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Linkages between vulnerability, resilience, and adaptive capacity

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Abstract

This article uses a systemic perspective to identify and analyze the conceptual relations among vulnerability, resilience, and adaptive capacity within socio-ecological systems (SES). Since different intellectual traditions use the terms in different, sometimes incompatible, ways, they emerge as strongly related but unclear in the precise nature of their relationships. A set of diagnostic questions is proposed regarding the specification of the terms to develop a shared conceptual framework for the natural and social dimensions of global change. Also, development of a general theory of change in SESs is suggested as an important agenda item for research on global change.

Keywords: Vulnerability; Resilience; Adaptive capacity; Systems analysis; Stability

1. Introduction

The terms vulnerability, resilience, and adaptive capacity, are relevant in the biophysical realm as well as in the social realm. In addition to being terms in colloquial language, they are widely used by the life sciences and social sciences, not only with different foci but often with different meanings. The reviews presented in this issue (Adger, 2006; Folke, 2006; Smit and Wandel, 2006) and other sources, document the diversity of interpretations and reformulations of these concepts across disciplines and problem areas as varied as evolutionary biology, ecology, cultural studies, and computer science, to cite just a few. Sometimes, the concepts are used interchangeably or as polar opposites.

This plurality of definitions is possibly functional to the needs of the different disciplinary fields, as well as being a reflection of the different intellectual traditions (Adger, 2006; Janssen et al., 2006), but sometimes it may also become a hindrance to understanding and communication across disciplines. This also may be the case in international research on global change, where understanding the dynamics necessarily involves the consideration of both the social and biophysical components and their mutual interactions.

This article represents an attempt to highlight the fundamental attributes of the three concepts, and to identify the conceptual linkages between them, through the use of a generic systems approach that can be specified for different concrete system types (social, ecological, but particularly socio-ecological). Without attempting a review, an effort has been made to incorporate the contributions from the principal scientific communities that have been investigating these concepts, particularly those that have more direct bearing on the analysis of their mutual conceptual relations. As the concepts have been used in many fields, it will be helpful to define the focus of the present analysis—the socio-ecological system (SES)—and offer a justification of why this is important for global change research.

The concept of vulnerability of the SES and its basic components are discussed in their general sense in the following section. The section on resilience introduces the concept of domains of attraction, essential in the notion of resilience, and discusses different levels of stability relevant for the study of SESs. These have implications for the applicability of the concept of resilience in the social

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sciences. The links between resilience and vulnerability are highlighted. A section on adaptive capacity in its broader and more specific forms as interpreted by different scientific traditions follows, with a discussion of the relations between adaptive capacity and the notions of capacity of response and resilience.

The final part of the article includes the outcome of the overall comparison and identification of linkages among the three concepts, with an indication of the major uncertainties involved. Without affecting the current use of vulnerability, resilience, and adaptive capacity within disciplinary areas, reaching some kind of agreement between social and natural scientists working together on global change on the way the concepts are used would represent an important step forward. To this end, a number of diagnostic questions are proposed to help guide the choices to be made. The results of the analysis presented in this article naturally lead to a suggestion for the research agenda on global change.

2. The socio-ecological system

Gallopín et al. (2001) have argued that the natural analytical unit for sustainable development research is the socio-ecological system or SES. An SES is defined as a system that includes societal (human) and ecological (biophysical) subsystems in mutual interaction (Gallopín, 1991).[1] The SES can be specified for any scale from the local community and its surrounding environment to the global system constituted by the whole of humankind (the "anthroposphere") and the ecosphere. Schellnhuber (1998) was the first to label the SES at the global scale as the "Earth System", and the term was later adopted by major international global environmental change research programs, represented in the Earth System Science Partnership (www.essp.org).

The need to investigate the whole SES arises from the increasingly recognized evidence that understanding and anticipating the behavior of the social and ecological components of the SES in many cases requires simultaneously taking into account both components; in other words, SESs are non-decomposable systems. Of course it is always possible to single out certain social or ecological components for study, and this strategy has provided important understanding of the components, as has been traditionally done with great success by social and natural scientists. However, there are important traits related to the behavior and future trajectory of the Earth System, for example, that cannot be understood through this analytical approach alone, because they emerge from the dynamic interplay between the social and ecological components. Many of the issues related to vulnerability, resilience, and adaptive capacity fall in this category (Walker et al., 2004; Turner et al., 2003).

[1]Also called social–ecological system (Berkes and Folke, 1998) and coupled human-environmental system (Turner et al., 2003).

Young et al. (2006) discuss a number of synthetic properties of globalization that require integrated treatment, such as connectedness, speed, scale, and diversity. At another scale, this non-decomposability of many core issues of sustainable development is nicely illustrated by very simple mathematical models of lake-and-managers systems (Carpenter et al., 1999). The analysis of the behavior of these coupled models provides various insights of strategic importance for sustainable management of shallow lakes. For example, unwanted collapse can occur even if the ecosystem dynamics are perfectly known and managers have perfect knowledge and control of human actions. It is also clear that these insights could not have been obtained by analyzing the lake dynamics and the societal dynamics separately. The analysis of the concepts discussed in this article will be made in the context of research on the dynamics of the global SES.

3. Vulnerability

Vulnerability is a concept that has been used in different research traditions (Adger, 2006; Smit and Wandel, 2006) but there is no consensus on its meaning. Depending on the research area, it has been applied exclusively to the societal subsystem, to the ecological, natural, or biophysical subsystem, or to the coupled SES, variously referred also as target system, unit exposed, or system of reference.

