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Incorporating Resilience in the assessment of Inclusive Wealth: An example from South East Australia

for *Beijer Discussion Paper Series*

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Abstract

This paper explores the consequences of changes in a system's resilience on the sustainability of resource allocation decisions, as measured by Inclusive Wealth (IW) (Arrow et al, 2003). We incorporate an estimate of resilience in IW by taking account of known or suspected thresholds that can lead to irreversible (or practically irreversible) changes in the productivity and value of assets and hence social welfare. These thresholds allow us to identify policies or projects that may be leading to an increased risk of decline in capital stocks (the wealth of the region). Such risks are not reflected through usual measures of current system performance (e.g. agricultural production). We use the Goulburn-Broken Catchment in south-eastern Australia as a case study to explore the significance and practicality of including resilience in inclusive wealth estimates.

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1. Introduction

Of the many challenges in assessing whether or not a country or region is embarked on a sustainable development pathway, two are particularly important; i) how to develop an acceptable, integrated measure that allows the inevitable trade-offs to be evaluated, and ii) how to take into account changes in the risks that significant losses in wealth may occur. The first is addressed by using an integrated stock-based approach such as the "inclusive wealth" measure (Arrow et al 2003).

The second issue, changes in risk, has been addressed by Maler et al (2006) but not yet applied, and forms the basis for this paper. It is allied to the issue of "strong" versus "weak" sustainability. Advocates of strong sustainability claim that substitutability between capital stocks cannot be assumed and so sustainability requires no decline in any capital stock. Weak sustainability assumes linear dynamics and substitutability between stocks. The notion of ecological resilience helps bridge the difference, since it focuses attention on capital stocks that have limits to how much they can be changed without losing the ability to recover. This in turn relates to the notion of critical natural capital, and acknowledges that some decline in natural capital stocks is justified if it leads to long term increased overall human wellbeing (Ekins et al 2003). It is the risk of exceeding critical thresholds that is likely to result in a decline in long term wellbeing and we address this by including an assessment of resilience in an inclusive wealth approach.

Resilience is the capacity of a system to remain in a given configuration of system states (a system "regime") in systems where multiple regimes are possible. By definition (Holling 1773, Walker et al 2004), the more resilient a system is the larger the shock (disturbance) it can absorb without shifting into an alternate system regime. If changes along some forecast development path increase the risk of a shift from one regime to another, then sustainability analyses should take these increases in risk into account in some quantifiable way. Perrings (1998), for example, identifies two different concerns in the analysis of the environmental consequences of economic change; the concern that desirable states or processes may not be 'sustainable', balanced by the concern that individuals and societies may get 'locked-in' to undesirable states or processes. Incorporating this into empirical sustainability assessments raises the problem of "how to measure changes in state given … the lack of physical measures of relevant changes in environmental variables." (Perrings 1998, p.513).

In considering how resilience can be incorporated into an operational measure of sustainable development, we refer to the resilience of a "preferred state" of the system. A decline in resilience should therefore be reflected as a decline in wealth. If the system is already in a non-preferred state (low productivity/ low value), the reverse is true.

Some steps have been made towards including resilience in sustainability assessments. Serrão, Nepstad and Walker (1996) discuss sustainability and resilience informally in the context of the Amazonian upland ecosystems. They make reference to the idea of environmental criticality, "a state of nature in which the extent and/or rate of environmental degradation passes a threshold beyond which current human use systems or levels of social welfare may not be supported, given a society's ability to respond" (p.7). This idea of a critical threshold is central to the quantification of resilience undertaken in this paper. Trosper (2002) applies resilience thinking to the functioning of institutions, showing how institutional functioning in Northwest coast indigenous American communities (including property rights and penalties for trespass) provided resilience in managing fisheries and other resources. Norton (1995) stresses the interpretation of resilience as the value of holding options open - an interpretation that, of course, presumes it is the resilience of the *current* (preferred) state we wish to maintain.

In a more formal approach, Perrings and Walker (1997) examine optimal management of a system subject to resilience effects, their application being fire-driven rangelands. They simulate choices of optimal grazing (the management or control variable) in circumstances when fire events can result in a change in the state of the rangeland. Perrings and Stern (2000) attempt to quantify a variable they call resilience, based on the long run productive potential of the system (semi-arid rangelands), which they model in terms of carrying capacity. Their approach is econometric, generating measures of changes in resilience with parsimonious data.

The objective of this paper is to examine and demonstrate the practical incorporation of resilience as a quantifiable variable into the measurement of sustainability, using the Inclusive Wealth measure. We begin with a brief account of the capital-theoretic approach used for measuring sustainable development - the “Inclusive Wealth” (IW) measure described by Arrow et al (2003) (Section 2). Section 3 explains ecological resilience and the roles of hysteresis and irreversibility. Section 4 shows how treating resilience as another “capital stock” allows it to be measured and priced in empirical assessments of IW. Section 5 presents an example from a current sustainability assessment project in Australia to illustrate the significant impact that a change in ecological resilience can have on an estimate of IW. Finally, Section 6 outlines how resilience might be applied more broadly than in an ecological context by looking at threshold effects in other forms of capital.

2. Brief Introduction to Inclusive Wealth

Standard aggregate sustainability analyses have been flow-based, with the sustainability condition taking the form of some constraint on total consumption (see Harris and Fraser 2002). The inclusive wealth (IW) approach, as the name suggests, switches the focus from flows to stocks, and accordingly imposes a sustainability condition based on *present values* of consumption flows. It captures conventional “weak sustainability” features based on substitutability of assets, but neither assumes nor requires any assumptions of optimality or even optimising behaviour.

The key theoretical elements of the model are given in Arrow et al (2003). An aggregate inter-temporal social welfare function is defined on a vector of consumption flows (goods and services). The instantaneous utility function is assumed to have the conventional properties (monotonically increasing, strictly concave) and welfare W_t is subject to a positive and constant utility discount rate, δ.

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

From this, sustainable development is defined as non-declining welfare W_t. What this means intuitively is that the *present value* of the future utilities must be maintained over time. This allows in principle for short term declines in instantaneous consumption, though such declines must be offset by future increases sufficient to prevent declines in the present value of utility of consumption (Dasgupta and Maler, 2001).

To make this definition of sustainable development operational, an innovation of the IW approach is to avoid any assumption of optimisation by, instead, specifying a "resource allocation mechanism" (α) which predicts consumption flows *C*, given the present capital stocks and knowledge on the future functioning of the economy (including technology). Social welfare can then be expressed as a function of the initial capital stocks and the resource allocation mechanism (α);

$$W_t \equiv V(\mathbf{K}_t, \alpha, t) \tag{2}$$

Equation 2 can be represented using the shorthand $V(\mathbf{K}_t, \alpha, t) = V_t$, which means that, instead of having to measure welfare in terms of future consumption (through utility), there is an equivalent in the form of *wealth*, the value of initial capital stocks.

