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Assessment of vulnerability to climate change using a multi-criteria outranking approach with application to heat stress in Sydney

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ABSTRACT

Climate change vulnerability assessment is a complex form of risk assessment which accounts for both geophysical and socio-economic components of risk. In indicator-based vulnerability assessment (IBVA), indicators are used to rank the vulnerabilities of socio-ecological systems (SESs). The predominant aggregation approach in the literature, sometimes based on multi-attribute utility theory (MAUT), typically builds a global-scale, utility function based on weighted summation, to generate rankings. However, the corresponding requirement for additive independence and complete knowledge of system interactions by analyst are rarely if ever satisfied in IBVA.

We build an analogy between the structures of Multi-Criteria Decision Analysis (MCDA) and IBVA problems and show that a set of techniques called Outranking Methods, developed in MCDA to deal with criteria incommensurability, data uncertainty and preference imprecision, offer IBVA a sound alternative to additive or multiplicative aggregation. We reformulate IBVA problems within an outranking framework, define thresholds of difference and use an outranking method, ELECTRE III, to assess the relative vulnerability to heat stress of 15 local government areas in metropolitan Sydney. We find that the ranking outcomes are robust and argue that an outranking approach is better suited for assessments characterized by a mix of qualitative, semi-quantitative and quantitative indicators, threshold effects and uncertainties about the exact relationships between indicators and vulnerability.

1. Introduction

Climate change adaptation is emerging as a significant field of research in a number of disciplines. It is premised on the fact that, even under the most optimistic scenarios of greenhouse gas emission reduction over the next hundred years, some degree of change in climate appears inevitable. Assessments of the vulnerability of a valued utility (e.g., health, shelter, security, economic prosperity) for a given population (e.g., locality, community, economic sector) to one or more climate-related hazards (e.g., heat waves, flood events, rise in sea levels) serve as planning tools in environmental decision-making. They help in identifying highly vulnerable communities, allocating adaptation resources, better understanding systemic weaknesses, monitoring the effects of adaptation measures, communicating risk and justifying policy to the public (Eriksen and Kelly, 2007; Füssel, 2007; Klein, 2003).

A large number of climate-related vulnerability studies can be found in the literature. Some vulnerability studies are based on mechanistic or economic modelling, especially those evaluating the impacts of climate stress on specific biological systems or economic sectors, usually agricultural (e.g., Belliveau et al., 2006; Gbetibouo et al., 2010; Luers et al., 2003). Others, often indicator-based, map vulnerabilities across geographical areas at a given scale (e.g., Hahn et al., 2009; O'Brien et al., 2004; Vincent, 2007; Wilhelmi et al., 2004). These assessments are generally meant to be precursors for more in-depth, impact analyses of vulnerable populations. We refer to assessments of vulnerability that are totally or partly based on indicators as indicator-based vulnerability assessments (IBVA). Although IBVA approaches have been applied to stressors other than climate (e.g., famine and poverty), in this paper we are concerned exclusively with climate-related stresses.

Most vulnerability assessment frameworks recognize both the external, geophysical determinants of risk, called *exposure* to climate stressors, and the internal, socio-economic and institutional processes generating vulnerability, usually referred to as the system's *sensitivity* to the stress in question and its *adaptive capacity* or lack thereof (Eriksen and Kelly, 2007; Klein, 2003; Parry et al., 2007).

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These are sometimes called the three dimensions of vulnerability and are seen as the outcome of the interaction of two traditions of vulnerability research in physical and social sciences—a synthesis that provides a better account of the contextual and social dynamics of climate hazards and the multiple linkages that govern their impacts (Adger, 2006; Füssel, 2007).

Proxy indicators are customarily used to construct indices of vulnerability to different stressors under each one of the above dimensions. The exercise is rendered more complex by conceptual and heuristic difficulties (what is vulnerability? by what proxies can it represented? what are the processes that reproduce it?) as well as methodological ones (poor prediction of climate variables at regional and local scales; quality of data; difficulty of quantifying the behaviour of socio-ecological systems). The usefulness of indicator-based vulnerability comparisons of nations has been called into question because of poor understanding of the complexity of processes generating vulnerability at that scale, as well as inconsistencies in data aggregation (Eriksen and Kelly, 2007; Klein, 2009).

One of the most significant methodological challenges of vulnerability metrics is to convert a selected set of indicators into a ranking of comparable socio-ecological systems, according to their vulnerabilities to one or more climate hazards. This process of aggregation is usually performed through weighted summation, sometimes on the basis of multi-attribute utility theory (MAUT). MAUT is a member of the family of Multi-Criteria Decision Analysis (MCDA) methods and can provide a powerful decision analysis approach that is widely used in economics, engineering, decision science and development studies. However, when weighted summation is used in the context of IBVA, its theoretical requirements are difficult to achieve in practice. As an example, additive aggregation typically converts indicators into comparable scales before building an additive utility function; this requires the additive independence of indicators, which is virtually impossible in IBVA (Clemen and Reilly, 1999). The uncertainties attached to stakeholder preference are not usually taken into account (Hinkel, 2011). For example, a methodology developed by de Chazal and Mark (2009) to incorporate multiple-agents in vulnerability assessments, nevertheless makes the unlikely assumption of a single, coherent score from each group of stakeholders, hence overlooking variable and/or uncertain opinion within each group. In fact, various sources of uncertainty in vulnerability assessment have been highlighted in the literature, and will be discussed below (Araújo et al., 2005; Barnett, 2001; Füssel and Klein, 2006; Fussel, 2010; Kelly and Adger, 2000; Malone and Brenkert, 2008; Parry et al., 2007; Patt et al., 2005b; Vincent, 2007). While some have argued that probabilities of impacts ought to be used in choosing adaptation options (New et al., 2007), probability distributions are much more difficult to use in conjunction with the social dimensions of vulnerability, especially adaptive capacity (Dessai et al., 2009).

