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A Resilience Approach to Integrated Assessment

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Abstract

Many of the failures in natural resource-use systems are due to failure of the ruling management paradigm. This command-and-control approach to management is underlain by four flawed assumptions: i) a focus on average conditions and particular time and space scales; ii) a belief that problems from different sectors in these systems do not interact; iii) an expectation that change will be incremental and linear, and iv) an assumption that keeping the system in some particular state will maximise yield, indefinitely. An alternative approach, based on resilience, assumes instead that social-ecological systems behave as complex adaptive systems with alternate attractors (alternate system regimes). Three attributes of these systems—resilience, adaptability and transformability—determine the topology of the system's stability landscape, and therefore the likelihood of regime shifts. Resilience governance and management is therefore concerned with learning how to avoid (or to cross) thresholds between alternate regimes and how to influence the positions of the thresholds.

Given the enormous uncertainty inherent in these systems, a resilience based approach needs to be complemented by the ability to assess whether, in fact, current or proposed levels and patterns of resource use are sustainable (will avoid regime shifts that lower social welfare). The inclusive wealth approach of Arrow et al. (2003) is suggested as an appropriate measure.

Keywords: Resilience, Sustainable development, Adaptive capacity, Transformation, Social-Ecological Systems, Human Wellbeing, Social Welfare, Wealth

1 Introduction: Partial Solutions Don't Work

With some exceptions, natural resource management policies are not working very well; current patterns and levels of natural and agro-ecosystem use are

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not sustainable. Applying "current best practice" is too often leading to unintended and unwanted outcomes. Hundreds of diverse social-ecological systems (agro-ecosystems, rangelands, forests, marine and freshwater systems) are failing to achieve their goals, with resulting social disruption and a decline in the resource base. Once-productive agricultural regions have severe, mostly unexpected, problems—salinisation, erosion, acidification, diseases, pollution. The resource bases of two billion people who depend on the ecosystem services of highly vulnerable drylands are increasingly unable to cope with environmental disturbances they previously absorbed. Many marine fisheries have already collapsed and many others are fully exploited and vulnerable.

In the majority of these regions, where the intentions are good (i.e., not counting the unhappily large proportion distorted by corruption and greed), the inappropriate resource use policies and management activities stem from inappropriate 'mental models'. People use and modify nature based on their mental models of how systems of people and nature work. Such models may be unarticulated but nevertheless guide preferences and choices. However, these models, or paradigms, often either ignore or inappropriately simplify vital aspects of the ways in which real-world systems actually work. The ruling mental model for resource use and development is still the command-and-control philosophy (deterministic, and viewing natural systems as highly controllable) that marked the early development of modern approaches to natural resource management. Initially, these attempts met with success, as evidenced by the advances in resource productivity and human welfare. As new regions were opened up and as modern systems were first introduced, things seemed to be going well. But now the initial successes are bedeviled by a variety of emerging secondary effects. The Goulburn-Broken (G-B) catchment in Australia's Murray-Darling Basin provides a good example.

From the early 1900s, for many decades agricultural production in the G-B indicated progress and sustainable use of resources. Originally, the water table in most of the region was more than 25m below the surface. Following clearing of trees in the upper catchment, more than a hundred years ago, excess water has flowed down and raised water tables, in some places already to the surface. As the water rises it brings with it large amounts of salt that have accumulated over thousands of years (via tiny amounts in rainfall) deeper in the soil profile. Once the water table reaches 2m below the surface, capillary action brings it and the salt to the surface, destroying the land for agricultural purposes. Water tables rise and fall in response to rainfall patterns, and in runs of very wet years it can rise significantly, often to the surface these days, causing millions of dollars worth of damage and, more significantly, leaving some places irreparably degraded (at least on a multi-decadal time scale) through salinisation. Only in the last few decades, since the first "bad" episodes occurred, has the risk of future losses in productivity associated with changes in hydrology and salinity been adequately recognised.

The mindset of the early developers of agriculture in the region was one of command-and-control. Their early interventions worked for them, in the short term. They believed they could re-structure the landscape in any number of ways to suit their needs. The changes they unknowingly or unthinkingly set in motion were in slowly changing variables with delayed feedbacks. In hindsight, of course, it is easy to criticise. And these early developers of the G-B catchment were not alone in their beliefs. All over the world this mental model was, and mostly still is, in place. It is still the prevailing paradigm, and it is underlain by four flawed assumptions:

1. A focus on average conditions (rather than extreme events), fixed (and short) time frames and fixed spatial scales (rather than multiple nested scales)

2. A belief that problems from different sectors in these systems do not interact, when in fact interacting sectors are a key feature of their dynamics

3. An expectation that change will be incremental and linear, when it is frequently non-linear and often lurching

4. An assumption that getting the system into, and then keeping it in, some particular state will maximise yield (broadly speaking) from the resource base, indefinitely. There is, however, no sustainable "optimal" state of an ecosystem, a social system, or the world. It is an unattainable goal.

