitivity it is common to use close surrogates such as poverty levels and income, and for coping or

adaptive capacity, measures might include education, institutional capacity, funding levels for disaster risk reduction, or insurance coverage. These are often less-than-adequate proxies for intrinsic vulnerability, and many of them are difficult to measure or data may be difficult to obtain. As Kasperson et al. (2005: 149) write, "political and social marginalization, gendered relationships, and physiological differences are commonly identified variables influencing vulnerability, but incorporating this conceptual understanding in global mapping remains a challenge."

Not all hotspots mapping efforts actually incorporate future climate change and variability. Some use past variability or extreme events as a proxy for future changes. However, those that do use general circulation model (GCM) outputs run into a number of issues. A fundamental challenge for vulnerability mapping that relies on accurate prediction of extremes, such as that for hazards or human vulnerability, is the limited ability of GCMs to capture historical variance or future extremes (IPCC 2012; Brown and Wilby 2012). The use of multi-model ensembles only tends to further reduce variance. The spatial resolution of the model outputs – ranging in resolution from 1 to 2° grid cells — is also a concern, and some efforts do not follow the best practice of using multiple models for a given SRES scenario.

Specific climate parameters that are required will differ based on the kind of hotspots assessment. For agricultural systems, water management, or natural hazard prediction, the most important variables would be anticipated change in rainy season onset, gaps in rainfall during growing seasons, changes in drought periodicity, changes in rainfall duration and intensity, and temperature increases beyond certain crop thresholds. These parameters are not easy to calculate, so hotspots efforts require a certain amount of expertise in climate data analysis. Although GCM outputs have uncertainties, it should be noted that hotspots mapping efforts that rely on long-term precipitation reanalysis data are also inaccurate in some regions, especially in developing countries where there is sparse rain gauge data.

Finally, Preston et al. (2011) highlight a number of temporal and scale issues that tend to plague vulnerability mapping. Often data layers are from inconsistent dates, scale mismatches in underlying data sets create spatial artifacts in the maps, and for mapping efforts that do use GCM outputs, the sensitivity and adaptive capacity variables represent current rather than future states. These issues are addressed again below.

3 Assessment of hotspots mapping efforts

In this section I review a range of hotspots mapping efforts covering broad vulnerability themes, assessing methods, strengths and weaknesses, and commonly identified regions. Table 1 provides a summary list of the studies and, to the extent provided in the reports, identifies important components of quantitative vulnerability per Füssel (2007). This table also includes studies described in the Supplementary Online Material. Map figures for all studies are included in the Supplementary Online Material, along with a table that summarizes each study's primary focus, audience, geographic scope, framework, methods, regions identified as most at risk from climate impacts, and funding sources.

3.1 Climate change exposure hotspots

There is a subset of hotspots mapping efforts that focus only on projected changes in temperature and selected precipitation parameters, that is, the "exposure" part of the IPCC formulation. Giorgi's (2006) Regional Climate Change Index (RCCI) was the first to depict climate hotspots based solely on climate model outputs. The RCCI measures changes by

Table 1 Hotspots mapping efforts reviewed for this paper

Reference	System	Valued attribute	External hazard	Temporal reference
Global hotspots mapping efforts (data driven)				
Giorgi (2006)	..	Implicit: Climate stability	Climate variability	2080–2099 against a baseline of 1960–79
Baettig et al. (2007)	..	No chg in probability distrib. of extremes	Increased probability of hot/wet/dry years	2071–2100 against a baseline of 1961–90
UK Met Office (2009)	Multiple	Multiple	Temperature change	When global temp increases by 4 °C
Piontek et al. (2013)	River flow, crop yields, ecosystems, malaria	Stability in systems vital to livelihoods	Temperature change	Based on timing of "crossing temp."
Samson et al. (2011)	Human population distribution	Implicit: Climate stability	Reductions in pop. carrying capacity	2050
McGranahan et al. (2007)	Coastal populations and lands	Human populations and land	Sea level rise	When sea levels rise by 8–10 m
CARE/Maplecroft and Thow and de Blois (2008)	Human populations	Human security	Climate hazards	1980–2000 hazards, 2071–2100 for GCMs
Ericksen et al. (2011)	Agriculture	Ag. productivity and food security	Changes in temperature and rainfall	2050
Fraser et al. (2013)	Soil moisture and agriculture	Agricultural productivity	Reduced precipitation and soil moisture	2045–2060 ("2050s"), 2075–2090 ("2080s")
Kok et al. (2010)	Rural livelihoods	Ag. productivity and food security	Global environmental change	Recent past
Parish et al. (2012)	Water	Water availability p.c. above a threshold	Climate change and population growth	2100
Döll (2009)	Ground water	Ground water recharge/availability	Climate change and population growth	2041–70 ("2050s")
De Stefano et al. (2010)	River Basin	Resilience to precipitation variability	Precipitation variability	2030 and 2050
Regional hotpots mapping efforts				
Busby et al. (2011) (Africa)	Human populations and governance sys.	Political stability and human security	A range of climate stressors	Past climate variability

