ARTICLE

Measuring sustainable development: the promise and difficulties of implementing Inclusive Wealth in the Goulburn-Broken Catchment, Australia

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A difficulty in measuring sustainable development is integrating measures of its key components (environment, economic, and social) in a way that allows comparison and assessment of tradeoffs and communication of results. This article presents a trial implementation of a sustainability measure called Inclusive Wealth. We do this by constructing an experimental model to estimate sustainable development through the measurement of capital stocks (built, human, natural, and resilience) in the Goulburn-Broken Catchment in Australia. By trialing the model over the period 1991–2001, we address practical issues associated with identifying capital stocks, estimating shadow prices, addressing risk, assessing intragenerational equity, and dealing with price changes. Results are presented as the basis for discussing hurdles to the implementation of regional sustainability measures and for highlighting outstanding theoretical and methodological issues that need resolution for sustainability measures to become a practical policy tool.

KEYWORDS: cost analysis, socioeconomic aspects, risks, assessment, sustainable development

Introduction

The assessment of sustainable development is beset by (at least) two key challenges: 1) the philosophical challenge of properly defining what is being measured and 2) the technical challenge of accurately measuring the component parts of the eventual sustainability indicator for the assessment to proceed. The first challenge is an “in principle” one that defines how relevant and plausible a sustainability indicator might be in a policy context, while the second concerns how accurate such an indicator might be.

In this article, we present a relatively new sustainable development measure called Inclusive Wealth (IW) (for more formal derivations and treatments, see Arrow et al. 2003 and Walker et al. 2010) and trial it at regional scale in the Goulburn-Broken Catchment (GBC) in Victoria, Australia. The GBC is one of the country’s most important “food bowls,” with dairy from irrigated pastures, horticulture, dry-land wheat and livestock production and, in the higher-altitude, higher rainfall areas, forest production. It is also a region where nature conservation and “lifestyle” are highly valued. In this trial assessment, we included all capital assets contributing to the dairy industry, dryland wheat and livestock production, nature conservation, and carbon sequestration. These sectors were chosen because the tradeoffs among them involve changes in land use.

To show the key contributions of this approach, we outline how we view IW in the context of the two challenges presented above. With regard to the first, philosophical challenge, the IW measure directly targets the “productive base” that generates society’s standard of living, that is, the collected set of “capital stocks” (produced, human, and natural)—or wealth—that provide us with our lifestyles. If the value of the collected set of stocks declines over time (IW falls), society can be deemed to be consuming its capital and risking its own future impoverishment. Thus, a
sustainability rule using IW would, at a minimum, ensure nondeclining IW (i.e., zero or positive wealth). This rule is analogous to defining sustainability as nondeclining social welfare, as operationalized in an economic sense, which is broadly consistent with framing outlined in the Brundtland Report (see WCED, 1987).

IW is an economic framework, which need not be relied on exclusively as a sustainability indicator, but at any given scale it can provide a meaningful policy constraint when considering development options. Moreover, the process of aggregation of stocks allows the direct consideration of policy tradeoffs, as natural assets always face competing uses, and using a capital-based framework allows an assessment of their contributions in alternative uses (and avoids the typical trap of them being treated as “free goods”).

With regard to the second, empirical, challenge, the process of construction of the IW measure uses shadow prices—measuring a capital stock’s marginal contribution to social welfare—to value individual stocks and then to aggregate them into a total wealth measure. Conventional monetary wealth measures are necessarily partial, measuring what can easily be appraised and valued. IW, by contrast, seeks to include “everything that matters”: this makes it difficult to implement, but this challenge is inherent in sustainability assessments, in which everything that matters ought to be included, by definition. The practical estimation of shadow prices is at the heart of the empirical challenge in implementing IW for use in the policy process. Shadow prices serve as social welfare weights in the construction of IW, and if these are significantly inaccurate, IW estimates (and changes in those estimates over time, which is what matters for sustainability) will be biased. For the purposes of this trial study, shadow prices are admittedly crude (as outlined later in the article), and the IW estimates provided here are definitely preliminary.