Adger (2006) examines the evolution of approaches to vulnerability originated in the social and the natural sciences. He concludes that vulnerability is most often conceptualized as being constituted by components that include exposure to perturbations or external stresses, sensitivity to perturbation, and the capacity to adapt.

Vulnerability, like resilience, is generally viewed as being specific to perturbations that impinge on the system; in other words, a system can be vulnerable to certain disturbances and not to others. Two other widely accepted points are (1) the multiscale nature of the perturbations and their effects upon the system and (2) the fact that most SESs are usually exposed to multiple, interacting perturbations (van der Leeuw, 2001; Turner et al., 2003). Vulnerability is also thought of as a susceptibility to harm, a potential for a change or transformation of the system when confronted with a perturbation, rather than as the outcome of this confrontation. However, diverse views regarding the precise meaning of vulnerability are also evident. Some of the differences are important for the task of identifying the relationships between vulnerability, resilience, and adaptive capacity, and will be discussed in what follows.

3.1. Perturbation, stress, hazard, or shock

For Turner et al. (2003), hazards are threats to a system, comprised of perturbations and stress (and stressors, the sources of stress). Perturbations are major spikes in pressure (e.g., a tidal wave or hurricane) beyond the normal range of variability in which the system operates, and commonly originate beyond the system or location in question. Stress is a continuous or slowly increasing pressure (e.g., soil degradation), commonly within the range of normal variability. Stress often originates within the system, and stressors often reside within it. For simplicity, the term perturbation will be used in this article to denote the external or internal processes interacting with the system and with the potentiality of inducing a significant transformation in the system, be it slow or sudden.

Perturbations are usually assumed to come from outside the system. But this may be an unduly restrictive definition. Both societal and ecological systems survive, thanks to a constant exchange of matter, energy, and information with their external environment. Those processes can give rise to modifications in the functioning or structure of the system triggered by changes in the system's environment (e.g., the effects of an earthquake on a population, dissemination of infectious germs in the environment of a person), by internal alterations (e.g., the impact of civil war on a country, the manifestation of a genetic disease in a person), or by the interaction among external and internal processes (e.g., the effects of a prolonged drought in a country with internal conflicts). Young (2005), discussing institutional dynamics in environmental and resource regimes, illustrates how the sources of stress may be internal, external, or both. Turner et al. (2003) explicitly state that the hazards acting on the system arise from influences outside and inside the system, and Kasperson et al. (2005) allocate a section to endogenous perturbations. In another field, Nicolis and Prigogine (1977) demonstrated for dissipative (open, far from equilibrium) systems the phenomenon of self-amplification of internal fluctuations (perturbations) and their ultimate breakthrough at the system level.

On the other hand, whether the disturbance is described as external or internal depends also on the scale at which the system has been defined. Earthquakes, hurricanes, or global economic crises are clearly internal phenomena for the global SES, but they are obviously external events for systems such as a Central American village.

3.2. Change or transformation of the system

In general, transformation is taken to mean harm or damage to a system (human, natural, SES). However, a different interpretation has been proposed on the basis of a systemic analysis of the concept of vulnerability (Gallopín, 2003). According to this conception, vulnerability is not always a negative property. It is possible to speak of positive vulnerability in cases where change leads to a beneficial transformation such as the emergence of a given social group from chronic poverty or the collapse of an oppressive regime. Young (2005) discusses situations where institutional crises become windows of opportunity for improvement even though they are dangerous events that can produce destructive outcomes. A similar ambivalence has been noted in relation to resilience, in the sense that "resilience is not always a good thing" (Walker et al., 2004).

Another aspect of the notion of change or transformation is its degree or depth. A system would not be called vulnerable if the effect of the perturbation is limited to the generation of trivial and ephemeral changes; those changes would hardly qualify as a "transformation" of or "damage" to the system. However, it is not always clear what is meant by the term. Changes in the system could range from variations in the behavior of some variables of the system up to radical changes in the structure of the system (as discussed later under resilience).

This is an important point, because, for some, the fundamental distinction between vulnerability and resilience lies in that vulnerability refers to the capacity to preserve the structure of the system while resilience refers to its capacity to recover from non-structural changes in dynamics (van der Leeuw, 2001). Sometimes, the concept of vulnerability is restricted to situations when the system suffers structural change (Gallopín et al., 1989; van der Leeuw, 2001; Young et al., 2006). Unfortunately, in practice, it is not always easy to decide when an observed change is behavioral or structural without investigating the system thoroughly. The previous discussion highlights the importance of specifying what is meant by "transformation", impact, or "harm" when discussing (or defining) vulnerability in the natural and social realms of the SES.

3.3. Sensitivity

The concept of *sensitivity* varies across authors; for instance, Adger (2006) defines it as "the extent to which a human or natural system can absorb impacts without suffering long-term harm or other significant state change"; Smit and Wandel (2006) talk about exposure-sensitivity, arguing that sensitivity is not separable from exposure. Luers (2005) also combines sensitivity and exposure, and defines sensitivity as the degree to which a system will respond to an external disturbance, and also includes in the concept the ability to resist change and the ability to return to a previous condition after the stress has been removed—properties that are usually seen as associated with resilience or with coping capacity. In discussions of climate (IPCC, 2001), sensitivity is the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea-level rise).

