Center for the Study of Institutional Diversity

CSID Working Paper Series

#CSID-2012-002

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April 25, 2012

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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 spirals as multi-scale and multi-level processes become more important. Here, we argue that addressing these multi-scale and multilevel challenges requires a collection of theories and models. We suggest that the conceptual domains 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. Here we attempt to eliminate this confusion and illustrate how sustainability, resilience and robustness can be used in tandem to address the multi-level and multi-scale challenges associated with global change.

Keywords:
Resilience, Robustness, Vulnerability, Sustainability, Feedback Control

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April 24, 2012

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 spirals as multi-scale and multi-level processes become more important. Here, we argue that addressing these multi-scale and multilevel challenges requires a collection of theories and models. We suggest that the conceptual domains 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. Here we attempt to eliminate this confusion and illustrate how sustainability, resilience and robustness can be used in tandem to address the multi-level and multi-scale challenges associated with global change.

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. The intent of this

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paper is to clarify the relationships between resilience, robustness and sustainability and suggest how they can be used in tandem 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 (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 in tandem to move global change policy forward.

ALIGNING THE CONCEPTS

"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 can't be sure about the implications of this information (Tejeda-Cruz et al., 2010; Golden et al., 2010). And yet 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 will 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 individuals and firms directed at becoming more sustainable should contribute to the sustainability of the entire global system. Unfortunately, fundamental properties of complex feedback systems suggest that this cannot be taken for granted. It is this fact that calls for a clear understanding of sustainability and its relationship to resilience and robustness.

Consider, for example, the reasonable 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. In the case of financial markets, Chichilnisky and Wu (2006) note that when individuals and firms use complex 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. Could this mean that individual firms and individuals acting "sustainably" might actually reduce the sustainability of the global system? As we will see below, this is a distinct possibility.

Avoiding a situation in which individual sustainability actions lead to loss of system sustainability requires that we 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 a natural moral dimension as well 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, 2004a,b). Consider, for example, the published "2015 Sustainability Goals" issued by the Dow Chemical Company[1]. Several of these worthwhile goals, including collaboration with communities for better health and safety, innovation in product safety and energy efficiency are quite general. Although these goals may promote the sustainability of Dow, it does not necessarily follow that they will contribute to sustainability of the global system in which the Dow Chemical Company is embedded. In Dow's "sustainable chemistry"[2] goal, the concept of sustainability again enters as an adjective. Here, the term sustainable refers to decisions about how Dow will invest in and structure its chemical production activities. Given these problems with how sustainability is interpreted in different contexts, we suggest that sustainability should be used to refer to a particular *decision making framework* for issues related to the interaction between human societies and the environment in which the *performance measures* used emphasize inter-generational, intra-generational, and inter-species equity (which can be formalized using the concept of inclusive wealth (Walker et al., 2010)). Further, sustainability *decision making contexts* are characterized by 1) collective action dilemmas, 2) complexity and uncertainty in human-environment systems, and 3) the potential for strong non-linearities, critical thresholds, and irreversibility. We suggest that this usage will remove unnecessary ambiguities.

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 are completely known) 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 across individuals within and across species (Howarth, 2007). 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 distribu-

[1]http://www.dow.com/commitments/goals/
[2]http://www.dow.com/commitments/goals/chemistry.htm

tion (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 equally difficult challenge of adequately characterizing the decision making context. It is with the latter that the concepts of resilience and robustness are most important.

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) have described 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 non-linearities, 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. Use of resilience concepts in a decision-making context requires the addition of performance measures (sustainability performance measures, for instance). Often the performance measure is implied. For example, Australian Catchment Management Authorities in New South Wales now state that their goal is "to develop resilient communities and agricultural systems" (see http://www.nrc.nsw.gov.au/content/documents/Framework%20for%20CAPs.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 (Scheffer et al., 2009; Elmqvist et al., 2003)) and refer to this as "specified resilience." "General resilience" on the other hand 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 (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, on the other hand, 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 operationalize the sustainability decision-making framework.