A further innovation in the use of IW presented here is the focus on the resilience of the systems that comprise key natural capital stocks. Many sustainability indicators capture changing quantities of natural resources and environmental assets without looking at the implications of those changes. One such implication can occur when a system is subject to thresholds beyond which it “changes state” in ways that have implications for sustainability. In this study, a food-production system can become unproductive when farmland is salinized, where the threshold involves the level of the water table. Changes in the “resilience stock” of the system—measured as changes in the distance from the threshold value—can be meaningfully captured in changes in the estimates of wealth. Values, or shadow prices, of resilience can be derived theoretically in the manner outlined in Walker et al. (2010).

It is useful to briefly compare IW to another aggregated sustainability measure, the Ecological Footprint (EF) (see, e.g., Wackernagel et al. 2002). While EF is often advocated as a “strong sustainability” measure (see, e.g., Neumayer, 2004), it does, like IW, aggregate different attributes into a single measure, and does not single out particular sets of natural assets that require specific preservation. Like conventional “weak sustainability” measures such as Genuine Savings (see, e.g., Pillarisetti, 2005), the aggregation in the EF is underpinned by an assumption of substitutability (in that attributes can be converted into a common metric, in this case land area). Despite their differences, both measures have aggregation and substitutability in common.

The in-principle value of the wealth approach is that it directly links changes in productive assets now to impacts on human well-being in the future to enable the analysis of environment/development tradeoffs based on impact on stocks of assets and to suggest “reinvestment” policies to improve the overall sustainability picture.

**Framework for Measuring Regional Wealth**

Formally, IW represents the summation of the real social values of all capital assets—human, manufactured, and natural—in a particular region (Arrow et al. 2003; Dasgupta, 2009). “Real social values” are calculated using shadow prices, which may well diverge from market prices for a variety of reasons (see, e.g., Arrow et al. 2003). We apply the extended IW framework to take account of changes in the risk or resilience of the system as described in Walker et al. (2010). For a point in time (t), these social values are derived as the number of units (Kij) of each asset or stock (i), multiplied by the shadow price of a unit of each stock (p). Our stocks include three categories of assets: human, natural, and built. In addition, following Walker et al. (2010), we add a fourth stock, resilience. Social capital is explicitly excluded from the calculations on the basis that it is an “integrating” capital: the greater the positive social capital, the more productive and sustainable will be the other capital stocks. Thus, social capital should be reflected in the values assigned to the capitals included in the IW measurement. (Similarly, farmland will be much less valuable in a war-torn or conflict-ridden country than in a well-governed one.) Our trial assumed (not unreasonably) that social capital, including social networks, norms, governance institutions, and so forth remained stable over the period of analysis (see Harris & Pearson, 2004 for further explanation).
The shadow price for any stock is defined as the marginal change in real social value for a marginal change in the current stock quantity. To incorporate resilience in this way, we must be clear about the “resilience of what, to what.” Analogous to how other stocks are treated, we measure both the quantity \( X \) and price \( q \) of the resilience stock today. We use the “distance” a stock is from a threshold level that causes a shift of that stock into a different stability domain (and therefore different value) as the measure of resilience. Not all stocks \((i)\) will be affected by a threshold. For stock quantities \( K_{hi} \) that are at risk of crossing a threshold at time \( t \), we establish the shadow price in each state. Let \( p_{ht} \) and \( P_{ht} \) be the shadow prices of stock \( K_{ht} \) for the two states in which it can exist. We also estimate the cumulative probability \((F_{jt})\) that the resilience stock may cross a threshold \((j)\) during the forecast period and \((S_{jt})\) the survival probability that the stock has not flipped before time \( t \); therefore \( S(X_{j,t}) = 1 - F(X_{j,t}) \).

\[
q_j = \frac{\partial S_{jt}}{\partial X_j} \sum_h \left[ p_{ht} K_{ht} - P_{ht} K_{ht} \right] \tag{1}
\]

Accordingly, the equation for estimating IW at a point in time \((V_t)\) is:

\[
V_t = \sum_j \left( p_{jt} \times K_{jt} \right) + \sum_j \left( q_{jt} \times X_{jt} \right) \tag{2}
\]

Sustainability is assessed by calculating the change in IW between two points in time. In other words, it is the net change in real social value, summed across all stocks, where \( \bar{p}_j \) and \( \bar{q}_j \) represent the constant shadow prices over the time interval \([0, T]\):

\[
V_T - V_0 = \sum_i \left[ \bar{p}_i (K_{iT} - K_{i0}) \right] + \sum_j \left[ \bar{q}_j (X_{jT} - X_{j0}) \right] \tag{3}
\]

Where \( V_T - V_0 \) is not negative (i.e., increasing or stable), the trajectory of change over the interval \([0, T]\) is said to be sustainable.