Table 1 (continued)

Reference	System	Valued attribute	External hazard	Temporal reference
Midgley et al. (2011) (Southern Africa)	Agriculture and human health	Mostly food security	Precip and temp change (average and maximum)	2050
Abson et al. (2012) (Southern Africa)	Socio-ecological systems	..	Aridity and rainfall variability	..
Liu et al. (2008) (Africa)	Agriculture	Food security	Impact ratios of climate change & CO2 fertil.	2030s
Thornton et al. (2008) (Africa)	Agriculture	Food Security	CC impacts on crop and livestock productivity	2050
Hagenlocher et al. (2013) (West Africa)	Agriculture and sub-sistence livelihoods	Food Security	Changes and extremes in climate parameters	Climate trends and variability since 1970
Yusuf and Francisco (2009) (S.E. Asia)	..	..	Climate hazards	Past climate variability
ESPON Climate (2011) (Europe)	Multiple	Multiple	Extreme events and Δ in average conditions	2071–2100
Schröter et al. (2005) (Europe)	Ecosystems	Ecosystem services	Δs in C0$_2$ concentra-tions, temp., and precip.	2080
Global hotspots mapping efforts (expert judgment)				
Warner et al. (2009/2012)	Livelihoods	Food security and in situ adaptation	An array of climate impacts/ rainfall variab.	Depends on the map
Schubert et al. (2007)	Political systems	Security and stability	Broad array of climate impacts	Mid to late 21st century
Scheffran and Battaglini (2011)	Political systems	Security and stability	Broad array of climate impacts	Mid to late 21st century

".." = not specified; Key: *system* of analysis (what is vulnerable?), the *valued attributes* of concern (why is it important?), the *external hazard* (to what is the system vulnerable?), and a *temporal reference* (when?). Regional and global "expert judgment" mapping efforts are addressed in the supplementary online material (SOM)

2080–99 against a baseline of 1960–79 in regional mean precipitation, mean surface air temperature, and in the interannual variability in precipitation and temperature. Giorgi uses a multi-model ensemble across a range of IPCC scenarios (A1B, B1, and A2) to define changes. The RCCI is a comparative index designed to identify the regions that will see the greatest relative changes in these variables, which are identified as hotspots. Note that a small RCCI value does not imply a small absolute change, but only a small climate response compared to other regions. The RCCI is calculated for 26 land regions (not on a pixel basis) from a set of climate change projections by 20 global climate models for the A1B, A2 and B1 IPCC emission scenarios.

The "hottest" hotspots are those in northern latitudes, which are predicted to experience the greatest temperature changes (Figure S1). The two most prominent hotspots are the Mediterranean, which will see declines in mean precipitation, and North Eastern Europe, which will see increases in winter precipitation and a strong regional warming relative to the global mean. Central America is the main tropical hotspot, which is predicted to see a decrease in precipitation and an increase in precipitation variability, followed by southern Africa. The global RCCI is limited by the representation of the hotspots (broad regions) and the fact that change measurements are bi-directional, and thus a strong increase in precipitation, which could be viewed as positive for some regions, is seen as equally problematic as a strong decrease in precipitation. On its own, the index says very little about vulnerability per se, but it has been applied together with socioeconomic indicators to identify socio-climatic hotspots in Brazil (Torres et al. 2012), and a similar approach was used to map hotspots in the U.S. (Diffenbaugh et al. 2008).

Baettig et al. (2007) introduced a Climate Change Index (CCI) which seeks to measure the strength of future climate change relative to today's natural variability. The index tracks increases in the probabilities of such events relative to a 1 in 20 year return cycle for the same events under current climatology. It is calculated based on GCMs running SRES A2 and B2 scenarios, with indicators such as additional hottest years, additional driest years, and additional extremely warm/wet/dry seasons (winter and summer months). According to the CCI, the largest changes in frequency will occur in the tropics and high latitudes. The CCI has the advantage that results are presented on a pixel basis, and they are also summarized by country for the benefit of policy audiences, and the scores are also relatively easy to interpret. The CCI depicts similar hotspots to the RCCI, except for the northern part of southern Africa and the Amazon, which are found to have much greater exposure to climate risks when compared to the present (Figure S2).

The RCCI and CCI contribute to the literature by describing changes to climate parameters that could serve as inputs to broader vulnerability assessments. However, despite claims to the contrary, both are clearly for academic audiences. By contrast, the UK Met Office has produced a map depicting the regional temperature changes associated with a 4 °C rise in global mean temperature (Figure S3). The map, produced in poster and online interactive forms, is intended for policy audiences, utilizing circles of various colors to highlight likely impacts. Areas with the greatest temperature changes include the Arctic and high northern latitudes, the western US, the Amazon, West Africa, southern Africa, and Central Asia.