The fallacy of the ruling paradigm becomes evident if, instead of addressing problems individually (the second flaw), these regions are considered as the feedback-dominated, interlinked systems of people and nature that they are. The uncertainties inherent in the dynamics of these systems and in their future environments preclude deterministic policies and call for more adaptive approaches. A major problem to overcome in the mindset of the policy-makers and managers involved is the problem of partial solutions. Partial solutions to problems in complex social-ecological systems do not work for very long.

This paper explores an approach to interpreting and analysing social-ecological systems that can provide a basis for sustainable development planning and policy, and as such it is in two parts. The first offers an alternative approach to natural resource policy and management—a resilience approach. A change towards such thinking is beginning, tentatively, in some places. But it has a long way to go to reach the paradigm shift status that is required. The second part of the paper addresses the question: "How can we know if the path we are on is sustainable?" Without knowing this we cannot know if proposed changes being made are in fact achieving sustainability. What, precisely, is the goal—just what is it we are trying to sustain? This part of the paper therefore deals with approaches to assessing sustainable development, and arrives at an integrative measure that incorporates changes in the resilience of critical system components.

2 An Alternative Approach: Resilience Management and Governance

In contrast to the command-and-control paradigm is an adaptive governance and management approach that includes uncertainty and disturbances. It aims to understand and manage the resilience of coupled social-ecological systems (SESs). The real threats in almost all regions are increasing likelihoods of dramatic regime shifts through declines in resilience of their ecological and social systems. Erosion of resilience results in increasing vulnerability to external shocks, such that it takes progressively smaller amounts of disturbance to push the system across a threshold into an alternate regime, with concomitant social, economic and ecological costs. For simplicity, in what follows it is taken that the system is currently in a desired regime. In many places it has already shifted into an undesirable one, and the problem is reversed—trying to reduce resilience to shift the system into a better regime. Resilience can be lost unwittingly. A focus on increased efficiencies of production and elimination of apparent redundancy, for example, can lead to loss of resilience. "Apparent" redundancy has been shown, in both ecosystems (e.g., Elmqvist et al., 2003) and management institutions (Ostrom et al., 1990), to provide the functional response diversity required to cope with changes in external conditions.

2.1 A Resilience Perspective

The essential feature of a SES is that the region concerned has a defined pattern of resource use around which humans have organised themselves in a defined social structure (resource management and consumption patterns and associated norms and rules). The aim of resilience management is to keep the system within a configuration of states (a regime of the system) that will continue to deliver at least existing levels of ecosystem goods and services, and to prevent it from moving into undesirable configurations (delivering fewer goods and services) from which it is either difficult or impossible to recover.

A basic tenet of a resilience approach is that SESs are essentially non-linear in their dynamics and are self-organising, conforming to the behaviour of complex adaptive systems (Levin, 1998). If there is no possibility of regime shifts and non-returnable thresholds (c.f. Scheffer and Carpenter, 2003) there is no fundamental problem in resource management or governance, because the system is always smoothly reversible within current technology and resource constraints. The system has only one regime, containing all states of the system. If a mistake is made, or the stakeholders change their minds (values), there is no fundamental difficulty in moving to another state of the system. In non-linear systems, however, the likelihood of alternate system regimes, with thresholds between them, is high. A shift (intended or unintended) from one to the other can be irreversible or very hard to reverse. Resilience management therefore places a clear emphasis on identifying alternate regimes and the capacity to avoid or change the thresholds between them.

Before examining the notion of resilience in more detail it is useful to first consider the overall patterns of SES dynamics, within which resilience plays a role; we need to have in mind the kinds of cycles and patterns of dynamics systems exhibit through time, and we need to be aware of the importance of the multiple scales across which systems function.

2.2 Adaptive Cycles and Cross-scale Effects

Based on observations of many different kinds of systems, a useful interpretation of the complex dynamics of SESs is that they tend to follow a series of a cycles, known as adaptive cycles, that pass through four phases (Gunderson and Holling, 2002). Two of them—a growth phase merging into a conservation phase—comprise a slow, cumulative period during which the dynamics of the system are reasonably predictable (referred to as the "foreloop" of the cycle). As the conservation phase continues, resources become increasingly locked up and the system becomes progressively less flexible and adaptive to external shocks. It is eventually, inevitably, followed by a chaotic collapse and release phase that rapidly gives way to a phase of reorganization, generally also relatively fast and during which innovation and new opportunities are possible. The release and reorganization phases together comprise an unpredictable, relatively fast period, termed the "backloop". The reorganization phase leads into a subsequent growth phase of a new adaptive cycle, which may resemble the previous growth phase or be significantly different.

The adaptive cycle is a metaphor of system dynamics through time, based on observed system changes, and it does not imply fixed, regular cycling. Observations show that systems can move back from conservation toward growth, or from growth directly into release, or back from reorganization to release (see Gunderson and Holling, 2002).

Finally, importantly, these systems function across a hierarchy of scales (O'Neill et al., 1986), and there is a corresponding hierarchy of adaptive cycles such that SESs exist as "panarchies"—adaptive cycles interacting across multiple scales (Gunderson and Holling, 2002). These cross-scale effects are of great significance in the dynamics of SESs.