**Process for Estimating Regional Wealth**

Calculating change in IW involves five steps.

**Step 1: Identify Critical Capital Stocks**

It is not practically feasible to include all stocks at fine levels of disaggregation. Our approach was to include only critical capital stocks, defined as those that (i) underpin the production of key goods and services (flows) in the region and (ii) are likely to change or (iii) have possible alternate states with significantly different consequences for goods and services. The important production flows for the catchment were clarified by stakeholder workshops, augmented with expert consultation at the policy and scientific level (see Harris & Pearson, 2004 for further explanation of the workshops and potential biases). The flows included were dairy production (based primarily on irrigated pastures) and processing, dryland agriculture and livestock production, nature conservation, and carbon sequestration. We then determined the natural, built, and human capital stocks that underpin each of these flows. Finally, to identify resilience stocks, we examined each of the natural stocks to determine which of them had or were likely to have thresholds of change in response to particular kinds of shocks. The final list of stocks and their role with respect to each flow is shown in Table 1 (with their associated shadow prices—see Step 3).

**Step 2: Assess Stock Quantities**

The quantity of each stock that contributes to each of the selected flows (e.g., the quantity of natural terrestrial ecosystems that contribute to grazing for livestock production) was determined for the years 1991 and 2001. To derive the total quantity of each stock in the catchment, we aggregated the quantities across the four selected flows, in a manner appropriate to each stock. Figure 1 presents the quantities of natural capital stocks in each of the assessed years.

**Step 3: Estimate Shadow Prices**

Shadow prices are formally defined as the present value of the perturbation to utility that would arise from a marginal increase in the quantity of the asset today (Arrow et al. 2003). We attempted to derive the shadow prices for each critical stock by assessing the value of the asset to each production flow, such as dairy production and nature conservation, and then deriving the total value-per-stock unit by appropriate aggregation across the flows. Implementing Steps 2 and 3 leads to identifying classes, or quality categories, within a stock that have different flows of social welfare. For example, native vegetation in “good” condition has a higher biodiversity value than that same area of vegetation in “poor” condition (e.g., heavily grazed by domestic livestock or infested with weeds). Similarly, agricultural land in good condition has a much higher value (shadow price) than land that has been salinized (see Harris &
Pearson, 2004 and Pearson, 2005 for further explanation of categories and values).

The Need for Forecasts

Any assessment of the present value of a capital asset takes into account, explicitly or implicitly, a forecast of what is likely to happen to that stock in the future. In the trial assessment of GBC we developed two plausible forecasts based on different expectations of rainfall conditions in the region. The “dry” forecast assumes that the below-average rainfall conditions prevailing in the region during the 1990s will continue over the next three decades. We assume that the per-unit values (shadow prices) of the capital stocks as measured in 1991 and 2001 are based on an expectation that the climatic conditions experienced in the 1990s will persist.

The “wet” forecast assumes above-average rainfall over the coming three decades and has implications for natural ecosystems, agriculture, and livestock production. With respect to natural terrestrial ecosystems, we assume that 30% of the area currently in poor condition will improve to the extent that it can be reclassified as being in good condition. For convenience, and with lack of better knowledge, we assume that this change takes place linearly over the forecast period. Similarly, we assume that 20% of the natural aquatic ecosystems will improve from poor to

