Regional clusters of vulnerability show the need for transboundary cooperation

Joern Birkmann\textsuperscript{1,}\textsuperscript{*}, Daniel Feldmeyer\textsuperscript{1}, Joanna M McMillan\textsuperscript{1}, William Solecki\textsuperscript{2}, Edmond Totin\textsuperscript{3}, Debra Roberts\textsuperscript{4}, Christopher Trisos\textsuperscript{5}, Ali Jamshed\textsuperscript{1}, Emily Boyd\textsuperscript{6} and David Wrathall\textsuperscript{7}

\textsuperscript{1} Institute of Spatial and Regional Planning, University of Stuttgart, Pfaffenwaldring 7, Stuttgart 70569, Germany
\textsuperscript{2} City University New York (CUNY), Hunter College, 695 Park Avenue, New York, United States of America
\textsuperscript{3} Ecole de Foresterie Tropicale, Université Nationale d’Agriculture du Benin, Kétou, Benin
\textsuperscript{4} School of Life Sciences, University of KwaZulu-Natal and eThekwini Municipality, Sustainable and Resilient City Initiatives Unit, Durban, South Africa
\textsuperscript{5} African Climate and Development Initiative and Centre for Statistics in Ecology, Environment and Conservation, University of Cape Town, South Africa
\textsuperscript{6} Lund University, Centre for Sustainability Studies, Lund, Sweden
\textsuperscript{7} Oregon State University, Department of Geography, Environmental Sciences, and Marine Resource Management, 104 CEOAS Administration Building, Corvallis, OR 97331, United States of America

\textsuperscript{*} Author to whom any correspondence should be addressed.
E-mail: joern.birkmann@ireus.uni-stuttgart.de

Keywords: regional vulnerability, transboundary, adaptation

Supplementary material for this article is available online

Abstract
Reducing vulnerability is essential for adaptation to climate change. Compared to approaches that examine vulnerability to a specific hazard, our analysis offers an alternative perspective that conceptualizes vulnerability to climate change as a phenomenon that is independent of any specific type of hazard but relevant to multiple hazards. Vulnerability is thus a product of structural inequality and systemic in nature. Based on two established index systems, we perform global analyses of specific phenomena—such as poverty, access to basic infrastructure services and forced migration—that influence and determine vulnerability. Our statistical and spatial analyses reveal an emerging pattern of climate vulnerability within regional clusters and shows that vulnerability is a transboundary issue, crossing political, sectorial and geographical borders and impacting shared resources. The spatial statistical hotspot analysis of vulnerability underscores that hotspots, for example of high vulnerability, state fragility, low biodiversity protection or forced migration, emerge in multi-country clusters. This aspect has often been overlooked, most attention to-date having been given to the positioning of individual countries within vulnerability rankings. In hotspots such as in the Sahel, East and Central Africa, as well as in Southern Asia and Central America, vulnerability is interwoven with high levels of state fragility, making adaptation solutions more complex. The recognition of the regional clusters and the transboundary nature of vulnerability calls for new research and action on how to strengthen transboundary approaches for vulnerability reduction, potentially enhancing prospects for successful adaptation.

1. Introduction: vulnerability points towards the adaptation gap

Vulnerability and adaptation often emerge as two separate discourses without a sufficient understanding of its various linkages. The adaptation gap is a concept that offers potential to better connect these discourses. The adaptation gap, an important concept in adaptation science, is defined as the gap between the current state of a system and a state that minimizes adverse impacts from existing climate conditions and variability (Coninck \textit{et al} 2018, UNEP 2018). With increasing climate change, but also with higher levels of inequality and poverty in a society,
this gap will get wider, and thus the impacts more severe.

Adaptation is not just about transforming systems to manage or reduce a specific climate-related hazard (e.g. drought, flood or extreme heat) but more fundamentally is about reducing vulnerability of populations and the systems they depend on through comprehensive climate risk management, including social protection systems (Roberts and Pelling 2018, Wilson et al 2020, Aleksandrova and Costella 2021, Galvin 2021, Nalau and Verrall 2021). Reducing vulnerability is key for adaptation to climate change since socio-economic development and governance contexts, including issues of poverty, equitable access to technology, to resources and to infrastructure (e.g. safe water access) significantly determine the capacity and ability of countries and people to respond to climate change and extreme events (UNFGCC 2011). Within the scientific discourse, for example in the IPCC, there is increasing evidence that adaptation to climate change cannot sufficiently be conceptualized by looking at temperature changes, mitigation or climatic hazards only, but rather by seeing vulnerability and the reduction of vulnerability as inseparable from adaptation (IPCC 2014b). Some authors even argue that there is a need for an overall shift from mitigation to adaptation in climate science (Sobel 2021), although this is also contentious. Current science underscores that adaptation needs to be intrinsically linked to vulnerability reduction (IPCC 2014a, 2019).

The United Nations (UN) Adaptation Gap Report (UNEP 2018), for example, shows that countries are differentially vulnerable and that climate risks and adaptation options vary significantly according to the economic status of the country. The report highlights that assessment of progress towards climate adaptation requires a shift away from measuring specific outputs of adaptation to measuring underlying adaptive capacity or the lack thereof (i.e. vulnerability). However, the UN report fails to outline the spatial configuration of these adaptation gaps. Furthermore, within other global scientific assessments, such as the IPCC Assessment Report, and recent scientific papers, key messages often disregard the spatial dimension of climate risks (IPCC 2014a) and vulnerability (Phillips et al 2020, Ebi et al 2021, Papathoma-Köhle et al 2021, Schleussner et al 2021) and therefore overlook an important aspect for developing evidence-based scientific solution spaces.