For Gallopín (2003), in its general sense, sensitivity is the degree to which the system is modified or affected by an internal or external disturbance or set of disturbances. Conceptually, it can be measured as the amount of transformation of the system per unit of change in the disturbance, i.e., $\partial\, \textit{transformation}/\partial\, \textit{perturbation}$

(Tomovic, 1963),[2] but in the simplest case it only specifies whether or not the system is sensitive to a given factor (Gallopín, 2003). In this view, sensitivity is an inherent property of an SES, distinguished from its capacity of response (the actual transformation may be smaller, depending on the capacity of response of the system). It is an attribute of the system, existing prior to the perturbation, and separate from exposure.

3.4. Capacity of response

The system's coping capacity (Turner et al., 2003), or capacity of response (Gallopín, 2003), is also called adaptive capacity by Adger (2006) and Smit and Wandel (2006) and the IPCC (2001). Turner et al. (2003) distinguish capacity to cope or respond from adaptive capacity, and consider both as components of the resilience of a system. They refer to adaptations as the system's restructuring after the responses. As noted by Smit and Wandel (2006), some authors apply "coping ability" to shorter-term capacity or the ability to just survive, and employ "adaptive capacity" for longer-term or more sustainable adjustments. In view of this lack of agreement, the term used here for this component of vulnerability will be "capacity of response" (of the system to the perturbations).

In general, capacity of response is the system's ability to adjust to a disturbance, moderate potential damage, take advantage of opportunities, and cope with the consequences of a transformation that occurs. Capacity of response is clearly an attribute of the system that exists prior to the perturbation.

3.5. Exposure

The other central concept related to vulnerability is exposure, meaning in general the degree, duration, and/or extent in which the system is in contact with, or subject to, the perturbation (Adger, 2006; Kasperson et al., 2005).

Exposure in most formulations is seen as one of the elements constituting vulnerability. However, Bohle (2001), building on proposals by Robert Chambers, recognizes a qualitative difference between exposure (defined as the external side of vulnerability) and coping (the internal side). Since, unlike sensitivity and capacity of response, exposure seems to be an attribute of the relationship between the system and the perturbation, rather than of the system itself, Gallopín (2003) did not consider exposure as a component of vulnerability. Rather, vulnerability is a function of the system's sensitivity and capacity of response, and the transformation suffered by the system is a function of its vulnerability, the properties of the perturbation, and the exposure of the system to the perturbation (Fig. 1).

[2]Of course, in many cases, the transformation is discontinuous, and therefore the expression above (strictly applicable for continuous change) should be replaced by a more appropriate one.

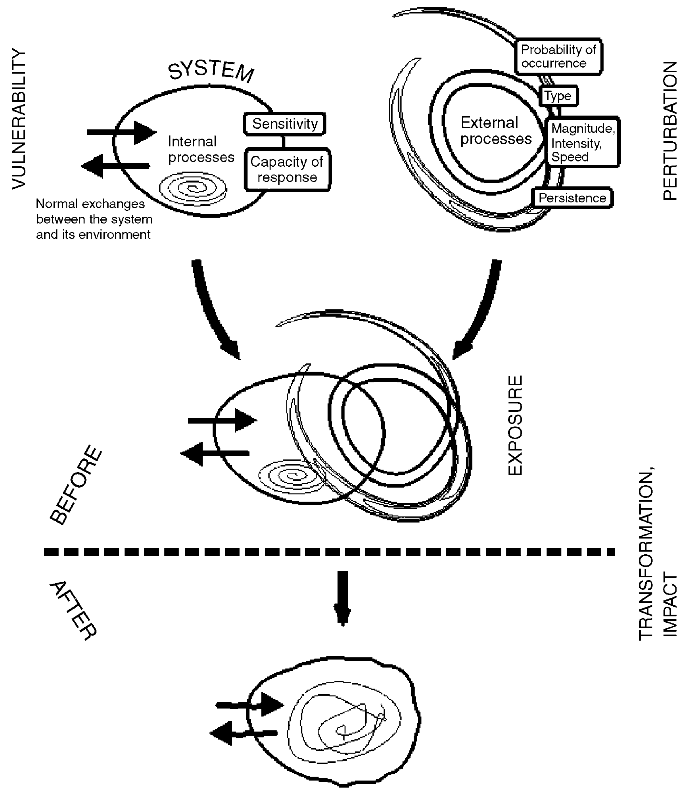

Fig. 1. Generic relations between vulnerability, threat, exposure, and impact or transformation of a system (social, natural, or SES) according to Gallopín (2003). Time moves from top to bottom of the figure. The target system is represented by an oval; its exchanges with its external environment are represented by arrows in both directions, and the normal operation of its internal processes is symbolized by a regular spiral. The components of the vulnerability of the system (its sensitivity and capacity of response) are highlighted with boxes. The considered (external) process or perturbation is represented by the looped shape at the right, with its relevant attributes in boxes. The exposure of the system to the perturbation is represented by the overlap between the two elements, and the transformed or impacted system is represented by the wobbly oval at the bottom.

From this perspective, a system (i.e., a city, a human community, an ecosystem) may be very vulnerable to a certain perturbation, but persist without problems insofar as it is not exposed to it. A person with low immunological defenses would be called vulnerable to infectious diseases, whether or not he or she is exposed to the infectious agent; software vulnerabilities existed before the Internet exposed every computer in the world to every hacker on the planet. From the perspective that includes exposure as a component of vulnerability, a system that is not exposed to a perturbation would be defined as non-vulnerable. The hypothetical person with low defenses would not be called vulnerable to infectious diseases if confined to a sterile environment.