Robustness is probably the most clearly defined of these three concepts measured in terms of the consistency/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 (Zhou and Doyle, 1998; Bhattacharyya et al., 1995), or a robust decision algorithm (Lempert et al., 2006; Regan et al., 2005). 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 doesn't vary much when some of the inputs do (Csete and Doyle, 2002). Since "shocks" are specific examples of variation in inputs, robustness can be interpreted as reduced sensitivity of outputs to shocks, and 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 in "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 3) analysis is explicitly concerned with trade-offs between performance and robustness and 4) between robustness to different types of shocks (Zhou and Doyle, 1998). These concepts do run through the resilience literature (e.g. Polasky et al., 2011) but are typically not defined as precisely (e.g. resilience often focuses on novel, poorly understood disturbances) as they are in the robust control context.

This precision allows robust control to be used to address specific decision and design problems under parametric (the dynamics of the system are fully understood but we can't measure or don't know certain parameters) and dynamic (we don't fully understand the dynamics of the system) uncertainty. However, this precision necessarily limits the capacity of robust control to address learning, adaptation, and transformation because of the need to define system boundaries clearly. The concept of "specified resilience" which implies a more careful definition of system boundaries is close to the concept of robustness but typically lacks the precise analysis of trade-offs core to robust control. In fact, 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 point out 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 (*sensu* Ostrom (1990, 2005)) that translate information (e.g biophysical information, information about actions agents, etc.) about a system into action that feeds back into the system. That is, effecting policies adds feedback loops to social-ecological systems (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* (how decisions translate into outcomes). Due to 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 adequately define the decision-making context and operationalize the sustainability policy design framework. Further, because the choice of performance measures involves ethical considerations, the humanities also play a critical role 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).

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 non-linearity, multiple stable attractors (Anderies et al., 2002), regime shifts (Scheffer et al., 2001; Folke et al., 2004), path dependencies and irreversibility (Carpenter et al., 1999), adaptability, and transformability (Folke et al., 2010; Walker et al., 2009). Resilience concepts can be used to both help define the decision-making context for short term decisions and provide understanding of how this context may change (transform) over longer periods. Robust control, on the other hand, 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. The term "narrower" here does not necessarily mean that robustness is nested

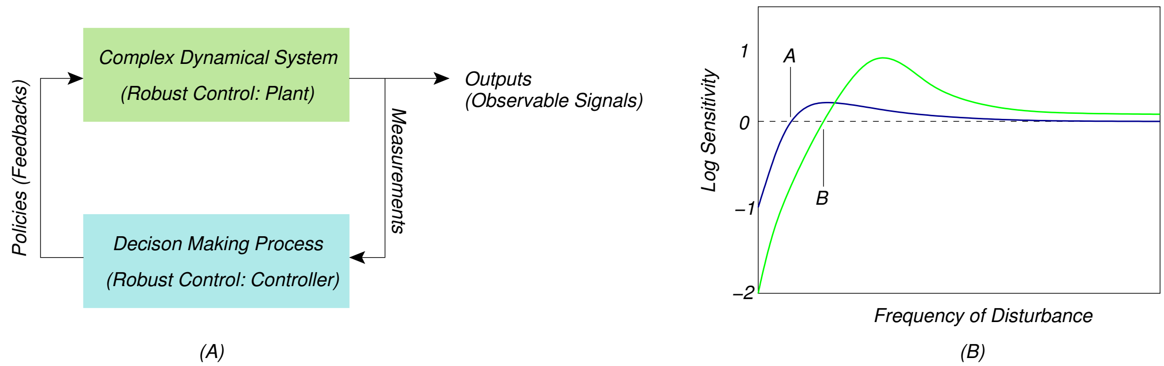

Figure 1: *(A) Simple depiction of a SES in terms of the "block" diagram common in feedback control. This diagram is very general and incorporates sustainability problems as a special case. (B) Frequency response curves showing robustness-fragility trade-offs. Frequencies for which the curve is below (above) zero are attenuated (amplified) by the feedback controller. See text for details.*

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.

