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A systematic review of dynamics in climate risk and vulnerability assessments

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Abstract

Understanding climate risk is crucial for effective adaptation action, and a number of assessment methodologies have emerged. We argue that the dynamics of the individual components in climate risk and vulnerability assessments has received little attention. In order to highlight this, we systematically reviewed 42 sub-national climate risk and vulnerability assessments. We analysed the assessments using an analytical framework with which we evaluated (1) the conceptual approaches to vulnerability and exposure used, (2) if current or future risks were assessed, and (3) if and how changes over time (i.e. dynamics) were considered. Of the reviewed assessments, over half addressed future risks or vulnerability; and of these future-oriented studies, less than 1/3 considered both vulnerability and exposure dynamics. While the number of studies that include dynamics is growing, and while all studies included socio-economic aspects, often only biophysical dynamics was taken into account. We discuss the challenges of assessing socio-economic and spatial dynamics, particularly the poor availability of data and methods. We suggest that future-oriented studies assessing risk dynamics would benefit from larger stakeholder involvement, discussion of the assessment purpose, the use of multiple methods, inclusion of uncertainty/sensitivity analyses and pathway approaches.

1. Introduction

Knowledge of likely climate-related hazards and their interactions in specific locations with the existing and future population and different kinds of assets enables the planning of adaptation measures and provides a rationale for their implementation (Oppenheimer *et al* 2014). Vulnerability and risk assessments that combine physical and socio-economic information to show climate change risks in a particular area or a sector have become a way to address the need for this knowledge (Preston *et al* 2011, Fünfgeld and McEvoy 2011).

In the past ten years, the vulnerability assessment literature has rapidly increased and can broadly be divided into three strands. First, there are publications that discuss the conceptual and methodological issues related to climate risk, vulnerability and their assessment in general, as well as assessment impli-

cations and usability for adaptation planning (Malone and Engle 2011, Fünfgeld and McEvoy 2011, Hinkel 2011, Joakim *et al* 2015, Dilling *et al* 2015, Preston *et al* 2011). The second strand is composed of empirical case studies, utilising a number of different indicator or scenario-based methodologies, often with visual representations of results (e.g. Rød *et al* 2015, KC *et al* 2015, Wolf and McGregor 2013, Veerbeek and Husson 2013), or a ranking of regions or countries (Brooks *et al* 2005, Haddad 2005). Third, there are studies that investigate the drivers and context of vulnerability (Morss *et al* 2011, Luers 2005, O'Brien *et al* 2007). In such studies, which are mostly qualitative and empirical, vulnerability is approached as a complex, constantly evolving and changing phenomenon that needs to be situated within interactions between biophysical and socio-economic elements (Luers 2005, O'Brien *et al* 2007, Adger 2006).

As a response to these developments, some have urged caution in terms of the ability to assess or measure vulnerability, highlighting the fact that it is difficult to know what it actually is, given it is a socially constructed concept (Hinkel 2011). Many studies have taken the Intergovernmental Panel on Climate Change's (IPCC) formulation of vulnerability from the Third and Fourth Assessment Reports as a conceptual starting point in their assessments (Schneider *et al* 2007). This includes incorporating exposure, sensitivity and adaptive capacity as a sum of a system's vulnerability to climatic stimuli. More recently, the IPCC has introduced the concept of climate risk, which includes hazard, exposure and vulnerability, in its Special Report Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation and in the Fifth Assessment Report (Cardona *et al* 2012, Oppenheimer *et al* 2014). The difference between these two conceptualisations is significant in three ways: 1) the latter frameworks broaden out the concept and highlight the importance of exposure and vulnerability; 2) the latter frameworks highlight the very point of risk occurrence, when all three components interact; 3) the latter frameworks bridge earlier disaster risk management and climate change vulnerability literature.

We argue that one crucial factor has received little attention so far: the dynamics of the components of climate risk and how it is addressed in the assessments. In order for risk reduction and adaptation strategies to be effective, they need to consider these dynamics and their interconnections (Dilling *et al* 2015). This is particularly important given that certain adaptation policies and strategies may reduce short-term risk probability, but increase long-term vulnerability and exposure (Cardona *et al* 2012). Moreover, since climate-related hazards are considered to intensify and become more frequent, the assessment of vulnerability based on historical trends or current state 'snapshots' may prove inefficient, and lead to negative consequences for planning and prevention (Lavell *et al* 2012).

We consider both vulnerability and exposure as essential elements in climate risk frameworks together with the hazards, similarly to the IPCC. Whilst there are numerous reviews focusing on vulnerability (e.g. Giupponi and Biscaro 2015, Bennett *et al* 2016, McDowell *et al* 2016, Räsänen *et al* 2016), few studies have explicitly focused also on exposure. This same disparity is also evident in the studies of dynamics of both concepts, with more discussion about vulnerability so far (e.g. Dilling *et al* 2015). In this study we focus on the dynamics of both exposure and vulnerability.

Most often, dynamics of vulnerability is understood as a shift or change in vulnerability over time (Eriksen *et al* 2005, Westerhoff and Smit 2009). The change drivers can be divided into internal ('endogenous'), and external ('exogenous'), the latter involving

the influence of larger indirect processes that may affect vulnerability but are not directly included into the assessment (Luers 2005, Leichenko and O'Brien 2002, Bennett *et al* 2016). For example, the concept of 'double exposure' highlights the simultaneous vulnerability of different sectors, groups or regions to consequences of both climate change and globalisation (O'Brien and Leichenko 2000). Furthermore, O'Brien *et al* (2007) propose contextual vulnerability as a multi-dimensional process of interaction between the society and climate and stress the dynamic interaction of contextual conditions with the exposed elements. Other early works on vulnerability conceptualisation also underline the dynamic nature of vulnerability and the flux of its components (Kelly and Adger 2000, Belliveau *et al* 2006). Since then, a number of approaches have emerged that have developed ways to address the dynamics in more detail. For example, the 'pathways approach' emphasises flexibility and the need for continuous monitoring and adjusting of the adaptation action as circumstances change (Burch *et al* 2014, Haasnoot *et al* 2013, Stafford Smith *et al* 2011, Wise *et al* 2014). Other strategies to do this have included dynamic landscapes (Fazey *et al* 2010) or participatory scenario planning (Brown *et al* 2016, Mitchell *et al* 2016), for example.

The term exposure has been used in a variety of meanings in the literature (Räsänen *et al* 2016). On the one hand, there are studies that approach it from the driver perspective, e.g. the concept of 'double exposure' (O'Brien and Leichenko 2000, Leichenko and O'Brien 2008) or the concept of 'multiple exposures' (Belliveau *et al* 2006, Bennett *et al* 2016), thus highlighting the presence and interaction of two or multiple drivers of change. In this perspective, drivers are not limited to climate change impacts, but also include other micro- and macro-scale socio-economic drivers of change, e.g. poverty, changes in agricultural practices, urbanisation, international trade and policies, and others. On the other hand, there are studies that use the IPCC-influenced perspective of exposure as a spatial concept (e.g. Dunford *et al* 2015, Preston *et al* 2007, Veerbeek and Husson 2013). The dynamics of exposure from this perspective is largely discussed in land-use related studies, as well as in the impact literature (Verbeek and Husson 2013, Nicholls *et al* 2008), and is often explored by using simulations of land-use change (Carter and Lawson 2011, Jenkins *et al* 2014, Koks *et al* 2014). This approach to exposure as to a spatial distribution of impacts/hazards is also the one used in the climate risk and vulnerability assessment frameworks (Schneider *et al* 2007, Cardona *et al* 2012, Birkmann *et al* 2013). Literature outside the climate change domain, such as land-use and spatial planning, whilst not explicitly focusing on climate change impacts, can offer valuable contributions to spatial dynamics (e.g. Verburg *et al* 2002, White and Engelen 2000).