A hybrid approach, based on climate parameters but tied to thresholds in four important sectors (water, agriculture, ecosystems and health), was recently developed by Piontek et al. (2013). The authors use the outputs of three GCMs simulating the highest representative concentration pathway (RCP8.5) to feed multiple Global Impact Models (GIMs), and then identify temperature thresholds in each sector where impacts could be considered to be severe. For example, the thresholds for the water and agriculture sectors are defined as the 10th percentile of the reference period distribution (1980–2010) of river discharge and crop

yields, respectively. For each GIM-GCM combination and at each grid cell they define a "crossing temperature" that is the global mean temperature change (GMTΔ) at which the sectoral metric crosses the respective impact threshold. Hotspot regions where thresholds are crossed for two or three sectors for a 4.5 °C GMTΔ are found in Figure S4, with high impacts found in the Amazon, the Andes, southern Mexico and Central America, southern and eastern Europe, the African highlands and parts of West Africa, and the Ganges basin. These results should be seen as conservative, given the stringent criteria for inclusion of severe impacts (>50 % of GIM-GCM combinations agreeing) used in the study.

3.2 Population dynamics and migration hotspots

There has been considerable policy interest in the impact of climate change on population dynamics, and particularly on migration (Black et al. 2011; de Sherbinin et al. 2011). This has spawned a number of efforts to map hotspots where climate change may affect population dynamics or lead to migration flows.

Samson et al. (2011) use the relationship between the distribution of human population density and climate as a basis to develop a global index of predicted impacts of climate change on human populations. The authors use an ecological niche model that identifies current population distribution in relationship to climate conditions, and then identifies how climate conditions may change in ways that they no longer support current densities. Their climate vulnerability index (CVI) combines regional climate–density relationships with predicted regional climate change. The climate variables that were found to have the highest predictive power for current population densities, and which were therefore used to determine areas of decline, include (A) annual mean temperature (°C), (B) mean temperature diurnal range (°C), (C) total annual precipitation (mm), and (D) precipitation seasonality (coefficient of variation).

A second climate-demography vulnerability index (CDVI) adds a third dimension, rapid population growth, to shows areas in which conditions that already support high population densities and where there is rapid population growth will see a decline in climate conditions. The authors ran their model using several climate projections. Figures S5 and S6 show the resulting maps. For the CVI, hotspots of high vulnerability are found in the Amazon basin, North Africa, Sudan, southern Africa, Central China, Mongolia, and eastern Australia. For the CDVI, the same regions become "hotter", while new areas are added in Central America, the U.S. Southwest, most of Africa, the Arabian Peninsula, Afghanistan, and Indonesia. Many of these are areas where climate change will amplify the conditions currently supporting low population densities, e.g., hot and arid regions that will become drier. Yet the CDVI clearly identifies a number of tropical humid regions (Amazon, Central Africa, and Indonesia) as hotspots as well. One limitation is the treatment of populations as homogenous, and therefore having similar sensitivity and adaptive capacity to climate change impacts.

A number of efforts have sought to identify hotspots of population vulnerability to sea level rise (SLR). Here I review a representative global assessment by McGranahan et al. (2007), which utilizes a Low Elevation Coastal Zone (LECZ) mask, representing coastal elevations from 0–10 m, to identify the regions that will be most affected by climate change impacts. Results are provided in spatial and tabular formats, providing estimates of population exposure within the LECZ for urban and rural areas by country. The method constitutes a simple overlay of the LECZ grid on a year 2000 population grid. The maps identify highly populated areas at high risk of coastal flooding and SLR, especially the Asian "mega-deltas" (Figure S7). The strength of this effort is that the methodology is simple and easy to understand, and the impacts of SLR are relatively certain, though the timing of specific sea level increments is a matter of some debate, and local impacts are hard to predict with global scale data sets.

3.3 Disasters and humanitarian crises

It is widely recognized that the greatest impacts of climate change will not necessarily be the result of secular changes in temperature and precipitation over decades, but rather will be the result of short-term variability and extremes (IPCC 2012). Important mapping efforts have been conducted by the World Bank (Dilley et al. 2005) and UNEP (UNISDR 2009) that assess current exposure to all natural disasters, including climate-related disasters of cyclones, droughts, floods, wildfires and landslides. These are not climate change hotspots per se, since they do not assess future scenarios, but the data layers have been used in a number of climate change hotspots efforts.