Value or wealth is now in principle an observable magnitude, measured by the quantity of the current stocks multiplied by their shadow prices. Assuming *V* is differentiable in **K**, and K_i is the *i*th capital stock, we can define the shadow price of the *i*th capital stock at time t as

$$p_{it} = \frac{\partial V(\mathbf{K}_t, \alpha, t)}{\partial K_{it}} \equiv \frac{\partial V_t}{\partial K_{it}} \tag{3}$$

The shadow price of a capital asset today is the *present discounted value of the perturbation to utility (U) that would arise from a marginal change in the quantity of the asset today*.
Note that an important proviso in this "inclusive" wealth model is that wealth must indeed be inclusively defined. For example, the value people put on the existence of nature conservation in some landscape needs to be included in the estimation of the shadow price of that landscape. A market price that reflects only its agricultural value is inadequate as a shadow price.

Change in welfare at a point in time is equivalent to the change in the capital stocks (valued by shadow prices)

$$dV_t / dt = \sum_i p_{it} dK_{it} / dt + \partial V_t / \partial t \tag{4}$$

The term $\partial V_t / \partial t$ represents the exogenous ("inevitable") effects of the passing of time on wealth. They are inevitable in the sense that they are not alterable by any actions taken by members of the population whose wealth is being considered. This term, variously referred to in the literature as the "value of time" or the "drift term", is zero, by definition, with an autonomous resource allocation mechanism. Estimating IW at two points in time allows for an assessment of sustainable development, based on the assumption that the resource allocation pattern over this period is sustainable if IW is non-declining (ie. $V_T - V_0 \geq 0$)

$$V_T - V_0 = \sum_i [p_{iT} K_{iT} - p_{i0} K_{i0}] - \int_0^T \left[\sum_i \frac{dp_{i\tau}}{d\tau} K_{i\tau} \right] d\tau \qquad (5)$$

The second part of the equation is the 'capital gains' term and deducts the endogenous price changes (see Arrow et al for a full explanation).

This paper focuses on the likelihood of a change in underlying variables that determine the state of a capital stock K_i, which leads to a change in the likelihood that the state of K_i itself will change, with an associated change in its value to society. If K_i does not change between two times it suggests there has been no change in IW. However, if the *risk* that K_i will change has increased this should somehow be included and reflected as a change in real wealth.

3. Resilience and vulnerability

The formal definition of resilience is the capacity of a system to undergo change while still maintaining the same structure, functions and feedbacks, and therefore identity (Walker et al 2004). This definition follows the original paper on the subject by Holling (1973), and places emphasis on the ability of a system to recover from a disturbance-induced change. We are concerned about what happens when a system exceeds its capacity for recovery.

A wide range of examples suggests that many ecological and social-ecological systems can exist in two or more "regimes" (configurations of states), separated by thresholds that occur on controlling (usually slowly changing) variables (Scheffer et al 2001, Walker and Meyers 2004). The flows of goods and services from capital stocks in the different regimes of the system can differ markedly. While the flows generated by a capital stock over time may show no change (because the state of the stock has remained within the same regime), an underlying control variable that determines the dynamics of the stock might be approaching a critical threshold. When the critical threshold level of this underlying variable is passed the structure and function of the capital stock abruptly changes (the stock moves into a new regime) with associated changes in the levels of flows. Therefore, as the threshold is approached, the risk of disruptions to the future supply of the goods and services increases.

From a sustainable development perspective it is important to know how far the system is from such critical thresholds, and how likely it is that it might cross the threshold. Using the ball-in-a-basin analogy of a system's stability properties, resilience of a system at any one scale has three components; latitude (the width of the basin), resistance (the steepness of the basin - how much force is needed to change the system) and precariousness (the current position and trajectory of the system in the basin) (Walker et al 2004). The edge of the basin marks an unstable equilibrium, a threshold, between two system regimes. A general measure of resilience is the distance from the stable equilibrium point to the unstable threshold (from the bottom of the cup to the edge) and an instantaneous measure is the distance from the current position of the system to the threshold (precariousness). We use the instantaneous measure here. This measure does not take into account the amount of force needed to change the position of the system in the basin (resistance); this is something that might be added later. For our purposes, the closer to the threshold, the lower the resilience of the stock, and the higher is the probability that the system will bifurcate, i.e. flip to the alternate state. The real value (shadow price) of the stock changes as the likelihood of crossing the threshold into the alternate regime increases. Of course, if the system already happens to be in an "inferior" regime then the reverse is true.

Relationships between the capital stocks of a system that determine welfare and the underlying controlling variables of those stocks fall into four main types (Figure 1). Most of them (fortunately) are likely to be of type (a) with no threshold effects, i.e., where changes in the underlying control variable are reflected by continuous changes in the stock. Stocks with patterns of dynamics of types (b), (c) and (d) need to be identified because they can exhibit sudden and dramatic changes. Changes in stocks of type (b) are fully reversible. In type (c) systems, when the controlling (slow) variable exceeds the critical threshold level, feedbacks in the system change and the trajectory of the system changes direction towards a new attractor (Walker and Meyers 2004). Recovery of the system to the original regime is much more difficult. Type (d) systems are an extension of (c) where the hysteretic return path intercepts the Y axis, and makes recovery impossible if change in the slow variable is the only option . The relative value of a regime change (change in shadow price) is greatest in stocks of type (d) followed by (c), then (b).