Given the proliferation of approaches and methods, it is pertinent to review the development of this field. To do this, we present a systematic review of sub-national climate risk and vulnerability assessments, using three criteria to distinguish the dynamics of vulnerability and exposure. We pose the following research question: how is the dynamics of climate risk components addressed in sub-national assessments? In conclusion, we show the implications this has for research and methodological development.

2. Understanding dynamics of climate risk

We recognise the variety of definitions of risk (e.g. risk being a result of consequence (impact) X likelihood (potential), McCarthy *et al* 2001), and their usage in different field varies. Regarding climate risk and vulnerability, Preston *et al* (2011), Fünfgeld and McEvoy (2011), Bennett *et al* (2016) have presented comprehensive reviews of conceptual approaches, framings, their operationalisation, limitations and strengths, as well as their applicability for spatial and adaptation planning. To summarise, it is fair to say that the current conceptual understanding of climate vulnerability and risk draws heavily on the work of the IPCC. In this particular study, we do not seek to re-frame the concepts nor definitions but aim to clarify and analyse how far current assessments account for dynamics in their design.

We use the IPCC's definitions and approaches (see tables 1 and 2) where vulnerability (being part of risk framework or the end result of earlier vulnerability framework) is the predisposition to be adversely affected, often due to certain socio-economic characteristics. We characterise each of the components based on the two most commonly used assessment frameworks: IPCC 2001/2007 vulnerability assessment framework (Schneider *et al* 2007, see table 1) and IPCC 2014 climate risk (Oppenheimer *et al* 2014, see table 2).

Dynamics has been explored in different fields within environmental and global change related disciplines in the last two decades. Dynamic as an adjective means a feature of a system that is characterised by continuous change, activity, or progress (Merriam-Webster 2016). In this paper, we refer to dynamics as the range of change over time, including nuanced to large-scale changes, and look at the three characteristics of assessment components: 1) dynamics (propensity to change over time); 2) projectability (ability of the attribute to be projected); 3) adaptability (ability to be influenced by adaptation interventions).

Within the IPCC 2001/2007 vulnerability assessment framework, vulnerability is composed of exposure, sensitivity and adaptive capacity. These can be characterised as follows: *exposure* is inherently dynamic, projectable and adaptable in the short and medium term. Whereas it may be challenging to measure or project exposure, observing certain

Table 1. Definitions and characteristics of the components of vulnerability.

Components of vulnerability	Definition of vulnerability (IPCC 2001/2007): the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. ^b	Characteristics of the component
Exposure	The nature and degree to which a system is exposed to significant climatic variations. ^a	dynamic ^c projectable adaptable
Sensitivity	The degree to which a system is affected, either adversely or beneficially, by climate variability or change. ^b	dynamic projectable adaptable
Adaptive capacity	The ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences. ^b	dynamic ^{c,d} projectable adaptable

^a IPCC TAR WG II, Annex B, Glossary of Terms, p 987

^b IPCC AR4 SYR, Appendix I: Glossary, p 89, 86, 76

^c Oppenheimer *et al* (2014)

^d Morss *et al* (2011)

drivers, for example trends of urbanisation, population growth and land-use development, may be possible (Morss *et al* 2011). *Sensitivity* is dynamic, adaptable and projectable. Projecting sensitivity is, however, challenging, since it is often related to certain socio-economic or demographic traits, the data on which may be limited and the projections may present high level of uncertainty (Adger *et al* 2009). *Adaptive capacity* is dynamic, projectable and adaptable. It is the element that can and should be targeted primarily by adaptation strategies, since it is seen as a precondition for adaptation, but is not necessarily directly translated into adaptation action (Schneider *et al* 2007).

In this study, we use the IPCC approach to climate risk as a joint result of interaction of hazards, vulnerability and exposure (Cardona *et al* 2012, Oppenheimer *et al* 2014). These components of climate risk can be characterised as follows: *hazards* are by nature dynamic. Our ability to understand, model and project them is constantly improving but scientific irreducible uncertainties are likely to remain (Dessai *et al* 2009). Currently, most of the current climate change projections go up to 2100, whereas vulnerability assessments are mostly based on present socio-economic data (Cardona *et al* 2012). Hazards can be characterised as 'non-adaptable' in that one cannot directly influence their occurrence with adaptation in the short or medium term (Cardona *et al* 2012). Their occurrence, however, can be influenced by mitigation actions in the long term. *Exposure* is characterised as in the 2007 IPCC report, although there is a major change in how it is defined, shifting focus from impact towards spatial conceptualisation (tables 1 and 2). *Vulnerability* is inherently

Table 2. Definitions and characteristics of the components of climate risk.

Components of climate risk	Definition of climate risk (IPCC 2014a): the potential, when the outcome is uncertain, for adverse consequences on lives, livelihoods, health, ecosystems and species, economic, social and cultural assets, services (including environmental services) and infrastructure ^a	Characteristics of the component
Hazard	The potential occurrence of a natural or human-induced physical event that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, and environmental resources. ^a	dynamic projectable non-adaptable in a short or medium period ^{b,c}
Exposure	The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected. ^a	dynamic projectable adaptable ^b
Vulnerability	The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. ^a	dynamic projectable adaptable ^{b,c}

^a IPCC AR5 SYR, Annex II: Glossary, p 123, 124, 127, 128

^b Oppenheimer *et al* (2014)

^c Cardona *et al* (2012)

dynamic since it is related to socio-economic aspects of objects at risk. It is adaptable and most often targeted by adaptation. IPCC suggests addressing vulnerability dynamics through the use of socio-economic scenarios, development trends and pathways (Cardona *et al* 2012). Additionally, using certain demographic projections (e.g. aging population, gender and poverty trends) may also prove beneficial (Morss *et al* 2011).

Whilst hazards are projected into the future in assessments, the other two components, exposure and vulnerability, are often not. The two latest IPCC reports also recognise that exposure and vulnerability are dynamic, vary across temporal and spatial scales, and call for more empirical, methodological and conceptual development of these issues especially at the regional or local level (Hewitson *et al* 2014, Cardona *et al* 2012). Hence, we look at how the dynamics of vulnerability and exposure are approached conceptually and methodologically at

these levels. This also contributes to the recent calls for more critical research on methods to assess future risks and vulnerabilities (McDowell *et al* 2016).