Table 1 The 1991 shadow prices and stocks, not accounting for regime shifts or resilience analysis, that underpin the production flow of valued goods and services in GBC. In the exemplar model, we consider the stocks that underpin a subset of four flows only: dairy production and processing, dryland agriculture and livestock production, nature conservation, and carbon sequestration. Shadow prices are estimated under the dry forecast, business-as-usual (BAU) policy. The overall shadow prices for each stock are derived by weighted summation of the values for each flow, depending on the nature of each stock (e.g., stocks deliver multiple benefits to different flows, such as natural terrestrial ecosystems to carbon sequestration and nature conservation).
good condition due to the flushing effect of increased rainfall. Under the wet forecast, we further assume that the productivity, and hence shadow price, of nonirrigated agricultural land will be 10% higher compared to continuing dry conditions. This is equivalent to assuming that all nonirrigated agricultural land moves into a higher productivity class, with a higher associated shadow price. Similarly, we assume that the productivity of livestock will decrease by 5% due to the increased incidence of disease, and that there will be a 5% reduction in the shadow price of public infrastructure, such as bridges and roads, and a 10% decrease in the shadow price of irrigation drains due to the destruction and increased maintenance costs associated with flooding.

**Estimating Shadow Prices**

As anticipated, assigning shadow prices proved the most difficult part of the assessment. In the analyses presented for this trial, we used only market prices and benefit-transfer analyses to assign shadow prices, and we concede immediately that for any real assessment this is inadequate. For each stock, an estimate of the price was determined for both 1991 and 2001. Independent sources were used to determine the prices in the two years wherever possible, in order that the prices are related directly to the stock quantities in the respective years (see last column in Table 1 for list of sources). To allow for comparison over time, all prices were then adjusted to 2001 Australian dollar purchasing parity, using either a producer price index (PPI) or the consumer price index (CPI). Different PPIs had to be employed for different stocks. For example, the Price Index of Articles Produced by the Manufacturing Industry was used to adjust prices for stocks produced by the manufacturing industry in GBC. The CPI was used for capital stocks that had significant input into various stages of production industries and were potentially traded directly to consumers. For example, the CPI was used to adjust the 1991 dollar estimate of human capital into 2001 dollar values.

The constant price \( p_i \) in Equation 2 over the period 1991 to 2001 was determined as the linear average between the adjusted 1991 and 2001 prices. Ideally \( p_i \) should represent the true average price over the time interval, based on information on prices in the intervening years. However, in the absence of this information, we assumed that prices changed linearly over the period. Table 1 gives estimates of the average shadow prices for all assessed stocks in GBC over the period in 1991 under the dry forecast.

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### Table 1 continued

| Stock                        | Unit | Dairy | Dryland Agriculture | Nature Conservation | Carbon Sequestration | Overall |
|------------------------------|------|-------|---------------------|---------------------|---------------------|---------|
| **NATURAL CAPITAL**          |      |       |                     |                     |                     |         |
| Natural Terrestrial Ecosystems (NTE) |      |       |                     |                     |                     |         |
| Good NTE on dairy land       | $/ha |       |                     | $78                 | $20,626             | $20,704 |
| Poor NTE on dairy land       | $/ha |       | $0                  | $0                  | $52                 | $11,625 |
| Good NTE on dryland ag       | $/ha | $0    | $293                | $78                 | $20,626             | $20,997 |
| Poor NTE on dryland ag       | $/ha | $0    | $293                | $52                 | $11,625             | $11,969 |
| Good NTE on other land       | $/ha |       | $78                 | $20,626             | $20,704             | $20,704 |
| Poor NTE on other land       | $/ha |       | $52                 | $11,625             | $11,676             | $11,676 |
| **Natural Aquatic Ecosystems** |      |       |                     |                     |                     |         |
| Good condition               | $/km |       | $14                 |                     | $14                 |         |
| Poor condition               | $/km |       | $2                  |                     | $2                  |         |
| **Forest Plantations**       |      |       |                     |                     |                     |         |
| Forest plantations           | $/ha |       | $25,957             |                     | $25,957             |         |
| **Agricultural Land (Non-irrigated)** |      |       |                     |                     |                     |         |
| Dairy pasture                | $/ha |       | $1,789              | $6,849              | $8,638              |         |
| Dryland agricultural land    | $/ha |       | $1,594              | $6,849              | $8,443              |         |
| Other converted land         | $/ha |       | $6,849              |                     | $6,849              |         |
| **Agricultural Land (Irrigated)** |      |       |                     |                     |                     |         |
| Irrigated dairy pasture      | $/ha |       | $8,944              | $8,215              | $17,158             |         |
| Irrigated horticultural land | $/ha |       | $8,215              |                     | $8,215              |         |
| **Livestock**                |      |       |                     |                     |                     |         |
| Dairy cattle                 | $/animal |       | $828                |                     | $828                |         |
| Beef cattle                  | $/animal |       | $522                |                     | $522                |         |
| Sheep                        | $/animal |       | $35                 |                     | $35                 |         |