One such effort was by CARE and Maplecroft (2008; Thow and de Blois 2008), which sought to identify the most likely humanitarian implications of climate change for the next 20–30 year period. The authors use the World Bank hazard hotspots — floods, cyclones and droughts — to map specific hazards associated with climate change in relation to factors influencing vulnerability. Beyond the climate hazards, two climate projections were used: percentage change in maximum dry periods under scenario A1B and future dynamics of drought risk from 2041–2070. To map sensitivity to climate impacts, the authors combined indicators to create separate indices of natural vulnerability (poor natural resource base), human vulnerability, social vulnerability, financial vulnerability, and physical vulnerability (infrastructure). These layers were then combined into an overall human vulnerability index (Figure S8). Hotspots include the Andes, the landlocked countries of sub-Saharan Africa as well as southern Mozambique and Namibia, Yemen, Afghanistan and Pakistan, Mongolia, and Myanmar. One weakness is that the authors do not combine the climate risks (past hazards and future scenarios) with the human vulnerability index in such a way as to draw out hotspots at the intersection of climate and societal vulnerability.

3.4 Agriculture and food security hotspots

There are a number of recent reports looking at climate change and food security hotspots. Under the Climate Change, Agriculture and Food Security (CCAFS) program, Ericksen et al. (2011) map hotspots of climate change and food insecurity in the global tropics using a series of spatial indicators for climate change and food security. Indicators for climate change were based on model runs from three models obtained through the Coupled Model Intercomparison Project (CMIP3), and featured factors such as reductions in length of growing season, areas where average annual maximum temperatures will exceed 30 °C (an important threshold for legumes), and areas where the rainfall coefficient of variation is >20 %. These were tallied into an index identifying the number of climate change thresholds important to agriculture that are likely to be exceeded. Indicators for food security include food availability (current crop yields and a food production index), access (GDP per capita, percent population living on less than $2/day, road density), utilization (stunting prevalence, wasting prevalence, malnourished children per sq. km, population using unimproved water sources), and resource pressure (population growth rate, arable land p.c.).

In a last step, the results are tallied by exposure, sensitivity and coping capacity components into eight vulnerability domains, from high-high-high to low-low-low. Although sophisticated, the resulting array of maps is challenging to interpret without specialized knowledge, and little attempt is made to highlight hotspot scenarios of greater concern or likelihood. Adding to the problems of interpretation, maps represent eight vulnerability dimensions in various shades of yellow, green, blue and red. Focusing on domains with high exposure, high sensitivity, and low coping capacity, which are helpfully mapped in red, hotspots include the forest belt of West

Africa, northwestern India and northeastern Pakistan, and in the lower Mekong that are highly affected by changes in growing season length. Areas of Nigeria, the lakes region of Africa, and large swaths of India will be affected by a change in average maximum daily growing season temperatures of >30 °C (Figure S9). Southern Nigeria and parts of the Gangetic plain will be severely affected by rainy season rainy day decreases of > −10 %.

Fraser et al. (2013) map drought vulnerability hotspots with reference to wheat and maize. Unlike the CCAFS maps, which portray seemingly small impacts, by circa 2050 broad swaths of the world are deemed vulnerable to declines of growing season soil moisture availability of greater than 25 %, including most of South America, the U.S. mid-West, Southern Africa, the Mediterranean Basin, Central Asia, western China, and Australia. When combined with reduced adaptive capacity, there are five wheat and three maize vulnerability hotspots. For wheat, these are the southeastern U.S., southeastern South America, the northeastern Mediterranean, and parts of central Asia, and for maize they are southeastern South America, parts of southern Africa, and the northeastern Mediterranean (Figure S10).

Kok et al. (2010) use an integrated assessment framework to assess livelihood security as a consequence of global change, assessing four patterns of vulnerability: smallholder farming in dryland areas, overexploitation of natural resources, competition for land for food and biofuels, and rapid urbanization in the coast fringe (Figure S11). Similar to Ericksen et al., the range of factors considered (resource rich; resource poor; poor water, better soils; developed) makes interpretation difficult, but there are swaths or resource poor areas with severe to moderate poverty that are more vulnerable to global change, including the Sahel, the Horn of Africa, Afghanistan, and small areas of western China. The Andes, southern Maghreb, Arabian peninsula, Iran and Pakistan and the rest of western China are deemed to be resource poor with only moderate poverty.

3.5 Water resources hotspots

There is a growing effort to map climate and water hotspots. Parish et al. (2012) sought to integrate climate and population data sources to develop first order per capita water availability projections at the global scale. Like many analyses, the authors sought to determine if there may be any new hotspots of water scarcity under a changing climate regime that would require planning and mitigation. Beyond identifying hotspots, the authors were interested in identifying the relative contributions of population and climate change as drivers of water availability. The study used climate projections and multiple SRES scenarios (A1B, B1, A2, and A1F1) as inputs to a hydrological model. To assess population growth, they apply SRES country-level population projections to the Landscan population grid, assuming a constant relative distribution of population within countries. The map depicting the A1F1 SRES scenario (high emissions) (Figure S12, bottom right) depicts quite disparate areas at high risk — ranging from the region surrounding the Great Lakes in the U.S. and Canada, to North Africa, to Iraq and Syria to Southern Russia. Some areas where one might expect increases in stress, e.g., China and India, are actually depicted as showing declining water stress across most scenarios (except in the A2 scenario) owing to projected increases in precipitation. The patterns are not very consistent across SRES scenarios, and there are many isolated "hotspot" pixels, making interpretation difficult.