2.1. Analytical framework

In the following, we present a three-step framework that will enable us to analyse if and how the dynamics of climate risk is addressed in empirical assessment cases.

1. Conceptual approach

In the introduction we discuss the literature on exposure and how dynamics is understood in it. Here, we use the IPCC-driven spatial approach to define the exposure, and from this perspective explore two different definitions of the term, (1) as a manifestation of a hazard, and (2) as a geographical location (figure 1). In the former, exposure is tightly coupled with a hazard and impact distribution, whereas in the latter exposure is considered to be a separate, explicitly spatial element referring to the presence of people or assets in the areas that may be affected by a hazard. Distinguishing these two types is significant for the operationalisation of the assessment and for the methodology.

Both approaches to exposure may include dynamics. According to the first definition, dynamics is related to the distribution of hazard impact and is also characterised by the nature of surroundings that may limit or exacerbate exposure (e.g. surface types, building types, elevation, and other). This approach often focuses on hazard dynamics, although it can also include the spatial dynamics of the area. The second definition of exposure is focused primarily on spatial changes in land use rather than on the impacts, and allows for more explicit tracking of land use changes.

To analyse the dynamics of vulnerability, we propose to use the four approaches suggested by Joakim *et al* (2015) (figure 2).

We acknowledge the confusion that may arise from assessing vulnerability (Schneider *et al* 2007), and assessing risk, where vulnerability is one of the components (Cardona *et al* 2012, Oppenheimer *et al* 2014, Birkmann *et al* 2013). While analysing the dynamics of vulnerability, we are primarily guided by the understanding of it as a certain socio-economic condition, or the predisposition of an object to be affected, as in the later IPCC frameworks. Thus, to distinguish 'vulnerability as an outcome' from 'vulnerability as pre-existing condition', we analyse whether adaptation measures have been included into the assessment (e.g. through economic valuation of adaptation options, simulation, discussion, adaptation pathways). We acknowledge that in some studies vulnerability may fall inbetween these two approaches, and we use our judgement while ascribing it to a certain approach.

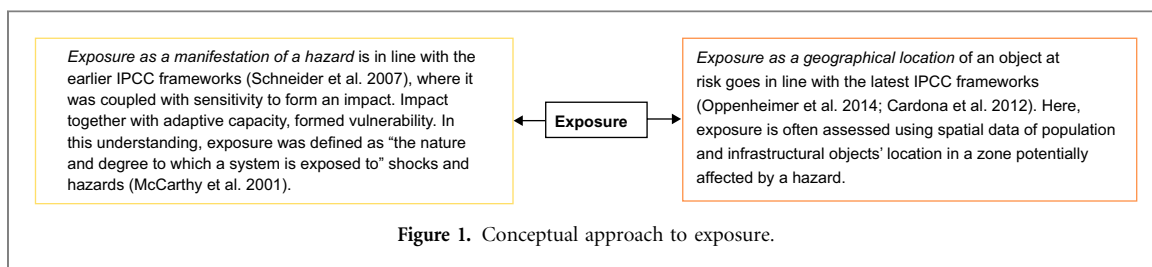


Figure 1. Conceptual approach to exposure.

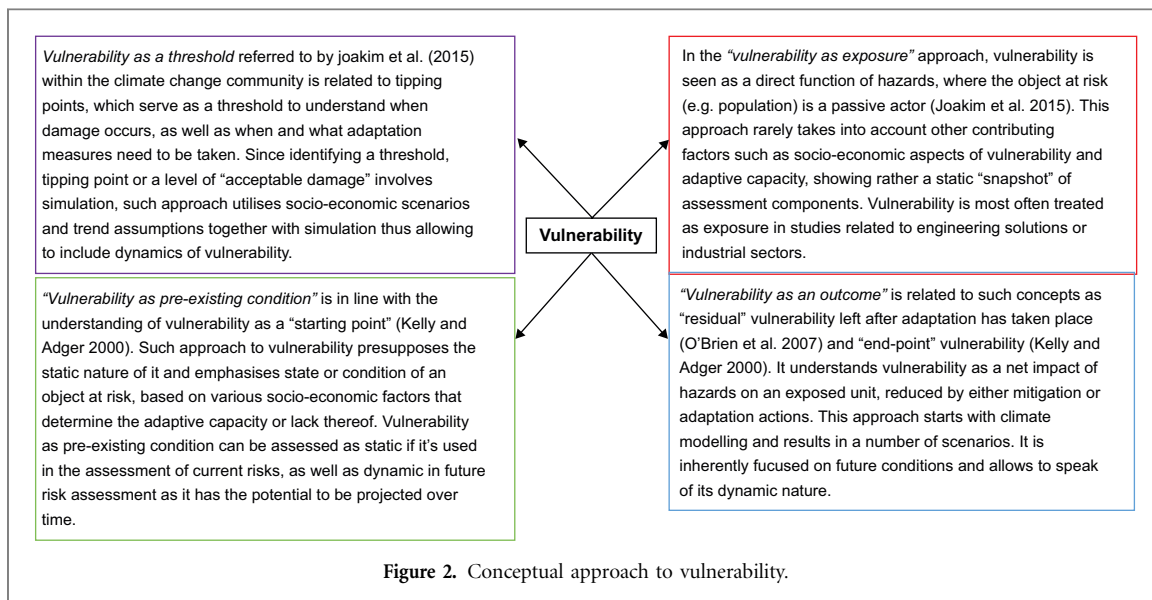


Figure 2. Conceptual approach to vulnerability.

2. *Timeframe: current vs. future risks*

Since we propose the understanding of dynamics as a range of changes over time, we look at the temporal frame of these assessments. If not expressed explicitly, the frame can be indicated by the data used for assessing exposure, vulnerability and hazards. Most often, the time frame can be identified by climate scenario period or climate data used. In our analysis, we separate assessments that deal with current risks, using current and/or historical data; and future-oriented risk assessments that use data about future conditions.

3. *Dynamic vs. static assessments*

We look at the change over time of vulnerability and exposure in the assessments. We expect to see this change reflected in the assessments through the methods and data used. Through literature, we have identified several methods that can be used to include dynamics, which serve as the preliminary guidance of our analysis.