As they move through the phases of an adaptive cycle, the dynamics of these social-ecological systems—the trajectories they actually follow out of the many possible trajectories that they could have followed—are determined by three key properties—resilience, adaptability and transformability (Walker et al., 2004). Considered collectively, and applied to the analysis of SESs, these three attributes constitute a resilience approach to governance and management. Each is dealt with in turn, but it is worth noting at the start an important distinction between resilience and adaptability, on the one hand, and transformability on the other. Resilience and adaptability have to do with the dynamics of a particular system; the dynamics of alternate regimes of the same system. Transformability refers to fundamentally altering the nature of a system so that it becomes a different system.

2.3 Resilience, Adaptability and Transformability

A conceptual basis for a resilience approach represents the dynamics of a SES in terms of a stability landscape, as described in Walker et al. (2004), with one or more basins of attraction. A "basin of attraction" is a set (a configuration, a regime) of system states within which a system tends to remain due to its own internal dynamics. It consists of all the starting points in the system's state space that lead to a common attractor. Some of these system regimes are desirable from a human perspective and others are undesirable, depending on the flows of goods and services. And of course the same basin may be deemed desirable and undesirable by different stakeholder groups.

The topology of the stability landscape is dynamic; the positions of the attractors get moved around, and the various basins of attraction get smaller and larger, or appear and disappear, as biophysical and social attributes of the system change (Scheffer et al., 2001). These drivers of changing topology (that, as we will see, determine the resilience of the system) can be either external—environmental, political, etc.—or internal; and the internal changes are to a significant extent a consequence of the phase of the adaptive cycle the system is in. For example, shrinking basins of attraction are characterisitc of late conservation phase systems.

2.3.1 Resilience

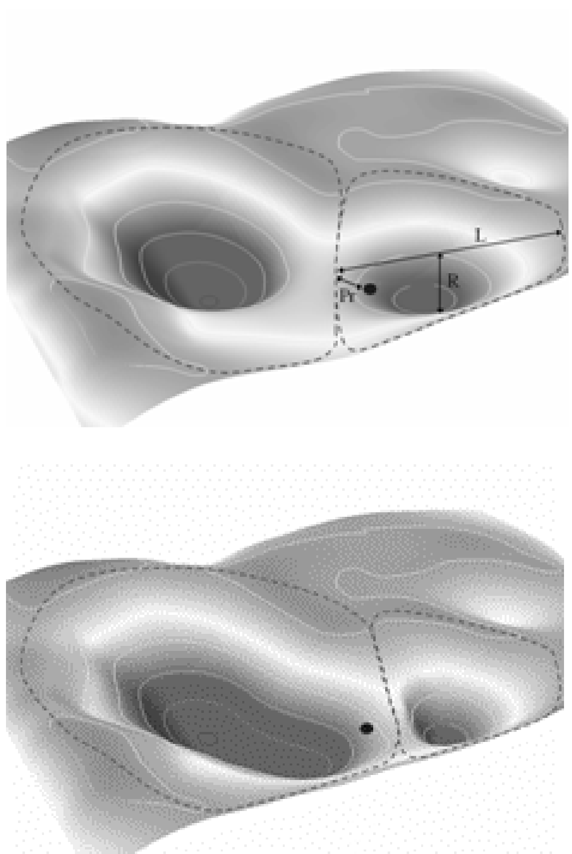
Resilience is formally defined (Walker et al., 2004) as the capacity of a system to absorb disturbance and to reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks—in other words, stay in the same basin of attraction.

We can think of resilience as a measure of the topology of such basins and the first aim is to identify the axes (dimensions) of the stability landscape that reflect changes in key variables of concern in the SES. With the dimensions agreed and defined, the aim is then to identify the attributes of the system that determine the sizes and shapes of the basins and the capacity to influence the trajectory of the system in the stability landscape.

Resilience analysis is about understanding which basin the system is in, where in that basin it is (in relation to the basin's boundaries), how to navigate (either to avoid going into an undesirable basin or to get from an undesirable to a desirable one) and how to alter the stability landscape to make such navigation easier or more difficult. It is also about understanding how exogenous drivers (rainfall, exchange rates) and endogenous processes (plant succession, predator-prey cycles, management practices) lead to changes in the stability landscape.

Figure 1, from Walker et al. (2004), is a representation of the four aspects of resilience that arise from this interpretation.

Latitude (L—the width of the basin) is the maximum amount a system can be changed before losing its ability to recover (before crossing a threshold



A)

B)

Figure 1: Stability landscapes and attributes of resilience (From Walker et al., 2004) A) Three-dimensional stability landscape with two basins of attraction showing, in one basin, the current position of the system and three aspects of resilience, L = latitude, R = resistance, Pr = precariousness. B) Changes in the stability landscape have resulted in a contraction of the basin the system was in and an expansion of the alternate basin. Without itself changing, the system has changed basins.

which, if breached, makes recovery difficult or impossible). Wide basins mean a greater number of system states can be experienced without crossing a threshold.

Resistance (R—depth of basin) is (literally) the resistance of the system to pressure or disturbance—the ease or difficulty of changing the system; how resistant it is to being changed. Deep basins of attraction (R, or more accurately, higher ratios of R:L) indicate that greater forces or perturbations are required to change the current state of the system away from the attractor. Resistance is related to the "speed of return" definition of resilience (e.g., Pimm, 1984).