This study aims to bridge this gap. Our quantitative research reveals that core phenomena that characterize high vulnerability to climate change (e.g. poverty, access to basic infrastructure service, state fragility) are not just emerging at the local or national scale, but have a strong regional dimension.

Research focused explicitly on regional vulnerability and environmentally critical situations at a regional scale goes back to the seminal work of Kasperson et al (1995), ‘Regions at risk’ (Kasperson et al 1995) already underscored that very local or global approaches might fail to identify the severely disruptive nature of environmentally critical situations at the societal level. Regional scale approaches allow the assessment of threats that are likely to affect more than one society or social-ecological system at once (Kasperson et al 1995). This research, however, was mainly case study driven and did not focus on a quantitative global picture about regional clusters of systemic vulnerability. In several ways, the research was more about risk. Liverman’s work (1999) and others (e.g. O’Brien et al 2004), expanded this regional analysis of vulnerability through the incorporation and integration of biosophysical and social vulnerability metrics to identify finer scale system processes.

Also in practice, adaptation priorities have been set particularly for national and local scales, such as with national climate assessments and National Adaptation Programs (UNFGCC 2020) or for specific livelihoods within local communities (e.g. rural communities and agriculture). Each country seems to consider climate change as an autonomous challenge that can be solved locally or at the country level (Räthzel and Uzzell 2009, Tranter and Booth 2015). Our research shows that the likelihood that societies and human-environmental systems shift from single to periodic crises, including challenges in recovery, is significantly determined by regional characteristics that shape vulnerability.

1.1. Definition of vulnerability

Vulnerability is the predisposition of people (and communities, cities, nations) or systems (e.g. infrastructure systems, human-ecological systems) to be adversely affected by hazards (e.g. climate extremes) (IPCC 2014a) due to internal (e.g. socio-economic or physical) and context conditions in which human-environmental systems are embedded (Turner et al 2003). Aspects that characterize multi-dimensional vulnerability to climate change are issues such as poverty, forced migration, state fragility and inequality, which constrain present and future capacities to adapt. Thus, vulnerability is a product of structural inequality and is systemic in nature. Vulnerability varies temporally and spatially (Cutter and Finch 2008). In this paper, we show that such phenomena that characterize high levels of vulnerability are found in regional clusters.

2. Measuring vulnerability

While it is widely acknowledged that poor and particularly extremely poor people have limited assets to respond to climate risks (UNEP 2018, Stringer et al 2020), it is increasingly evident that also the broader development and governance context of a country significantly influence the predisposition of people
to be adversely affected by climate change. State fragility captures, for example, the decline of capacities of governmental institutions to provide effective support to people at risk (Fund for Peace 2020). In Somalia or Iraq, for example, where state fragility is high people and communities are especially vulnerable to climate hazards due to the poor enabling condition and governmental protection (Eklöw and Krampe 2019, Peters et al 2019, Mawejeje and Finn 2020, World Bank 2020). In contrast, in countries with low state fragility, governmental institutions can buffer adverse impacts by providing adaptation support, for example, in terms of early warning systems or recovery support after shocks, such as droughts or other climate hazards. This phenomenon can also be observed in the current COVID-19-pandemic (UN Security Council 2020).

In this study we draw upon two established comprehensive indicator-based risk assessments: the INFORM Index (2019) and WorldRiskIndex (WRI) (Birkmann et al 2011, Welle and Birkmann 2015) that bring together global country-level data that measures many different aspects of vulnerability. These indices are based on large sets of global socio-economic and governance data (see supplement (available online at stacks.iop.org/ERL/16/094052/mmedia)).

The core aspects that these indices use to operationalize vulnerability include:

- poverty (population living in extreme poverty);
- income inequality (GINI-index);
- lack of human development and human capital;
- gender inequality (gender inequality distribution [INFORM], percentage of females in schools and in parliament [WRI]);
- governance indicators (e.g. corruption, state fragility);
- health and health infrastructure indicators (physicians per 10 000 people, life expectancy [WRI] and child mortality [INFORM]);
- food security (percentage of undernourished people [WRI]),
- malnutrition in children under 5 years (INFORM); sanitation (percentage of population with access to safe water and sanitation [WRI]);
- preparedness (percentage of people with no life insurance [WRI]); environmental conditions and habitat protection (WRI);
- and forced migration and up-rooting (INFORM).

Both indicator systems examine, in addition to overarching national context conditions (e.g. governance institutions and public infrastructure) and national averages, indicators of inequality and differential vulnerability within nations (e.g. wealth distribution and vulnerable groups). A detailed overview and specific justification of the indicators used is provided in the supplementary material (see supplement) and additional information can be found from the original sources of these two indices (Birkmann et al 2011, Welle and Birkmann 2015, Marin-Ferrer et al 2017).