**Note:** AUS$=1.316 US$ at December 1991 exchange rate; natural terrestrial ecosystem (NTE); natural resource management (NRM)
The basic IW framework measures the net impact of changes in the quantity of different stocks over time in a particular region. As the quantity of a stock changes, its shadow price changes, and the net impact of the changes in price and quantity across all stocks is assessed by means of Equation 2. Given the difficulty of assessing prices with only limited data, we have used the constant (average) price between 1991 and 2001 for purposes of the exemplar model. We examine the implications of this assumption in our discussion on accounting for price changes.

**Step 4: Accounting for Risk: Assessing Thresholds and Resilience Effects in Natural Capital**

Two threshold effects are considered. The first is where two different states with different shadow prices exist, but the shift between states is not probabilistic. The value of land for nature conservation is an example. The value to nature conservation depends on the percentage of the landscape covered by native vegetation. The relationship is nonlinear, with a marked jump in the value at around 30% cover (Bennett & Ford, 1997). In this case, we define different categories of condition in which the stock may exist (<30% natural vegetation cover and >30%) with different shadow prices. Under these circumstances, the shadow price does not change as the stock nears the threshold, but only once it crosses the threshold.

Second, and most importantly for the region, is the threshold-related risk of potential salinization of agricultural land and land under native vegetation. Salinization occurs when groundwater tables (GWT) rise to within 2 meters (m) of the soil surface. Once water tables reach the 2m threshold, water is drawn to the soil surface by capillary action. Despite the long-term trend of rising GWT, over the period 1991–2001, GWT have actually dropped by an estimated 0.5m, due to the below average rainfall over the previous decade (further explanation is found in Walker et al. 2010).

We estimated that 60% of the irrigated agricultural land, 40% of the nonirrigated agricultural land, and 25% of the land under native vegetation is susceptible to salinization. These factors make up the critical stocks, $h$, that would be affected if the 2m water-table threshold was to be exceeded. In each case, the shadow price of the stocks $h$ in the salinized state was assumed to be 1% of the nonsalinized state. The cumulative probability ($F_t$) at time $t$ of crossing the 2m threshold during the 30-year forecast period was calculated as the product ($I_t$) of the probability of crossing the 2m threshold in any particular year:
where \( X \) is the distance at time \( t \) of the GWT from the 2m threshold as shown in Figure 2.

Equation 4 was applied in the exemplar model by forecasting the depth to the water table in 2030 under the two climatic forecasts (wet and dry) and assuming a linear increase between the current depths (1991 and 2001) and the depth in 2030 (Table 2). The cumulative probability of exceeding the threshold (Equation 4) was calculated for a 30-year forecast in each case (i.e., based on forecast increases in water-table depth until 2020 for the 1991 forecast and until 2030 for the 2001 forecast).

**Step 5: Determining the Change in Inclusive Wealth**

The final step is to calculate the change in IW, operationalizing Equation 3 between 1991 and 2001. It is the change in IW over time (not the absolute measure of IW at any point) that provides the assessment of sustainable development. The constant prices identified in Equation 3 change depending on the form of analysis conducted. For example, to determine the change in IW between 1991 and 2001, the constant price is the average of the 1991 and 2001 prices. But if the change in IW associated with a policy option is under investigation, then the constant price is the average of the two prices, for example the average price between Policy 1 (e.g., Business as Usual) and Policy 2 (e.g., Double Production).