The choice of including or not including exposure as a component of vulnerability has consequences. In the first case, vulnerability becomes a property of the relationship between the system and its environment (specifically between the system and the perturbation), rather than a property of the target system. The concrete characterization of vulnerability (i.e., indices, maps, etc.) needs to take into account the full set of possible combinations of situations, and must be changed if the distribution of exposure changes (for instance, when alternative climate scenarios are examined).

On the other hand, if exposure is externalized from vulnerability, exposure is a relational property, and vulnerability is a property of the system, becoming expressed/revealed when the system is exposed to the perturbation. Vulnerability in this view is a system attribute existing prior to the disturbance, although it is often related to the history of disturbances to which the system was exposed in the past (hence the importance of the system's history). If the vulnerability of different target systems could be characterized on the basis of their sensitivity and capacity of response, their exposure to a particular perturbation could be independently determined, and the harm or outcome of the resulting transformation of the system could be estimated from the composition of the two factors. Using a climate change example, only one map of vulnerability would be needed, that could be overlaid with different maps of exposure resulting from diverse models or scenarios. Therefore, the difference between the two perspectives is not trivial, reflecting on the possibilities for generalization and also the design of policies to reduce vulnerability.

The differences between sensitivity, response capacity, and exposure can be illustrated with two very simplified examples. The first refers to the effects of a flood on a community. The most precarious homes are hit harder by a flood than the solid ones (sensitivity). Oftentimes, the poorest homes are located in the places most susceptible to flooding (exposure). The families with the greatest resources have a greater availability of means to repair water damage (response capacity). The magnitude of the final impact will also depend on the intensity, magnitude, and permanence of the flood (attributes of the perturbation). The second example refers to the impacts of the spread of an infectious disease in the population of a region. The population segment constituted by children and the elderly is likely to exhibit more serious symptoms if infected than the rest of the population (sensitivity). The high-income sector often has better access to medical care and medicines (capacity of response). In this particular example, the likelihood of entering in contact with the germs (exposure) might be evenly distributed across the population.

4. Resilience

Resilience, a concept originated within ecology, is also applicable in the realm of social systems and SESs. For instance, Adger (2000) defines social resilience as the ability of groups or communities to cope with external stresses and disturbances as a result of social, political, and environmental change.

The concept of resilience has a rich history (see Folke, 2006), sometimes with a considerable stretch from its original meaning. There is also a body of thought around resilience and the "adaptive cycle"—a metaphor for the dynamics of ecosystems later extended to the social aspects and SESs—referring to the concept of "panarchy" or cross-scale dynamics and interplay between nested adaptive cycles (Gunderson and Holling, 2002; see also Folke, 2006). These ideas, interesting as they are, fall outside the scope of this article.

The concept of domains or basins of attraction is central to the notion of resilience. It essentially means the portion of the state space of a dynamic system that contains one "attractor" toward which the state of the system tends to go, and is therefore one region of the state space where the system would tend to remain in the absence of strong perturbations. "State of a system" means "any well-defined condition that can be recognized if it occurs again" (Ashby, 1956) or, in more precise terms, the set of values adopted by all the variables of the system at a given time.

If the state of the system changes in time, then the succession of states through time can be interpreted as defining a trajectory (also called an orbit) of the system, going from some initial state to the current state to some future state and (possibly, but not necessarily) to a final state. This "trajectory" unfolds in an abstract state space defined by the number of variables of the system. Each state of the system is represented by a point in the state space. Fig. 2 illustrates a trajectory for a system with only two state variables, X_1 and X_2, that define the state space.

The trajectory tends to move in time toward, or remain in, an attractor of the system. This could be a point or steady state, a stable closed orbit (a limit cycle), a "strange" (chaotic) attractor, an open-ended trajectory that never reaches a steady state, or more complicated geometries when the system has many state variables. In general terms, an attractor characterizes what the behavior of a system settles down to. If the attractor is a fixed point, the system will tend to reach that state (steady state or dynamic equilibrium) where it will tend to remain

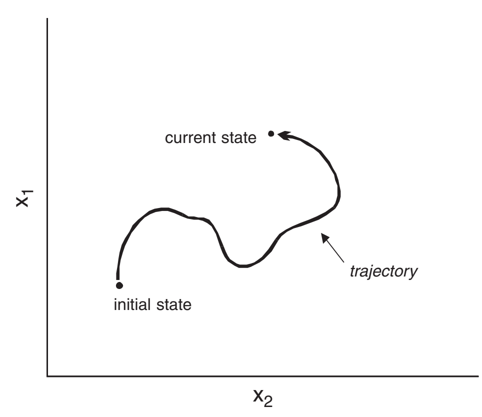

Fig. 2. A trajectory of a two-variable, dynamic system depicted in the state space (here, a plane defined by all possible values of state variables X_1 and X_2).

thereafter. Given that all real systems are permanently exposed to perturbations, a state often will be pushed away from the steady state, but will tend to return to it. When the attractor is a trajectory, the state of the system will tend to move toward it when pushed away by perturbations, but will never reach constancy; it will change periodically (if the attractor is a limit cycle) or along an open path in the state space; in these cases, nearby states will tend to go toward the trajectory, but not to a fixed point.