While the INFORM and WRI index systems use in part different indicators and data sources, they are largely in agreement, particularly as to the most vulnerable and least vulnerable countries (Feldmeyer et al 2021). Moreover, Garschagen et al (2021) compared four global risk and vulnerability index systems (INFORM, WRI, ND-GAIN, global climate risk index) and found that the robustness and agreement of results across the different indices measuring vulnerability, exposure and risks are highest in terms of the socio-economic and institutional aspects of vulnerability, while less agreement exist in terms of exposure to hazards and risk. There are other indicator and index systems that operationalize human vulnerability to hazards and climate change at different scales (see e.g. Cutter et al 2003, Chen et al 2015). All of these different index-based approaches have been critiqued in terms of their validity, usefulness and ability to measure intangible aspects (see Bakkensen et al 2017, Hallegatte and Engle 2019, Rufat et al 2019, Visser et al 2020). While critique is justified, it is important to acknowledge that both indicator systems we apply have been validated in terms of internal consistency (see Welle and Birkmann 2015, Marin-Ferrer et al 2017) and other studies also show the usefulness of such indices (e.g. Almeida et al 2016, Nasiri et al 2016, Brito 2018). Therefore, we argue that it is valuable to use these indices but while doing so it is important to take care when interpreting or using such indicators for defining priorities, because the quantification of intangible aspects of vulnerability, such as governance, cannot capture the full complexity of such dynamic phenomena.

Our study breaks ground in three main ways. First, we take a data-driven approach to identify spatial patterns and clusters of high vulnerability in terms of an average vulnerability score of each country based on two complex index systems (INFORM and WorldRiskIndex) for assessing most vulnerable countries. Second, we examine spatial hotspots of vulnerability using Gi-Statistics focusing on the following selected indicators: life expectancy, state fragility, biodiversity protection, access to water, and number of displaced people. Third, we examine linkages between vulnerability and state fragility.

3. The missing spatial dimension

Global assessments rank individual countries according to their level of risk. While the ranking of individual countries is interesting for national policymakers, insufficient attention has been given to how individual country vulnerability profiles are...
associated with those of neighbouring countries. There is an increasing awareness that more regional and transboundary adaptation and risk management approaches are needed (IPCC 2018, Nadin and Roberts 2018, Benzie and Persson 2019, Booth et al 2020), but in practice, concepts and approaches are often linked to national or local approaches focusing on a specific hazard as a starting point, such as flood risk management (Heikkila et al 2013, Tilleard and Ford 2016) or specific hazard warning systems (Reidmiller et al 2018).

Another large body of research on transboundary risk and adaptation examines specific topics, such as transboundary rivers basins and watershed management. The studies consider broader development and governance issues (Heikkila et al 2013, Tilleard and Ford 2016) focusing on institutional capacities and cooperation within specific transboundary organizations. Tilleard and Ford (2016) developed an indicator and criteria-based evaluation framework for 42 transboundary basins in Europe, Middle-East and Africa. The study reveals that the adaptive capacity in transboundary water basins is still low partly because of insufficient financial and technical resources. They conclude that capacity for cooperation and adaptation across transboundary river basins is largely framed by the development and governance conditions of riparian states. We investigate the role of such governance conditions in determining adaptive capacity and vulnerability at a global scale.

4. Analysis methods and data

4.1. Data sources

In order to examine global spatial patterns and characteristics of systemic human vulnerability, we analyse existing quantitative empirical national-level data. We draw on three established global assessments as a basis for the analysis: namely, the INFORM Index (1) (values from 2019 were used, see Chen et al 2015, INFORM 2019), the WorldRiskIndex (2) (2019 with updated data for the components, for the methodologies, see Birkmann et al 2011, Birkmann and Welle 2016) and the Fragile States Index (3) (values from 2019, see Fund for Peace 2020). In each case, the most recent available iteration of these indices was used (for more details see the supplement). Most of the indicators are based on data of international organizations, such as the World Bank. The index values used are the vulnerability scores given by the WorldRiskIndex and the vulnerability scores given by the INFORM Index. Both of these indicator systems (INFORM and WorldRiskIndex) also include exposure and hazard indicators and thus examine risk, however, we draw only on the vulnerability component of each index for our calculations as we are focusing specifically on vulnerability and not risk in this study.

The underlying index approaches used to assess vulnerability, namely the WorldRiskIndex and INFORM Index, are described in detail in the supplementary material. Within the development process of both index systems, statistical tests and expert consultations were undertaken to assess the robustness and validity of the approach and the indicators used (see Welle and Birkmann 2015, Marin-Ferrer et al 2017).

In this study, we do not question the validity of these established indicator systems (as these have already been validated) but rather focus on analysing the spatial dimension of their results. Internal and external validation of both indices and their indicators have been recently examined with updated data. The reliability test and sensitivity analysis suggested that indices are internally valid and also vulnerability values correlate with hazard impact intensity, such as mortality, at global and regional scale (see Birkmann et al 2021). Since sensitivity analysis and reliability tests were already conducted, we preformed covariance, correlation and regression analysis on selected indicators. Our initial assumption that, for example, poverty as a macro-indicator is very highly correlated with displacement or inequality within a society (GINI index) was not confirmed by the correlation analysis (see supplement). The analysis shows that some indicators highly correlate, but others do not. For example, poverty, gender inequality, biodiversity protection do not correlate, while poverty and lack of access to improved water sources do (see supplement). In addition, literature suggests that a correlation coefficient of up to 0.7 (Burton 2015) or 0.8 (Shi et al 2019) is acceptable for selecting and keeping the indicators, and the majority of indicators in both indices fall below this threshold. Multiple regression analysis shows that, for example, governance, medical services, gender inequality and biodiversity (WRI) and number of uprooted people, people affected by disaster, and prevalence of undernourishment (INFORM) did not significantly regress with multi-dimensional poverty as used in the INFORM index. Similarly, multiple regression analysis of other indicators shows that no single indicator (e.g. poverty or gender inequality, access to water source) can explain all the variables that are relevant for vulnerability (see supplement). This suggests that there is an added value of having different and multiple indicators. Even though some redundancy exists in these index systems used, we argue that these indicators have a relevance for measuring multi-dimensional vulnerability. For example, poverty and access to safe water sources are different issues. Thus, even if they correlate, we still consider both as important since they speak to different aspects and needs that have to be addressed through adaptation and risk reduction policies. Consequently, vulnerability indicator-systems should not only be validated in terms of their statistical performance, but even more important is the justification of each indicator in terms of its relevance to the underlying
Table 1. Selected indicators and their relevance for systemic vulnerability (see full list in supplement).