While the methods to include the dynamic dimension into vulnerability and exposure assessments differ due to types of data used, it is possible to cluster them into the following categories:

1. Indicators of change in a larger context: external indicators of change (Leichenko and O'Brien 2002), national socio-economic scenarios, global development trends and pathways (Cardona et al 2012, Oppenheimer et al 2014)

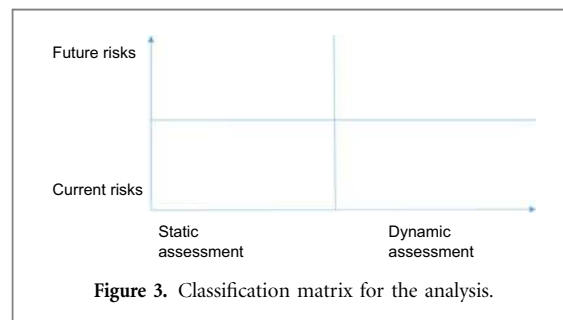
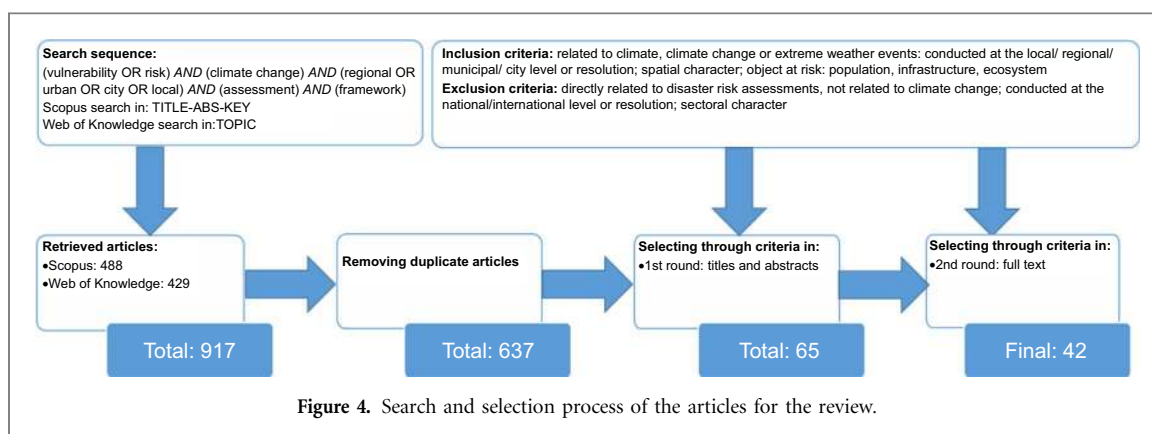


Figure 3. Classification matrix for the analysis.

2. Indicators of change in a sub-national context: projecting indicators of current state over time, local socio-economic scenarios, development plans and adaptation pathways (Cardona et al 2012, Oppenheimer et al 2014)
3. Simulations (of thresholds, land-use, adaptation and non-adaptation, adaptive capacity etc).

Naturally, these three criteria are interlinked, as the choice of a timeframe may influence the conceptual approach and the inclusion of dynamics, and this consequently leads to the choice of methods, although this path is not necessarily clear in all cases.

For our analysis, we placed all assessments into a classification matrix (figure 3), according to the conceptual approach, timeframe and inclusion of dynamics. The axis 'Current and future risks' represents the temporal frame of an assessment. The axis 'Static and dynamic assessment' indicates the inclusion of dynamics with data and methods.



Thus, four ways of categorising the assessments emerge. The category ‘Future risks/Static assessment’ includes studies that conduct assessments of future risks, using future climate projections combined with current/historical socio-economic data to assess vulnerability. For exposure, the choice of this category is influenced by the conceptual approach. The category ‘Future risks/Dynamic assessment’ represents studies that have assessed future risks by using future climate projections, as well as changes over time in vulnerability and exposure with the use of various methods. The category ‘Current risks/Static assessment’ includes studies that have assessed current risks and vulnerabilities, using current or historical data. Naturally, current risk assessments do not presuppose inclusion of dynamic components, since there is no change over time. Therefore, we assume the category ‘Current risks/Dynamic assessment’ to be inapplicable.

3. Methods and data

We chose a systematic search and review methodology (Grant and Booth 2009) of sub-national level assessments, since they allow for a finer resolution of climate risk and vulnerability assessments. Another reason for focusing on this level is the better suitability of such assessments for adaptation planning and policy-making (Fünfgeld and McEvoy 2011). We focused on studies where population and built environment are the objects at risk, since these elements are most susceptible to change from within and outside. We did not set any limitation on time frame; however, the earliest article of the final review pool dates to 2006.

We systematically searched for studies through SCOPUS and Web of Knowledge, as they contain the biggest database of articles in social and environmental sciences (Landauer *et al* 2015). Two searches were performed on 28th September 2015. See figure 4 for details of the search process, as well as the inclusion and exclusion criteria.

Since the research question explores not only ‘if’ but also ‘how’ dynamics is included, we used the

qualitative content methodology with a directed approach (Hsieh and Shannon 2005). Thus, we have pre-identified categories for conceptual and methodological approaches through literature review to guide our analysis, and left sections for open inputs in order to retrieve information that would advance the methodological categories. We developed a questionnaire to retrieve the information (see table 3). The sections and categories were coded into Excel 2013 template (Microsoft, Redmond, WA, USA) and the two of the co-authors performed the analysis, sharing a pre-coded Excel template. The final result was an Excel sheet that contained information on how many studies have included certain types of methods and conceptual approaches, as well as open-ended questions that allowed us to gain insights into other methods used. Additionally, we analysed the data both vertically and horizontally, i.e. looked at the conceptual and methodological applications of each, connections between them, and the application and prevalence of certain methods and conceptual approaches across all studies. Last open input section on remarks and notes of each study allowed us to reflect on the connections between purpose and methods, purpose and inclusion of stakeholders, as well as limitations, data, conceptual and methodological approaches used. The final results were color-coded and placed into the classification matrix (figure 3).

We acknowledge the limitations of the keyword search resulting in not capturing all relevant articles (e.g. Ford *et al* 2013, Nicholls *et al* 2008, Maloney and Preston (2014) could have been included in the review but were not retrieved based on our search sequence). We also acknowledge other literature that can provide valuable insights. For example, resilience assessments that focus on coping/adaptive capacity, or impact studies that are commonly (but not exclusively) used in economic, land-use, infrastructure planning and development with a primary focus on hazards and impacts (Fünfgeld and McEvoy 2011, Noble *et al* 2014). Our focus on empirical vulnerability and risk assessments is motivated by the following reasons: a) vulnerability and risk assessments and framing have become one of the most common tools in adaptation planning and are

Table 3. Questionnaire sections.

Background/bibliographic information	<ul style="list-style-type: none"> – year of publication – type of literature (scientific literature, grey literature, official documents/reports) – short description of the study – geographic area (country, municipality, city where applicable) – object at risk (population, infrastructure/built environment, ecosystem) – spatial scale (open input, inputs included: municipality, county, city, regional, sub-regional, local, village, river basin levels) – temporal scale of the assessment (current or future risks, year input for future risks)
Conceptual approach	<ul style="list-style-type: none"> – conceptual approach to vulnerability (as per Joakim <i>et al</i> 2015), here we included both vulnerability as an element of risk framework (IPCC 2014b) and vulnerability as a joint function of exposure, sensitivity and adaptive capacity – conceptual approach to exposure
Methods to include dynamics and data used	<p>Pre-identified methods through the literature review:</p> <ul style="list-style-type: none"> – Simulations – Scenarios (climate, socio-economic) – Trends and pathways – Development plans – Drivers of change at macro-scale (external drivers of change) – Projecting current indicators over time – Other methods and data (open input)
Summary and remarks	<ul style="list-style-type: none"> – Open input: short summary of the study, notes on stakeholder participation, notes on the purpose of assessment, remarks on any discrepancies in timeframe of the data used

seen as a critical component of climate change adaptation processes at the local level (Fünfgeld and McEvoy 2011, Mukheibir and Ziervogel 2007, Romieu *et al* 2010, Preston *et al* 2011); b) they are better suited for the assessments where population is an object at risk as they help to explore the socio-economic sources of risk or vulnerability; c) such assessments allow the assessment of all three essential components: socio-economic, spatial and biophysical, as well as their interaction. For these reasons, we did not include ‘impact’ or ‘resilience’ in keyword searches, but also did not exclude these results from our retrieved articles. Our search retrieved 637 hits and resulted in a sample of 42 empirical cases after detailed screening, which we consider enough to provide insights into our research question.

