Research

Aligning Key Concepts for Global Change Policy: Robustness, Resilience, and Sustainability

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ABSTRACT. Globalization, the process by which local social-ecological systems (SESs) are becoming linked in a global network, presents policy scientists and practitioners with unique and difficult challenges. Although local SESs can be extremely complex, when they become more tightly linked in the global system, complexity increases very rapidly as multi-scale and multi-level processes become more important. Here, we argue that addressing these multi-scale and multi-level challenges requires a collection of theories and models. We suggest that the conceptual domains of sustainability, resilience, and robustness provide a sufficiently rich collection of theories and models, but overlapping definitions and confusion about how these conceptual domains articulate with one another reduces their utility. We attempt to eliminate this confusion and illustrate how sustainability, resilience, and robustness can be used in tandem to address the multi-scale and multi-level challenges associated with global change.

Key Words: *fragility; global change; governance; institutions; resilience; robustness; sustainability*

We dedicate this work to the memory of Elinor Ostrom, a wonderful friend and collaborator to all of us. She has made a profound impact on the emerging intellectual domains of sustainability, resilience, and the robustness of social-ecological systems. As a social scientist, she connected core ideas regarding institutions and governance to the dynamics of natural systems. She will be dearly missed; we can take some comfort in knowing that her intellectual legacy will guide research for years to come.

INTRODUCTION

Global change policy must address problems across multiple spatial scales, temporal scales, and levels of organization in the context of major potential shifts in key drivers of the global system. The concepts of sustainability, resilience, and robustness each have strengths for addressing particular types of problems at particular scales and levels of organization, but none covers the full range of relevant scales, levels, and problems. We suggest that taken together, they may. Our intent is to clarify the relationships between resilience, robustness, and sustainability and suggest how they can be used together to provide a framework for global change policy development and implementation. To do so, we focus on problems and conflicts that arise when considering how these terms are used across research domains associated with resource governance and emphasize the importance of the distinction between goal setting, i.e., choosing performance measures, and practical policy implementation concerns. Finally, with the aid of theoretical and empirical examples, we attempt to resolve these conflicts and suggest how sustainability, resilience, and robustness can be used together to move global change policy forward.

ALIGNING THE CONCEPTS

After at least 50 years of development in the academic literature, sustainability is now a mainstream concept. Lubin and Esty (2010) go so far as to define the "sustainability imperative" and compare it to other business megatrends. The authors note that most executives know that they must respond to the challenge of sustainability or jeopardize the competitiveness, and perhaps even the survival, of their organizations. Yet few businessmen or other readers have a clear vision of how to meet this challenge. Consumers are now confronted with sustainability information on many products they buy, but cannot be sure about the implications of this information (Golden et al. 2010, Tejeda-Cruz et al. 2010). Nevertheless, it is individual actions by firms and consumers that will likely drive change associated with concerns over sustainability and with addressing global challenges. This raises an important question: How might voluntary actions by multiple individuals and firms based on sustainability concerns affect properties of the global system in which they occur? Put simply, does individual sustainability add up to global sustainability?

On the face of it, actions of individual citizens, firms, nongovernmental organizations (NGOs), and governments directed at becoming more sustainable should contribute to the sustainability of the entire global system somehow; taking some action has to be better than doing nothing. There are two problems with this chain of reasoning. First is the simple question of whether voluntary pro-environmental behaviors have any real impact. Except for some rare cases such as the U.S. Environmental Protection Agency's (EPA) 33/50 program (Arora and Cason 1995, Khanna and Damon 1999), there is significant empirical evidence (e.g., Rivera and De

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Leon 2004, Pizer et al. 2011) and theoretical evidence (e.g., Segerson and Miceli 1998, Prakash and Potoski 2007) that voluntary environmental programs have little effect. Voluntary programs suffer from the same collective action problems that are at the core of all environmental problems. Worse yet, such voluntary actions may provide a false sense that we are addressing real sustainability issues and generate complacency while, in fact, we are accomplishing nothing. The second problem is more subtle. Even if voluntary environmental behaviors did generate real impacts at the individual level, fundamental properties of feedback systems suggest that there can be no guarantee that effective pro-environmental behavior, however well intentioned, will contribute to system-level sustainability. It is this fact that calls for a clear understanding of the relationship between sustainability concepts in their well-developed academic sense and resilience and robustness in order to direct the energy and enthusiasm for action embodied in the sustainability imperative.

Consider the suggestion of Lubin and Esty (2010) that firms pro-actively engage the sustainability imperative and capture the so-called eco-premium. By this, they mean that firms should focus on outperforming competitors on regulatory compliance and environment-related cost and risk management. Firms should also engage in a widespread strategy to optimize natural resource efficiencies and risk management across their value chains. Here, the sustainability imperative is just one of many activities in which most firms engage as part of a more general strategy: hedging their individual risks. But what does this imply for the global system? In the case of financial markets, Chichilnisky and Wu (2006) note that when individuals and firms use elaborate financial instruments to manage risk, the complexity of the associated contractual obligations can transform individual risks and amplify them into correlated or collective risks, which can increase macroeconomic volatility. Haldane and May (2011) illustrate how behaviors of individual banks aimed at reducing their risk can cause individual bank-level shocks to propagate through the banking system via interbank lending processes. It is important to emphasize that complexity is not a necessary ingredient for the emergence of system-level instability as a result of individual actions. Beale et al. (2011) show that even in a simple network with just two banks, there is a fundamental tension between reducing the risks that individual banks face and reducing systemic risk that generates a difficult dilemma for bank regulators. This is the same basic tension that results from incentive structures that prevail in open-access regimes that privilege what is good for the individual over what is good for the system that leads to the overuse of unregulated resources. So could individual citizens, firms, NGOs, and governments acting "sustainably" actually reduce the sustainability of the global system? As we demonstrate below, this is a distinct possibility.

We argue that avoiding such a situation requires carefully aligning notions of sustainability with key concepts from system dynamics to understand the effect individual actions have at the system level. It is insufficient, and even dangerous, to assume that individual actions will aggregate up to generate system-level sustainability. There are three essential ingredients to this alignment: (1) a dynamic representation of the relationship between human decision-making processes, capital stocks (including natural, human, and human-made), and sustainability; (2) analytical tools that enable the systematic study of nonlinear feedback systems with uncertainty; and (3) a conceptual framework to connect (1) and (2). Fortunately, the first ingredient is already well developed. Very simple bioeconomic models have long been used to explore the essential components of unsustainable resource use: the basic disconnect between individual and group welfare in the absence of effective governance (Gordon 1954) and the challenge of inter-temporal valuation of capital stocks even with effective governance (Clark 1973). These simple models have been extended in numerous directions and now constitute a significant part of the literature on sustainability.