The theoretical and practical challenges posed by aggregation of MCDA problems have been recognized by many authors (Böhringer and Jochem, 2007; Clemen and Reilly, 1999; Ebert and Welsch, 2004; Füssel, 2007; Figueira et al., 2005; Hinkel, 2011; Keeney and Raiffa, 1993; Klein, 2009). However, to the best of our knowledge, no paper on vulnerability to climate change has focused on this issue from an IBVA perspective, even less suggested alternatives to utility-based approaches for IBVA. There is clearly a need for aggregation methods that can tackle the problems discussed above (e.g., uncertainty, lack of common scale for indicators and absence of additive independence of indicators). Our paper is concerned with this particular methodological problem. Specifically, we argue for a different approach to the generation of vulnerability rankings. The approach, based on a family of techniques known as Outranking Methods, generates rankings of comparable objects through structured pair-wise comparisons without resorting to a utility function. Three significant advantages of these methods are that they (a) do not convert non-commensurate variables into a common scale and can hence more easily aggregate indicators of different scales (e.g. cardinal, ordinal, interval) and different nature (e.g., environmental, social, economic etc), (b) do not require indicator additive independence and c) can better accommodate uncertainty in preference structures and imprecision in measured conditions than conventional additive aggregation procedures (Polatidis et al., 2006). Outranking methods, first proposed by Roy (1968), were developed in the field of multi-criteria decision analysis (MCDA), a sub-discipline of decision science, in order to aid policy-makers in choosing between different alternative actions under conflicting criteria and a high level of uncertainty (Brooks, 2003; Figueira et al., 2005; Hokkanen and Salminen, 1997). Outranking approaches have been criticized for axiomatic violations such as rank reversal and intransitivity, as well as difficult data requirements in large, complex problems (Figueira et al., 2010; Wang and Triantaphyllou, 2008). Nevertheless, they appear to have strong descriptive validity and have been successfully deployed in a range of decision-making contexts (De Boer et al., 1998; El Hanandeh and El-Zein, 2010; Geldermann et al., 2000; Hokkanen and Salminen, 1997; Kangas et al., 2001; Papadopoulos and Karagiannidis, 2008; Pohekar and Ramachandran, 2004).

We reformulate IBVA problems within an outranking framework and apply a widely-used outranking method, ELECTRE-III, to assess the relative vulnerabilities to heat stress of 15 local government areas (LGA) in metropolitan Sydney. We compare additive and multiplicative aggregation to ELECTRE III aggregation and assess the robustness and sensitivity of ELECTRE III rankings. For the remainder of the paper, we adopt a definition of vulnerability, generally agreed upon in the literature, as a measure of potential harm, in the present or future, to one or more valued attributes of a socio-ecological system from single or multiple hazards (Brooks, 2003; Füssel, 2004, 2007; Luers et al., 2003; Metzger et al., 2005).

In the remainder of the paper, we first describe major sources of uncertainty in IBVA then present the problem of aggregation and the challenges emanating from it. Next, we develop an outranking framework for aggregation as an alternative to global-utility aggregation. We illustrate fundamental features of the proposed framework through a simple example. Finally, we apply the methodology to the assessment of vulnerability to heat of a number of 15 local councils in Sydney and compare rankings generated by the outranking approach to those yielded by additive and multiplicative aggregations.

2. Uncertainty in indicator-based vulnerability assessments

Uncertainty in any assessment of vulnerability to climate change emanates from a number of sources, at both the biophysical and social ends of the analysis. The most significant uncertainty is arguably an epistemic one attached to predictions of global circulation models (GCMs) and due to processes and feedback mechanisms that are unknown, poorly understood or difficult to quantify (Füssel and Klein, 2006; Heal and Kriström, 2002; Patt et al., 2005a; Reilly et al., 2001). The process of downscaling GCM predictions to regional and local levels adds another layer of uncertainty mostly due to unknown processes at these scales or poor precision due to the spatial resolution of GCMs, or both. All of these sources of uncertainty are important and have received significant attention in the literature (e.g., Adger and Vincent, 2005; Hawkins and Sutton, 2009; New et al., 2007). However, in this paper, we are concerned with the additional uncertainty attached to indicator-based studies that combine the biophysical and socio-economic ends of risk assessment, typically represented by the three dimensions of exposure, sensitivity and adaptive capacity.