4. Results and discussion

First, we present a brief bibliometric analysis of the reviewed assessments.⁴ Second, we identify general

¹ In the following section, we refer to the reviewed articles in square brackets. For the complete references, see supplementary material 1 (stacks.iop.org/ERL/12/013002/mmedia).

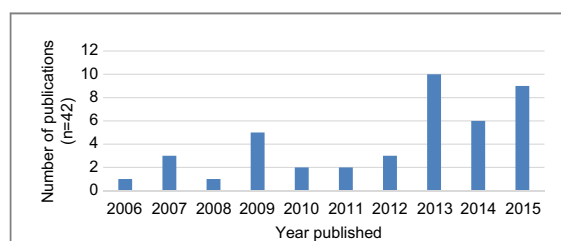
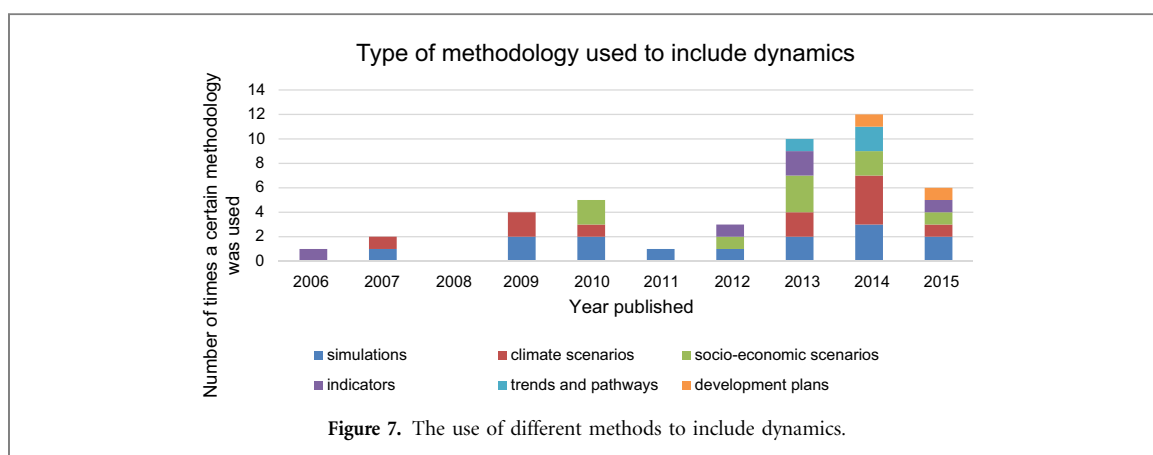
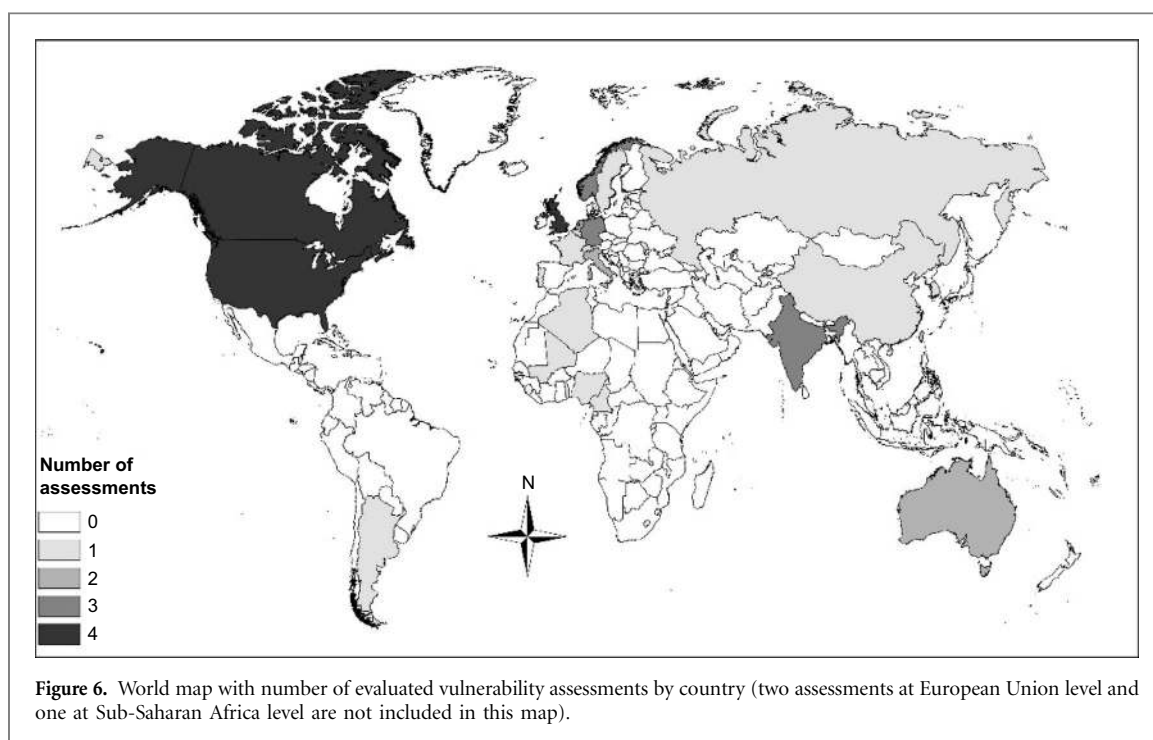


Figure 5. Reviewed assessments by the year of publication.

trends and observations regarding the inclusion of dynamics into exposure and vulnerability assessments. We continue with a discussion of linkages between conceptual approach, methods and dynamics inclusion, and further observe methodological and conceptual limitations.

4.1. Bibliometric analysis

We reviewed 42 sub-national risk and vulnerability assessments according to the analytical framework presented above. Figure 5 shows the year when the assessments were published. Overall, the number of assessments has grown substantially in recent years, with 25 out of the 42 assessments (60%) published in the year 2013, or later. A third of the assessments



were in the field of urban studies, while almost as many (28%) analysed generic vulnerability to climate change. Another recurring field was risk management (17% of the assessments), while other 17% introduced or evaluated assessment methodologies.

The geographical range of the assessments analysed was wide, with all the continents represented. USA, UK and Canada were the top three countries, with four assessments each (figure 6). Other European countries were also well represented, as well as India.