Precariousness (Pr) is the current position and trajectory of the system in the basin relative to the edge; how close it is to a limit or "threshold".

Panarchy (Pa) the fourth aspect, represents the influence from scales above and below; how the first three attributes are influenced by the states and dynamics of the (sub)systems at scales above and below the scale of interest.

Thresholds between system regimes result from (and are marked by) a change in feedbacks in the system. The changed feedbacks lead to differences in function and therefore structure, and the system tends towards a different equilibrium (attractor).

2.3.2 Adaptability

Adaptability is the capacity of actors in a system to manage resilience. A characteristic feature of complex adaptive systems is self-organization without intent (Levin, 1998), and although the dynamics of SESs are dominated by individual human actors (or collective action by groups) who do exhibit intent, the system as a whole does not (as in the case of a market). Nevertheless, because human actions dominate in SESs, adaptability of the system is mainly a function of the social component—the collective capacity of individuals and groups acting to manage the system. Their actions influence resilience, either intentionally or unintentionally. Their collective capacity to manage resilience, intentionally, determines whether they can successfully avoid crossing into an undesirable system regime, or cross back into a desirable one. (Note that, being internal to the system, the changes actors induce can feed back to changes in their values and actions).

There are four ways actors can influence resilience, corresponding to the four aspects of resilience. They can move thresholds away from or closer to the current state of the system (by altering (L) above), move the current state of the system away from or closer to the threshold (altering Pr), or make the threshold more difficult or easier to reach (altering R). In addition, actors can manage cross-scale interactions to avoid or generate loss of resilience at the largest and most socially catastrophic scales (altering Pa). Note that SESs can move from one basin of attraction to another either by the system crossing a threshold, or by a threshold moving across the system (Figure 1).

2.3.3 Transformability

When a society finds itself trapped in an undesirable basin that is so wide and deep that movement to a new basin or reconfiguration of the existing basin is beyond its ability, the only option may be to configure an entirely new stability landscape—one defined by new state variables, or the old state variables supplemented by new ones. Transformability is the capacity to create such a new stability landscape—the capacity to create untried beginnings from which to evolve a new way of living. It is therefore defined as the capacity to create a fundamentally new system when ecological, economic, or social conditions make the existing system untenable. It means introducing new components and new ways of making a living, and often a change in the scales that define the system. New variables can either be introduced or allowed to emerge.

There are many examples of SESs becoming locked in and unable to transform until it is too late (salinized agricultural systems; dams, floodplains and flood control; forest fire suppression at ever larger scales). How can society develop transformability and avoid such lock-ins?

Tensions may occur between maintaining the resilience of a desired current configuration in the face of known (and some unknown) shocks, and simultaneously building a capacity for transformability, should it be needed. How can we foster or maintain the flexibility that will be required to cope with unforeseen challenges? This is a new field and little is known about the attributes required for transformability, but they will likely emphasize novelty, diversity and organization in human capital—diversity of functional types (kinds of education, expertise, and occupations); trust, strengths, and variety in institutions; speeds and kinds of cross-scale communication. These all fall within the remit of adaptive governance, a good account of which is given in Dietz et al. (2003).

2.4 Resilience, Adaptability and Transformability in managed SESs

In evolved systems that have been subjected to strong selection pressures for millennia (like mammalian bodies), the three aspects of resilience (L, R and Pr) have co-developed and are strongly inter-related, with strong feedbacks preventing threshold crossings. For example, the equilibrium temperature of humans in the "alive" regime is perilously close to a threshold temperature marking a shift into the "dead" regime. The reason has to do with the fact that our bodies perform better at this higher temperature than at a safer, somewhat lower one; and more than ten million years of heterotherm evolutionary selection have ensured the existence of strong feedback processes that prevent us crossing the threshold.

Recently developed SESs, (managed fisheries, virtually all agro-ecosystems, for example), have very short co-evolutionary histories. We cannot, therefore, rely on long-selected relationships with appropriate strong feedback controls, and the likelihood of crossing thresholds, as we edge towards them in quests for higher performance and increased efficiencies in production, is high. Witness the many examples of collapsed fisheries and salinized or otherwsie degraded agricultural regions. Various kinds of interventions will be required to manage the different apsects of resilience (L, Pr and R). Some will affect only one attribute, others will affect more than one. Changing the diversity of species in an ecosystem, for example, will alter both L and R. And the appropriate interventions for influencing L, Pr and R will depend on Pa—the influence of the relative adaptive cycle phases of the focal scale system and scales above and below. Therefore, while substantive qualitative assessments can probably be made of each of them, attempting to make such separate estimates is not advocated. In assessing resilience, however, ensuring that each is considered, and then considering them collectively, will ensure a more complete and better focused assessment than would be achieved without such a consideration.