Although simple deterministic models with mild nonlinearities generate sufficiently complex dynamics to study the basic features of sustainability problems, they are not sufficient to design solutions. Real-world systems not only exhibit complex nonlinear dynamics, they also exhibit complexity of a different sort: the sheer number of interacting elements that compose them. This type of complexity brings with it deep uncertainty that makes policy-making very difficult in practice. This fact underlies the need for the second ingredient, which, like the first, is quite well developed. There is a range of specialized, powerful tools for the analysis of nonlinear feedback systems with uncertainty (e.g., robust control and viability theory) that complement the basic tools of dynamical systems theory (e.g., stability and bifurcation analysis). What is lacking is the third ingredient that connects these powerful tools, which have been developed primarily to analyze designed systems with tightly defined boundaries, to the kinds of open, self-organizing systems of interest to the sustainability discourse. We argue that resilience and robustness provide a rich set of ideas from which to build a framework for governing highly uncertain systems and for addressing sustainability challenges. We emphasize that we are not advocating the development of a new conceptual domain through the integration of ideas from resilience, robustness, and sustainability. Rather, we are calling for something much more modest: the careful alignment of a rich set of existing ideas for use in practical policy processes.

The first step is to clearly distinguish sustainability as a goal or, more precisely, as a measure of system performance from the processes associated with achieving that goal, where the

concepts of resilience and robustness become important. For example, when used as an adjective as in the common phrase "sustainable development", sustainability has a relatively clear connotation: something related to human welfare is maintained or increased over some temporal scale. There is also a natural moral dimension that involves choices about how this welfare is distributed intra- and inter-generationally (Howarth and Norgaard 1990, Howarth 1995, 1997). There are several precise definitions of sustainability along these lines that relate to decisions about consumption and investment (Pezzey 2004*a,b*). Early explorations of the sustainability concept were based on dynamic asset allocation problems in the context of economic growth models in which the traditional decision set, including consumption and investment in human-made capital, was extended to include the option to invest in natural capital (see Common and Perrings 1992 for an excellent overview). Despite these quite general yet concise characterizations, it seems that "[t]he considerable disagreement [regarding] the conceptual and operational content of [sustainability]" noted by Common and Perrings (1992:7) 20 years ago remains with us today.

An internet search on "corporate sustainability" generates examples of stated goals to promote sustainability in the corporate sector. These include improved product safety, increased energy efficiency, increased resource use efficiency, collaboration with communities for better health and safety, and reduced greenhouse gas (GHG) emissions. Except for reducing GHG emissions, none of these goals are explicitly dependent on considerations other than sound management principles, and it is not clear what meaning the term sustainability adds in this context. To avoid this lack of clarity, rather than attempt to ascribe conceptual and operational content to the term sustainability, we suggest it should be used to refer to an analytical framework to guide actions across all levels of organization related to the way human societies operate and interact with their environments. Actions, in turn, require decision making. Thus, sustainability involves particular choices about decision-making frameworks to guide action.

Any decision making framework requires at least two components: clearly defined performance measures, and an understanding of the decision-making context, i.e., how decisions translate into outcomes. Sustainability performance measures emphasize inter-generational, intra-generational, and inter-species equity. Sustainability decision-making contexts are characterized by: collective action dilemmas; multi-level decision processes coupled with multi-scale environmental systems that generate endogenous dynamics; and complexity, uncertainty, potential for strong nonlinearities, critical thresholds, and irreversibility. Taken one step further, if we interpret ecology (the study of the relationships between organisms and their environment)

broadly to include human-made components as in industrial ecology (Ayres and Ayres 1996, Graedel and Allenby 2010) or as in the ecology of medical care (White et al. 1961, Knox 1978, White 1997, Dovey et al. 2003), sustainability involves the generation of knowledge about the dynamics of coupled social-ecological systems (SESs) and the creative application of that knowledge to design both physical and governance infrastructure to conform to the collectively determined performance measures. We suggest that this usage of sustainability is consistent with the historical development of the term, will remove unnecessary ambiguities, and will better serve meaningful action.

The distinction between the performance measure and decision-making context aspects of sustainability thus defined is very important. Sustainability in a world with no uncertainty (i.e., the dynamics of the system are perfectly understood), and in which collective action challenges do not arise (i.e., construction, monitoring, and enforcement of institutional arrangements governing resource allocation and collective action can be achieved at low cost), reduces to normative questions regarding how opportunities for the "good life" are distributed among individuals within and across species (Howarth 2007). In this case, applying formal tools such as the inclusive wealth framework (e.g., Walker et al. 2010, UNU-IHDP and UNEP 2012) to distribute productive capacity fairly within and across generations is relatively straightforward. It is with issues relating to the decision-making context that sustainability science challenges mount quickly and in clearly defined layers. For example, if we add only uncertainty that can be characterized in probabilistic terms, sustainability resolves to choices concerning the fair distribution (as defined by the performance measures listed above) of resources, services, and lotteries. It is clear that sustainability challenges mount rapidly as additional characteristics of the decision-making context are considered. Namely, not only must we address the extremely difficult problem of defining performance measures and the decision-making process itself, we must address the challenge of adequately characterizing the decision-making context. It is with the latter that the concepts of resilience and robustness are most useful.

Most people have an intuitive notion of resilience: the capacity to sustain a shock and continue to function and, more generally, cope with change (Walker et al. 2004, 2006). Within the scientific domain, resilience has evolved into an intellectual framework for understanding how complex systems self-organize and change over time. Carpenter and Brock (2008) describe resilience as a "broad, multifaceted, and loosely organized cluster of concepts, each one related to some aspect of the interplay of transformation and persistence." Understanding this interplay and the related concepts of strong nonlinearities, critical thresholds, and

irreversibility in human-environment systems is obviously important for characterizing the sustainability decision-making context. Resilience is a powerful tool in this regard.