Both the general incorporation of dynamics, as well as the range of methods used to include dynamics in assessments has increased over the years (figure 7), although this might be due to an overall increase in the number of assessments conducted, as previously stated. Simulations, scenarios and indicators have been used throughout the years, while the use of development plans, trends and pathways has emerged only recently. However, their use is still limited

compared to the rest of the methodologies. The use of climatic scenarios is prevalent in the assessments. Another noteworthy observation is that newer assessments regularly combine several methods for the inclusion of dynamics, while older assessments tend to use one or two methods.

4.2. Review of dynamics in exposure and vulnerability

We placed reviewed assessments into the categories according to the framework presented in section 3 (figures 8 and 9). Out of 42 studies, 26 assess future risks and vulnerabilities. Out of 26 future-oriented risk and vulnerability assessments, only nine included dynamics into both vulnerability and exposure [4, 6, 14, 15, 16, 19, 23, 25, 35].

1. Dynamics of exposure

In several studies [4, 14, 17, 19, 21, 34], we used our judgement to identify how exposure was conceptualised, because it was not explicitly mentioned.

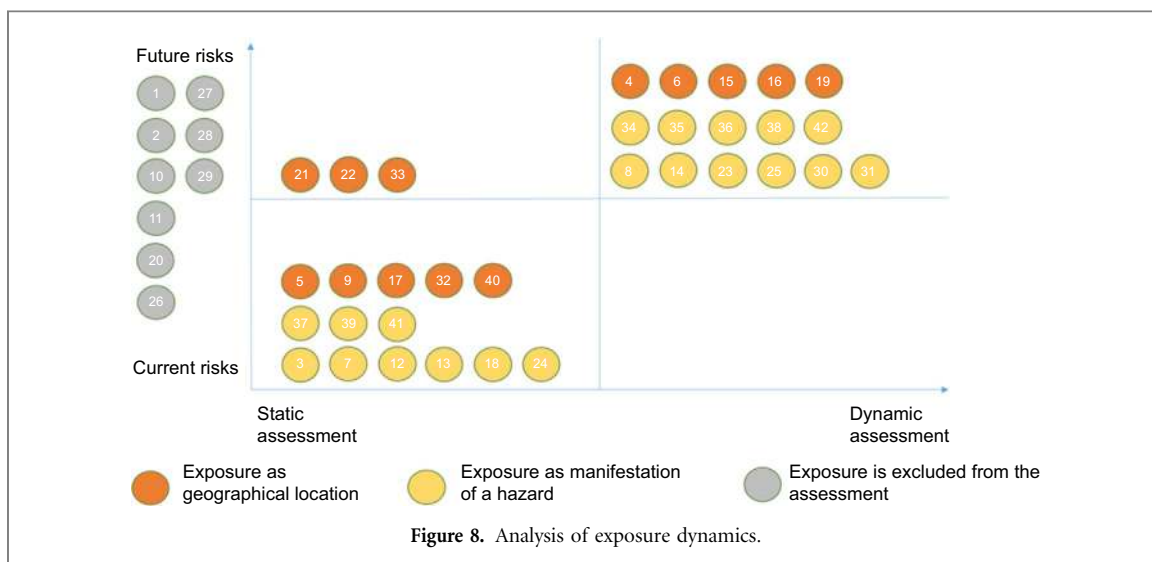


Figure 8. Analysis of exposure dynamics.

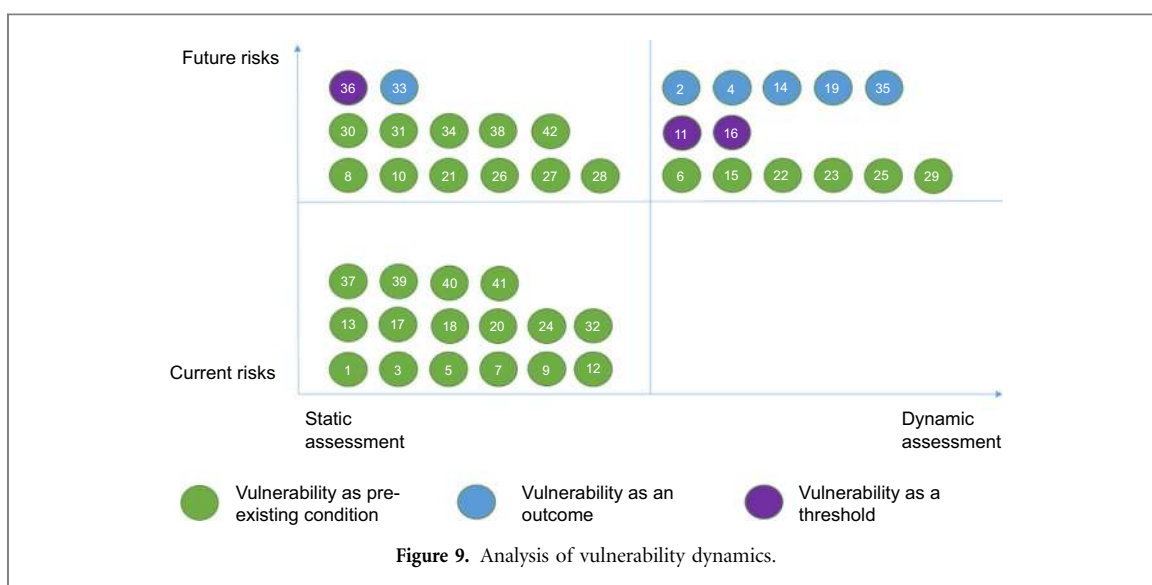


Figure 9. Analysis of vulnerability dynamics.

Out of 42 studies, nine omitted exposure from their assessment. From the remaining 33 studies, 13 treated exposure as ‘geographical location’ and 20—as ‘a manifestation of a hazard’. This can be linked to the prevalence of IPCC 2001/2007 vulnerability framework use in the assessments, since this approach does not include hazards as a separate element, and presupposes the inclusion of exposure as ‘a manifestation of a hazard’ in most cases.

Approximately half (16 out of 33) of the studies included the dynamic aspect into exposure assessments. Out of 16 dynamic assessments, only five treated exposure as a ‘geographical location’. We placed the remaining 11 assessments treating exposure as ‘manifestation of a hazard’ into ‘Future risks/Dynamic assessment’ category, when these studies included climatic projections and scenarios (hazard data). These assessments did not use spatial plans, trends or land-use projections to reflect spatial change over time [8, 14, 34, 35, 36, 38]. This can be explained by the chosen conceptual approach to exposure and/or

lack of data for spatial projections. However, we suggest that such cases may benefit from the inclusion of future spatial data, since current land-use and people/asset distribution may change over time. Two studies did not indicate a clear timeframe of the assessment, but simulated different sea level rise (SLR)- and flood inundation levels with various return periods [23, 42], focusing on hazard data.

The three studies in the ‘Future risks/Static assessment’ category represent studies that assessed future risks and vulnerabilities, while using future climatic projections together with the current spatial data [21, 22, 33].