All of the foregoing emphasises the importance of uncertainty, disturbance, feedback interactions and unpredictability in SES dynamics. A resilience approach to planning and management maximises the chances of avoiding serious declines in the system. But even if it is adopted, given the multiple ways in which resources are being used, and the many changes in them through new developments, it is virtually impossible to be sure that, overall, things will not get worse. We need some way of knowing this; knowing whether indeed the system has avoided shifts into regimes delivering less than before. In the face of this high uncertainty and multiple feedbacks we need a way to assess whether current levels and patterns of using resources in a SES are sustainable—can the desired flows of goods and services be maintained? Or, considering an SES over some defined past period, did the pattern of resource use during that period result in unwanted and unacceptable changes in the capacity of the system to deliver goods and services? We need a way to measure whether or not the development path of a SES is sustainable in terms of at least maintaining social welfare in the long term. Hence the second part of this paper.

3 Measuring and Modelling Sustainable Development

To complement a resilience based policy to resource governance and management, what is the best way to measure progress?

How can we know if the path we are on is sustainable? Can the current resource allocation continue without leading to a decline in human wellbeing?

How can we know which of two paths (options) is the best in terms of longterm human wellbeing?

How can we know if, on balance, a particular development option is "worth it", i.e., will it lead to an increase in long term human wellbeing?

These questions have driven the development of a measurement and modelling approach that is still under trial, but reported on in what follows.

At the start, three important points need to be made:

Partial measures (ie multiple independent indicators), like partial management solutions, are inadequate. The measurement of sustainable development is bedeviled by such partial and inevitably incomplete lists of indicators. Because GDP, NNP and GNP are single indicators, never intended as overall measures of sustainability or human wellbeing, governments augment them with other measures. However, these other measures were developed independently and do not contribute to an integrated assessment that allows for evaluation of the inevitable tradeoffs between resources (human, natural or manufactured).

Indicators like the Genuine Progress Indicator (Hamilton, 1998) are interesting in themselves but are of limited use in policy or management. They do not indicate the interrelationships amongst the different measures, and they cannot say what will happen to all the other measures if one of them goes (or is made to go) up or down.

The major drawback of most environmental sustainability indices is that they do not adequately address the economic or ecological significance of a change in the indices concerned. How much change is enough or too much? What are the economic, environmental and social implications of a change? Nor are substitution possibilities between different components made explicit. The imperative for policy makers is to explicitly show tradeoffs and for this they need an inclusive, integrated measure of change.

An integrated measure is sometimes misunderstood as being some kind of black box number that hides all the component measures (indicators) that contribute to it. Quite the contrary; the whole point about an integrated measure is that enables the user to see just how and why the overall index has changed as a result of changes in the components. It therefore allows sensitivity analyses of the overall index, explicitly addressing how trade-offs between different components have affetced (or, if used in an investigative mode, will affect) the overall outcome.

Sustainability of what, and for whom? Any attempt to measure sustainability has to deal with values. It has to deal with assessing the value of future benefit streams from the capital stocks that produce them. Without assessing this value we cannot compare alternative resource allocations. If current levels and patterns of use are leading to lowered social welfare (i.e., are not sustainable), unless we know the relative values of the various flows of goods and services flowing from the different resource uses, we cannot determine the extent of changes needed to make it sustainable. Furthermore, the conditions of social welfare used to judge sustainability will differ across sectors of society. In Australia, what is considered crucial to wellbeing for an Aboriginal living in remote savanna country is very different to what is crucial to an IT professional in central Sydney, or a farmer in the Murray-Darling Basin. What is considered to be a decline in social welfare by one sector may be considered as just fine by another.

Current values of capital stocks depend on a forecast of the future. The assessed value of a country's livestock is made under the expectation that the world will continue to demand meat. If we knew the world population was to become vegan in a year's time, the value of the livestock would drop dramatically. The value of every capital asset depends on some implicit or explicit forecast of the future.

Assessing sustainability, therefore, inevitably involves, whether recognised or not, a forecast of the future and a value assessment of what is being—or not being—sustained. When it comes to presenting an integrated assessment of sustainability this leads to a requirement to always present more than one estimate; it is of little value, and in fact misleading, to present a single, integrated estimate of sustainability. At the very least it is necessary to bracket the range of futures (scenarios) with at least two explicit (and plausible) forecasts. And the differences between sectors of society in terms of their different valuations of goods and services from capital assets also needs to be made clear. So for each forecast the values of resource allocation need to be assessed based on at least two different social welfare functions, encompassing the range in the society. If all assessments indicate that the system is on a sustainable development trajectory, there is no problem. If all assessments indicate the contrary, radical change is needed. Where some do and some do not indicate sustainability, the differences will point to what needs attention to resolve the differences.

3.1 Inclusive Wealth as an integrated measure of sustainable development

With these points in mind we can address what kind of integrated measure will best meet the needs. The progression, in economics, from GDP through "green" GDP, to the Genuine Savings estimate (Hamilton and Clemens, 1999) points the way. An extension of Genuine Savings, that seems to achieve what is needed, is the measure of Inclusive Wealth (IW), as described by (Arrow et al., 2003, —hereafter referred to as ADM).