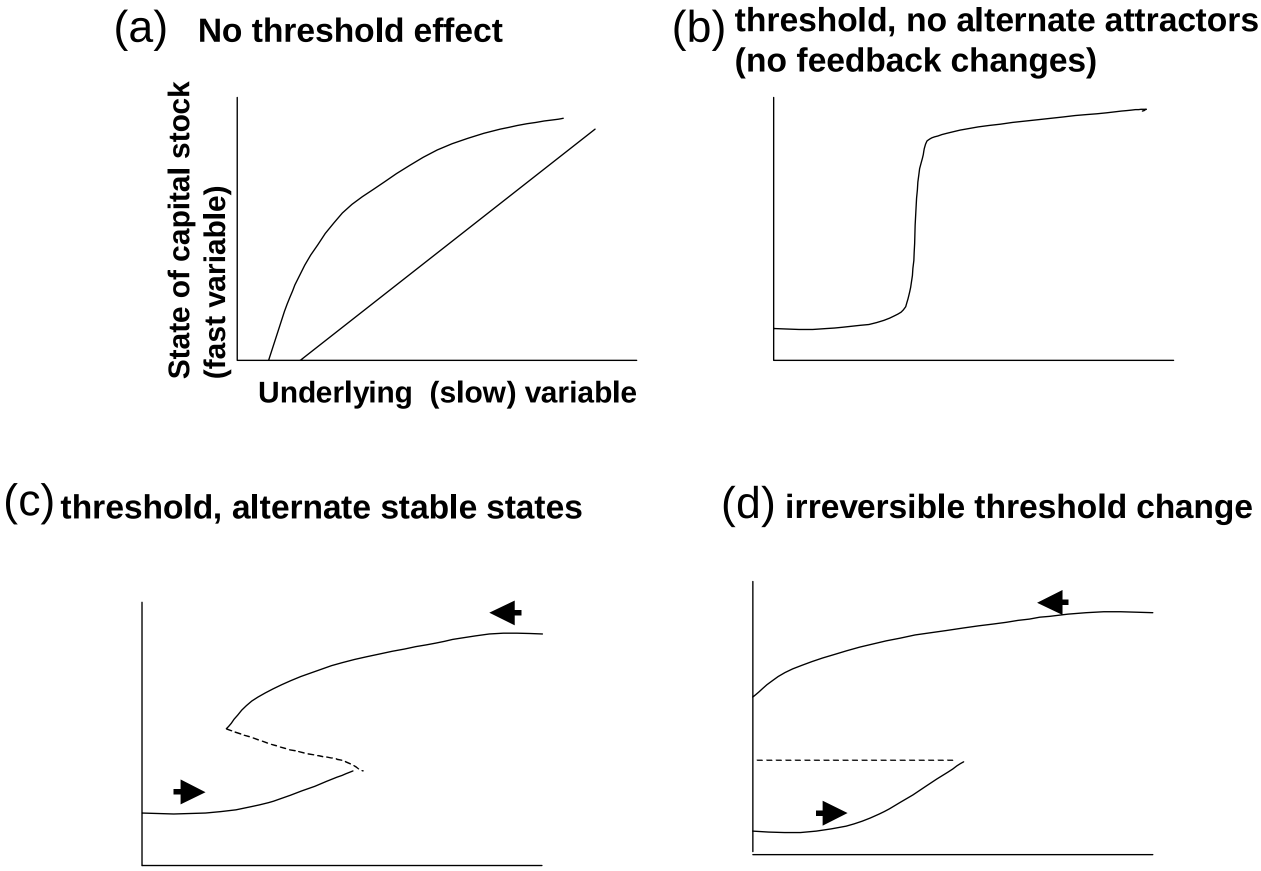

Figure 1. Relationships between the state of a capital stock and the underlying variable that determines its dynamics. In (a) there is no discontinuity and the nature (and value) of the capital stock varies continuously with a change in the underlying (often slowly changing) variable. In (b) there is a very sharp (sometimes discontinuous) change in the capital stock, but it is reversible. In (c) there is a discontinuous change that is reversible but with a hysteretic return path, and in (d) the change is irreversible. The arrows indicate the direction of change in the underlying (slow) variable.

4. Including resilience in the Inclusive Wealth Model

Inclusion of resilience in the IW model is discussed, though not resolved, by Arrow et al (2003). They use the shallow lake example (Scheffer et al 2001) to illustrate that IW (and hence Genuine Investment) can be employed in non-convex systems (ecological and economic systems) as well as convex systems, neither requiring an assumption of economic optimality. Additionally they demonstrate that it is possible to extend the IW model to an uncertain world. However, they did not address the question of determining the shadow price on resilience. On the other hand, Maler et al. (2007) have developed a general formula for such a price[1]. Such expressions are detailed below and estimates of their significance are provided in section 5.

Incorporating resilience in IW: Practical considerations

Maler et al. (2007) propose adding to the IW model a resilience stock that is a measure of how close the system is to a shift. The shadow price of the resilience stock reflects the expected change in future social welfare from a marginal change in resilience today. Estimating the price of resilience separately enables us to determine its significance in policy and management decisions and therefore how much attention it warrants. We will start with the assumption that there is only one stock of interest, namely the resilience stock. We will later introduce other stocks.

For each underlying variable that has a threshold effect resulting in a discontinuous change in the state of one or more capital stocks, we define a resilience stock *X*, equal to the current distance from the threshold. As the distance declines, so does the capital stock of resilience (*X*).

Let $F(X_0, t)$ be the cumulative probability distribution of a flip up to time t if the initial resilience is X_0. We assume that the flip is irreversible. It is quite easy to extend the analysis to the reversible case, but that is not needed for the application in this paper. In order to

[1] Maler, K.-G., Li C.-Z. and G. Destouni, Beijer Discussion Paper Series 208,

simplify formulas, let us introduce the survival function $S(X_0,t)=1-F(X_0,t)$, which gives the probability that the system has not flipped before time *t*.

Assume that $U_1(t)$ is the net benefit at time t if the system has not bifurcated at that time and let $U_2(t)$ be the net benefit if the system has bifurcated before (or at) *t*. Then one can show that expected welfare is (see Maler et al. 2007)

$$E(W(X_0))=\int_0^\infty \left[S(X_0,t)U_1(t)+F(X_0,t)U_2(t)\right]e^{-\delta t}dt \tag{6}$$

The price (*q*) of one more unit of resilience is estimated by marginally perturbing a generalised form of equation 6 by a small amount of the stock of resilience X_0, that is, the stock of resilience at time 0

$$q(0)=\frac{\partial E(W_0)}{\partial X_0}=\int_0^\infty \frac{\partial S\left(X_0,t\right)}{\partial X_0}\left[U_1(t)-U_2(t)\right]e^{-\delta t}dt \tag{7}$$

We now introduce three more stocks; capital Y that affects the probability of a bifurcation (for example the stock of pumps that are used to control the water flow), the land area sensitive to salinisation, L^{sen}, and the land area not sensitive to salinisation, L^{un}. We assume that these two areas will not change over time. The benefits in the two states in sensitive land before a flip is given by $U_1(L^{sen}, s)$ and after a flip $U_2(L^{sen},s)$). Finally, let the benefit for unsensitive land be $U_3(L^{un},s)$. It is easily seen that expected welfare is now

$$E(W)=E(W,Y,L^{sen},L^{un})=\int_{s=0}^{\infty}\left[S(X,Y,s)U_1(Y,L^{sen},s)+F(X,Y,s)U_2(Y,L^{sen},s)+U_3(L^{un},s)\right]e^{-\delta s}ds$$

The accounting prices are respectively

$$\begin{aligned}
q_X(0)&=\int_0^\infty\left[\frac{\partial S(X,Y,s)}{\partial X}U_1+\frac{\partial F(X,Y,s)}{\partial X}U_2\right]e^{-rs}ds\\
q_Y(0)&=\int_0^\infty\left[\frac{\partial S(X,Y,s)}{\partial Y}U_1+\frac{\partial F(X,Y,s)}{\partial Y}U_2\right]e^{-rs}ds\\
q_{L^{sen}}(0)&=\int_0^\infty\left[S(X,Y,s)\frac{\partial U_1}{\partial L^{sen}}+F(X,Y,s)\frac{\partial U_2}{\partial L^{sen}}\right]e^{-rs}ds\\
q_{L^{un}}(0)&=\int_0^\infty\frac{\partial U_3}{\partial L^{un}}e^{-rs}ds
\end{aligned} \tag{8}$$

As long as the area of the two types of land does not change during the period under study, the two last shadow prices are not interesting. We will in the sequel assume this is the case. On the other hand, the first two are crucial for a study of wealth changes.