Similar assessments have been conducted by Döll (2009) for climate change and population impacts on groundwater resources, focusing on ground water recharge rates, and De Stefano et al. (2010) for international river basins to future climate change-induced water variability. Döll finds more consistent evidence across the GCMs utilized, with patterns of high vulnerability to decreases in groundwater resource availability in North Africa, Senegal

and Mauritania, Namibia and western South Africa, and northeastern Brazil. De Stefano finds high projected water runoff variability by 2030 for the Colorado Basin in the U.S. Southwest, the Parana in South America, basins in West Africa and southern Africa, the Mekong, and southern China.

4 Discussion and conclusions

This paper reviewed a range of global and regional (in the Supplementary Online Material) hotspots mapping efforts. While hotspots maps are issued with increasing regularity, there are a number of fundamental issues that need to be addressed. In this section I briefly assess data and methodologies, identify regions that are consistently identified as hotspots, address communication and design issues, discuss hotspots maps as tools for decision making, and identify paths for future research.

4.1 Data and methodologies

There are a number of common conceptual and methodological approaches that are found across multiple mapping efforts. One is the frequent use of the IPCC conceptualization of vulnerability, which either directly or indirectly served as the basis for six of the efforts reviewed, although not all adequately addressed the three components. As already discussed, there remain challenges in data availability and mapping scales for a number of socioeconomic variables relevant to the mapping of sensitivity and adaptive/coping capacity. Often, proxies such as poverty and malnutrition are used to measure social vulnerability, yet it is acknowledged in the literature that this is a multidimensional, time dependent and often complex concept that is difficult to capture in static maps (Kasperson et al. 2005). More fundamentally, the SREX framework (IPCC 2012) – which separates exposure and vulnerability - may yield better results for policy audiences since it translates more easily into a risk management approach.

Climate projections tend to be more common in hotspots studies of biophysical systems, especially as inputs to other models, and are rarely used for social or "general" vulnerability assessments (exceptions include Midgley et al. 2011; CARE and Maplecroft 2008). Apart from Busby et al. (2011), climate and security mapping efforts appear to be less sophisticated, relying to a greater extent on expert opinion (e.g., Schubert et al. 2007). Overall, there are strong disciplinary influences reflected in each of the approaches. The RCCI and CCI are entirely grounded in climate science, the CVI in ecology, the livelihood systems mapping in integrated assessment (Kok et al. 2010) and development practice (Warner et al. 2009; Thornton et al. 2008), and most agriculture and water hotspots maps are generated by modelers.

Many hotspots mapping efforts are affected by the spatial scale and uncertainties in the available global data sets. Kok et al. point out that there is a gap between local vulnerability assessments, which address context-specific situations with more detailed data, and the kinds of analyses possible for global VAs, which are based on aggregated data and rather crude assumptions about the underlying mechanisms being assessed. Bridging this gap will prove to be difficult.

4.2 Where are the hotspots?

Based on the figures and Table S2 found in the Supplementary Online Material, there are a number of regions that are found to be vulnerable across a range of climate impacts and

systems, sectors, and groups. These include North Africa, the Sahel, the Horn of Africa, parts of southern Africa, Central America, and the Andes. In Asia, the picture is less consistent, but western China and Central Asia are fairly consistently identified, and often India as well. Parts of Europe, North America and South Asia are also found to be vulnerable to agricultural production declines. Many small islands states, particularly in Oceania and the Caribbean, are highly vulnerable to SLR and storm surge, but these islands rarely show up in global mapping efforts because they are too small to map adequately at global scales. A number of the data-driven GIS modeling efforts produce patterns that are not always intuitive, and the number of map outputs makes summarizing overall patterns difficult.

One obvious question is, Do the data-driven maps show patterns that would not have been identified in an expert assessment approach or based on a broad understanding of past patterns? This depends on the mapping efforts, but for the most part it appears that regions that have the lowest levels of economic development are typically found to be most at risk in global hotspots mapping assessments, which suggests that patterns are not radically different from what one might expect a priori. Indeed, many hotspots were already identified as having high vulnerabilities by the IPCC (Parry et al. 2007). However, the specific sub-regions identified vary from effort to effort, and the climate change exposure and SLR hotspots do include areas that are economically advanced because they are climate-driven.

4.3 Design and communication of results

Maps are fundamentally a communication tool, answering the question, Where should I focus my attention? Maps have been proven particularly effective in risk communication (Dransch et al. 2010). Yet, some maps reviewed in this article are more effective than others in drawing attention to specific locations. For data driven maps, the "speckling" that results from isolated pixels showing up as hotspots is problematic from a policy communications perspective. A majority filter (moving window or spatial averaging) could reduce the speckling at the risk of some information loss (compare Figures S14a and S15b), and better convey uncertainties. The abrupt discontinuities across borders create problems for interpretation: they may be an artifact of using national level vulnerability and resilience indicators, or they may reflect real changes in on-the-ground vulnerability based on differing governance structures.