It is important to point out that resilience is a system-level concept and is distinct from sustainability in that it is not normative, i.e., it does not include specific choices about performance measures: We seldom hear of sustainable dictatorships, but there are resilient dictatorships. The use of resilience concepts for decision making requires the addition of performance measures. Often, the performance measure is implied. For example, Catchment Management Authorities in New South Wales, Australia, now state that their goal is "to develop resilient communities and agricultural systems" (see http://www.nrc.nsw.gov.au/content/documents/Framework% 20for%20CAPs2.pdf). However, from the context in which such statements are made, a sustainability performance measure is implied, and the goal of developing resilience is an acknowledgment that catchments are operating in a sustainability decision-making context. Resilience researchers have recognized the need to address the question of "resilience of what to what" (Carpenter et al. 2001) in relation to particular regime shifts (e.g., specific measures of early warning signals or functional diversity; Elmqvist et al. 2003, Scheffer et al. 2009). When the "of what to what" is clear, this is referred to as specified resilience. In contrast, general resilience refers to broader system-level attributes such the ability to build and increase the capacity for learning and adaptation (Walker et al. 2009, Folke et al. 2010). The resilience lens is useful for making suggestions about broad categories of investment such as in the capacity to learn, adapt, and transform without being too specific about what this actually means in practice, i.e., how much it costs, who pays, who benefits, etc. Thus, although resilience thinking provides heuristics for living in a complex world, its system-level nature limits its utility in concrete decision analysis, at least in its current state of development.

Robustness, in contrast, explicitly links the dynamics of systems to performance measures. As such, it can be used to link resilience ideas about the nature of persistence and transformation in complex systems to performance measures and to operationalize the sustainability decision-making framework. Robustness is probably the most clearly defined of these three concepts measured in terms of the consistency or precision of its use in the literature. It is typically associated with designed systems or computational methods and algorithms: a robust statistical method (Huber 1972, Huber and Ronchetti 2009), a robust control system (Bhattacharyya et al. 1995, Zhou and Doyle 1998), or a robust decision algorithm (Regan et al. 2005, Lempert et al. 2006). In these contexts, robustness captures the idea that some computational method or system (mechanical or biophysical) works well, even though the information available about the system is incomplete or imperfect. Put another way, and perhaps more precisely, robustness means that the output from a system or

algorithm varies little when some of the inputs vary (Csete and Doyle 2002). Because shocks are specific examples of variation in inputs, robustness can be interpreted as reduced sensitivity of outputs to shocks; if outputs are related to the continued functioning of the system, then robustness and resilience are related.

We focus on robustness as used in the robust control literature and in economics. Here, the term control should not be interpreted as "command and control". Controls are merely processes inserted into a system that gather information about the system, transform this information in some way, and feed it back into the system. In the context of human-environment systems, they should thus be thought of as policies. Like resilience, robust control is concerned with the dynamics of complex feedback systems (Doyle et al. 1992, Anderies et al. 2007), of which human-environment systems are examples. Robustness differs from resilience, at least in practice, in at least four respects: (1) analysis begins with a precise definition of a performance measure; (2) the nature of uncertainty in the system, and thus the system boundary, is precisely defined; and analysis is explicitly concerned with trade-offs (3) between performance and robustness and (4) between robustness to different types of shocks (Zhou and Doyle 1998). These concepts run through the resilience literature (e.g., Polasky et al. 2011) but are typically not defined as precisely as they are in the robust control context; for example, resilience often focuses on novel, poorly understood disturbances.

This precision allows robust control to be used to address specific decision and design problems under parametric uncertainty (i.e., the dynamics of the system are fully understood, but we cannot measure or do not know certain parameters) and dynamic uncertainty (i.e., we do not fully understand the dynamics of the system). However, this precision necessarily requires that the system boundaries be clearly defined, which then limits the capacity of robust control to address learning, adaptation, and transformation. The concept of specified resilience, which implies a more careful definition of system boundaries, is close to the concept of robustness. There have been several rigorous analyses of the specified resilience of specific SESs in terms of the size of basins of attraction of desirable states, which measures the size of a disturbance a system can tolerate before its behavior changes fundamentally (Carpenter et al. 1999, Anderies et al. 2002, 2006, Anderies 2005, Peterson et al. 2009). Viability theory (Aubin 1991) offers an interesting link between specified resilience and robust control that has recently been applied to sustainability problems (De Lara and Martinet 2009). It is a rigorous approach for computing the basin of attraction, the so-called "viability kernel", for desirable long-run outcomes and for devising policies to insure the system remains in the desired basin. However, we are unaware of any study that conducts a precise analysis of the trade-offs associated with maintaining specified resilience or of tools

Fig. 1. (A) Simple depiction of a social-ecologial system in terms of the block diagram common in feedback control. This diagram is very general and incorporates sustainability problems as a special case. (B) Frequency response curves showing robustness-fragility trade-offs. Frequencies for which the curve is below (above) zero are attenuated (amplified) by the feedback controller. See text for details.
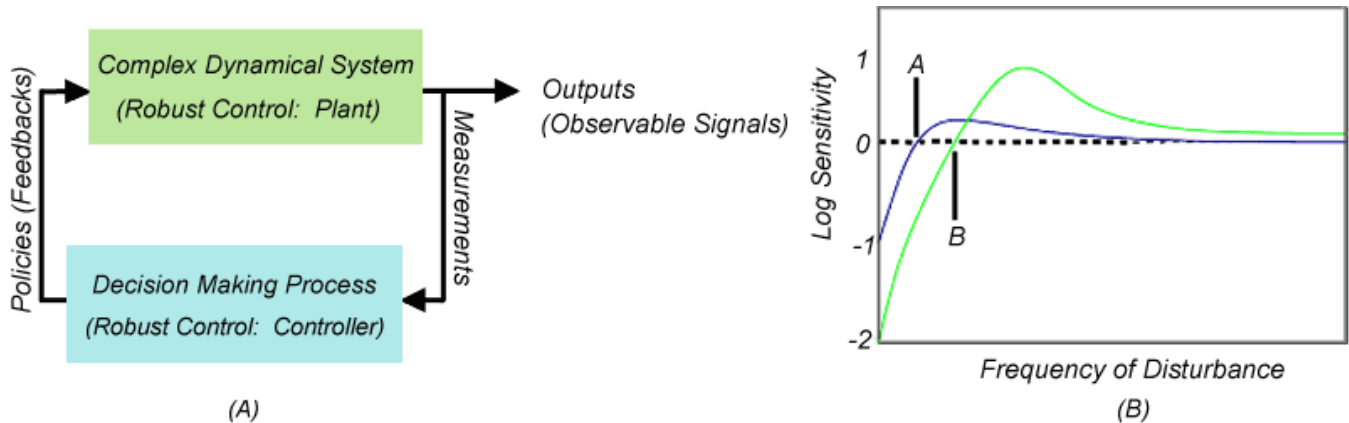
that allow such analysis (e.g., an analog to frequency response analysis from robust control). Because of its emphasis on the combination of specified resilience and general resilience, resilience theorists intentionally do not attempt to circumscribe all the uncertainty in a particular system. Having said this, it is important to note that the distinction between general and specified resilience, and between resilience and robustness more generally, is related to the issue of system boundary definition. It is often possible to redefine system boundaries so that what is perceived as general resilience for one system boundary becomes robustness or specified resilience for another system boundary definition.