| Indicator                        | Relevance for measuring vulnerability                                                                 | Literature                                                                 |
|---------------------------------|--------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------|
| Lack of access to an improved water source | People without improved water sources are vulnerable to diseases caused by unclean water and could become more vulnerable in the aftermath of a hazard. Moreover, climate change and its impacts can further increase the number of deaths due to waterborne diseases and infections like diarrhoea. | Brooks et al (2005), Bollin and Hidajat (2013), Pandey et al (2017), United Nations (2018), UNEP (2018), Gupta et al (2020) |
| Dependency ratio                | Dependents are more susceptible to harm from hazards and extreme events. Dependents are often limited in mobility and thus lack the capacity to individually 'move out of harm's way' in the case of a hazard. | Cutter et al (2003), Cutter and Finch (2008), Chen et al (2013), Sorg et al (2018), Chan et al (2019), Gupta et al (2020) |
| Extreme poverty                 | Poverty is the deprivation of essential goods, services and opportunities. Poverty is one of the key drivers of vulnerability. | ADB (2004), UNDP (2007), World Bank (2008), UNDRR (2009), Rufat et al (2015), Carrão et al (2016), United Nations (2018) |
| GINI index                      | Income inequality within a society brings about situations of spatial segregation and uneven resource access that makes a society more vulnerable to climate change. | Cutter et al (2016), Rasch (2017), Tselios and Tompkins (2019) |
| Fragile state index             | Countries with high levels of state fragility have higher political instability and weak governance, and thus are less in the position to support people at risk. | Crawford et al (2015), Rahman (2018), Andrijevic et al (2020) |
| Gender parity in education      | Gender parity in education is an indicator for gender equity. Education forms an important resource and an enabling condition for adaptation. | UNDP (2009), Dückers et al (2015) |
| Biodiversity & Habitat          | Ecosystem richness provides important environmental services that vulnerable communities often depend on (e.g. indigenous groups). | Klein et al (2014), Feldmeyer et al (2019) |

indicandum. Selected indicators and their justification as measures for systemic vulnerability are presented in table 1.

Additionally, as nations vary widely in size, we complement the analysis results with statistics on population size. These population calculations are based on the population statistics of the World Bank for 2019 (World Bank 2019) and the median probabilistic projections from the United Nations (UNSD 2019).

4.2. Statistical methods

For the spatial analysis of global vulnerability patterns (figure 1), we calculate the average of the two vulnerability indices (INFORM and WorldRiskIndex) for each country. Based on the resulting average vulnerability values for each country, we then classify all countries into seven vulnerability categories using the equal count method.

To analyse the vulnerability of each country in relation to their neighbouring countries, we conducted a hotspot analysis (figure 2). We performed this spatial hotspot analysis on the average vulnerability values (calculated for figure 1), and additionally for five selected core aspects of vulnerability: state fragility, low biodiversity protection, forced migration and up-rooting, poor access to piped water, and life expectancy. These five aspects of vulnerability cover diverse and important characteristics of human vulnerability to climate change. Indicators of these five aspects are drawn from the above described indicator systems. The hotspot analysis calculates the Getis-Ord Gi∗-Statistic. Spatially connected high values are determined by their Z-values and p-values. A single feature of a high value on its own does not form a hotspot, only if surrounded by other features with high values. For more details regarding the statistical method of the hotspot analysis see (Ord and Getis 1995) and the supplement.

In addition, we perform an analysis of the relationship between vulnerability and state fragility in order to examine our theses that governance and institutional issues are a major factor of vulnerability. In order to do this, we first aggregate the average vulnerability values to regions and then compare these with a third index: the Fragile States Index (Fund for Peace 2020), also aggregated to regions. The regional classification used is based on the geographical regions (the intermediate region and sub-region level) of the United Nations Statistical Division (UNSD 1999).
5. Results

5.1. Global regional clusters of vulnerability
The global map of vulnerability (figure 1) classifies countries according to their level of vulnerability (figure 1). This map reveals that high national vulnerability appears to be spatially clustered. While vulnerability varies widely among countries, this assessment (figure 1) reveals that there are clusters of several highly vulnerable countries, not just individual vulnerable countries in isolation. The spatial analysis shows that high vulnerability is concentrated in regional clusters in Central America, Asia, the Middle East and in several regions of Africa, particularly across the Sahel, Central and East Africa. The results of figure 1 are further analysed using a spatial hotspot analysis (Gi-Statistic) (see figure 2(a)). The high confidence intervals (99% and 95%) seen in figure 2(a) underscore the relative significance of African regions in terms of priorities for vulnerability reduction.