Reports by Busby et al. (2011), Warner et al. (2009, 2012), and Midgley et al. (2011) are professionally designed, and the maps are cartographically appealing. Busby provides map zooms for specific sub regions, which aids greatly in legibility (Figure S14). However, for most maps, their frequently small size and lack of contextual information (subnational boundaries, road networks, major cities) makes it difficult to identify the locations of hotspots. Some important areas such as small island states or major urban areas, where vulnerabilities are likely to be greatest, are often completely obscured on global scale maps. Maps zoomed to areas of vulnerability with greater contextual information could be used to address these concerns.

Researchers coming from the climate and integrated assessment communities tend to produce map arrays depicting multiple scenarios. This reduces legibility and can lead to confusion in the reader's mind since there is seldom any guidance on how to interpret the range of scenarios, or whether under certain assumptions one outcome is more likely than another. Thus, on the one hand, the range of scenarios highlights uncertainties, which is important for risk management, and on the other, the lack of guidance can result in information overload. As Patt and Dessai (2005:427) point out, users have varying abilities to understand probabilistic information, and "people will either choose to ignore information that is too complicated for them, or will respond in ways that disproportionately makes use of some types of information over others." One approach commonly employed by the

climate research community is to provide cross hatching of various densities on maps representing climate ensemble outputs, which indicates the percentage of scenarios that agree on the direction of change. This could be useful for hotspots mapping.

A broader issue is that the proliferation of hotspots mapping risks overloading decision makers with either too much or conflicting information (see Figure S16). Furthermore, where identified hotspots do not conform to decision makers' mental models, it is an open question as to whether decision makers will accept results. This brings us to the topic of maps as tools for decision making.

4.4 Hotspots maps as tools for decision making

One common assumption is that hotspots maps hold out the potential for more "transparent" and data driven decision making with regards to adaptation funding allocations, much as indicators are presumed to distill complex information in ways that are useful to decision making (Abson et al. 2012). A common assertion by map authors is that their results will be useful to policy audiences.

Yet hotspots efforts tend to be plagued by a lack of specificity regarding who precisely constitutes the "policy audience". While aid agency clients may indeed use the maps to identify priority areas for investments (see Table S2 for funders), it seems unlikely that national or local policy makers will take up the maps as planning tools. Many country level decision makers distrust global/regional mapping efforts because they don't understand/accept the methods, or question data inputs if they are not from their own national agencies. There is little direct evidence that the maps actually influence investments or adaptation activities, but Preston et al. (2011) suggest that maps may serve as boundary objects that facilitate discourse.

More broadly, there is a risk, should the maps actually influence decisions, that quantification gives decision-makers the false impression that the information is more "objective" (Preston et al. 2011). Yet the framing of issues and selection of indicators cannot be presented as purely the result of objective scientific criteria. By reifying vulnerability and resilience, and relying on proxies, other qualitative aspects such as culture, power relations, and local ecological knowledge can be overlooked or downplayed (Adger 2006; Kasperson et al. 2005). Seemingly innocent and value neutral, maps could play an important role in framing societal responses to climate change and its impacts in ways that are surely not neutral.

With increased attention and funding being devoted to adaptation, there is now a financial incentive for countries to portray themselves as highly vulnerable to climate impacts (Klein 2009). Yet, should donors use hotspots maps to guide investments, there is a potential to reward countries with poor governance should they be identified as the most vulnerable. Conversely, there is a moral hazard that countries could suffer funding "triage" if they are deemed overly vulnerable to climate impacts. The role of hotspots maps in political discourse and guiding decisionmaking deserves more attention.

4.5 Suggestions for future research

Some have suggested an alternative "hot systems" approach, which consider perturbations to socio-economic and ecological systems in disparate geographic locations (Shen et al. 2010). Similar to "syndromes" (Lüdeke et al. 2004), this approach would identify system characteristics across locations as well as teleconnections owing to "expanding markets and flows of resources, people, information and power relations", with a focus on "particular combinations of events and conditions in geographically disparate systems [that] can lead to … crises" (p.15). While more complex than simply mapping local processes, there is no fundamental reason why

the results of such "hot systems" approaches cannot be mapped. For example, Lüdeke et al. map global change syndromes in much the same way that hotspots have been mapped (Figure S13). This would add sophistication to current efforts by better reflecting direct and indirect drivers of change and real-world teleconnections.

There are a number of other potentially fruitful areas for further research. A useful next step in this research would be to take spatial outputs of essentially similar hotspots mapping efforts, and overlay them to see if results are broadly similar (Figure S16). Another area for further research would be to interview decision makers at aid agencies in government agencies concerning the impact that the maps had on resource allocation decisions. Finally, it would be interesting to use eye-tracking software and other cognitive research tools being applied in the field of data visualization to understand how the human brain processes the information contained on the maps with a goal of improving their communication efficacy (Montello and Freundschuh 2005).