The estimation of the streams of benefits, U_1 and U_2 are conventional. For each year estimate the value of sales and subtract the costs including capital costs. It might be thought that the current land prices would be appropriate. However, that is not the case. Assume that land is bought and sold on perfect markets for land. The current price on land would then be a possible estimator. However, if the market actors have the same information and forecasts as "we" have, the market price would be the accounting price of sensitive land, as given by the third equation . However, that is not sufficient information to calculate the interesting shadow prices q_X and q_Y. On the other hand, if the actors on the land market are completely myopic and do not take the possibility of a future flip into account when they do their decisions on buying and selling land, the current land price $q^{sen}(0)$ would reflect their present value of future net benefits, and the land price could be used to evaluate the correct shadow price of resilience and "pumps". In the absence of a defence of such an assumption, we need to estimate explicitly the benefit streams. If land becomes completely unproductive for ever after salinisation, then presumably U_2 is zero. U_1 can be estimated by looking at the net revenues of the farmers under present conditions, assuming that there are no forecasted future changes in prices and technology. Then we will easily obtain an estimate of U_1

Next, we need to know the cumulative probability distribution of a bifurcation. The easiest way would be if the probability distribution for a flip is constant over time, say $\theta e^{-\eta X_0}$, where X_0 denotes the initial resilience stock. Note that θ denotes a hypothetical benchmark probability for a flip if the initial resilience stock X_0 would be zero, and η is a parameter measuring how fast the flip probability decreases as the resilience stock increases. To simplify, let us assume discrete time. Then the cumulative distribution, that is the probability that there has been a flip before or up to period t is $F(X_0,t) = 1-(1-\theta e^{-\eta X_0})^t$, and the corresponding survival function becomes

$$S(X_0,t) = (1-\theta e^{-\eta X_0})^t \qquad (9)$$

Under these simplifying assumptions, the accounting prices are

$$q_X(0)=\sum_{t=0}^{\infty}\left(\frac{\partial S(X,Y,t)}{\partial X}U_1+\frac{\partial F(X,Y,t)}{\partial X}U_2\right)\frac{1}{(1+\delta)^t}$$
$$=(U_1-U_2)\sum_{t=0}^{\infty}\frac{\eta\theta t(1-\theta e^{-\eta X_0})^{t-1}e^{-\eta X_0}}{(1+\delta)^t} \tag{10}$$

provided that U_1 and U_2 are constants. Similarly, we can also derive the shadow price on the stock Y.

In empirical work, it may be practical to replace the infinite time horizon with a finite, especially if the present value has to be calculated numerically without evaluating the sum. The easiest way to do that is just to replace infinity with a high enough number in the formulas above. In addition, in empirical applications, the flip probability at a future point in time may need to be calculated according to the predicted resilience level at the time instead of the constant initial level. With X_0 as a starting point, if we predict the resilience stock to be X_t at a future date t, the flip probability at that date will be $\theta e^{-\eta X_t}$.

5. An example: Including resilience in estimating IW in a catchment in SE Australia

The Goulburn-Broken Catchment (GBC) in South East Australia is one of the country's most important agricultural regions. The lower third of the catchment (300,000 ha) is used for irrigation, 80% of it for dairy pastures. In addition to agricultural production, nature conservation has been identified as a significant flow to regional welfare. A trade-off exists between the two flows since declines in the native vegetation cover associated with agricultural expansion have resulted in the disappearance of many species and reductions in other species.

To estimate IW for the GBC we identified all the significant flows to regional welfare and then measured all the constituent capital stocks. For the purposes of this paper we used only a subset of these stocks. To include resilience we also identified any underlying (controlling) variables that cause threshold effects in these capital asset stocks. Three such variables were identified: (i) a rising ground water table in irrigated agricultural land, (ii) vegetation connectivity in regard to nature conservation, and (iii) the condition of irrigation infrastructure.

5.1 Groundwater and salinity dynamics in agricultural land

Removal of native vegetation to allow for cultivation has led to rising water tables and associated salinity; a looming problem that has put this system at risk (Anderies et al, 2005). Tree clearing in the upper catchment reduced transpiration, allowing more rainfall to penetrate through to the groundwater. The addition of irrigation water in the lower catchment, imported mostly from dams in the upper catchment but also from the Murray River outside the catchment, exacerbates the problem. Rising water tables mobilise salt deposits in the soil profile and when the water tables reach c.2m below the surface, the water (with the dissolved salt) is drawn to the surface by capillary action. The salt can be flushed back down through the soil profile by irrigation or rain, but this again adds to the height of the water table. Half the GBC irrigation region is estimated to be at risk of high groundwater tables and salinity. Salinity and waterlogging have important, independent impacts on agriculture. We consider here only the impacts of salinity as it has a strong threshold effect.

Two episodes of high rainfall years, in the 1950s and the early 1970s, caused significant crop losses in several areas. The response to these episodes was the installation of a system of some 500 pumps that keep the water table below 2 m, discharging the pumped water via drainage channels into the Murray River. When the 'cap' on the allowable amount of exported salt into the Murray river has been reached, the water is pumped into evaporation basins. This results in two relationships between rainfall and water table depth: a historical one when the water table was rising, and a current one that includes the effect of pumping. It is the latter we have used in our analysis.

Horticultural crops are more sensitive to salinity than pastures and the consequences of exceeding the 2m threshold are therefore more severe. Some (periodic) production is possible with pastures when water tables are within 2m of the surface, and so the shadow price for dairy in the two regimes differs less than for horticulture.

When the water table was 20m below the surface the state of the "stock" of soil that produces pasture (basically the top 1m of the soil) was the same as it is when the water table had risen to 3m below. However, once the water table rises above 2m the stock of soil is radically changed; it shifts into a different regime - degraded salinised soil. In terms of IW, when the water table is 3m below the surface, although current agricultural production hasn't changed, the real value of the capital stock of soil is less than when the water table was at 20m, because the risk of salinisation has increased.

The dynamics of the water and salt in terms of their twofold effect on agriculture are shown in Figures 2 and 3. The alternate regimes for water are reversible (Figure 2), with a hysteretic effect. The controlling (slow) variable is the amount of native vegetation (presented as the percent of original vegetation that is cleared). The hysteresis effect is due to the fact that growth and transpiration of trees are affected by salinity and water logging in the upper soil, so in the re-vegetation direction (as opposed to the de-vegetation, or clearing direction) more trees are needed to effect the same amount of water uptake that occurs via trees in non-salinised soil. The smaller hysteresis in the case with pumping is due to the fact that water uptake is due to both trees (which are affected by waterlogging and salinity) and pumps (which are not).