IW is a measure that captures social welfare (in an inter-temporal sense) by measuring a society's total asset base, valued at shadow prices. (Note that a shadow price is the real value to society as a whole of having one more unit (or one unit less) of an asset). IW allows for substitution between individual assets over time (for some to be built up as others are drawn down), while at the same time incorporating adjustments for risk. As a sustainability measure it therefore lies somewhere in-between "strong" and "weak" sustainability. It recognises the inevitability of (and need for) inter-capital conversions; without those societies could not have developed and could not exist under strict strong sustainability criteria. The IW measure also recognises that there are limits to how much various capital components (especially natural capital) can be used or changed—i.e., it recognises that some components are non-substitutable, and it recognises resilience and risk. As a national measure, IW is designed to sustain the asset base of society as a whole because it is an appropriately aggregated measure.

Social welfare is the present value aggregate of all humans' well being, current and future (including happiness, health, etc). There is no direct way of measuring it, but an equivalent is to measure the amounts and value' of all the capital stocks (human, manufactured and natural) that underpin welfare. A stocks approach is in line with the resilience approach to policy and management, in that it deals with the states of the system and their potential for producing flows, rather than the fluctuating flows themselves.

The sum of the capital stocks, appropriately weighted by their values in terms of contributing to social welfare (their shadow prices), is a measure of a country's (or a region's) inclusive wealth. Therefore, a country is achieving sustainable development if its inclusive wealth is non-declining over time. A brief account of the theory, based on ADM, is given in Appendix 1. Before we can discuss how Inclusive Wealth might be assessed we need to consider how it is influenced by the resilience of the systems involved—an aspect not directly included in the ADM framework.

3.2 Risk, resilience and inclusive wealth

If the risk of natural capital declining in the future increases, even though current natural capital itself may not be exhibiting any changes, the relative value of the stock has decreased, and therefore wealth has declined. This is an important and under-estimated aspect of sustainable development and it is illustrated by the example from the Goulburn-Broken catchment, describer earlier. When water tables there were below 10m the system had great resilience to wet periods, but as they approach 2m the resilience declines—it takes a smaller and smaller wet period to push the system across the threshold, and the risk of a salinised landscape therefore increases significantly. Though the land still produces the same flows of crops when the water table is 3m below the surface, as it did when the water table was 10m below, it is not as valuable.

In discussing the problems facing the development of an Environmental Sustainability Index, the World Economic Forum's Global Leaders for Tomorrow Environment Task Force (Anonymous, 2001) concludes that "...because sustainability relates both to the distance a society is from critical pollution or resource consumption thresholds and how fast these thresholds are being approached, the concept of sustainability has proven hard to translate into clear signals for policymakers".

It is therefore necessary to include an explicit method for incorporating risk—in terms of changes in resilience—into the IW measure. The method proposed in a joint study of the Stockholm Municipal region and the Goulburn-Broken (G-B) Catchment in SE Australia is given as an example.

In this study we propose to assess resilience as a parallel stock (KRi) for each capital stock (Ki), and assess its accounting price (KRpi). Adding $[(KRi).(KRpi)]$

to the stock assessment (see Appendix 1) raises IW when marginal change in resilience is positive, and decreases it when resilience has declined.

To get the necessary estimates for the capital stocks, the process will involve assessing three aspects:

- the likelihood that a threshold exists; and if there is,
- the probability of crossing the threshold (how close is it, and what is the trend of the system),
- the consequences of crossing the threshold.

The first two will provide the estimate of the resilience stock', and the consequences of crossing the threshold will form the basis of the shadow price of the resilience.

3.3 Implementing the IW approach

The IW assessment in the G-B study involves a number of steps, briefly summarised below:

- Identifying a) key regional outputs; the key goods and services (the sustainability "of what"), and b) scenarios. This is done in conjunction with the region's stakeholders. The scenarios help to determine the key goods and services and, considered as forecasts, are necessary for valuing the stocks;
- Conceptualising production systems to identify the capital stock inputs to each of the key outputs. This involves quantifying the stocks, and estimating their resilience (as outlined above);
- Valuation of the stocks—assigning shadow prices to the stocks (see later, under Discussion);
- Estimating Inclusive Wealth. The values of a stock for each flow need to be aggregated to form a single stock value. IW is then a linear summation of the various human capital, manufactured (built) capital and natural capital stock amounts weighted by their shadow prices. As an illustration, Table 1 shows a reduced version of the process for the G-B Catchment;
- Developing a model that can provide the several estimates of inclusive wealth that are needed based on different forecasts of the future and reflecting different societal values. The model also allows assessment of the consequences of alternative patterns of resource allocation on each estimate of IW. Could we have done better, with a different pattern of resource use? Finally, it also allows for sensitivity analyses of stock and shadow price estimates.

Capital stocks

Production flows	Natural		Human		Built	
	Native vegetation	Converted land	Skills	Labour	Roads	Irrigation canals
Dairy prodn.	X	X	X	X	X	X
Horticulture. prodn	X	X	X	X		X
Crop & grazing	X	X	X	X		
Forestry	X		X	X	X	
Nature conservation	X		X		X	
...	X		X	X	X	X
overall	AP1Q1	AP2Q2	AP3Q3	AP4Q4	AP5Q5	AP6Q6

Table 1: The production system "model" for assessing critical stocks, using a reduced example of the matrix of capital stock inputs to the set of regionally important production flows in the Goulburn-Broken catchment, Australia. The values are the products of the accounting (shadow) price (AP) and the quantity (Q) of each stock in the "production" of each flow.