If a system has only one attractor, in due course its state will end there; such a system is called globally stable. However, systems containing non-linear relations between their variables (as is the case for all SESs) usually possess more than one attractor, and therefore surprises can occur as the state of the system shifts from the domain of influence of one attractor (known as the domain or basin of attraction) to that of another. Fig. 3 shows a system with three basins, one containing a steady state (attractor A), the other a stable cycle (attractor B), and the third containing a stable trajectory (attractor C). The complete figure depicts the "stability landscape" of the system, represented by the configuration of all basins of attraction, including the boundaries separating them. The stability landscape is part of the structure of the system, depending on the values of the parameters (fixed or very slowly varying factors) of the system. In a dynamical system with multiple attractors, a continuous variation in some critical parameter can result in discontinuous changes in the stability landscape of the system (Fig. 4). These discontinuities are called bifurcations in the mathematical theory of dynamical systems (Tu, 1994; Butenin, 1965) and catastrophes in catastrophe theory (Thom, 1972).

Holling (1973) introduced a new, non-equilibrium vision in ecology with the concept of ecological resilience, arising from the analysis of different empirical studies, mathematical models, and experience with managed ecosystems. He showed that even natural, undisturbed ecological systems are often in transient states and demonstrated that many of them are multistable; that is, they have two or more domains of attraction where the system variables tend to remain. Within each domain, the system's state may fluctuate widely (i.e., may be highly unstable) but if it tends to stay within the boundaries of the domain, the system is resilient. Resilience was originally defined by Holling (1973) as "a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables" (p. 14) and, more recently, by Walker et al. (2004) as "the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks—in other words, stay in the same basin of attraction". Folke (2006) reviews the concept in detail.

Note that resilience, in terms of the stability landscape, implies the ability of a multistable system to keep the values of its state variables within a given domain of attraction in the face of perturbations, and is not concerned with the stability or constancy of the state *within* the basin. This concept is called *ecological resilience*; in principle, ecological resilience can be measured by the magnitude of

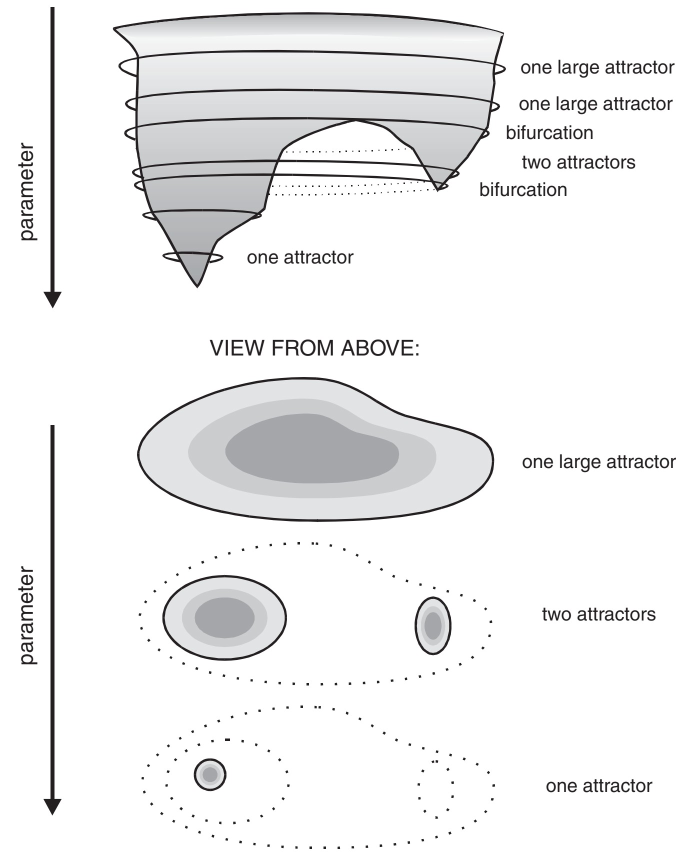

Fig. 4. Qualitative changes in attractors. Continuous variation of a parameter can cause attractors to shrink, split, or disappear. The upper part of the figure is a three-dimensional representation; the lower part is a view from above, at three sections of the solid shape.

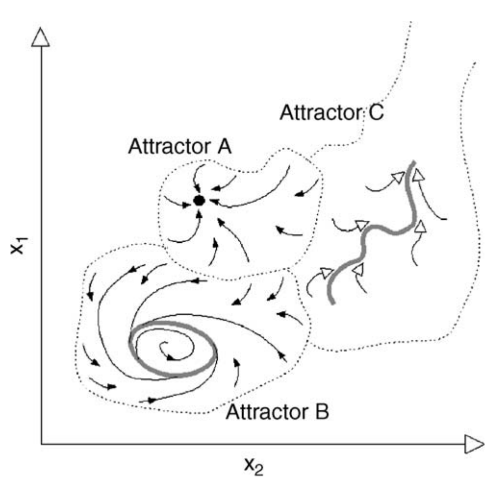

Fig. 3. State space of a two-variable system with three attractors, indicating the respective basis of attraction with dotted lines.

the perturbation that can be absorbed before the state of the system falls outside its domain of attraction.[3]

By contrast, the concept of stability as commonly utilized focuses on the behavior of the system near an equilibrium point or trajectory, and can be measured by the speed at which the system returns to the stable point or trajectory following a perturbation. This is essentially the concept of resilience defined by Pimm (1984) and called *engineering resilience* by Holling (1996). It is equivalent to the well-known mathematical concept of local stability (Hahn, 1967; Tu, 1994; Nicolis and Prigogine, 1989).