Consider the simple representation of a SES as a feedback system shown in Figure 1(A). For this system, resilience (the capacity to maintain structure and function in the face of shocks) and robustness (preservation of particular characteristics despite uncertainty in components or the environment) are very similar. Depending on what processes are included in the Complex Dynamical System (called the "plant" in the controls literature) and the Decision Making Process (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 and thereby allow for development within the current stability domain (Folke et al., 2010) and if we choose for "particular characteristics", the existence of a level of organic complexity that includes humans, then robustness includes resilience and adaptability. Note, Csete and Doyle (2002) would refer to "changing external drivers" as the environment and "internal processes" as modules and protocols. Finally, if we allow for a set of dynamics, typically operating on a larger time scale in the boxes, we can allow for "transformability" or "evolvability" according to Csete and Doyle (2002) (evolution is the ultimate case of transformability on very large time scales and adaptability on shorter time scales.). The difference between these concepts in *theory* is simply what dynamics (adaptability and transformability are simply classes of dynamics) one includes in the boxes. In *practice*, however, including dynamics concerning adaptability and transformability in the boxes is just too difficult. Thus robust control practitioners simply don't 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, are 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 (overall system robustness) Folke et al. (2010).

Csete and Doyle (2002) have made this point using an extremely simple, linear example of the feedback system shown in Figure 1(A). One way to visualize this fundamental trade-off is using a frequency response diagram like that shown in Figure 1(B). The x-axis is the frequency of the disturbance (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 less than 0, the system reduces the effect (adapts to, attenuates) of the shock. If it is greater than 0, it amplifies the shock (makes things worse). Two different policies are shown. For shocks of frequency less than A, the blue policy offers some robustness (resilience). For frequencies above A, this policy amplifies the shock. This is a fundamental property of (linear) feedback systems. Reducing sensitivity to shocks of frequency less than A necessarily incurs a cost of *increased* sensitivity to shocks of frequency greater than 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 less than B). Note however the green policy is much more sensitive to shocks of frequencies above 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 prove that the integral of the log sensitivity function is zero (e.g. for the green curve in 1(B), 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 (due to 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 - e.g. any time a system becomes well adapted to a particular set of drivers (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 a particular instantiation of the feedback system shown in Figure 1 based on the model presented by Csete and Doyle (2002) (See Appendix for the feedback diagram and mathematical details). This system could represent a group of farmers who decide on how much land to cultivate next season (a in Figure A.1) based on this year's harvest (y in Figure A.1) and whether they met or exceeded their target harvest. After making the cultivation decision, harvest is impacted by variation in rainfall (d in Figure A.1). The feedback here is simple: information about last year's harvest (y in Figure A.1) 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 as shown in Figure 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, *ceteris paribus*, using a simple feedback rule based on adjusting cultivated land in proportion to deviation between actual and target output (a so-called proportional controller), farmers can 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 (or feedbacks) 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 impact of hidden fragilities is illustrated in Figure 2. The panels show the outputs from the simple feedback system (see appendix). Here we set the desired output to be 5 units with an external, sinusoidal disturbance regime with amplitude 2 and period 60 (the time scale is arbitrary - could be days, weeks, months, etc.). We illustrate the affect of one parameter in the system: the *gain*. Gain is a measure of the strength of response of the controller (farmer) to variations in the output signal - e.g. how rapidly can the farmer adjust the area cultivated. Figure 2 (A) shows 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). The black horizontal line is the desired output. If farmers do not attempt to deal with the disturbance, i.e. exert no control, the output signal is simply the desired output plus the disturbance - i.e. farmers always cultivate at the same level and just accept what the weather does to their crop. In this case, output varies between 3 and 7. If they impose some level of feedback

