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Vulnerability: From the conceptual to the operational using a dynamical system perspective

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ABSTRACT

This work proposes to address a lack of conceptual consensus surrounding the concept of vulnerability, by fostering a minimal definition as a measure of potential future harm, and by basing it on a stochastic controlled dynamical system framework. Harm is defined as a normative judgment on a trajectory. Considering all the possible trajectories from an initial state leads to the definition of vulnerability indicators as statistics derived from the probability distribution of harm values. This framework 1) promotes a dynamic view of vulnerability by eliciting its temporal dimension and 2) clarifies the descriptive and normative aspects of a system's representation. As illustrated by a simple model of lake eutrophication, this work makes vulnerability a precise yet flexible concept which fosters discussion on trade-offs between vulnerability sources, and also on adaptation. Links with economics, with control theory, and with algorithmic methods such as dynamic programming are highlighted.

1. Introduction

This work proposes an operational definition of vulnerability, based on a stochastic dynamical system framework which accounts for its uncertain evolution and for the actions that may be undertaken to impact it. Vulnerability is defined in a most general way as a measure of potential future harm. It is an oft-used concept in the literature dealing with the potential negative impacts of natural hazards and social and environmental change. However, vulnerability concepts and tools originate from several different communities (Adger, 2006; Eakin and Luers, 2006; Miller et al., 2010). Consequently, there is a lack of consensus around conceptual definitions of the term and this breeds vagueness (Hinkel, 2011). Thus, despite the existence of similar operational protocols, unified frameworks in or across research fields are largely missing (Costa and Kropp, 2012).

This work does not ambition to study vulnerability under all its aspects, nor to review the many branches of scientific literature in which it is a meaningful concept. Rather, it aims at constructing a formal framework around a very general definition of the term, and at connecting it to some of the existing literature on vulnerability in environmental modeling and social and ecological systems. Making such connections seems particularly relevant in a context of global change, in which computational frameworks to assess vulnerability to various natural hazards have been burgeoning in recent years (e.g. Balica et al., 2013; Giupponi et al., 2013; Lardy et al., 2014; Martin et al., 2014; Papathoma-Köhle et al., 2015); yet each of these models relies on a slightly different understanding of what vulnerability is conceptually.

The minimal definition of vulnerability as a measure of potential future harm comes from a formal analysis of the term (Wolf et al., 2013). It is the lowest common denominator in most vulnerability definitions in the literature (Hinkel, 2011). To our knowledge, our framework constitutes the second attempt at mathematically formalizing the concept of vulnerability after that by Ionescu et al. (2009), who argue that such a formalization is warranted for several reasons, namely making vulnerability assessments systematic, clarifying the concepts and their interpretations, avoiding analytical inconsistencies and practical omissions, and facilitating the development of computational approaches. These motives stress that formalization is useful regardless of the case at hand, and whether or not a dynamical system formulation is available.

We propose to start with a very general mathematical formulation, and then to interpret it in the context of vulnerability literature. We argue that this approach provides both a formal basis and

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a great flexibility for the discussion of vulnerability concepts. Indeed, mathematics remain a non-ambiguous reference for discussing concepts, especially in cases in which they may be interpreted in several relevant ways. In that sense, flexibility appears as a prerequisite to bridging the gap between conceptual definitions and their many possible operational translations. In the case of vulnerability, flexibility is sorely needed because of the wide range of fields that use the concept, as it is present in the climate change literature (see e.g. Turner II et al., 2003; Adger, 2006; Parry et al., 2007), in the natural hazards literature (e.g. Birkmann, 2006; Fuchs, 2009; Peduzzi et al., 2009), in the social-ecological systems (SES) literature (see e.g. Peterson, 2002; Anderies et al., 2007; Rodriguez et al., 2011; Rives et al., 2012), but also in the development economics literature (see e.g. Christiaensen and Boisvert, 2000; Hoddinott and Quisumbing, 2003; McCulloch and Calandrino, 2003; Béné et al., 2012).

Besides, a *controlled* stochastic dynamical system perspective also provides a link between vulnerability and the capacity to act. This connection is often explicitly highlighted in the literature (Turner II et al., 2003; Gallopín, 2006; Smit and Wandel, 2006), to the extent that vulnerability is often associated with a limited ability to act (McCarthy et al., 2001; Adger, 2006; Parry et al., 2007). Furthermore, the notion of control is associated to vulnerability through so-called robustness-vulnerability trade-offs (Anderies et al., 2007; Rodriguez et al., 2011) which arise when increasing robustness to a set of shocks inevitably leads to increased vulnerability to another set of shocks.