5 Conclusion

This paper reviews a number of global and regional hotspots mapping efforts, assessing data and methods, the hotspots identified, and their efficacy as tools for risk communication and decisionmaking. Efforts to date can largely be characterized as supply-driven academic exercises rather than responding to demands from the policy community. Yet in a world where human security is potentially imperiled by temperature increases of >4 °C, and where "loss and damage" has become part of the UN Framework Convention on Climate Change lexicon, demand for hotspots maps will likely increase as decisionmakers seek to identify where impacts will be greatest and what adaptation measures, if any, are possible.

References

Abson DJ, Dougill AJ, Stringer LC (2012) Using principal component analysis for information-rich socio-ecological vulnerability mapping in Southern Africa. Appl Geogr 35:515–524

Adger N (2006) Vulnerability. Glob Environ Chang 16:268–281

Baettig MB, Wild M, Imboden DM (2007) A climate change index. Geophys Res Lett 34, L01705

Barnett J, Lambert S, Fry I (2008) The hazards of indicators: insights from the Environmental Vulnerability Index. Ann Assoc Am Geogr 98(1):102–119

Birkmann J, Wisner B (2006) Measuring the Un-Measurable. UNU-EHS SOURCE No. 5, Bonn, Germany: UNU-EHS

Birkmann J, Krause D, Stiadi N, Suarez D, Welle T, Wolfertz J (2011) World risk report. UNU and IEHS, Bonn

Black R, Bennett SRG, Thomas SM, Beddington JR (2011) Migration as adaptation. Nature 478:447–449

Brown C, Wilby RL (2012) An alternate approach to assessing climate risks. Eos 93(41):401–402

Busby JW, Smith TG, White KL (2011) Locating climate insecurity: where are the most vulnerable places in Africa? Climate Change and African Political Stability Program Policy Brief No. 3

CARE and Maplecroft (2008) Humanitarian implications of climate change: mapping emerging trends and risk hotspots. CARE International, Geneva

Davies RAG, Midgley SJE (2010) Risk and vulnerability mapping in Southern Africa: a hotspots analysis. OneWorld Sustainable Investments (Pty) Ltd, Cape Town

de Sherbinin A, Warner K, Ehrhart C (2011) Casualties of climate change. Sci Am January 2011: 64–71

De Stefano L, Duncan J, Dinar S, Stahl K, Strzepek K, Wolf AT (2010) Mapping the resilience of International river basins to future climate change-induced water variability, vol 15, Water Sector Board Discussion Paper. The World Bank, Washington DC

Diffenbaugh NS, Giorgi F, Pal JS (2008) Climate change hotspots in the United States. Geophys Res Lett 35, L16709

Dilley M, Chen R, Deichmann U, Lerner-Lam A, Arnold M (2005) Natural disaster hotspots. World. Bank, Washington, DC

Döll P (2009) Vulnerability to the impact of climate change on renewable groundwater resources. Environ Res Lett 4:035006. doi:10.1088/1748-9326/4/3/035006

Dransch D, Rotzoll H, Poser K (2010) The contribution of maps to the challenges of risk communication to the public. Int J Digit Earth 3(3):292–311

Eakin H, Luers A (2006) Assessing the vulnerability of socio-environmental systems. Annu Rev Environ Resour 31:365–394

Ericksen P, Thornton P, Notenbaert A, Cramer L, Jones P, Herrero M (2011) Mapping hotspots of climate change and food insecurity in the global tropics. CCAFS Report no. 5. Copenhagen, Denmark

ESPON Climate (2011) Climate change and territorial effects on Regions and local economies. Applied Research 2013/1/4. Final Report, Version 31/5/2011

Fraser EDG, Simelton E, Termansen M, Gosling SN, South A (2013) "Vulnerability hotspots": integrating socio-economic and hydrological models to identify where cereal production may decline in the future due to climate change induced drought. Agr Forest Meteorol 170:195–205

Füssel H-M (2007) Vulnerability: a generally applicable conceptual framework for climate change research. Glob Environ Chang 17:155–167

Giorgi F (2006) Climate change hot-spots. Geophys Res Lett 33, L08707. doi:10.1029/2006GL025734

Hagenlocher M, Lang S, Holbling D et al (2013) Modeling hotspots of climate change in the Sahel using object-based regionalization of multidimensional gridded datasets. IEEE J Sel Top Appl Earth Obs Remote Sens. doi:10.1109/JSTARS.2013.2259579

IPCC (Intergovernmental Panel on Climate Change) (2012) Managing the risks of extreme events and disasters to advance climate change adaptation. In: Field CB et al (eds.) Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp

Kasperson RE, Dow K, Archer E, Caceres D, Downing T et al (2005) Vulnerable people and places. Chapter 6 In: Millennium ecosystem assessment. Island Press, Washington, DC