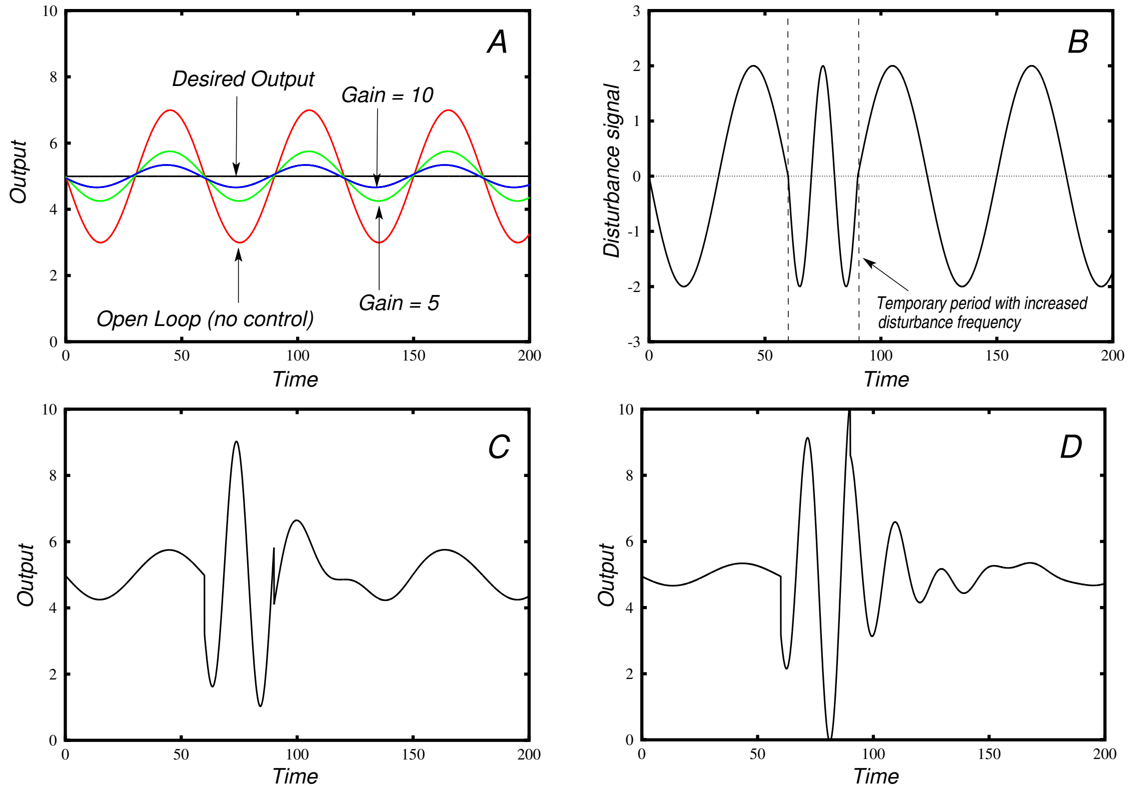

Figure 2: *(A) An illustration of the power of feedback control. The red curve is the output with no feedback control. It follows the rainfall disturbance regime exactly. The higher the gain, the better the feedback controller can do in keeping the output near the desired state - i.e. the blue curve 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 the gain is 5. (D) System response to the disturbance signal shown in (B) when the gain is 10. See text for further discussion.*

control in the system, they can drastically reduce this fluctuation. The higher the gain (actors are more responsive), the lower the output fluctuation (compare gain=5 and gain=10). In fact, if they increase the gain enough, they can eliminate this fluctuation almost completely. Humans have been very good at this, indeed.

Now let us explore the hidden cost of building feedbacks into systems to suppress the effects of environmental variation. Figure 2 (B) shows the disturbance signal with a temporary change of disturbance regime - the frequency increases by a factor of 3 for a period of 30 time units. With no feedback, the output signal exactly follows the disturbance and varies between 3 and 7 regardless of the frequency of the disturbance. However, with feedback, higher frequency disturbances are amplified. Consider Figures 2(C) and (D). When the disturbance frequency is low (1/60) from time 0 to 60, feedback suppresses the disturbance (range of variation is reduced from 3-7 to 4-6 (gain=5, panel (C)) or 4.5-5.5 (gain = 10, panel (D)). Referring to the green example in 1(B), 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 from $t = 60$ to $t = 90$, feedback dramatically amplifies the disturbance. The range of variation increases to 1-9 when the gain is 5 (panel (C)) and to 0-10 when the gain is 10 (panel (D)). Again Referring to the green example in 1(B), this frequency (1/20) would be to the right of point B where the sensitivity is increased (log sensitivity > 0). This very simple example clearly 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. For example 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 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 who must cope with variation in the amount and temporal distribution of water volumes in the Pumpa river. They found that the institutional arrangements developed by the farmers were highly tuned and were able to significantly increase robustness to headgate washouts, reduced river flows, and temporal shifts in river flow. 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 which 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 on engineering considerations. This ignited an old conflict between farmer groups that had been previously resolved 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 local communities' better understanding of the local context will enable them to make better use of resources than a central agency. 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 utilization of this novel resource. Existing "position rules" (sensu Ostrom et al., 1994), institutions that define roles in a community, may generate a group of elites with disproportionate power who capture financial resources for their own use (Fritzen, 2007; Dasgupta and Beard, 2007; Iversen et al., 2006; Platteau, 2004). 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 revealed fragilities in the systems.