2. Dynamics of vulnerability

Out of 42 studies, the overwhelming majority (33) approached vulnerability as ‘pre-existing condition’. We placed studies that conceptualised vulnerability ‘as a threshold’ and ‘as an outcome’ along the ‘Future risks’ axis. ‘Vulnerability as exposure’ was not identified in this review. We

have treated future-oriented assessments with ‘Vulnerability as pre-existing condition’ approach when they did not attempt to simulate adaptation, nor mentioned adaptation taking place. Accordingly, those future-oriented assessments that included adaptation simulation [2, 4, 19, 33, 35] were identified as ‘Vulnerability as an outcome’ (i.e. residual vulnerability, O’Brien *et al* 2007). ‘Vulnerability as a threshold’ is a rare approach that is similar to outcome, but involves simulation of thresholds (e.g. mortality thresholds with heat temperatures, as in [16]), simulation of inundation tipping points [36] or identifying levels after which citizens are not able to cope with or adapt to climate change impacts [11]. This approach requires the identification of acceptable levels of damage, which can be rather challenging, and should include participation of stakeholders [36].

Out of 26 future-oriented assessments, half used current socio-economic data combined with future climate data. This can be explained by limitations in data availability, as noted by some of them [8, 26, 27, 28]. This approach of combining future climate projections with current socio-economic and spatial data is more pronounced in assessing vulnerability, although three examples of exposure were identified. In some assessments using current and historical data, assumptions were made in terms of usability of current assessments to make future vulnerability projections [4], and for future decision-making [3, 13]. Several assessments were conducted as an academic exercise in order to advance methodological literature, which influenced the data used [1, 12, 14, 21, 31, 33, 42].

4.3. Linkages between conceptual approach and choice of methods

The choice of methods to include dynamics of exposure is heavily dependent on the conceptual approach. Thus, all future-oriented studies that chose ‘exposure as a manifestation of a hazard’ approach utilised climate scenarios and projections [14, 23, 25, 30, 31, 34, 35, 36, 38], or simulated flood return periods and SLR-levels [35, 42]. Only one study strengthened climate scenarios with land-use projections within the chosen approach [25]. Within future-oriented assessments of exposure as ‘geographical location’, the most commonly used method was the simulation of land-use, land-use scenarios and urban development plans [4, 6, 15, 16, 19]. Table 4 summarises our findings in terms of methods used within each conceptual approach. We argue that within the approach ‘exposure as a manifestation of a hazard’ bio-physical data (i.e. climate projections) should be complemented with future spatial data.

We observed several methodological differences in the application of approaches to vulnerability. One of

Table 4. Methods to include dynamics in exposure based on conceptual approach.

Conceptual approach to exposure	Methods to include dynamics
Exposure as a manifestation of a hazard	Climatic projections, climate modelling, climate scenarios, SLR-simulations, heat or flood inundation simulation
Exposure as geographical location	Urban spatial scenario modelling, land-use plans, land-use modelling

the most widely-used methods to include dynamics of vulnerability was the use of socio-economic scenarios, which were used in all three approaches to vulnerability. However, certain methods are typical of or even exclusive to certain approaches. For example, the conceptualisation of vulnerability ‘as a threshold’ involves simulation of certain thresholds or ‘tipping points’. In such studies, simulation was coupled with the use of demographic projections and socio-economic scenarios. ‘Vulnerability as an outcome’ was similar to ‘vulnerability as a pre-existing condition’, but it advanced the approach by simulating adaptation measures or adaptation plans, along with the use of socio-economic scenarios. This allowed for a deeper understanding of risk-increasing factors, locations of ‘where to adapt’, as well as the choice of adaptation measures [19, 35]. Particularly, in [35] scenarios of adaptation (business-as-usual, opportunistic adaptation, active adaptation) were developed in order to understand and assess the consequences of adapting and non-adapting, while in [33] authors took an economic approach by calculating costs with and without spatial adaptation. Such methods, as projecting current indicators over time, as well as including macro-scale indicators of change, were not widely used but still present [14, 22, 23, 25].

Overall, the approach to vulnerability ‘as an outcome’ seemed to be the most data and resource demanding, but simultaneously most comprehensive in terms of assessments of future risks. The approach to vulnerability as ‘a pre-existing condition’ was the most common, and suitable for both assessments of current and future risks. This approach is more suitable for understanding the patterns of risk, as well as mapping risks, rather than identifying adaptation measures and their effect. ‘Vulnerability as a threshold’ requires modelling skills, and preferably stakeholder involvement to determine thresholds. This approach also allows to set the priorities for adaptation areas and objects. Table 5 summarises our findings on the methods to include dynamics into three conceptualisations of vulnerability.

We suggest that upon availability of resources, several methods should be included in assessments, combining e.g. socio-economic scenarios with adaptation simulation, socio-economic scenarios at the local scale, strengthened by macro-scale context

Table 5. Methods to include dynamics in vulnerability based on conceptual approach.

Conceptual approach to Vulnerability	Methods to include dynamics
Vulnerability as a threshold	Demographic projections, impact threshold simulation, simulation of hazard scenarios coupled with socio-economic scenarios
Vulnerability as a pre-existing condition	Simulation of population growth, urban growth and development scenarios, indicators projected over time
Vulnerability as an outcome	Urban development plans, simulation/discussion of adaptation measures, local development scenarios including external and internal change factors, scenarios for adaptation, socio-economic growth scenarios, population growth scenarios, adaptation pathways

development trends and pathways, identification of major driving forces of local development together with the population growth.

4.4. Conceptual and methodological observations and limitations

Assessing vulnerability and climate risks can be challenging, particularly conceptualising what vulnerability is and what should be included in the assessments (Hinkel 2011). The literature proposes various concepts, approaches and methodologies, as we have presented above. Throughout the review process, we have observed differences in definitions, concepts and frameworks used, which have ultimately determined what has been included in the assessments. Some have omitted spatial elements, i.e. exposure [e.g. 1, 2, 10, 11], while others have included this in ‘physical attributes of vulnerability’ [26, 27, 28, 29]. Several studies broke down vulnerability into e.g. institutional, attitudinal, asset, social and other subtypes [2, 15, 13]. The question of what should be included is closely linked with what is the object at risk, what is the context (O’Brien *et al* 2007), and what is the purpose of the assessment. These observations are in line with the previous reviews of the assessments and their operationalisation (Preston *et al* 2011, Fünfgeld and McEvoy 2011).

The results of our review, particularly the inclusion of socio-economic data in all of the reviewed studies, show that when population and infrastructure are objects of an assessment, vulnerability is not seen as a direct impact of a hazard. All studies have included socio-economic aspects, while several studies have also put them into a larger national and international context [2, 6, 35]. This shows the acknowledgement of climate vulnerability and risk perceived as not just a physical occurrence, but also a socio-economic phenomenon that is changing and evolving within the macroscale conditions.

The purpose of assessments influences the choice of conceptual approaches, methodologies, as well as the data included. ‘Vulnerability as a threshold’ allows for the identification of ‘hot-spots’ and prioritisation of adaptation measures. If the purpose of an assessment is to choose spatial or socio-economic adaptation measures, ‘vulnerability as an outcome’ can be chosen, entailing a simulation and a discussion of adaptation options. ‘Vulnerability as pre-existing condition’ can be useful for investigating causes of vulnerability, as well as understanding the linkages between different elements and their role in risk formation.