LINKING THE CONCEPTS FOR POLICY SCIENCE
Policies, in the broadest sense, are rules (institutions, as in Ostrom 1990, 2005) that translate information about a system (e.g., biophysical information, characteristics of agents, etc.) into action that feeds back into the system. That is, effecting policies adds feedback loops to SESs regarding the actions that human participants must, must not, or may take given the condition of other variables in the SES. This point is critical: Most, if not all, SESs are feedback systems. It is because of this aspect of SESs that resilience and robustness are so important; they highlight the difficult challenges associated with building feedbacks into complex systems.

As discussed above, any decision-making/policy-design framework, of which sustainability is a particular example, requires at least two components: clearly defined performance measures; and an understanding of the decision-making context, i.e., how decisions translate into outcomes. Because of the complexity and uncertainty that characterize the sustainability decision-making context, a set of sustainability

science tools, of which resilience and robustness are examples, is needed to define the decision-making context adequately and operationalize the sustainability policy design framework. Further, because the collective choice of performance measures involves complex ethical considerations and practical governance challenges, the social sciences, history, and other humanities disciplines play critical roles in sustainability scholarship. In the remainder of this section, we link the concepts of resilience and robustness and discuss how they can be used in service of the emerging field of sustainability science (Clark 2007). We focus on the dynamics generated by the feedbacks between outcomes of decision-making processes (i.e., the policies) and the natural systems affected by those decisions (Fig. 1A). We do not address the challenges associated with the decision process itself. We recognize that in many real-world situations, developing effective governance regimes for collective decision processes that heterogenous stakeholder groups accept as legitimate is likely more challenging than understanding the social-ecological feedback systems in which such processes are embedded. We also acknowledge that the decision process itself may affect the dynamics of the feedback system. These issues are beyond the scope of this paper. Here, we address how robustness and resilience ideas inform our understanding of essential features of feedback systems at the heart of sustainability decision-making contexts and how they may be used to help appropriately link decision processes across scales and levels of organization.

Are resilience and robustness the same?
The short answer is yes and no. Resilience provides a broad scientific basis for understanding persistence and transformation in complex systems (Carpenter and Brock

2008). The collection of ideas associated with resilience include self-organization, strong nonlinearity, management strategies for systems with multiple stable attractors (Perrings and Walker 1997, Anderies et al. 2002, Janssen et al. 2004, Perrings and Walker 2004), regime shifts (Scheffer et al. 2001, Folke et al. 2004), path dependencies and irreversibility (Carpenter et al. 1999), adaptability, and transformability (Walker et al. 2009, Folke et al. 2010). Resilience concepts can be used both to help define the decision-making context for short term decisions and to provide understanding of how this context may change or transform over longer periods. In contrast, robust control provides a narrower, systematic analytical framework for short- to medium-term decision and policy design questions under uncertainty given performance measures and the decision-making context informed by basic theory from feedback systems.

Here, the term narrower does not necessarily mean that robustness is nested within resilience. Narrower, rather, means that those who apply robustness ideas strongly emphasize general principles associated with feedback systems and typically demand a tighter problem specification than those working with resilience concepts. Broadly speaking, robustness focuses on designing fail-safe systems within a defined range of uncertainty, and resilience emphasizes trying to build safe-fail systems capable of learning, self-organizing, and adapting to change. The use of multiple redundant systems in engineered systems is, to some extent, built-in adaptation. However, there is no real adaptation (i.e., development with change) to changing conditions. These backup subsystems provide the same functionality to sustain the system exactly as it was before the change. Resilience would emphasize overlapping redundancy in which subsystems can perform similar functions with the capacity to modify higher level functions slightly in the face of change. In this way, resilient systems can learn, self-organize, and evolve with change. As such, resilient systems can adapt in a broader sense than can robust systems. This distinction, however, is more a matter of practice than theory.

Consider, for example, the simple representation of a SES as a feedback system (Fig. 1A). For this system, resilience (i.e., the capacity to maintain structure and function in the face of shocks) and robustness (i.e., preservation of particular characteristics despite uncertainty in components or the environment) are very similar. Depending on which processes are included in the complex dynamical system (called the "plant" in the controls literature) and the decision-making process (called the "controller" in the controls literature), the meanings of robustness and resilience can be made equivalent. For example, if we include adaptability, the capacity of a SES to adjust its responses to changing external drivers and internal processes thereby allows for development within the current stability domain (Folke et al. 2010), in the plant and if we select for particular characteristics, the existence of a level of

organic complexity that includes humans, then robustness includes resilience and adaptability. Note that Csete and Doyle (2002) would refer to changing external drivers as the environment and to internal processes as modules and protocols. Finally, if we allow for a set of dynamics, typically operating on a larger time scale in both boxes, we can allow for what resilience scholars refer to as transformability and what Csete and Doyle (2002) refer to as "evolvability" (evolution is the ultimate example of transformability on very large time scales and adaptability on shorter time scales). The difference between these concepts in theory is simply which dynamics (adaptability and transformability are simply classes of dynamics) are included in the boxes. In practice, however, including dynamics concerning adaptability and transformability in the boxes is just too difficult. Thus, robust control practitioners simply do not include them, and robustness becomes a special case of resilience.

Here, we hope to move beyond these semantics and focus attention on the core issue: all complex systems that can adapt and transform involve complex regulatory feedback networks. Such regulatory feedback networks are fundamental to generating basins of attraction and the capacity to adapt and transform, i.e., to generate and maintain complexity. What robustness focuses on, in part, is the inherent hidden fragilities that are fundamental to complex regulatory feedback networks and that are typically only revealed through failure. Robustness provides a systematic approach to explore robustness-fragility trade-offs in these systems. A critical link between robustness and resilience that follows from this point is that building the capacity to adapt and transform brings with it its own set of fragilities! Resilience theorists express a similar idea in different language: transformation at one scale in a system, which may be related to an inherent fragility in a system module, is a necessary part of maintaining resilience at other scales in the system (i.e., overall system robustness; Folke et al. 2010).