Klein RJT (2009) Identifying countries that are particularly vulnerable to the adverse effects of climate change: an academic or a political challenge? Carbon and Climate Law Review 3:284–291

Kok MTJ, Lüdeke MKB, Sterzel T, Lucas PL, Walter C, Janssen P, de Soysa I (2010) Quantitative analysis of patterns of vulnerability to global environmental change. PBL, Den Haag/Bilthoven

Liu J, Fritz S, van Wesenbeeck CFA, Fuchs M, You L, Obersteiner M, Yang H (2008) A spatially explicit assessment of current and future hotspots of hunger in Sub-Saharan Africa in the context of global change. Global Planet Change 64(2008):222–235

Lüdeke MKB, Petschel-Held G, Schellnhuber HJ (2004) Syndromes of global change. GAIA 13(1):42–49

McGranahan G, Balk D, Anderson B (2007) Low Elevation Coastal Zone (LECZ) urban–rural population estimates. NASA SEDAC, Palisades

Midgley SJE, Davies RAG, Chesterman S (2011) Climate risk and vulnerability mapping: Status quo (2008) and future (2050). Report produced for UK Department for International Development (DFID)

Montello DR, Freundschuh S (2005) Cognition of Geographic Information. In: McMaster RB, Usery EL (eds) A Research Agenda for Geographic Information Science. CRC Press, Boca Raton

Myers N (1990) Threatened biotas: expanded hot-spots analysis. Environmentalist 10:243–256

O'Brien KL, Eriksen S, Nygaard L, Schjolden A (2007) Why different interpretations of vulnerability matter in climate change discourses. Clim Pol 7:73–88

Parish ES, Kodra E, Steinhauser K, Ganguly AR (2012) Estimating future global per capita water availability based on changes in climate and population. Comput Geosci 42:79–86

Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) (2007) Climate change 2007: impacts, adaptation and vulnerability. Cambridge University Press, Cambridge

Patt A, Dessai S (2005) Communicating uncertainty: lessons learned and suggestions for climate change assessment. C R Geoscience 337:425–441

Piontek F, Müller C, Pugh TAM et al (2013) Multisectoral climate impacts in a warming world. Proc Natl Acad Sci. doi:10.1073/pnas.1222471110, early online edition

Preston B, Yuen EJ, Westaway RM (2011) Putting vulnerability to climate change on the map: a review of approaches, benefits, and risks. Sustain Sci 6:177–202

Samson J, Berteaux D, McGill BJ, Humphries MM (2011) Geographic disparities and moral hazards in the predicted impacts of climate change on human populations. Glob Ecol Biogeogr. doi:10.1111/j.1466-8238.2010.00632.x

Scheffran J, Battaglini A (2011) Climate and conflicts: the security risks of global warming. Reg Environ Chang 11(Suppl 1):S27–S39. doi:10.1007/s10113-010-0175-8

Schröter D, Cramer W, Leemans R et al (2005) Ecosystem service supply and vulnerability to global change in Europe. Science 310:1333–1337

Schubert R, Schellnhuber HJ, Buchmann N, Epiney A, Grießhammer R, Kulessa M, Messner D, Rahmstorf S, Schmid J (2007) Climate change as a security risk. Earthscan and German Advisory Council on Global Change (WBGU), London

Shen X, Downing TE, Hamza M (eds) (2010) Tipping points in humanitarian crisis: from hot spots to hot systems. Studies of the University: Research, Counsel, Education (SOURCE) Publication Series of UNU-EHS, No. 13/2010

Thornton, PK, PG Jones, T Owiyo, RL Kruska, M Herrero, V Orindi, S Bhadwal, P Kristjanson, A Notenbaert, A Bekele, A Omolo (2008) Climate change and poverty in Africa: mapping hotspots of vulnerability. AfJARE 2(1) March 2008

Thow A, de Blois M (2008) Climate change and human vulnerability: mapping emerging trends and risk hotspots for humanitarian actors. Maplecroft, and CARE International, Geneva

Torres RR, Lapola DM, Marengo JA, Lombardo MA (2012) Socio-climatic hotspots in Brazil. Clim Change 115:597–609

UNISDR (2009) Global assessment report on disaster risk reduction. United Nations, Geneva

Warner K, Erhart C, de Sherbinin A, Adamo SB, Chai-Onn T (2009) In search of shelter. UNU, Bonn

Warner K, Afifi T, Henry K, Rawe T, Smith C, de Sherbinin A (2012) Where the rain falls. UNU and CARE, Bonn

Yohe G, Malone E, Brenkert A, Schlesinger M, Meij H, Xing X, Lee D (2006) Global distributions of vulnerability to climate change. Integr Assess J 6(3):35–44

Yusuf AA, Francisco H (2009) Climate change vulnerability mapping for Southeast Asia. EEPSEA, Singapore