4 Discussion

This paper has addressed the two most pressing issues confronting the achievement of sustainable development:

- getting an understanding of resilience into policy arenas and replacing the mindset of command-and-control partial solutions, with a resilience management and governance approach,
- developing an integrated assessment model of sustainability that includes risk, through assessment of resilience, along the lines of the Inclusive Wealth approach.

Making these two approaches operational is the big challenge, and I conclude with a brief discussion of what I see as the main hurdles.

4.1 Resilience

Resilience theory and practice has come a long way since C.S. Holling's 1973 paper, and there is a growing use of the concept in many different parts of the world. A survey of papers in just one journal, "Ecology & Society", is evidence of this. The required next big steps are twofold:

1. In systems with a single, dominant threshold and associated regime shift (e.g., shallow lakes, Carpenter, 2003) both the theory and application

are clear. But in more complex social-ecological systems where two, three or even more possible regime shifts can occur, at different scales and in different domains (ecological, social, economic), we have yet to develop a comprehensive theoretical basis for their interactive effects, or the best way to include them in developing a program for resilience analysis and management. The significance of this is nicely illustrated by the conceptual model of Fernandez et al. (2002) for a number of different semi-arid regions. In each case the simultaneous existence of a biophysical threshold (along a gradient such as grass cover) and a social threshold (along a gradient such as the debt to income ratio) leads to complex dynamics that can result in a degradation or desertification "trap". Based on comparison of a number of case studies within the Resilience Alliance, work is underway to develop an approach to understanding and analysing such threshold interactions, and some results will appear in a forthcoming special edition of "Ecology & Society".

2. Related to the multiple regime shift problem is the issue of specified (or targeted) resilience, versus general resilience. In an earlier paper (Carpenter et al., 2001) we addressed the problem of resilience "of what" "to what". A moment's thought makes it clear that to operationalise resilience for a particular system we need to know just what it is that we wish to make resilient, and to what sorts of shocks. In the Goulburn-Broken catchment, with its salinity problem, we want to make the agricultural production potential of the soil resilient in the face of wet periods. In the lakes example (Carpenter et al., 2001), the intention is to make the clear water regime (no algal blooms) resilient to fluctuating amounts of external inflows of phosphate. It seems obvious. But a problem arises; making one part of a system very resilient to one set of external shocks can lower the resilience of some other part of the system to a different set of shocks. It is analogous to the HOT (highly optimised tolerance) model of Doyle and Carlson (2000), which claims that systems evolve to be both robust and fragile. The basic idea is that systems respond to the most frequent kinds of disturbances they experience and hence become very resilient (robust) to them, but (since they seldom encounter them) they do not self-organise in ways to make them resilient to very infrequent disturbances, and hence are very fragile in that regard. Deliberately increasing the resilience of one part of a system to one set of shocks will lower its resilience in other ways.

The challenge we face is to incorporate both specified and general resilience into a resilience analysis and management program. Resilience has a cost. Building adaptability may involve some duplication (maintaining redundancy, reducing efficiency, and so forth). If we can identify the consequences and likelihood (i.e., the risk) of a known regime shift then we can determine how much it is worth investing in resilience—or at least we can assess the likely consequences of not investing in it. So it is easier to include the specified resilience, the regime shifts that we know about or suspect and want to avoid. But it is much harder to justify maintaining general resilience—preventing erosion of diversity, increasing tightness of feedbacks, maintaining or increasing modularity in the system—in the face of pressures (in efforts to increase profits) to do the reverse.

A full discussion of this topic is not appropriate here, but a hind-sight comment illustrates the point: Following the recent tsunami tragedy in SE Asia, several separate reports indicated that damage and loss of life were much less (resilience was higher) where shorelines remained vegetated with broad bands of mangroves. In the absence of a formal analysis of this episode I quote a commentary from a United Press International report in The Washington Times, Jan 10 2005: "If only the mangroves were intact, the damage from the tsunami would have been greatly minimized. Ecologists tell us that mangroves provide double protection—the first layer of red mangroves with their flexible branches and tangled roots hanging in the coastal waters absorb the first shock waves. The second layer of tall black mangroves then operates like a wall withstanding much of the sea's fury." The economics of the costs of maintaining mangroves (foregone profits to tourism and prawn farming) vs. the infrequent massive cost of a tsunami would make an interesting study. But that's not the point. That becomes specified resilience again. What about the next unexpected and perhaps novel shock, to different parts of those regions? What are the attributes that would most increase their general resilience (including resilience to tsunamis)? And how can we assess the appropriate levels of investment in general resilience? For now, the tsunami example merely illustrates the need for work on how to incorporate both specified and general resilience into a resilience analysis and management approach.