Following this brief presentation on our main motivations for proposing a mathematical approach to vulnerability definition, the rest of this work is as follows. Section 2 presents the dynamical system framework that we propose, and this starts with a paragraph that completes this introduction by outlining this framework and showing how available literature backs our choices (Section 2.1). Then, Section 3 illustrates these concepts using a simple dynamical system model of lake eutrophication (Carpenter et al., 1999), while Section 4 discusses them; both Sections also illustrate how policy design and the system's representation dynamically impact one another. Section 5 provides concluding remarks.

2. A dynamical system framework for vulnerability

2.1. Overview of the framework

Let us imagine a healthy-looking economy or ecosystem right before it crashes, when the unemployment rate is still low, or biodiversity still high. In such cases, the present situation is good but is about to deteriorate dramatically. Conducting an assessment of the system based on a single stage in the present or near future is like taking a snapshot of it: it gives a static view of the system. By contrast, observing its trajectory over a longer time-frame is more relevant since it gives a dynamic view of it and may help anticipate its undesirable evolution.

This observation suggests that vulnerability indicators can be more relevant when encompassing an entire time frame, rather than a single date. Yet, time is only one of four types of variables one needs to consider within a general stochastic controlled dynamical system formulation. The three other are the system's state, the actions – called control within the mathematics of control theory – implemented to manage it, and the uncertainty that affects it. Upon interpretation of that formulation in the context of vulnerability literature, we propose that vulnerability concepts are related to one another by abstraction over one of these categories of variables, either by aggregation – such as for time – or by selection. Our presentation of the framework is to start with all four categories of variables, then abstract them one at a time until only the initial state remains, as detailed in Fig. 1 and justified from the literature in the remainder of this section.

Section 2.2 proposes a starting point through a representation of a system at a given stage t that is both descriptive and normative. Its descriptive side relies on a general dynamical system formulation of a single-stage evolution from stage t to $t+1$. This formulation is very similar to that of Ionescu et al. (2009) in their attempt at proposing a formal approach for vulnerability, but it explicitly considers the role of uncertainty as a determinant for the future state of the system, along with its present state and the control actions that are implemented. Section 2.2 also makes the normative side explicit compared to previous formulations, through the introduction of a single-stage harm function associated to a state at stage t.

Then, Section 2.3 aggregates over time to provide a system's representation over the entire period $[0, T]$ of interest, whereas Ionescu et al. (2009) mainly base their discussion on vulnerability on evolutions over a single time step. Vulnerability of an entity depends on uncertain dynamics over time (Wolf et al., 2013), a fact that is often overlooked or kept implicit (Liu et al., 2008), even though vulnerability to a natural hazard may be apparent only long after the event's occurrence (Menoni et al., 2002; Lesnoff et al., 2012). As demonstrated by the development economics literature, acknowledging that vulnerability should be measured over several future periods can help learn about its determinants (Christiaensen and Boisvert, 2000). For example, a household's trajectory over several periods must be taken into account in order to measure chronic poverty and vulnerability to poverty (McCulloch and Calandrino, 2003). Hence the need for a framework centered on the idea of possible future trajectories to which harm values are associated. Trajectories depend on controls and uncertainty over $[0, T]$, but also on the initial state of the system, as illustrated by the concept of path dependence (Preston, 2013).

After that, Section 2.4 considers all the uncertain scenarios over $[0, T]$ to propose an operational definition of vulnerability. Indeed, each uncertain scenario yields a different trajectory, so one cannot assess vulnerability from only one of the possible trajectories. Instead, the possible values of future harm are considered through the occurrence probabilities of these possible trajectories, leading to obtaining a probability distribution function (pdf) of these harm values. Then, a relevant statistic derived from this pdf is a measure of potential future harm, in other words vulnerability. Though it may seem like a strong choice, aggregating harm values from all trajectories into a single vulnerability indicator is advocated by previous formal analyses of the concept of vulnerability (Ionescu et al., 2009; Wolf et al., 2013).

Finally, Section 2.5 draws connections between vulnerability indicators and the search of appropriate control policies for vulnerability minimization and avoidance. This is achieved by selecting one or several control policies among all possible options. Once a policy is chosen, vulnerability only depends on the initial state. There are two ways of choosing an appropriate policy (Ionescu et al., 2009): through vulnerability minimization, or by choosing policies that keep vulnerability below a reference value. In the latter case, that reference value may be chosen to reflect stakeholders' preferences. It then explicitly connects vulnerability with the notion of threshold it is often associated to (e.g. Luers et al., 2003; Luers, 2005; Béné et al., 2011), and it separates what is satisfactory from what is not. Yet, that reference value may also be related to vulnerability assessed assuming a baseline policy. Then, finding a policy that lowers vulnerability compared with this baseline is associated with adaptation (e.g. Luers et al., 2003; Ionescu et al., 2009; Sandoval-Solis et al., 2011).