In any dynamical system, the property of multistability implies that the behavior of the system may change qualitatively in a way that is surprising to an external observer; for instance, a cumulative series of small perturbations of the state of the system, each individually reversible, may finally move the state of the system over the boundary of the current basin of attraction, thus flipping it into another (possibly undesirable) domain where it will tend to remain. This is precisely the behavior exhibited by many ecosystems under management (Holling, 1986; Gunderson and Holling, 2002).

Those sudden shifts in behavior occur in the absence of structural change in the system. Holling (1986) also showed that in a number of cases, the size and shape (and the genesis or disappearance) of the domains of attraction can change because of the unperceived evolution of parameters of the system (implicitly assumed constant), which are often affected by long-term management or are internally determined by processes that link variables. Thus, the stability domains themselves may expand, contract, and disappear in response to changes in slow variables, resulting in the loss of resilience of the system (similar to the changes depicted in Fig. 4). Resilience can operate at different scales, and it has been noted that there can be losses of resilience at some scales thereby increasing it at other, higher scales (Walker et al., 2004).

In this context, three types or levels of stability may be distinguished. The first, local stability or engineering resilience, refers to the behavior of the trajectories of the system in the neighborhood of an attractor, within a given domain of attraction. The second level refers to changes in the state of the system between the different domains of attraction, within the stability landscape of the system. The capacity of the system to remain within the same domain of attraction is called ecological resilience. The third level includes changes in the stability landscape itself. This is the domain of structural stability of dynamical systems, the capacity of the system to preserve the topology of its trajectories (the qualitative features of its stability landscape) under perturbations of the dynamic equations of the system (Tu, 1994). Structural instability represents the possibility of a true transformation of the original system into a different one.[4]

Among the various theoretical approaches to real-life complex systems, the one derived from the theory of dissipative structures (developed essentially by Ilya Prigogine and collaborators) seems particularly suitable for investigating the dynamics of structural change and persistence in SESs. The theory of dissipative structures shows that open, self-organizing systems maintain their structural order by keeping their internal state far from thermodynamic equilibrium, through active exchanges with their environment. Those dissipative structures are in principle stable as long as the exchanges with the environment are maintained and as long as the continuously occurring fluctuations (or perturbations) are absorbed within the framework of the given dynamic regime. However, any structure of a non-equilibrium system may be driven beyond a threshold into a new regime when the fluctuations exceed a critical size. At that point, after going through phases of instability and high entropy, the system may evolve to a different stable regime with a new characteristic structure (Nicolis and Prigogine, 1977, 1989; Prigogine and Stengers, 1979).

As noted by Adger (2000), the concept of resilience cannot be transferred uncritically from the ecological sciences to social systems. But using the concept for social systems (and for SESs) does not really imply that there are no essential differences in behavior and structure between social and ecological systems. The legitimate use of the concept only requires the assumption that the state space of the system considered contains more than one basin of attraction. This is a natural assumption for all kinds of non-linear dynamical systems (although the applicability of the concept of dynamical systems to social systems might not be acceptable to some social scientists).

When the concept of resilience is unlinked from the notion of multistability, it becomes very difficult to distinguish it from structural stability, or even from local stability or adaptive capacity. This is one risk with some of the recent reformulations of resilience, such as making adaptive capacity and self-organization properties of resilience (Carpenter et al., 2001). It is sometimes said that vulnerability is the flip side, or the antonym, of resilience (Folke et al., 2002). However, this is by no means clear; obviously a resilient system is less vulnerable than a non-resilient one, but this relation does not necessarily imply symmetry.

Resilience is clearly related to the capacity of response component of vulnerability, and thus it would be less than the flip side of vulnerability. A more fundamental difference is that resilience, as discussed earlier, applies to the preservation of the behavior of the system as expressed

[3]Recently, Walker et al. (2004) proposed latitude, resistance, precariousness, and panarchy as essential attributes of resilience; other resilience measures could be derived from these.

[4]Note that the new system may result from adding new components and relations, but also from losing or modifying components or relations. In this sense, structural instability is somewhat more general than the concept of transformability as recently defined by Walker et al (2004).

by its state remaining within the considered domain of attraction, while vulnerability refers to transformations that may go beyond a single domain. The flip side of vulnerability would be a concept that denotes capacity to maintain the structure of the system against perturbations, even if its resilience is overcome; robustness is a good candidate.[5]

Moreover, resilience seems to be a proper subset of capacity of response, at least for the social component of the SES. Capacity of response includes, for most authors, not only the resilience of the system (maintenance within a basin) but also coping with the impacts produced and taking advantage of opportunities. The relation of resilience to the sensitivity component of vulnerability is also unclear. A sensitive system may or may not be resilient. An insensitive system (i.e., an "armored system") may exhibit low vulnerability and low resilience (it is the exposure to perturbation that builds resilience in natural systems). Sensitivity may open a system to threats, but an insensitive system may be unable to adapt and seize opportunity. The concept of resilience does not include exposure (similar to vulnerability as adopted here) but refers to the reaction of the system when exposed to perturbations. On the other hand, a history of past exposures may be important to build resilience (Holling, 1973, 1985, 1986).