Globally, about 1.6 billion people reside in countries classified as most vulnerable, as calculated by the sum of the population in the two most vulnerable categories (see figure 1 and table 2). In contrast, the sum of the population of all countries in the two least vulnerable categories is 826 million. Thus, nearly twice as many people are living in most vulnerable countries compared to the number living in less vulnerable countries. Moreover, the total population of the countries in the highest vulnerability category is projected to double by 2050, while the population of those in lower vulnerability categories is projected to increase to a lesser rate or even decrease (see table 2).

Together, figure 1 and table 2 reveal the regional dimension of vulnerability and show that most vulnerable country groups globally are also those areas with large and growing populations.

5.2. State fragility and regional vulnerability
The analysis of hotspots of state fragility (figure 2(b)) using the Fragile States Index shows clusters of multiple countries that encompass very different socio-economic, ecological and political conditions and systems. These regional clusters can be seen in Central Africa, West Africa and East Africa, and in the Middle East.

Additionally, the comparison of the fragile states index and the average of the vulnerability indices aggregated to the scale of internationally defined regions (figure 3) show that regions of high vulnerability are often also characterised by high levels of state fragility. Regions with high vulnerability and high state fragility include many regions in Africa and also South Asia, while those with both low vulnerability and low state fragility appear largely in Australia/New Zealand and Northern Europe (figure 3). Although regions with low vulnerability and low state fragility, such as Australia/New Zealand, will also have to prepare for climate change (e.g. increased fire risk) and also encompass specific vulnerable groups, it is particularly regional clusters with very high vulnerability and high state fragility that have limited resources and insufficient institutional capacities to support people at risk. These clusters face climate change and related hazards (e.g. droughts, sea-level rise) in addition to already existing structural development challenges, many of which reflect the colonial period legacy.
5.3. Hotspot analyses of selected vulnerability characteristics

Vulnerability is a result of many complex interlinked issues concerning health, poverty, migration, gender inequality, education, institutions, lack of governance capacities and infrastructure often made more complex by past patterns of colonization and economic subjugation, for example in Africa. The hotspots shown in figures 2(b)–(f) provide a spatial analysis of selected additional characteristics of systemic vulnerability. These maps along, with example cases described in this section, serve to illustrate the significance of vulnerability and its regional dimension.

5.4. Hotspots of displacement and up-rooting

Hotspots of displacement and up-rooting (figure 2(e)) are primarily clusters in Africa and Southwest Asia (99% confidence interval) often encompassing more than five countries. This trans-boundary displacement and up-rooting, is largely coupled with an erosion of livelihood security and limited adaptive capacities of communities. Significant displacement is evident in Central, East and West Africa. Other regional hotspots emerge in the Middle East. Such hotspots of displacement and up-rooting have a regional nature because, for example, larger displacements due to conflicts or climate hazards (e.g. floods, droughts) influence the country of origin, but also those countries that receive displaced people. Furthermore, conflicts in one country also spill over to other countries, for example in the Sahel zone (IDMC & NRC 2020) or at present in the province of Tigray. Many at-risk populations are simultaneously impacted by conflict and climate stressors. For example, flooding along the White Nile in Uganda and South Sudan devastated vulnerable communities.
Table 2. Population of the countries in each vulnerability category.

| Categories of vulnerability | Population 2019 | Estimated population 2050 | Change 2019–2050 | Estimated population 2100 | Change 2019–2100 |
|-----------------------------|----------------|----------------------------|------------------|----------------------------|------------------|
| 7 (most)                    | 936 272 286    | 1 875 526 000              | +100%            | 3 266 665 000              | +249%            |
| 6                           | 661 441 024    | 1 029 921 000              | +56%             | 1 367 800 000              | +110%            |
| 5                           | 1 922 937 100  | 2 345 834 000              | +22%             | 2 144 145 000              | +12%             |
| 4                           | 2 245 946 291  | 2 457 833 000              | +9%              | 2 141 090 000              | −5%              |
| 3                           | 1 013 966 214  | 1 109 011 000              | +9%              | 1 070 216 000              | +6%              |
| 2                           | 485 904 821    | 587 594 000                | +21%             | 585 354 000                | +20%             |
| 1 (least)                   | 339 614 254    | 313 902 000                | −8%              | 250 943 000                | −26%             |

This table shows the sum of the population of all countries within each of the seven vulnerability categories (see figure 1) using the population statistics for 2019 (World Bank 2019) and the growth in population by 2050 and 2100 (UNSD 2019; see methods section and supplement).

that were displaced because of violent conflicts and were then uprooted again by flooding (IDMC & NRC 2020).

5.5. Hotspots of lack of access to piped water
The lack of access to piped water is a proxy for broader deficiencies in the provision of basic infrastructure. Within the 99% confidence interval, hotspots include countries such as Niger, Nigeria, Chad, Sudan, Ethiopia, Uganda and Kenya (see figure 2(d)). These are mostly dryland regions. Yemen and Pakistan are also classified as hotspots within the 90% confidence interval. In Africa these hotspots are characterized by larger regional clusters, such as in West, Central and East Africa, while Yemen and Pakistan are located further away from each other.
While initiatives to improve the access to safe and piped water are being promoted at various spatial scales, the clustering within Africa underscores the need to consider the regional dimension. The increasing dispute about large-scale water infrastructure, such as the Grand Ethiopian Renaissance Dam, shows the necessity for strengthening this regional perspective.