Csete and Doyle (2002) make this point using an extremely simple, linear example of the feedback system shown in Fig. 1A. One way to visualize this fundamental trade-off is using a frequency response diagram (Fig. 1B). The x-axis is the frequency of the disturbance (e.g., weather shock), and the y-axis is a measure of the log of the ratio of the amplitude of the output to the input. If this measure is < 0, the system reduces the effect of the shock on the output (i.e., adapts to or attenuates it). If it is > 0, the system amplifies the shock (i.e., makes things worse). Sensitivity relationships are shown for two different policies. For shocks of frequency < A, the blue policy offers some robustness (resilience). For frequencies > A, this policy amplifies the shock. This is a fundamental property of linear feedback systems. Reducing sensitivity to shocks of frequency < A necessarily incurs a cost of increased sensitivity to shocks of frequency > A. One can change the policy (green) to increase the robustness (resilience) of the system both by

expanding the range of frequencies it can handle (point B) and by how much it attenuates them (the green policy is below the blue policy for frequencies < B). Note, however, that the green policy is much more sensitive to shocks of frequencies > B: it amplifies these shocks by a factor of 10 as opposed to 2 or 3 for the blue policy. This illustrates the fundamental cost of robustness: hidden fragilities. For any linear system, one can demonstrate that the integral of the log sensitivity function is zero, e.g., for the green curve (Fig. 1B), the area between the curve and zero to the left of point B exactly cancels the analogous area to the right of point B. This law (Bode 1945) has been referred to as conservation of fragility (Csete and Doyle 2002). Although this is a very simple example, it is very likely that this feature extends to more complex regulatory networks; any time a system becomes well adapted to a particular set of drivers (i.e., frequency of external shocks in the example), it entrains hidden fragilities.

Examples and case studies

The discussion above is a compact explanation of a very complex set of phenomena. However, for those unfamiliar with ideas from control theory, it does not provide much intuition. Here, we provide a more intuitive example of the feedback system (Fig. 1) based on the model presented by Csete and Doyle (2002; see Appendix 1 for the feedback diagram and mathematical details). This system could represent a group of farmers who decide on how much land to cultivate in the next season (a in Fig. A.1) based on the current year's harvest (y in Fig. A.1) and whether they met or exceeded their target harvest. After making the cultivation decision, harvest is affected by variation in rainfall (d in Fig. A.1). The feedback here is simple: information about the current year's harvest is used to make a decision that affects land cultivation in the following season (x, which is the measured value of y, is compared to r; Fig. A.1). At this point, it is important to emphasize the power of feedback: in this simple system, armed only with the knowledge that increasing cultivated land increases yields, farmers can use a simple feedback rule based on adjusting cultivated land in proportion to deviation between actual and target output (a so-called proportional controller) to come quite close to achieving their target yield in the face of weather variation. More complex planning such as estimating rainfall for the coming year is not necessary. Further, this simple feedback rule will work even if the parameters that govern the dynamics vary widely (see Csete and Doyle 2002 for details). In other words, only a basic understanding of system dynamics is required to insert a feedback and drive the system to a desired output. Now comes the bad news. As we illustrate below, this simple feedback rule must be tuned to a particular pattern of variation in rainfall over time and will necessarily perform poorly (a hidden fragility) if this pattern of variation changes. Controlling systems with feedbacks is relatively easy in theory; understanding where the fragilities lie is much more difficult.

The effect of hidden fragilities is illustrated by the outputs from the simple feedback system (Fig. 2). Here, we set the desired output to be 5 units with an external, sinusoidal disturbance regime with amplitude of 2 and period of 60 (the time scale is arbitrary and could be days, weeks, months, etc.). We illustrate the effect of one parameter in the system: the gain. Gain is a measure of how rapidly the farmer adjusts the area cultivated. We show three example output signals (Fig. 2A): red corresponds to a case in which farmers do not respond to rainfall variation and cultivate the same area each year, green to a case in which farmers are moderately responsive, and blue to a case in which farmers are very responsive. If farmers always cultivate at the same level and just accept what the weather does to their crop, output varies between 3 and 7 units. If they impose some level of feedback control in the system, they can dramatically reduce this fluctuation. The higher the gain (i.e., actors are more responsive), the lower the output fluctuation. In fact, if the gain is high enough, the fluctuation can eliminated almost completely. Humans have been very good at this historically.

Now, let us explore the hidden cost of building feedbacks into systems to suppress the effects of environmental variation. Consider a situation in which there is a temporary change in the disturbance regime whereby the frequency increases by a factor of three for a period of 30 time units (Fig. 2B). With no feedback, the output signal exactly follows the disturbance and varies between 3 and 7 units regardless of the frequency of the disturbance. However, with feedback, higher-frequency disturbances are amplified. When the disturbance frequency is low (1/60) from time 0 to 60, feedback suppresses the disturbance, and the range of variation is reduced from 3–7 to 4–6 (gain = 5, Fig. 2C) or to 4.5–5.5 (gain = 10, Fig. 2D). Referring to the green curve in Fig. 1B, this frequency (1/60) would be to the left of point B, so the sensitivity (range of variation) is reduced (log sensitivity < 0). When the frequency of the disturbance is increased to 1/20 during the period $t = 60$ to 90, feedback dramatically amplifies the effect of the disturbance on the output. This is because 1/20 is to the right of point B (Fig. 1B), where sensitivity is increased (log sensitivity > 0). In fact, the range of variation increases from roughly 2 (output varies between 4 and 6) to 8 (output varies between 1 and 9) when the gain is 5 (Fig. 2C), and to 10 (output varies between 0 and 10) when the gain is 10 (Fig. 2D). This very simple example illustrates the inherent fragilities that creep in when we try to control a given system by introducing feedback loops.