**Results: IW in GBC**

Before presenting our results, we stress that our objective was to explore the promise, weaknesses, and difficulties of implementing IW and present the results as a basis for this discussion, not to provide a comprehensive sustainability assessment. This is an illustrative exercise, based on an analysis of the stocks underpinning only four flows and using unfined shadow-price estimates. We present the results only to show how IW could be used to inform policy and to uncover practical and theoretical hurdles to its use. They cannot be used as the basis for any policy decisions in GBC.

**Monitoring IW Over Time: Was the Pattern of Resource Allocation Sustainable?**

To illustrate IW as a tool for monitoring sustainable development, we calculated the change in IW over the period 1991–2001 for two different climatic forecasts (wet and dry, as described in Step 3). Including resilience considerations, we find that between 1991 and 2001, IW in GBC increased under both forecasts. Notably, under the dry forecast it increased by AUSS6.9 billion (US$5.2 billion), with natural capital contributing 92% of this growth (Figure 3). This difference between 1991 and 2001 under the dry forecast is about 19% of the 1991 IW value. The increase in natural capital under the dry forecast is mainly due to the decreased risk of salini-

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Table 2: Assumed depths to the water table (m) in 1991 and 2001 and forecast depths in 2030 under different climatic and policy conditions. Cumulative probabilities (%) were calculated through 2030 (i.e., over a 40-year period from 1991 and 30-year period from 2001), assuming a linear increase in the depth to the water table between 1991, 2001, and 2030.

|                         | 1991 | 2001 | 2030 Business as Usual | 2030 Double Production |
|-------------------------|------|------|------------------------|------------------------|
|                         |      |      | Dry | Wet | Dry | Wet | Dry | Wet |
| **Irrigated Agricultural Land** |      |      | 2.5 | 2.1 | 3   | 2.3 |     |     |
| Depth                   | 3    | 3.5  | 2.5 | 2.1 | 3   | 2.3 |     |     |
| \( F_{1991} \)          |      |      | 100%| 100%| 100%| 100%|     |     |
| \( F_{2001} \)          |      |      | 100%| 100%| 99.96%| 100%|     |     |
| **Nonirrigated Agricultural Land** |      |      | 4   | 3.5 | 4.5 | 3.7 |     |     |
| Depth                   | 3.5  | 4    | 4   | 3.5 | 4.5 | 3.7 |     |     |
| \( F_{1991} \)          |      |      | 85.69%| 97.18%| 70.78%| 93.57%|     |     |
| \( F_{2001} \)          |      |      | 59.34%| 85.69%| 38.78%| 75.37%|     |     |
| **Native Vegetation**   |      |      | 5.5 | 4   | 6   | 4.5 |     |     |
| Depth                   | 4.5  | 5    | 5.5 | 4   | 6   | 4.5 |     |     |
| \( F_{1991} \)          |      |      | 7.55%| 38.78%| 5.43%| 20.34%|     |     |
| \( F_{2001} \)          |      |      | 3.09%| 26.70%| 1.97%| 11.66%|     |     |
zation in irrigated land, specifically irrigated dairy pasture and horticultural land during this forecast (see Table 2 for GWT depths under forecasts).

The wet forecast also resulted in an increase in wealth, indicating that the resources in GBC were used sustainably between 1991 and 2001. However, the magnitude of change under the wet forecast was only 16% of that found under the dry forecast. The difference between the forecasts illustrates the sensitivity of IW estimates to expectations of the future and shows the care required in interpreting the results.

Built capital is found to have decreased by AUS$270 million (US$210 million) over the period 1991–2001 under both forecasts. These decreases are mainly due to the reduction in dairy-processing plants in the region (arising from individual strategies of international companies) and lack of reinvestment by companies or government into new assets. Under the wet scenario, there are additional losses to public infrastructure and irrigation systems because of increased flooding. Human capital, by contrast, is estimated to have stayed constant with no significant change in human labor over time.

If salinization risk is not included in the estimate, IW is found to increase under both forecasts, by AUS$840 million (US$640 million) under the dry forecast and AUS$830 million (US$630 million) under the wet forecast. This result shows that accounting for the salinization risk delivers the same direction of wealth (i.e., nondeclining), but the magnitude is dramatically different; under the dry scenario, wealth increases by 12% while under the wet scenario, wealth increases by 75%. Consideration of risk can have a marked impact on the IW estimates.