Figure 3 represents the soil fertility change due to salt dynamics in relation to changes in water table depth on a time scale of one or two decades. Salt disperses clay particles leading to reduced infiltration and poor plant growth conditions and these changes in the soil structure and fertility mean that, on a decadal time scale, the regime shift is, in practical terms, irreversible. Over much longer time scales, *if* trees can be maintained, the salt will eventually be flushed down. The broken line in Figure 3 indicates that this long-term return to a fertile (low salt) top soil will only take place when the water table is considerably lower than the 2m depth. This hysteresis effect is due to inter-annual fluctuations in rainfall. As long as the 2m threshold is within range of a wet period "spike", salt will again be drawn up to the surface.

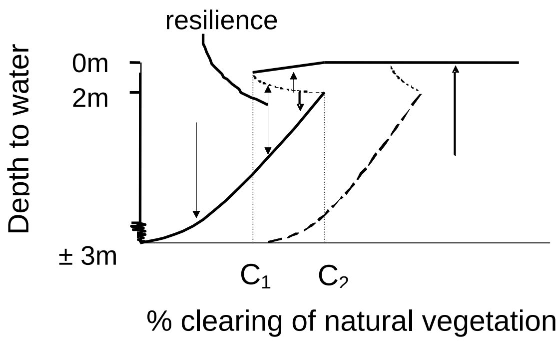

Figure 2. Equilibrium levels of water table depth in the Goulburn-Broken Catchment in relation to natural vegetation cover, with (dashed line) and without (solid line) pumping. The stable equilibrium represented by the dashed line occurs under significantly less natural vegetation cover (significant higher clearing) owing to the effects of pumping (equivalent to mechanical trees). C1 and C2 are the critical levels of clearing that lead to threshold changes in the equilibrium level of the water table in the direction of clearing (C2) and re-vegetation (C1).

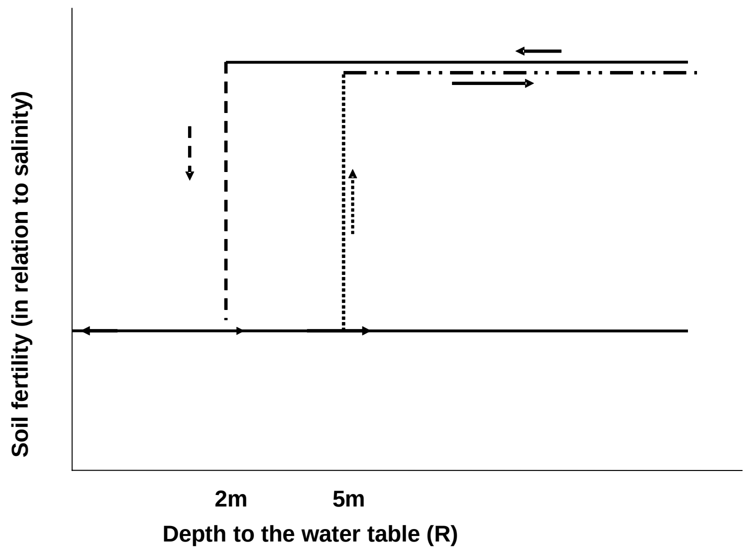

Figure 3. Dynamics of soil fertility (due to salinity) in relation to depth to the water table. The solid lines depict the equilibrium levels of salt over the short (c.20year) term with downward dashed line being the unstable threshold at around 2m depth. The broken (dash-dot) line represents the longer term (multi-decadal) equilibrium with the c.5m unstable threshold in the return direction (i.e., declining water table).

Resilience at any one time in this system is measured by the distance from the water table to the 2m threshold. We include the measure in the estimate of inclusive wealth by estimating the probability that the system will shift from the non-saline to the saline regime**.** A particular feature of the GBC's recent climatic history that complicates the following story about changes in inclusive wealth is that the region has been gripped by an unusual drought for more than a decade. The result has been a slight lowering of the water table and therefore (in contrast to the general trend over the previous 80 years) an increase in resilience with respect to salinity.

5.2 Incorporating resilience with regard to salinity in a measure of IW

An estimate of IW at a single point in time has no real meaning. It is the *change* in IW that matters, since it is the change over time that allows us to assess the sustainability of particular projects or policies. There are two ways in which change in IW is of interest: i) The difference in IW between two points in time, as a monitoring procedure to detect if the resource allocation in effect at time 1 was sustainable. ii) The difference between two resource allocation options (eg, proposed policy options), as a comparative procedure to determine the difference in IW that will result from the two options.

To determine changes in IW under either (i) or (ii) a forecast of how the various stocks will change into the future is required in order to calculate the shadow prices.

Forecasts, stocks and shadow prices

Forecasts

IW relies on economic and stock quantity forecasts to derive shadow prices. We have defined two forecasts for the period 2001 to 2030. Both relate to climatic conditions in the Goulburn-Broken Catchment, which we assume affects only the depth of the groundwater table. For the purpose of this analysis, we ignore any direct affects of climatic changes on dairy and horticultural production. Both forecasts share the same history of groundwater table movement between 1991 and 2001, decreasing from 3m to just above 3.5m. We assume linear changes in the groundwater table between 2001 and 2030. The two forecasts are:

(I) Re-establishment of the **Normal Climate Conditions**, which produce average rainfall and evaporation, resulting in a rising water table that is assumed to reach 3m below the surface by 2030.

(II) Continuation of the current, unusual **Dry Climatic Conditions** which have resulted in the lowering of the water table between 1991 and 2001. Based on current trends, we assume that the water table falls to 5m below the surface by 2030. (Note: There is a view in the region, based on predictions from climate change models, that the current dry conditions may in fact become the norm.)

Shadow prices

We have identified four stock categories in all, three of which have entered into the analysis and have associated shadow prices:

(i) Stocks of dairy and horticultural land not subject to a regime shift (non-salinisable, see Table 1 for price and quantity data),

(ii) Stocks of dairy and horticultural land which are subject to a regime shift (salinisable, see Table 1), and

(iii) Stocks of resilience. Our single resilience stock of salinity is the distance from the water table to the 2m threshold. As we describe later, however, there may be more than one kind of resilience stock.

The salinisable and non-salinisable lands should in reality have different shadow prices, and the numbers presented in Table 1 are therefore not shadow prices as such, strictly speaking. They are more "ideal shadow prices" conditional on no future regime shifts (as the lands are equally valued in all other aspects except the regime shift risks). These prices will be used for calculating the monthly-equivalent loss due to a flip from the normal to the disturbed state.

The fourth stock is the stock of pumps used to lower the water table, and therefore to enhance resilience. For this assessment it does not change, and we do not therefore include it. We discuss it again later, when changing the stock of pumps becomes a policy alternative.

To demonstrate the impact of resilience on an IW assessment, we make the simplifying assumption that all capital stock quantities are held constant ($K_{t1}=K_{t2}$) and only the stock of resilience (X_j) changes.