5. Adaptive capacity

The concept of adaptive capacity has been reviewed by Smit and Wandel (2006). Here, only the fundamental traits of the concept will be explored. Adaptability (or adaptive capacity)[6] was originally defined in biology to mean an ability to become adapted (i.e., to be able to live and to reproduce) to a certain range of environmental contingencies. Adaptness is the status of being adapted, and an adaptive trait or an "adaptation" is a feature of structure, function, or behavior of the organism that is instrumental in securing the adaptness (Dobzhansky, 1968). Adaptness is not a generic property, but it refers to a certain environment or range of environments, and different organisms, different populations, or different species are adapted to different environments. Dobzhansky noted that high adaptness is not the same as high adaptability; a species may be highly adapted to a special and constant environment but have little capacity to adapt to others or to changes in its environment.

In general, a species, population, or individual may also become better adapted by improving its condition in its environment, even in the absence of changes in the latter. This is more so with human systems, capable of learning and technological progress. Of course, in the human realm, and thus also in the SES, the criterion for adaptness goes far beyond "being able to live and reproduce"; it includes the viability of social and economic activities, and the quality of human life. Adaptability or adaptive capacity of human systems also can be defined as the capacity of any human system from the individual to humankind to increase (or at least maintain) the quality of life of its individual members in a given environment or range of environments (Gallopín et al., 1989). As noted by Smithers and Smit (1997), while the responses of biological systems to perturbations are purely reactive, the responses of human systems are both reactive and proactive.

From these considerations, a generic concept of adaptive capacity of an SES would seem to involve two different components, namely (1) the capacity of the SES to cope with environmental contingencies (to be able to maintain or even improve its condition in the face of changes in its environment(s)) and (2) the capacity to improve its condition in relation to its environment(s), even if the latter does not change, or to extend the range of environments to which it is adapted.

In more recent usage in the field of climate change, adaptive capacity is defined as "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" and adaptation is defined as an "adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates, harms, or exploits beneficial opportunities," including anticipatory and reactive, autonomous or spontaneous and planned, and public and private (IPCC, 2001). However, Kasperson et al. (2005) distinguish between adjustments and adaptations. For them, adjustments are system responses to perturbations or stress that do not fundamentally alter the system itself, they are commonly (but not necessarily) short-term and involve relatively minor system modifications. Adaptations are system responses to perturbations or stress that are sufficiently fundamental to alter the system itself, sometimes shifting the system to a new state.

The IPCC further distinguishes between adaptation as actions that operate upon the system itself and mitigation, or actions that operate upon the origin and attributes of the perturbation (i.e., reducing greenhouse gases emissions). This concept of adaptive capacity is clearly limited to coping with changes in the environment of the system (actually to climate change) and seems to exclude the element of increasing adaptness when the environment does not change. One question that arises is whether the concept of adaptive capacity of the SES should include this second element. It would seem that, at least with reference to the human component of the coupled system, it might be of interest not to reduce *a priori* the general concept of adaptive capacity.

[5]The concept of robustness has not been analyzed here, as it is still much debated. Robustness here is used simply as the converse of vulnerability and basically to denote the ability of the system to preserve its structure in the face of perturbations (Tu (1994, p. 160) uses robust as synonymous of structurally stable). Many other definitions of robustness have been proposed (see Anderies et al., 2004; Jen, 2003).

[6]Adaptability and adaptive capacity are usually treated as synonymous (i.e., Smit and Wandel, 2006; IPCC, 2001).

Another issue is the relationship between adaptive capacity of an SES and capacity of response, as used here for the component of vulnerability. The IPCC treats both concepts as synonymous, but, as mentioned in the preceding paragraph, it uses a definition of adaptive capacity that may be too restrictive for use in broader problems of the dynamics of the global SES. In general terms, adaptive capacity would seem to be broader than capacity of response; specific adaptations may include modifying the sensitivity of the system to perturbations, increasing its resilience (indeed, Walker et al. (2004) define adaptability as the capacity of humans to manage resilience in the SES), and reducing the exposure of the system to perturbations. However, this will depend on the concrete definitions for adaptive capacity and capacity of response adopted in the investigation of a coupled SES.

The relations between the concepts of adaptive capacity and resilience are more unclear, because of the diversity of views. As mentioned by Smit and Wandel (2006), some authors equate adaptive capacity with resilience and social resilience. Gunderson (2000) defines adaptive capacity as system robustness to changes in resilience, Carpenter et al. (2001) use adaptive capacity as a component of resilience that reflects the learning aspect of system behavior in response to disturbance, and Walker et al. (2004) define adaptability as the collective capacity of the human actors in an SES to manage resilience, including making desirable basins of attraction wider and/or deeper, and shrinking undesirable basins; creating new desirable basins, or eliminating undesirable ones; and changing the current state of the system so as to move either deeper into a desirable basin, or closer to the edge of an undesirable one.

6. Conclusions

The analysis of the concepts of vulnerability, resilience, and adaptive capacity from a systemic perspective in the context of research on the dynamics of the global SES shows that these concepts are related in non-trivial ways. If care is not used, the field of human dimensions research can become epistemologically very messy.

For instance, it seems natural to view vulnerability and resilience as related properties of an SES. But the specific nature of the relation is not obvious. The views expressed in the literature range from considering vulnerability as the flip side of resilience to have resilience as one of the components of vulnerability. However, vulnerability does not appear to be the opposite of resilience, because the latter is defined in terms of state shifts between domains of attraction, while vulnerability refers to (or at least also refers to) structural changes in the system, implying changes in its stability landscape. Moreover, resilience is an internal property of the system, not including exposure to perturbations.