The previous example illustrates the manifestation of fragilities for a given system when external drivers change. Fragilities can also be introduced with endogenous change. Many societies have developed institutional and organizational structures to cope with disturbances; irrigation systems are archetypal examples. In this case, these structures introduce new fragilities, regardless of whether the external drivers

Fig. 2. (A) An illustration of the power of feedback control. Curves indicate three output signals: red: no control (farmers do not respond to rainfall variation and cultivate the same area each year), green: gain = 5 (farmers are moderately responsive), blue: gain = 10 (farmers are very responsive), black: desired output. Under no feedback control (red), the curve follows the rainfall disturbance regime exactly. The higher the gain, the better the feedback controller can do in keeping the output near the desired state, i.e., the blue curve is closer to the desired output than the green curve. (B) Disturbance regime with a temporary period in which the disturbance regime temporarily changes to a higher frequency. (C) System response to the disturbance signal shown in (B) when gain = 5. (D) System response to the disturbance signal shown in (B) when gain = 10. See text for further discussion.
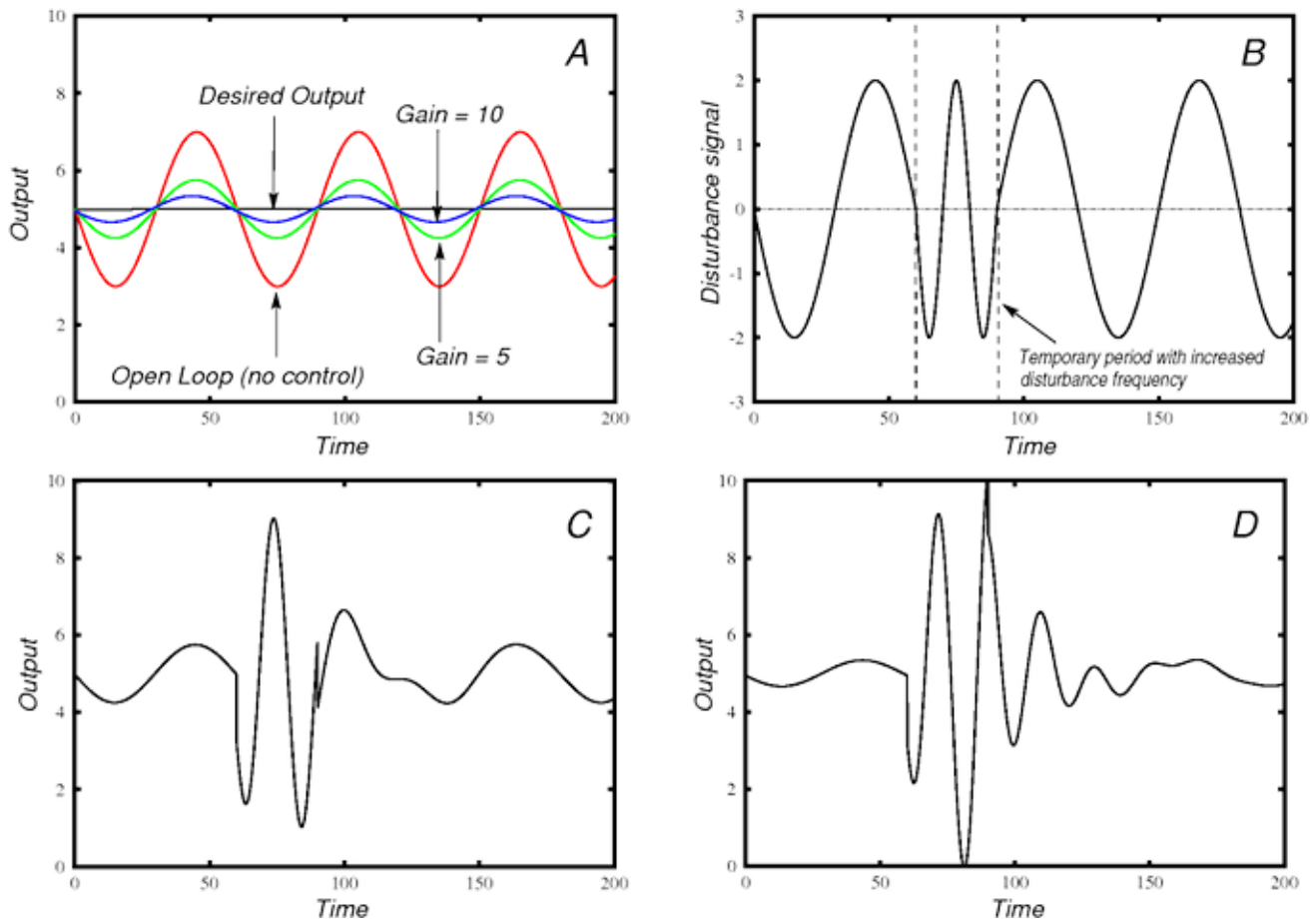
change. For example, Cifdaloz et al. (2010) applied the robustness approach to the Pumpa irrigation system in Nepal. They used the institutional robustness framework of Anderies et al. (2004) and dynamic modeling to explore the robustness characteristics of the institutional arrangements for canal operation and water distribution. This system consists of 120 households that must cope with variation in the amount and temporal distribution of water volumes in the Pumpa River. Cifdaloz et al. (2010) found that the institutional arrangements developed by the farmers were highly tuned and were able to increase robustness to headgate washouts, reduced river flows, and temporal shifts in river flow significantly. Further, they showed how the institutional arrangements, which consist of adaptive rules, can cleverly take equity and fairness issues into account.

Qualitative case-study information suggests that these institutional arrangements are tuned to the internal logic of the system. Specifically, they focus on coordination problems that depend critically on biophysical and social contextual factors such as the physical working of the canal, the system size, steep terrain and small land holdings that allow for visual proximity of farmers for coordination and monitoring, and historical seniority of water rights that make sequential rotations possible without conflict. Such contextual factors

help solve many collective action problems and allow the farming community to focus energy on robust coordination mechanisms for water and labor allocation. However, because the local context solves some problems for them, the community will have little incentive to develop institutions to address those problems. The Pumpa system is likely vulnerable to novel collective action dilemmas introduced by exogenous disturbances and change outside the system and beyond the water and labor allocation problems it is tuned to address.

Although we have no data to determine whether this vulnerability has been exposed in the Pumpa system, other case studies are illustrative. In the Chiregad irrigation system in the Dang district in western Nepal, an intervention (shock) by the state involved installing a new cement-lined canal through some fields based solely on engineering considerations. The location of the new canal did not consider property rights, igniting an old conflict between farmer groups over land access that had been resolved previously by virtue of the way in which the canal system had been constructed (Shivakoti and Ostrom 2002). The farmers had no means to resolve this conflict using social and institutional mechanisms. Once the biophysical context was altered, this social vulnerability was exposed.