5.6. Hotspots of low biodiversity protection
Indicators that measure the level of biodiversity and its protection and actions towards retaining natural ecosystems are seen as important components of adaptive capacities. Biodiversity and its protection are captured by indicators that encompass, for example, species habitat, species protection and biodiversity (Wendling et al 2020). The hotspots analysis (figure 2(c)) shows different regional patterns compared to the indicators assessed above. A larger cluster of countries in the Arabian Peninsula and in Central Asia faces severe challenges in terms of a lack of species and habitat protection. The degradation of the Aral Sea is a prominent example of biodiversity and habitat degradation at regional scale in that area. Yet, in mapping hotspots of low biodiversity protection, we acknowledge that protected areas will not be sufficient to reduce vulnerability of biodiversity to climate impacts, as illustrated by mass coral reef bleaching events within marine protected areas, and by many regional hotspots of biodiversity degradation located in North America, Europe and Asia (see e.g. Newbold et al 2016). The vulnerability of societies to climate change impacts on biodiversity underpinning ecosystem services is a more complex aggregate of what biodiversity has already been lost and what can be protected or restored in future. However, the status of the environment and biodiversity protection are seen as proxies that can hint towards adaptive capacities particularly for marginalized groups that are highly dependent on environmental services for their livelihoods.

6. Discussion
The different quantitative analyses highlight that spatial hotspots of vulnerability do not emerge in a single country alone but rather in larger regional clusters. Areas with high overall vulnerability are country clusters defined by multiple challenges and development constraints, which go beyond single issues such as extreme poverty or wealth. Various regional clusters of high vulnerability are characterized by poverty, but also high levels of income inequality and state fragility, making solutions complex and complicated. The multi-dimensional and regional nature of vulnerability shown in this study means that in these clusters national level approaches will not be sufficient to reduce vulnerability. Within countries, especially larger countries like India, there are also sub-national clusters of high vulnerability, which are also important to analyse and address, and this can be done within national adaptation programmes. However, it is crucially important that at the same time the multi-country hotspots, particularly in Africa, are addressed with transboundary approaches.

Transboundary adaptation approaches exist and can be enhanced to address these challenges. For example, 54 African countries launched the Africa Adaptation Initiative in 2015 to accelerate coherent adaptation actions across the continent and enhance understanding of transboundary risk (Oluborode 2018). The Great Green Wall for the Sahara and Sahel Initiative is another example of transboundary adaptation approaches involving more than 20 countries. These approaches offer an opportunity to strengthen the resilience of communities at a large scale, from Senegal to Djibouti (Oluborode 2018).

We also have to acknowledge that root causes of vulnerability are linked to historical processes, such as patterns of underdevelopment and exploitation embedded within colonialism and imperialism. Hence, addressing root causes of different phenomena that characterize vulnerability is difficult and touches upon complex social, historical and cultural conditions.

At present, many risk and vulnerability assessments focus on the country level and overlook the transboundary scale of several challenges linked to vulnerability. Our analysis and a continuous monitoring of regional clusters of vulnerability can inform and accelerate regional level adaptation, particularly if multilateral development banks such as the African Development Bank account for such issues. As major hotspots of regional vulnerability are found in Africa, for example, future research needs to explore how existing regional economic commissions (e.g. in Africa SADC, ECOWAS and EAC) could act as important brokers of transboundary adaptation.

The benefits of regional cooperation throughout Africa have recently been highlighted by the coordinated response of the African Union and regional institutions to the COVID-19-pandemic (Alden and Dunst 2020, Wetzel 2020, Oloruntoba 2021a, 2021b). While there is an increasing recognition that strengthening regional connectivity is important (World Bank 2021), adaptation needs to be better integrated into existing regional processes. For regionally focused adaptation approaches in Africa (such as the Great Green Wall), supportive regulatory frameworks, political will and financial resources remains a critical issue for effective transboundary adaptation (Nadin and Roberts 2018). We acknowledge that undertaking transboundary adaptation is challenging, resource-intensive and difficult to integrate.
However, strategic investment in strengthening institutional capacities and enabling common adaptation framework across countries and creating incentives for collaboration are essential aspects of building climate resilience particularly in regional clusters of high vulnerability.

7. Conclusion

Reducing vulnerability and strengthening adaptation to climate change is a critical element of sustainable development. Many researchers, policy makers and discourses still connect vulnerability and adaptation primarily to individual hazards (floods, droughts, etc) or specific levels of global warming. In addition, adaptation and risk reduction efforts are often based on a relatively limited scope, with actions often taking place at community or local levels; hence outcomes are often assessed by underestimating the complexity of interactions among multiple climate change risks. The discussion about the feasibility and effectiveness of adaptation strategies needs to better account also for the regional dimension of vulnerability.

Even though countries within a regional cluster of high vulnerability (see figures 1–3) are quite different in terms of cultural context, demographics, ethnic identity, geographic extent and hazard context, it is very likely that the vulnerability in these regional clusters implies severe limitations across all groups and communities wanting to build resilience to climate change and ensure more sustainable development. Vulnerability in these clusters results from a dynamic interplay of various phenomena operating at multiple scales.