One of the identified bottlenecks in assessing vulnerability and exposure dynamics and projecting them into future is poor availability of data, particularly future socio-economic data. Even if datasets that can be used in assessing current vulnerability are available, they often offer little help in assessing future vulnerability. There are, nevertheless, ways to overcome this problem, and new datasets can be generated. For instance, there are numerous methodologies to predict demographic and land-use changes (Brown *et al* 2013), and these land-use maps can then be used in assessing the spatial configuration of exposure and vulnerability. There are also other options for obtaining data; for example, many have downscaled global or macro-regional socio-economic scenarios (van Ruijven *et al* 2014, Vigié *et al* 2014), and data can also be gathered using participatory methods, surveys and interviews (Tellman *et al* 2015, Ordóñez and Duinker 2015, Djoudi *et al* 2013, Corobov *et al* 2013). Additionally, we suggest that further involvement of stakeholders, particularly local administrations, may increase the availability of socio-economic and spatial data through co-production, benefiting both the accuracy of assessment results, and their usability by the local administration and decision-making.

Another bottleneck is related to the uncertainty and accuracy of the projections. Whilst one might have data about future population, this data often cannot be used to assess the future levels of education, income, health and other important socioeconomic aspects. This is because estimating these changes is difficult, although some methods for forecasting changes have emerged recently (van Ruijven *et al* 2014). Overall, there is widespread uncertainty in predicting future vulnerability because of scarcity and reliability of data. In general, we question how usable the data is, and call for the data to be critically evaluated. This is even more important when dynamic vulnerability, rather than static vulnerability, is assessed. However, literature suggests ways to deal with the uncertainty by e.g. producing a range of alternative future pathways, instead of one most plausible scenario, and urges to plan adaptation action against a range of alternatives to ensure robust decision-making (Adger *et al* 2009, Dessai *et al* 2009, Lempert *et al* 2006, Offermans *et al* 2009, Haasnoot *et al* 2012). The inclusion of

adaptation pathways often involves computer modelling and allows for the inclusion of dynamic changes within the system (Haasnoot *et al* 2012, Haasnoot *et al* 2014, Kwakkel *et al* 2015). Additionally, sensitivity analyses and different tools for probability distributions can be used. Several studies in this review used sensitivity analyses, and some methods for probability distribution (e.g. Dunford *et al* 2015, Giupponi *et al* 2013, Jenkins *et al* 2014), as well as discussed/simulated adaptation options and used adaptation scenarios (e.g. Van de Ven *et al* 2010, Boughedir 2015, Angell and Stokke 2014). We encourage the use of uncertainty and sensitivity analyses, as well as of adaptation pathways; here impact assessment literature can contribute (Haasnoot *et al* 2012). As for the dynamics of exposure, whilst several studies used land-use simulation tools, also other non-climate literature can offer insights and tools for future spatial change (e.g. Verburg *et al* 2002, White and Engelen 2000).

Overall, no data set is best, but a combination of multiple sources of information, as well as the inclusion of a range of uncertainties, can provide more robust understanding of change, regardless of spatial resolution (Hewitson *et al* 2014).

5. Conclusion

We have systematically reviewed the empirical cases of climate risk and vulnerability assessments at the sub-national level in order to see if dynamics of vulnerability and exposure is taken into account and how this is done methodologically.

As a conceptual basis for the analysis of vulnerability dynamics we have used the classification suggested by Joakim *et al* (2015). One of the most common ways to approach vulnerability was 'as pre-existing condition', which is in line with several dominant frameworks in the field (IPCC 2001/2007, Turner *et al* 2003). This approach is often used to explore, understand and trace the causes of vulnerability and often serves a practical purpose of identifying 'hot-spots' or most vulnerable population groups and areas. The dynamics was included in such assessments through future socio-economic projections and population growth simulations, local development scenarios and indicators projected over time. The other most commonly used approach 'vulnerability as an outcome' is in line with more recent frameworks (Cardona *et al* 2012, Oppenheimmer *et al* 2014, Birkmann *et al* 2013). Vulnerability in this case is the net result after adaptation measures have been taken. Thus, methodologically it advances the previous approach by simulating adaptation measures, including adaptation pathways or discussing adaptation measures, and is often used for adaptation planning and choosing particular adaptation options. The third identified conceptual approach, 'vulnerability as a threshold', was less

commonly used. Methodologically it involves the identification of thresholds until damage becomes 'unbearable' through the simulation of hazard and/or exposure. Such method is particularly helpful for the choice and timing of adaptation measures.

Regarding the exposure, we distinguished between two major types suggested in literature: 'exposure as a manifestation of a hazard' and 'exposure as a geographical location'. The former approach is more typical of earlier vulnerability assessments (IPCC 2001/2007, Turner *et al* 2003), while the latter of the more recent ones (Cardona *et al* 2012, Oppenheimmer *et al* 2014, Birkmann *et al* 2013). In many studies the conceptual difference was not clear; in such cases the data and the methods have been helpful to identify the approach. Exposure as 'a manifestation of a hazard' has been assessed by mapping the hazards (inundation, precipitation, heat levels, SLR), whereas the exposure as 'a geographical location' represents purely geographical layer (map, land-use plans, etc). This predetermines the methods to include the dynamics in exposure: through climate modelling, climate change scenarios, SLR simulations in the former case, and through the simulation using future land-use and development plans in the latter case. In our review, we have come to the conclusion that mapping exposure as 'a manifestation of a hazard' would benefit from supplementing future hazard data with the future spatial data. Whilst not focusing explicitly on climate change impacts, land-use and spatial planning literature has much to contribute here methodologically (e.g. Verburg *et al* 2002, White and Engelen 2000).

Overall, we conclude that over half of the reviewed studies assessed future risks and vulnerabilities. Dynamics of either exposure or of vulnerability was only included in half of the future-oriented studies. The inclusion of dynamics in both vulnerability and exposure was observed in less than 1/3 of the future-oriented studies. Our results show that the number of studies that include dynamics has increased in the last five years. Naturally, we identify many constraints that limited the inclusion of any future data in the assessments. In the first place, these constraints included data availability, which is particularly relevant for vulnerability dimension, i.e. inclusion of future socio-economic data. Unavailability of future spatial data has not been mentioned in exposure assessments. The inclusion of future spatial data is seen as an advantage, rather than a necessity for future-oriented assessments, where exposure is treated as 'a geographical location'.

These conclusions evoke the following thoughts on the general understanding of vulnerability and risks: although the role of socio-economic factors in climate change risk formation is largely recognised in the literature (Räsänen *et al* 2016), the biophysical factors still prevail in the future-oriented sub-national assessments. More methodological developments are needed in addressing future socio-economic change

and its scenarios and projections at the sub-national level, which can be used along with the climatic projections of that region. In this study, we look at the dynamics of vulnerability and exposure separately within the assessments. We argue that there is a need to examine the interaction of changing exposure, vulnerability and hazards in a certain place at a certain point in time. We further point out that little is known about how adaptation influences these processes over time.

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