Another example involves the movement toward decentralized interventions by governments and NGOs to inject financial resources, rather than centralized capital investment, into local systems to promote development. The idea is that a better understanding of the local context by local communities will enable the communities, rather than a central agency, to make better use of resources. Unfortunately, existing institutions and social structure that have become tuned to local context and history often do not have the capacity for, or may even prevent, the effective use of this novel resource. Existing position rules (as in Ostrom et al. 1994), that is, institutions that define roles in a community, may generate a group of elites with disproportionate power who capture financial resources for their own use (Platteau 2004, Iversen et al. 2006, Dasgupta and Beard 2007, Fritzen 2007). This process, referred to as elite capture, reduces the effectiveness of development interventions and may generate conflict within the community. In all these cases, outside shocks reveal fragilities in the systems.

Taken together, these cases suggest that institutional adaption to the local context (i.e., the internal logic of the system and a stable disturbance regime) may weaken their capacity to cope with external shocks and changes in the disturbance regime. A critical question is whether the impetus to develop institutional arrangements to cope with exogenous novel disturbances can be introduced artificially. To what extent would these conflict with existing institutions?

MOVING FORWARD

Thus far, we have attempted to clarify the relationships between sustainability, resilience, and robustness. We have articulated the broad principles associated with each concept and explored robustness concepts in more detail with a specific case study and a theoretical example. We are now in a position to suggest how these concepts may be aligned to address global change policy challenges. Robustness provides concepts and tools to develop detailed understanding of fundamental properties of feedback systems with clearly defined boundaries. Resilience provides a framework to think about how multiple systems, each operating at their characteristic temporal and spacial scales, interact across scales. Finally, sustainability, as defined here, provides a framework to translate understanding of feedback systems into meaningful action through policy discourse.

We emphasize the need for alignment of these concepts because of the nature of global change. In a world in which local systems are not linked or only weakly linked to other systems, institutions can adapt to a stable internal structure and disturbance regime associated with the local biophysical and social context. In this case, ideas from robust control are sufficient to understand a given system's capacity to cope with disturbance and inherent fragilities in the system. However, as local systems become more connected economically, socially, and ecologically through global change, they are subjected to potential changes to their internal structure and the disturbance regime they must face. This process occurs on larger temporal and spatial scales and across multiple levels of organization, limiting the practical utility of robustness ideas. Resilience theory offers ideas to address multi-scale and multi-level change that nicely complement robustness ideas in a policy design framework. We suggest that such a framework should include the following two key elements.

First, reserve the term "sustainability" to refer to an analytical framework to guide action, supported by a decision-making framework in which the performance measure and decision-making context have the broadly defined characteristics discussed herein. Sustainability merely defines a superstructure, a skeleton to support a discourse about the interaction between human societies and the environment. The conceptual and operational flesh of the discourse is supplied by the full range of academic disciplines. Considerable effort will be required to address the difficult challenge of designing participatory decision processes, i.e., governance regimes, and normative frameworks to select collectively a performance measure that is perceived as legitimate by all relevant stakeholders. Given a legitimate performance measure, operationalizing the sustainability decision-making framework requires that the decision-making context be characterized. The skeleton for sustainability is the recognition that a functioning biosphere is a precondition for economic and social development (Folke et al. 2011).

Second, resilience and robustness ideas can be used within the broader context of sustainability science to help characterize important aspects of the decision-making context. Specifically, these concepts can be used in a complementary fashion to address issues regarding three types of challenges that map roughly to three time scales. (1) Dealing with uncertainty and disturbances in SESs in their present configurations, i.e., maintaining the function of what we have. This challenge is typically relevant on shorter time scales (months to years). (2) Adapting existing systems incrementally to new types of uncertainty and disturbances, that is, continuous active adaptations with a changing environment. This challenge is typically relevant on intermediate time scales (years to decades). (3) Transitions or transformations toward new SES configurations as existing SESs become untenable. Such transformations are a necessity for shifting toward development pathways that satisfy the performance measures that define the sustainability decision-making framework. This challenge is typically relevant on longer time scales (multiple decades to centuries). It is important to note that identifying temporal scales for transformations requires some care. Transformation involves the creation of new stability landscapes and new basins of attraction (Folke et al. 2010). It is this process that may take decades. The final stage of transformation, the movement from one basin of attraction to another, can happen very rapidly (months to years) and may even come as a surprise.

As per our earlier discussion, definitions of resilience and its different aspects, e.g., specified versus general resilience, are scale dependent; what constitutes short, intermediate, and long time scales is system dependent. The relative nature of time scales and system boundaries also affects the interpretation of system robustness. Thus, the relationships between different types of challenges and their relevant time scales listed above should be interpreted with some caution. However, for the general class of problems facing human societies at present, the classification above is a useful starting point. With that in mind, resilience and robustness can be used in tandem to address three key challenges.

Challenge I (shorter term): The concepts of specified resilience and robustness are roughly equivalent for addressing these shorter-term challenges. They both can be used to study the capacity of systems to maintain some range of outputs given variation and uncertainty. Resilience focuses on sizes of basins of attraction, thresholds, regime shifts, and the capacity of SESs to manage them by affecting the topology of basins of attraction, avoiding thresholds, or actively crossing them as appropriate. Robustness focuses on fundamental principles of feedback systems, the design of robust policies, and fundamental robustness-fragility trade-offs associated with different policy designs or governance structures focused on reducing the sensitivity of a given system output such as food production to a clearly defined class of

disturbances and uncertainties. Although both can be used for policy design in specific systems, robustness and resilience can be used in tandem to understand how robustness-fragility trade-offs add up. Recall our question in the introduction as to whether actions by individual actors at different levels of organization aggregate up to global sustainability. This translates into a question of how networks behave in which each node is a feedback system, each with its own fundamental robustness-fragility trade-off characteristics. Being part of a network exposes each node to novel shocks; the network structure itself may propagate exogenous shocks experienced by individual nodes through the network, as in the banking example. Given the dynamic complexity associated with even a single, isolated feedback system (Fig. 2), the dynamic complexity of a network of feedback systems can increase very rapidly. Thus, it is highly unlikely that uncoordinated actions of actors at different scales will scale up in a nice predictable way. The key lesson from resilience is that we need to understand the cross-scale implications of policies that operate at different scales for the system as a whole.