Resilience would appear to be more obviously related to one of the components of vulnerability, the same that is variously called adaptive capacity, coping capacity, coping, or capacity of response. But again it is unclear whether resilience includes capacity of response, or is an element of the latter. Given that capacity of response, as an element of vulnerability, is supposed to refer to the response of the system to structural changes, it would appear that resilience should be considered as a subset, or a component, of capacity of response.

The conceptual links between adaptive capacity as an attribute of an SES and capacity of response as a component of its vulnerability are not clear beyond the confirmation of the existence of the relationship. If adaptive capacity in general is considered to include also improvements in the adjustments of the system to its environment even in the absence of changes in the latter, then it is clearly more general than capacity of response. Another point is that adaptive capacity can include reactions of the system that modify its sensitivity to perturbations, and its exposure to them. As described in the vulnerability section, capacity of response also has been distinguished from adaptive capacity using the criteria of short- or long-term adjustments, or of their timing, but in this case both terms have been viewed as belonging to vulnerability.

Fig. 5 summarizes the conclusions on the major conceptual relations among the three concepts. The comparative analysis of the concepts of vulnerability, resilience, and adaptive capacity puts in evidence important similarities and differences, and in some cases contradictions, between the concepts as specified, or utilized, in different fields of inquiry. The comparison also shows that there is no generally accepted meaning for these concepts. The lack of general agreement on the concepts when considered one by one becomes more visible when they are taken together.

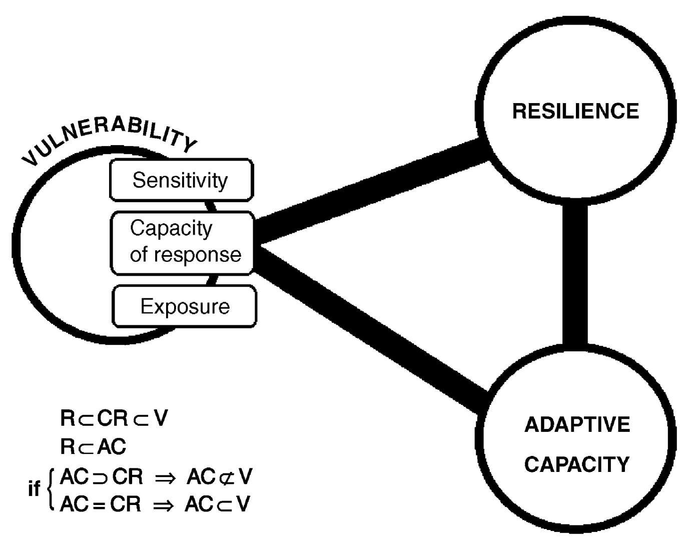

Fig. 5. A diagrammatic summary of the conceptual relations among vulnerability, resilience, and adaptive capacity as described in this article. The signs represent relationships between sets: $\subset$ = "subset of"; $\not\subset$ = "not a subset of"; R, V, AC, and CR stand for resilience, vulnerability, adaptive capacity, and capacity of response, respectively.

Interdisciplinary research on the Earth System and SESs at other scales would clearly benefit from having a general, self-consistent set of these basic concepts that could be applied across disciplines. Therefore, there is a need to develop clear (and, hopefully, shared) specifications of the concepts in the abstract, ecological, and social senses, that are mutually compatible; this can be critical for the interactions between social and natural sciences in the study of the Earth System and coupled SESs at other scales.

Some of the questions that ought to be considered in the process have been identified as:

- What is meant by "harm" or "transformation" (structural change, shifting domains of attraction, moving away from equilibrium states or trajectories)?
- Is positive vulnerability a useful notion?
- Does vulnerability apply to internal perturbations?
- Is vulnerability a property of the system or of the relationship between the system and the perturbation?
- Is negative (perverse) resilience a suitable concept?
- Does adaptation include improvements of the system in a non-changing environment?
- Is adaptive capacity the same as capacity of response?
- Is resilience the same as adaptive capacity?

In this article, answers have been proposed for each of the questions, but what is essential for good research on the global SES is that these definitions are not only scientifically and epistemologically valid, but also that they are *shared* by the research communities in the social and natural sciences cooperating on the study of the dynamics of global change. It is hoped that the present analysis contributes to that.

Ultimately, vulnerability, resilience, and adaptive capacity (and robustness) are different manifestations of more general processes of response to changes in the relationship between open dynamical systems and their external environment. This suggests that an interesting and useful line of research could be represented by the investigation of the general dynamics of change in SES.[7]

A general theory of change and transformation of SESs would involve the relevant internal dynamics of the SES, including aspects such as local stability, resilience, structural stability, and self-organization *sensu* Prigogine (Nicolis and Prigogine, 1977, 1989), the various forms of interaction of the system with its environment (including both threats and opportunities), and the kind of resulting deleterious or beneficial transformation of the system. The investigation of change and transformation of the SES would require the collaboration of social and natural scientists, as well as system theorists and mathematicians, and it could be an appropriate item for a research agenda on global change.

[7]An interesting step in this direction is the development of the adaptive and renewal cycle by the Resilience Alliance (see Folke, 2006) although up to now the adaptive cycle is more of a metaphor or a model than a general theory of change in SES.

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