Table 1. Stock quantities and prices in 1991 and 2001 for dairy and horticultural land

Stock characteristics	Quantity (ha)	Price ($/ha)			
		1991		2001	
		Current regime	Alternate regime	Current regime	Alternate regime
Dairy land non-salinisable	48 000	$448.29	N/A	$385.85	N/A
Dairy land subject to salinity	192 000	$448.29	$44.83	$385.85	$38.59
Horticultural land non-salinisable	4 800	$723.00	N/A	$677.16	N/A
Horticultural land subject to salinity	19 200	$723.00	$7.23	$677.16	$6.77

N/A –not applicable to this stock as it is not subject to a regime change

Market prices are used as a proxy for ideal shadow prices in the current regime[2]. There are significant problems with using market prices as shadow prices and some of these are listed in the discussion. However, this paper is focused on how to incorporate resilience in IW, not the

[2] Both dairy and horticultural land price data are derived from net present value calculations of land rent based on ABS (2001) and ABS (1998) collated for the GBC.

calculation of IW per se, and the prices are therefore used only to illustrate the method. Accordingly, the 1999 shadow price for the stock of salinisable dairy land in the current regime is, for instance, taken at the market price of \$448.29 per ha (*p*), with an estimated price of dairy land in the alternate regime as \$44.83 per ha (*P)* (10% of current value). The greater reduction in value of horticultural land when it shifts into the salinised regime is based on the lower sensitivity of pastures to water tables in the upper 2m compared to fruit trees. The estimated price of salinised land in Table 1 (i.e., 10% or 1% of current land value for dairy and horticultural land, respectively) is higher than suggested by other investigations of the land value of salinity to farmers, which generally claim that saline land has no commercial value (eg, Whish-Wilson and Shafron, 1997).

Including the value of resilience in IW at a point in time

There are three steps to including resilience to salinity in estimates of IW. The first is to estimate the cumulative probability $F(X_0,t)$ of the stock crossing the threshold at a future time *t*. We used the data for monthly water table depths since 1974 from a central site in the region to derive the probability of a rise in the water table of a particular magnitude within any one year. We did this using a best fit function to the relative frequency of magnitudes of monthly rises in the water table. As explained earlier, this relationship includes pumping activities.

For a given initial resilience stock X_0, i.e. the distance between the actual water table and the threshold of 2m below the surface, we make forecasts about the future trends of water tables and calculate the expected resilience level X_t for all time $t>0$. Since we use discrete time in this empirical illustration, we may refer to a future "time" t as a future month t, $t=1,2,...,m$. Conditional on no flips in previous months, the probability of a flip in month t can thus be expressed by $\theta e^{-\eta X_t}$. Based on monthly observations from the GBC region, the parameters were estimated to be $\theta = 0.4583$ and $\eta = 2.75$, where the initial water table was about 3m below. Thus, the survival probability up to month t becomes

$$S(X_0,t)=\prod_{t=1}^{m}(1-0.4583e^{-2.75X_t}) \tag{11}$$

The corresponding cumulative flip probability is simply $F(X_0,t)=1-S(X_0,t)$. Note that the trend of expected future resilience levels X_t depends on the initial level X_0 according to a certain stochastic process. Following the scenario of the "normal" climatic conditions, the water table would rise from the 2001 level of 3.5m below surface to 3m, implying a loss in resilience stock by 5 decimetres. If the "dry" climatic conditions are assumed, then the water table would fall further to 5m resulting in an increase in the resilience stock by 15 decimetres.

In the second step, we calculate the marginal price of the resilience stock per decimetre at our initial year 1991 by

$$q(0) = \sum_{t=0}^{480} \frac{\Delta S(X_0, t)(U_1 - U_2)}{(1+\delta)^t} \qquad (12)$$

where $\Delta S(X_0, t)$ denotes the increase in survival probability at month t due to a hypothetical increase[3] in the initial resilience stock (i.e. a fall in the water table) by 1 decimetre. The monthly-equivalent loss[4] caused by a flip is calculated by $U_1 - U_2 = (0.04/12)\times\left(0.90\times 192000\times 448.29 + 0.99\times 19200\times 723.00\right)$, where we use an annual discount rate of 4% (about $\delta = 0.04/12 \approx 0.33\%$ monthly rate of discount). The expression within the second parenthesis on the right-hand-side is the total loss in present value caused by a flip. As touched upon in the theory section, we use $m = 480$ months to approximate the theoretical infinity.

Based on the "normal" climatic scenario, we calculated the change in survival probabilities due a 1 decimetre increase in the resilience stock, as depicted in Figure 4. While the lower curve *scdf* depicts the survival curve conditional on an initial resilience stock of 10 decimeters, the upper one shows the survival curve from a counterfactual initial resilience stock of 11 decimeters, as of the first month in 1991. It is seen that with higher initial (and subsequent) resilience levels, the survival probability is higher at each future point in time. Applying the formula in (12), we obtain the 1991 resilience price per decimetre as $\$4570530$. The GBC's inclusive wealth thus becomes

[3] We assume that the expected future resilience stocks would improve by the same amount. This is a different assumption as compared to Maler et al (2007), when the effect of a change in the initial water table diminishes over time.

[4] In this paper, we treat utility and its monetary value with no distinction. In other words, we assume a linear-in-income-utility function with marginal utility normalized to unity.

$$\begin{aligned}\omega_{1991} &= \sum_i p_{it} K_{it} + \sum_j q_{jt} X_{jt} \\ &= (448.29{+}723.00)\cdot 192000{+}(448.29{+}723.00)\cdot 48000 + 4570530\cdot 10 \qquad (13) \\ &= \$326\,814\,900\end{aligned}$$

i.e. about \$327 million, where the last term in the middle line represents the value of resilience stock being 10 decimetres. The corresponding 1991 resilience price following the "dry" scenario is calculated to be \$5711672, and the inclusive wealth turns out to be \$338226300, about \$338 million. Although the wealth numbers are informative for the scale of the economy, it has no real meaning on its own for welfare comparisons. It is the change in IW that matters, which we come to in the following two sections.