Challenge II (intermediate term): Here, the concept of adaptability, as defined by Folke et al. (2010), from resilience theory becomes important. It implies the capacity to cope with the changing geometry of basins of attraction and perhaps to influence that geometry. The tools of robustness are not well suited for this. Having said this, the inherent trade-offs associated with adjusting responses is not made clear in the adaptability concept. Robustness can contribute here: As society adapts within a basin, the dynamics change. For each set of dynamics that might be encountered along the adaptive path, robustness tools can be used to analyze rigorously the robustness-fragility trade-offs associated with that set of dynamics. This analysis might then influence the next adaptive adjustment by helping to make choices about how society navigates the robustness-fragility trade-offs for each set of dynamics it encounters along the way. In this way, robustness analysis is an integral part of the adaptive process by helping navigate short-term dynamics along the intermediate-term adaptive path. Resilience, on the other hand, emphasizes visioning about what all these adaptive paths might be to provide input to the robustness analysis. The relative strengths of robustness and resilience ideas are leveraged to cope with multi-scale and multi-level problems.

Challenge III (longer term): Here, the concept of transformability becomes important, i.e., the capacity to transform a system completely when the present system becomes untenable (Walker et al. 2004, Folke et al. 2010). However, transformability requires continual investment in some sort of broader, difficult to define adaptive capacity. How should society invest? In this context, robustness and resilience ideas can be combined for a comprehensive learning program. Robustness analysis can help reveal hidden fragilities that might induce a need for transformation. This

can help direct learning efforts at better understanding how these fragilities might be revealed and what might be needed to deal with them, i.e., where to invest in transformative capacity. Resilience ideas, emphasizing learning and collaborative processes, can be used to inform decisions about investment in more general learning (more general insurance) to maintain the capacity of society to react more effectively to unknown change and hidden fragilities and find innovative new mechanisms for transformative change.

As with any policy, global change policy requires that localities, cities, nations, and groups of nations develop institutions that guide decision-making processes at multiple scales. We argue that the sustainability decision-making framework as defined herein should guide development of global change policy. We need to structure decisions by multiple actors at multiple levels of organization and scales that together tend to select for development trajectories that meet sustainability performance criteria. When sustainability is conceptualized in this way, the importance and respective roles of the full range of academic disciplines, including the humanities, social and natural sciences, decision science, and engineering, become clear. The emerging field of sustainability science that serves to characterize the sustainability decision-making context is organized around a core research program that focuses on understanding the complex dynamics that arise from interactions between human and environmental systems (Clark 2007). Resilience and robustness theories are well placed to contribute significantly to this endeavor. They connect cutting-edge research on complex systems to the practical question of what collections of interdependent institutions and incentive structures can most effectively generate social capacity to manage and guide interactions between nature and society toward more desirable development pathways.

Moving global change policy forward will require a policy design framework built around multiple deliberative decision processes involving a wide range of stakeholders operating at multiple scales and levels of organization. Robustness and resilience ideas can help inform how these decision processes should be linked across scales and levels of organization. Finally, resilience and robustness ideas will contribute to the set of tools with which to systematically address policy challenges I–III to operationalize the sustainability imperative at the global scale.

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Appendix

The model used for the example is a very simple, general linear model, easily found in most textbooks on feedback control. I have chosen to refer to the instance of this model that appears in Csete and Doyle (2002) so that interested readers can cross reference that very interesting presentation. But there is nothing particularly special about the model.

The model is shown as a traditional feedback diagram in Figure A.1. Circles represent addition or subtraction. Going around the loop starting at A: the area of cultivated land (a) is disturbed (d) by weather to produce yield (y). The yield is sampled and transformed into a measuremet (mental model of farmer). The measurement is compared to the desired value (r). The culivated land is adjusted based on the difference between desired output and a measurement of the output ($u = r - x$).
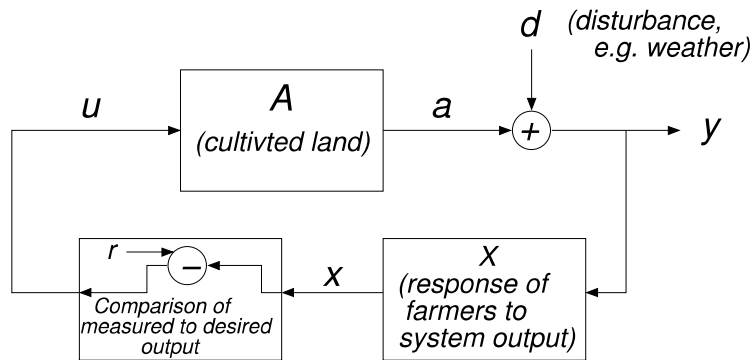

Figure A.1: *Block diagram of simple feedback system.*

The mathematical representation is:

$$y = d + a \tag{1}$$

$$u = r - x \tag{2}$$

$$\dot{x} = k_1 y - k_2 x \tag{3}$$

$$\dot{a} = gu \tag{4}$$

The key paramter is the gain, g, i.e. how fast a changes in response to u.

Basic ODE model for use with XPPAUT

Interested readers may explore the model (its fun!). You will need to download the XPPAUT package (which is availabe for Windows, Mac OS X, and several UNIX flavors) from the XPPAUT Home Page[3].

---

[3]http://www.math.pitt.edu/ bard/xpp/xpp.html

```
#Simple feadback model modified from Doyle.


par k1=0.01,k2=0.1,g=0.1,dmax=0,rmax=0.5,omega=1
par switch=1,p1=60,p2=20,hfson=50,hfsoff=60


#functions
f(x,a,b)=if(x<a)then(0)else(if(x<b)then(1)else(0))


#Equations and hidden variables-----------------------
r = rmax
d = dmax*v*(1-f(t,hfson,hfsoff)) + dmax*v1*f(t,hfson,hfsoff)
y = d + a
u = r - x


#differential equations==------------------


# oscilators - shocks
duo/dt = uo*(1 - uo^2 - v^2) - (2*Pi/p1)*v
dv/dt = v*(1 - uo^2 - v^2) + (2*Pi/p1)*uo
duo1/dt = uo1*(1 - uo1^2 - v1^2) - (2*Pi/p2)*v1
dv1/dt = v1*(1 - uo1^2 - v1^2) + (2*Pi/p2)*uo1
init uo=-1,v=0,uo1=-1,v1=0


#feedback system
dx/dt = k1*y -k2*x
da/dt = g*u


aux yout = y
aux uout = u
aux rout = k2*r/k1
aux dist = d


@ yp=yout, total=200, xhi=200, yhi=10, maxstor=100000


done
```