Taken together, these cases suggest that institutional adaption to the local context (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 impetus to develop institutional arrangements to cope with exogenous novel disturbances can be artificially introduced. To what extent would they conflict with existing institutions?

MOVING FORWARD

Thus far we have attempted to clarify the relationships between sustainability, resilience, and robustness. We are now in a position to suggest how these concepts may be integrated to address global change policy challenges. We emphasize the need for integration 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, intuitions 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 key elements:

1. Shift focus away from thinking about long-term goals or system properties in the context of sustainability. Rather, we argue that it is more useful to think of sustainability as referring to a certain subset of elements in the enormous set of all possible decision-making frameworks. Specifically, "sustainability" refers to a choice of a particular performance measure and decision-making context with the characteristics discussed in Section . That is, just as the couplet (x, y) describes every point in the plane, the couplet (*performance measure, context*) describes every possible decision-making framework. "Sustainability" refers to a set of points in the decision-making framework space. The decision about which of these points to pick involves normative considerations and issues regarding the nature of the participatory process by which it is picked. Once the "sustainability" point is picked, *operationalizing* it requires "sustainability science".

2. Resilience and robustness ideas can be used to guide sustainability science. These concepts can be used in a complementary fashion to address issues regarding three types of challenges that map roughly on to three time scales:

   I. 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),

   II. Adapting existing systems incrementally to new types of uncertainty and disturbances (i.e. continuous active adaptations with a changing environment). This challenge is typically relevant on intermediate time scales (years to decades), and

   III. Transitions (transformations) towards new SES configurations as existing SESs become untenable. Such transformations are a necessity for shifting towards development pathways that satisfy the performance measures that define the sustainability decision making framework. This challenge is typically relevant on longer time scales (involving multiple decades to centuries).

   As per our earlier discussion, definitions of resilience and its different aspects (e.g. specified versus general resilience, etc.) are scale dependent and 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 reasonable approximation. With that in mind, resilience and robustness can be used in tandem as follows:

- **Challenge I (shorter-term)**: The concepts of specified resilience and robustness are roughly equivalent. 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 (governance structures) focused on reducing the sensitivity of a given system output (e.g. food production) to a clearly defined class of disturbances and uncertainties. Both can be used for policy design in highly uncertain environments that are expected to persist over the short term.
- **Challenge II (intermediate-term)**: Here the concept of adaptability, as defined by Folke et al. (2010) (see Section) from resilience theory becomes important. It implies the capacity to cope with the changing geometry of basins of attraction and to perhaps 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 may be encountered along the adaptive path, robustness tools can be used to rigorously analyze the robustness-fragility trade-offs associated with that set of dynamics. This analysis may then influence the next adaptive adjustment by helping 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 - the capacity to completely transform a system when the present system becomes untenable (Walker et al., 2004; Folke et al., 2010) - becomes important. 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 effort 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 better react to unknown change and hidden fragilities and find innovative new mechanisms for the 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, becomes 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 incentive structures can most effectively generate social capacity to manage and guide interactions between nature and society toward more desirable development pathways.

Taken together, a policy design framework built around deliberative processes involving a wide range of stakeholders that systematically addresses policy challenges I-III with the appropriate combination tools provided, in part, by resilience and robustness theories provides a strong foundation for moving global change policy forward.

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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 ($u = r - x$).

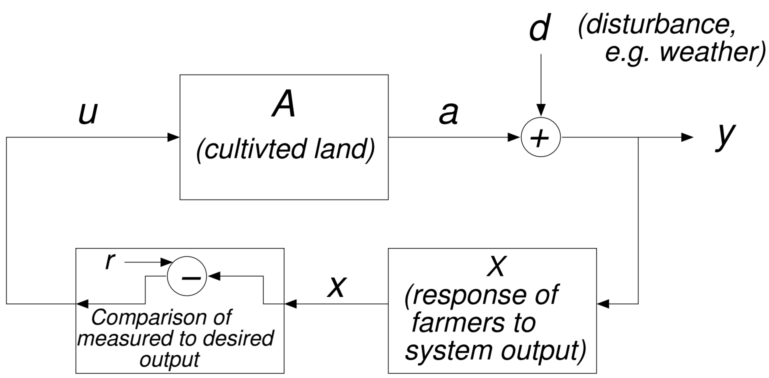

Figure A.1: *Block diagram of simple feedback system.*

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
```