The results from the different quantitative analyses presented in this paper provide new insights about the regional nature of vulnerability. This new framing of vulnerability as transboundary will, when coupled with regional analysis, produce a new set of vulnerability and adaptation science to close the regional adaptation gap. Addressing such regional challenges would require special funding mechanisms (e.g. GAP Fund) that offer a window of opportunity to better link specific themes and spatial scales. Research networks including the IPCC can serve as vehicles to develop these new and ever more pressing analytical and assessment needs.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iD

Joern Birkmann [https://orcid.org/0000-0001-8733-3964]
Coninck H D et al 2018 Strengthening and implementing the global response Global Warming of 1.5 °C (Special Report) ed IPCC (Geneva: IPCC) In press

Crawford A, Daiz A, Hammill A, Parry J-E and Zamudio A N 2015 Promoting Climate-Resilient Peacebuilding in Fragile States (Manitoba: International Institute for Sustainable Development)

Cutter S L, Ash K D and Emrich C T 2016 Urban–rural differences in disaster resilience Ann. Am. Assoc. Geogr. 106 1236–52

Cutter S L, Boruff B J and Shirley W L 2003 Social vulnerability to environmental hazards Soc. Sci. Q. 84 242–61

Cutter S L and Finch C 2008 Temporal and spatial changes in social vulnerability to natural hazards Proc. Natl Acad. Sci. USA 105 2301–6

Dückers M, Frerks G and Birkmann J 2015 Exploring the plethora of context and consequences: an empirical test of a theory of disaster vulnerability Int. J. Disaster Risk Reduct. 13 85–95

Ebi K L, Boyer C, Ogden N, Paz S, Berry P, Campbell-Lendrum D, Dückers M, Frerks G and Birkmann J 2015 Exploring the plexus of the Intergovernmental Panel on Climate Change (Geneva: Intergovernmental Panel on Climate Change) pp 1–34

Eklöw K and Krupic F 1999 Climate-related Security Risks and Peacebuilding in Somalia (SIPRI Policy Paper 53) (Stockholm: Stockholm International Peace Research Institute)

Feldmeyer D, Birkmann J, McMillan J M, Stringer L, Leal W, Djalante R, Pinho P F and Livengood E 2021 Global vulnerability hotspots: differences and agreement between international indicator based assessments Clim. Change accepted

Feldmeyer D, Wilden D, Kind C, Kaiser T, Goldschmidt R, Eklöw K and Krampe F 2019

Garschagen M, Doshi D, Reith J and Hagenlocher M 2021 Transformational adaptation in drylands Curr. Opin. Environ. Sustain. 50 64–71

Garschagen M, Doshi D, Reith J and Hagenlocher M 2021 Comparing global climate and disaster risk indexes—how consistent and robust are their results? Clim. Change accepted

Galvin K A 2021 Transformational adaptation in drylands Curr. Opin. Environ. Sustain. 50 64–71

Garschagen M, Doshi D, Reith J and Hagenlocher M 2021 Comparing global climate and disaster risk indices—how consistent and robust are their results? Clim. Change accepted

Gupta A K, Negi M, Nandy S, Kumar M, Singh V, Valente D, Petrossio I and Pandey R 2020 Mapping socio-environmental vulnerability to climate change in different altitude zones in the Indian Himalayas Ecol. Indic. 109 105787

Hallegatte S and Engle N L 2019 The search for the perfect indicator: reflections on monitoring and evaluation of resilience for improved climate risk management Clim. Risk Manage. 23 1–6

Heikilä T, Gerlak A K, Bell A R and Schmeier S 2013 Adaptation in a transboundary river basin: linking stressors and adaptive capacity within the Mekong River Commission Environ. Sci. Policy 25 73–82

IDMC & NRC 2020 Global Report on Internal Displacement 2020 (Geneva: Internal Displacement Monitoring Centre)

INFORM 2019 INFORM report 2019. Shared evidence for managing crises and disasters

IPCC 2014a Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Geneva: IPCC)

IPCC ed 2018 Global Warming of 1.5 °C (Special Report) (Geneva: IPCC)

IPCC 2014b Summary for policy makers Climate Change 2014: Impacts, Adaptation and Vulnerability ed C B Field et al (Cambridge: Cambridge University Press) pp 1–34

IPCC 2019 Summary for policymakers Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems: Summary for Policymakers ed V Masson-Delmotte et al (Geneva: Intergovernmental Panel on Climate Change) In Press accepted

Jamshed A, Birkmann J, Ahmad Rana I and Feldmeyer D 2020 The effect of spatial proximity to cities on rural vulnerability against flooding: an indicator based approach Ecol. Indic. 118 106704

Kaspersen J X, Kaspersen R E and Turner B L 1995 Regions at Risk: Comparisons of Threatened Environments (UNU Studies on Critical Environmental Regions) (Tokyo: United Nations University Press)

Klein R, Midgley G F, Preston B L, Alam M, Berkhout F, Dow K and Shaw M R 2014 Adaptation opportunities, constraints, and limits Climate Change 2014: Impacts, Adaptation and Vulnerability ed C B Field et al (Cambridge: Cambridge University Press) pp 899–943

Liverman D M 1999 Vulnerability and adaptation to drought in Mexico Nat. Resour. J. 39 99–115

Marin-Ferrer M, Vernacini L and Polanisiak K 2017 Index for Risk Management—INFORM: Concept and Methodology, Version 2017 (EUR: Scientific and Technical Research Series vol 28655) (Luxembourg: Publications Office) p 90

Maweje J and Finn A J 2020 South Sudan Economic Update: Poverty and vulnerability in a Fragile Environment (Washington, DC: The World Bank)

Nadin R and Roberts E 2018 Moving Towards a Growing Global Discourse on Interdisciplinary Adaptation (London: Overseas Development Institute)

Narum J and Verrall B 2021 Mapping the evolution and current trends in climate change adaptation science Clim. Risk Manage. 32 100290