4.2 Integrated Assessment through Inclusive Wealth

Several questions confront the implementation of inclusive wealth as a measure of sustainable development. Issues of appropriate scale (national to local regions) raise problems from trans-boundary movements of capital; the development of a production systems approach for determining critical capital stocks needs more work; we have yet to trial the incorporation of resilience estimates. The most important issue, however, is the estimation of shadow prices. Part of our present work is the development of a modelling framework that will enable calculation of IW values based on two input data sets; i) levels of critical capital stocks, at different times, and ii) sets of shadow prices, where each set of shadow prices corresponds to a particular combination of a future forecast and a sector composition of society. By definition, a shadow price is the value to society as a whole of a marginal change in an asset. If the society was comprised mainly of farmers, or of IT specialists, the shadow prices would be different. The success of the whole approach relies on being able to derive credible shadow prices, and we need to explore how best to incorporate the considerations above into IW estimates in a way that they will help inform resource allocation policies.

The shadow price assigned to each of the stock classes should reflect the net present value of all the identified regional flows from that stock. Four current techniques are used to estimate shadow prices:

- market prices (for stocks that are readily traded in an open market, e.g., cows in a dairy production flow);
- adjusted market prices (for stocks traded in a limited market, e.g., land in horticulture);
- econometric production functions (for stocks included in a primarily marketed production function, e.g., water in agricultural production);
- use of information from elsewhere (ie. benefit transfer for stocks that have no market characteristics, e.g., native vegetation in a particular area, using a value from somewhere else where it has been marketed).

The combination of these techniques may not be sufficient for the task at hand, and being able to derive credible shadow prices is a research area that is of high priority, for economists and ecologists together. This does not only apply to assessing Incusive Wealth. To repeat an earlier statement—any attempt to measure sustainability has to deal with assessing the value of future benefit streams from the capital stocks that produce them.

A Appendix 1

Derivation of Inclusive Wealth (as a measure of sustainable development), based on Arrow et al. (2003).

Since sustainable development is non-declining social welfare, a social welfare function (W) is defined by a single consumption good C in a utility function ($U(C)$) which is strictly concave and monotonically increasing, and with a positive discount rate ($\delta > 0$)

$$W_t = \int_t^{\infty} U(C_t) e^{\delta(t-1)} d\tau \tag{1}$$

ADM use a general “resource allocation mechanism” (α) which forecasts consumption flows C and their associated shadow prices (see below). They define $\{C_t, R_t, K_t\}_t^{\infty}$ as an economic programme from time t to infinity, where R is a vector of resource flows and K is a vector comprising a comprehensive list of capital stocks (human, natural and built).

The mechanism α is presumed to be autonomous, so that economic variables at date $\tau(\geq t)$ are functions of K_t and $(\tau - t)$ only. We can then express social welfare as a function of the initial capital stocks and the resource allocation mechanism;

$$W_t \equiv V(K_t, \alpha, t) \tag{2}$$

represented using the shorthand $V(K_t, \alpha, t) = V_t$. This means that now, instead of having to measure welfare in terms of future consumption (through utility), there is an equivalent in the form of initial capital stocks. However, an important aspect is that it is the value of current capital stocks, where value (the shadow price) is determined by the quality and quantity of the stock, based on forecasts of future resource use. For many reasons, market prices are unlikely to equate to these shadow prices (e.g., no markets for some capital stocks, others do not include forward looking values, etc.) so a crucial part of an inclusive wealth approach is to estimate prices which account for the real social values of the capital stocks, including their future values and uses.

Given the value function V, derivation of the shadow prices (in theory) is straightforward. Assuming V is differentiable in K, and K_i is the i^{th} capital stock, we can define the shadow price of a capital stock as

$$P_{it} = \frac{\delta V(K_t, \alpha, t)}{\delta K_{it}} \equiv \frac{\delta V_t}{\delta K_{it}} \tag{3}$$

Shadow prices are defined in terms of a hypothetical perturbation to an economic forecast. Specifically the accounting price of a capital asset is the *present discounted value of the perturbation to U that would arise from a marginal change in the quantity of the asset.* For changes to capital stocks (Ki) and utility (U) occurring at some later date, the change in utility is discounted back to the net present value (described in equation 1) changing the social welfare function (W). This change in welfare, resulting from changes in capital stocks, is represented in the shadow prices (p_i),

$$P_{it} = \frac{\delta W_t}{\delta K_{it}} \tag{4}$$

The challenge in using the IW framework is that deep and detailed knowledge of patterns of resource allocation, of possibilities for technical substitution, and particularly of complex ecological processes, is required in order to make plausible forecasts of future paths of consumption and resource use and hence an assessment of the sustainability or otherwise of its development.

To determine (using IW) if sustainable development has occurred, welfare needs to be assessed at two points in time, and it can be measured by the change in the value of capital assets, without the capital gains on the assets that have accrued over the period (Equation 5). Any big changes in capital stocks that have induced significant changes in their shadow prices (induced rarity, for example, would be taken into account in this way). Full details are given in ADM.

$$V_t - V_o = \sum_i \Big[p_{it} K_{it} - p_{io} K_{io} \Big] - \int_o^\tau \Big[\sum_i (dp_{it}/d\tau) K_{it} \Big] d\tau \tag{5}$$

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