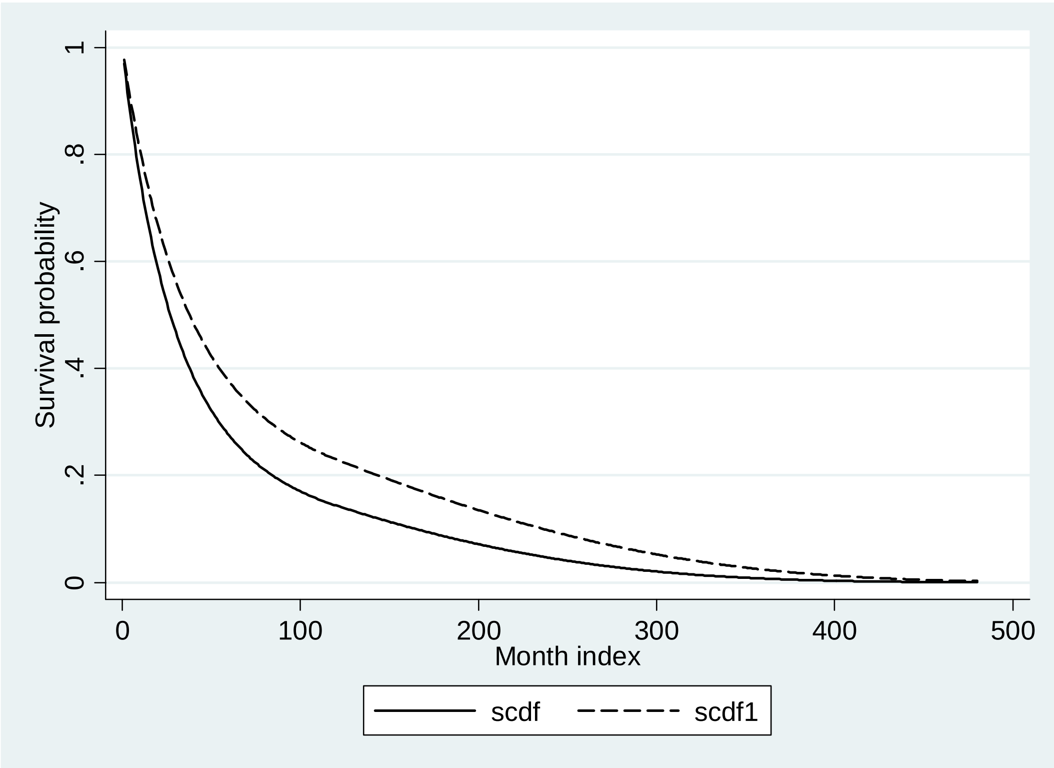

Figure 4. Survival curves conditional on different initial resilience levels

Resilience and change in IW over time

Change in IW can be calculated at constant prices for small changes in the resilience stock. For larger changes, however, the effect of price movement should also be taken into account as shown in (5) in order to make more precise welfare comparisons. In this section, we study the welfare changes between 1991 and 2001 based on constant 1991 prices. Over the time period concerned, the resilience stock increased by 5 decimetres due to a water table fall from

3 to 3.5 meters. Using the constant price at the initial year 1991, i.e. $\$4570530$ per decimetre for the "normal climate" scenario, the corresponding changes in IW is calculated to be $4570530 \cdot 5 = \$22852650$, about $23million. This corresponds to about 7.0% of the total wealth in 1991. For the "dry climate" scenario, the increase in IW is $28 558 360, i.e. about 8.4% of the 1991 inclusive wealth. Stated another way, if we expect the resilience stock to continue increasing in the future (dry conditions), the 0.5m change between 1991 and 2001 is valued at $28.5 million. On the other hand, if we expect the resilience stock to decrease again in future (normal conditions) the 0.5m change between 1991 and 2001 is valued at $23 million. The greater change in IW under the "dry" scenario highlights two aspects to do with including resilience in this assessment: i) if resilience is initially high an increase in its amount is worth less than when it is initially small and ii) given the same initial resilience, but different development forecasts, the initial resilience price is higher for forecasts that involve higher estimates of future resilience.

Table 2. Change in Inclusive Wealth between 1991 and 2001 using constant prices

Forecast	Change in wealth not including resilience	Change in IW including resilience	
(I): Normal Climatic Conditions	$0	$ 22 852 650	7.0%
(II): Dry Climatic Conditions	$0	$28 558 360	8.4%

From Table 2, it is seen that the growth in wealth not including resilience does not change between forecasts because we have held all other stocks constant (i.e., K_i and K_h). Including the effect of resilience, we find the 2001 IW is higher than that in 1991 (ex-post), meaning that the inter-temporal welfare has been improved during the period. These intuitive results support the importance of forecasts in wealth estimates and highlight the important role that the resilience stock plays in estimating wealth.

Resilience and change in IW to assess policy options

The calculation in the previous section is based on the assumption of the business-as-usual pumping activities. From a policy point of view, it is interesting to study the value of an Enhanced Pumping (EP) policy, with increased pumping capacity. As shown by Arrow et al (2003), the accounting prices can be used both for welfare comparisons over time and project evaluations of alternative states along the time line.

For simplicity, let us suppose that the water table in 1991 could be instantly decreased by EP by 1m (10 decimetres) from the actual 3m level. Following the path from the initial resilience stock of 3m, the maximum inter-temporal wealth is as derived earlier to be about $300 million. The question here is how the welfare measure would increase if the water table was, instead, 4m. As a first-order approximation, this increase can be calculated by multiplying the constant 1991 resilience price with the decrease in water table. This turns out to be

$$q_Y(0)dY_0 = q_X(0)dX_0 = \text{ 4570530*10=\$45 705 300}$$

i.e. about $46million, for the "normal climate condition", where $q_y(0)$ denote the accounting price per unit of EP capacity and dY_0 the increase in the EP stock. With this simple model, the value of the enhanced pumping capacity is exactly equal to the value of enhanced resilience enabled by the EP. For the "dry climate" scenario, we have

$$q_Y(0)dY_0 = q_X(0)dX_0 = 5711672 * 10 = \$57116720$$

i.e. about $57million. Applying the cost-benefit rule, it may be claimed that if the cost of EP to reduce the initial water table by 1m was less than the value(s) above, then it is socially profitable to adopt the enhanced pumping; otherwise not.

It is worth mentioning that the calculations above are based on an instant change in the pumping capital with an immediate effect on resilience enhancement. In reality, it could take years to install the pumps and build drainage water channels. In this case, it is obvious that the costs and benefits during this transition period should be better accounted for. As our aim with this exercise is to illustrate the use of the IW theory for evaluating projects in an ideal setting, we avoid such complications.

Sensitivity analysis

Our analysis above is based on the cumulative probability function (11) where the monthly probability of a flip is equal to $0.4583e^{-2.75\cdot 1.0} \approx 0.029$ given that the "normal" resilience stock is 1.0m (a water table of 3.0m below surface). To generate such a monthly flip probability, however, there are many other parameter pairs (θ,η) that satisfy $\theta e^{-\eta X} = 0.029$ with the same resilience stock, such as $(\theta,\eta) = (0.25, 2.15)$ and $(\theta,\eta) = (0.125, 1.45)$.

Although the different pairs generate the same flip probability for the "normal" resilience stock of 1m, they may result in rather different flip probabilities for alternative resilience stock levels. Thus, the choice of a parameter pair may imply very different resilience prices. In table 3, we show that calculated price per decimetre resilience stock at the reference year 1991 for the different sets of parameters. It is seen that the results are sensitive to the choice of parameters describing the flip probability function. The larger the "speed parameter" η, the more sensitive the flip probability is to a change in the initial resilience stock, and thus the larger the resilience price per meter is. This implies that the resilience prices should be interpreted with caution due to possible uncertainties involved in the flip probability model.