Nasiri H, Mohd Yusof M J and Mohammad Ali T A 2016 An overview to flood vulnerability assessment methods Sustain. Water Resour. Manage. 2 331–6

Newbold T et al 2016 Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment Science 353 288–91

O’Brien K et al 2004 Mapping vulnerability to multiple stressors: climate change and globalization in India Glob. Environ. Change 14 303–13

Oloruntoba S O 2021a How regionalism has helped Africa manage the COVID-19 pandemic (available at: https://theconversation.com/how-regionalism-has-helped-africa-manage-the-covid-19-pandemic-161924) (Accessed 06 July 2021)

Oloruntoba S O 2021b Unity is strength: Covid-19 and regionalism in Africa Int. Spect. 56 56–71

Oluborode A J 2018 Africa versus climate change loss and damages: exploring AU regional channels for influencing national policy J. Afr. Foreign Affairs 5 207–26

Ord J K and Getis A 1995 Local spatial autocorrelation statistics: distributional issues and an application Geogr. Anal. 27 286–306

Pandey R, Jha S K, Alatalo J M, Archie K M and Gupta A K 2017 Sustainable livelihood framework-based indicators for assessing climate change vulnerability and adaptation for Himalayan communities Ecol. Indic. 79 338–46

Papatheo-Köhle M, Thaler T and Fuchs S 2021 An institutional approach to vulnerability: evidence from natural hazard management in Europe Environ. Res. Lett. 16 044056

Peters K, Mayhew L, Slim H, Van Aalst M and Arrighi J 2019 Double vulnerability: the humanitarian implications of intersecting climate and conflict risk (London: ODI)

Phillips C A et al 2020 Compound climate risks in the COVID-19 pandemic Nat. Clim. Change 10 386–8

Rahman M A 2018 Governance matters: climate change, corruption, and livelihoods in Bangladesh Clim. Change 147 313–26

Rasch R 2017 Income inequality and urban vulnerability to flood hazard in Brazil Soc. Sci. Q. 98 299–325

Räthzel N and Uzzell D 2009 Changing relations in global governance: humanitarian aid, environmental hazards and urban vulnerability Soc. Sci. Res. 38 363–78

Rahman M A 2018 Governance matters: climate change, corruption, and livelihoods in Bangladesh Clim. Change 147 313–26

Reidmiller D R, Avery C W, Easterling D R, Kunkel K E, Lewis K L M, Maycock T K and Stewart B C 2018 Impacts,
Risks, and Adaptation in the United States. Fourth National Climate Assessment, Volume II (Washington, DC: USGCRP)

Roberts E and Pelling M 2018 Climate change-related loss and damage: translating the global policy agenda for national policy processes Clim. Dev. 10 4–17

Rufat S, Tate E, Burton C G and Maroof A S 2015 Social vulnerability to floods: review of case studies and implications for measurement Int. J. Disaster Risk Reduct. 14 670–86

Rufat S, Tate E, Emrich C T and Antolini F 2019 How valid are social vulnerability models? Ann. Am. Assoc. Geogr. 109 1131–53

Schleussner C-F, Pfeiffer P, Andrijevic M, Vogel M M, Otto F E L and Seneviratne S I 2020 Capturing the multifaceted phenomena of socioeconomic vulnerability Nat. Hazards 11 308

Shi Y, Ge X, Yuan X, Wang Q, Kellett J, Li F and Ba K 2019 An integrated indicator system and evaluation model for regional sustainable development Sustainability 11 2183

Sobel A H 2021 Usable climate science is adaptation science Clim. Change 166 8

Sorg L, Medina N, Feldmeyer D, Sanchez A, Vojinovic Z, Birkmann J and Marchese A 2018 Capturing the multifaceted phenomena of socioeconomic vulnerability Nat. Hazards 11 308

Stringer L C, Frazer E D G, Harris D, Lyon C, Pereira L, Ward C F M and Simelton E 2020 Adaptation and development pathways for different types of farmers Environ. Sci. Policy 104 174–89

Tilleard S and Ford J 2016 Adaptation readiness and adaptive capacity of transboundary river basins Clim. Change 137 575–91

Tranter B and Booth K 2015 Scepticism in a changing climate: a cross-national study Glob. Environ. Change 33 154–64

Taelor V and Tompkins E L 2019 What causes nations to recover from disasters? An inquiry into the role of wealth, income inequality, and social welfare provisioning Int. J. Disaster Risk Reduct. 33 162–80

Turner B L et al 2003 A framework for vulnerability analysis in sustainability science Proc. Natl Acad. Sci. USA 100 8074–9

UN Security Council 2020 Weakest, Most Fragile States Will Be Those Most Affected by COVID-19 (available at: https://blogs.worldbank.org/africacan/weakest-most-fragile-states-will-be-those-most-affected-by-covid-19) (Accessed 05 February 2021)

World Bank 2008 The World Bank annual report 2008: year in review (available at: https://documents1.worldbank.org/curated/en/452391468323718231/pdf/462560 WBAR00EN1ry0Sept020080English.pdf) (Accessed 10 November 2020)

World Bank 2019 World Development Indicators: Population, Total (available at: https://data.worldbank.org/indicator/SP.POP.TOTL) (Accessed 25 February 2021)

World Bank 2020 Somalia Country Environmental Analysis: Diagnostic Study on Trends and Threats for Environmental and Natural Resources Challenges (Washington, DC: World Bank Group)

World Bank 2021 World Bank Group Steps up Support to Deepen Regional Integration in Africa (Washington, DC: World Bank Group)