Table 3. Sensitivity analysis with different parameter pairs

Parameter pair (θ, η)	Forecast	The 1991 resilience price per decimetre
(0.4583,2.75)	Normal	$4 570 530
	Dry	$5 711 672
(0.25, 2.15)	Normal	$3 144 708
	Dry	$3 852 056
(0.125,1.45)	Normal	$1 770 415
	Dry	$2 012 951

5.3 Discussion of the salinity application

The GBC example shows that including resilience can make a significant difference to the estimate of changes in IW. The change in IW over the period 1991 to 2001, incorporating the resilience measure, indicated that the sustainability of using the system over that period depended on the climate forecast expected into the future. Our analysis is, however, partial as we have assessed only a limited number of stocks and suppressed all changes in those stocks in order to focus on the effects of including resilience.

Had normal climatic conditions prevailed during the period 1991 to 2001, the likely outcome would have been rising water tables, a lowering of resilience and a decrease in IW. The unusual dry conditions during the decade actually led to an increase in IW, especially so under the forecast of continuing dry conditions. Under both policy options (current and Enhanced Pumping, in our partial analysis) the system has not actually moved into the saline regime, but it is more likely to do so under current pumping.

We need to note the following limitations of our analyses:

1) The results are constrained by available data and cannot be used in any real world sense. In particular, the relationship between rainfall variation and the probability of crossing the 2m water table threshold needs to be refined. Its present formulation (derived from sparse data) leads to sensitive and quite spectacular differences between the normal and dry climatic

forecasts. The sensitivity analysis results in Table 3 show clearly that it is important to get a model for water table changes that will stand up to scrutiny before any recommendations could be made, for example in regard to policy options for enhanced pumping.

2) Market prices and proxies have been used for shadow prices. This requires a number of assumptions to be made about how the land market operates (e.g., perfect competition, the extent to which non-agricultural services such as nature conservation are included) and how the catchment operates now and during the forecast period (e.g., saline land has no/ minimal productive capacity). Currently the GBC land market "believes" that salinity is controlled and hence salinity does not significantly influence the prices. This is why we have used the same price for land that is non-salinisable and for the current regime of land that is salinisable. Obtaining credible estimates for shadow prices remains a major hurdle in the wider application of the inclusive wealth approach.

3) We have assumed that once the threshold is crossed there is no return within the forecast period. In the case of the GBC this is a reasonable assumption. It will not be so in all cases, and this could be handled by adding consecutive time period analysis to the base equation for inclusive wealth (equation 10).

6. Multiple thresholds and regime shifts

The salinity example has outlined the process for including the resilience of a single regime shift on two stocks (horticulture land and dairy land). In reality most social-ecological systems have more than one possible regime shift and each of these shifts affects a number of different stocks. As an illustration, we briefly outline two additional possible regime shifts in the GBC.

Nature conservation. Native vegetation is a significant part of the biodiversity itself, but it also determines the diversity and abundance of animal species, with a threshold effect. There are three aspects of native vegetation that determine its nature conservation value: the total extent of native vegetation, its condition (whether heavily grazed by livestock, harvested, burned, etc.) and its connectivity. Several studies (e.g., Andren 1994, Bennett and Ford 1997) have shown that, combining the total extent and connectivity, there is a marked threshold effect of the type in Figure 1 (b) when vegetation cover reaches around 30%. It is not a step function, but it is a steeply changing relationship. In terms of biodiversity the region can be considered as having alternate regimes, above and below a vegetation cover of 30%. The slow, controlling variable is the cover of native vegetation. Response types of this nature are quite different from the Figure 1(c) type in which there are alternate stability regimes for the fast variable for a range of values of the slow variable. However, from the point of view of estimating IW it is convenient to consider the probability of crossing the threshold as a resilience stock that influences the likelihood of a regime shift.

Irrigation infrastructure: A third kind of state change has been suggested in the GBC for one of the built capital stocks - irrigation canals. The canals need regular, costly repairs. They were originally built and maintained by State and Federal agencies but are now owned by a privatised body that includes the irrigators. Repairs can only be paid for out of profits when excess water is available for sale beyond the annual growers' entitlements. However, because the region has been in a drought for several years, maintenance requirements have been mounting. It is mooted that the costs of repairing some canals will be higher than the expected returns from the dairy operations they serve. This is, of course, a common aspect of economic cost/benefit analysis. In the context of our assessment, the "flip" does not involve any complex dynamics (as in Fig 1 d or e). "Resilience" is not involved, in that there are no stochastic dynamics that could push the canal condition across the "worth repairing" threshold. But it does involve a flip in terms of economic decisions, a point of no return regarding the economic viability of the canals, i.e., it is a "tipping point". If there were significant changes in prices of crops, or in canal repair technology, the situation could be reversed and it could be economically viable to repair the canals (the threshold would have changed). However, given that neither of these is very likely over the time frame being considered by the irrigators, realising that canal condition has a threshold point beyond which repair is economically not viable, and knowing where that threshold is (ie, the state of canal condition), becomes part of the set of thresholds that managers need to be aware of, and managing.

These examples of multiple thresholds and their impacts on the stocks within a region like the GBC will result in a matrix of capital stocks impacted by possible regime shifts and a number of resilience stocks (Table 4). The consequence of multiple thresholds and associated resilience stocks is very complex, and we have not attempted to address them in this paper.

Table 4. Multiple resilience stocks and the associated capital stocks which will change, depending on the likelihood of regime shifts (the resilience stocks declining to 0).

		Resilience Stocks		
		Rising water table & salinity	Native vegetation connectivity	State of irrigation infrastructure
Capital Stocks	Dairy land	✓		✓
	Horticultural land	✓		✓
	Water Infrastructure			✓
	Native fauna	✓	✓	
	Native flora	✓	✓	

7. Conclusion

Resilience is a necessary inclusion in any comprehensive measure of sustainable development. It is difficult to incorporate because of uncertainties about the positions of thresholds and threshold effects, but our analysis has shown that even if accurate data are not available an initial assessment of the significance of resilience can be undertaken by answering three key questions:

1. Is there a known or suspected alternate regime in a stock's forecast?
2. If so, how will a shift into the alternate regime affect social wellbeing (including which other capital stocks it affects and by how much)?
3. What is the probability of the stock crossing the threshold? (which requires some estimate of the state of the stock, where the threshold might be, and therefore the "stock" of resilience)

The GBC example (acknowledging its limitations) has shown that the effect on IW of including a small change in the likelihood of a shift to a saline regime was large. This indicates in a pure cost-benefit manner the maximum expenditure for maintaining the current regime. Assessing the effects of resilience associated with a single potential regime shift on single stocks is substantially easier than the complex notion of multiple regime shifts affecting many stocks.

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