**Policy Application**

We use a proposed policy under discussion in GBC to illustrate the application of IW to the problem of assessing proposed projects or policy changes. We explore the outcome of perturbing the 2001 land-use allocation with a proposal to retire half the agricultural land (primarily in the dryland agricultural area) in the interests of improving natural ecosystems and their functioning, and to double production on the remainder of the agricultural land. We compare the outcome under this scenario—Double Production (DP)—to a continuation of current trends—Business as Usual (BAU). In assessing this policy application, we use constant 2001 prices with predicted 2030 stock quantities, where stock quantities are assumed to be 2001 unless perturbed by the policy as detailed below.

The forecast changes in capital stocks as a result of the DP policy are: i) 50% of the agricultural land is retired by 2030, all of it being nonirrigated dryland agricultural land, which is converted to natural terrestrial ecosystems in poor condition and used for nature-conservation purposes; ii) All the remaining agricultural land moves from its present productivity class to a 50% higher productivity class (with a higher associated shadow price). We assume that both these transformations occur linearly over the forecast period. Under the policy, the 2001 shadow price of any unit of dryland agricultural land therefore reflects the expectation that 50% of the land is to be retired to nature conservation by 2030 and the
remaining 50% of the land is to double in production by 2030.

We also include the impacts of increased native vegetation cover on biodiversity. Once the cover of native vegetation (natural terrestrial ecosystems) gets above 30% for the whole catchment, the nature-conservation value associated with this stock increases significantly (Bennett & Ford, 1997). This native vegetation threshold is a straightforward step-wise function: before the 30% threshold is reached, each additional unit of native vegetation has a relatively low value; once the cover of native vegetation exceeds 30% of the landscape, all further marginal increases have a higher value. We have included the estimated increase (35%) by weighting the pre-threshold and post-threshold prices by the proportion of the forecasted three decades that would be in each state. Assuming a linear retirement of land over the next 30 years, the 30% cover threshold is reached in ten years under the DP scenario.

The GWT were assumed to rise or fall linearly over the 30-year scenario period, assuming depths as given in Table 2. Increased vegetation cover under the DP scenario results in increased transpiration, and therefore lower GWT as compared to the BAU scenario. However, the gains under the DP scenario would be partly offset by a higher rainfall period. The impact of the changed expectations of the future that would occur under the DP scenario is therefore examined under both climatic forecasts.

Under the dry climatic condition, the BAU policy results in a considerably higher IW value. Conversely, under the wet forecast the DP policy results in a higher value of wealth. The difference between the BAU and DP policy results can be interpreted as the maximum amount society could pay to keep the GWT further away from the surface (i.e., at a lower probability of crossing the threshold). The reduction in wealth under the wet forecast is principally related to the decrease in resilience stock associated with a rising GWT. Therefore, in addition to the IW results based on the aggregate set of shadow prices, we also analyzed IW based on shadow prices that reflect the view of a particular sector of society.

Sectoral IW can be included in a variety of ways; we chose to adjust the aggregate social shadow prices to reflect IW as if the entire current population were composed of the sector under consideration.

We estimated a modified set of shadow prices (for the same changes in stock quantities) for a so-called “green” sector. These prices reflect substantially higher values accorded to nature conservation and related flows than the societal average. We have assumed that the proportional differences in value placed on flows, such as dairy and nature conservation, are equivalent to the proportional differences in the shadow prices of the stocks underpinning those flows. For example, we estimate that the green sector values nature conservation 50% higher than society on average, and have therefore assumed the shadow prices of all stocks with respect of their value to nature conservation to be 50% higher. Analogously, we estimated dairy and dryland agricultural flows to each be 25% lower and carbon sequestration 50% higher.

Our estimates of change in IW between 1991 and 2001 from the perspective of the green sector show a similar pattern to those of the aggregate society, although the values of IW are generally much lower. Significantly, under the dry BAU forecast, the green sector has a slightly higher IW than the aggregate. This is due to the increased weighting placed on natural capital by the green sector and the significant increase in natural capital under the dry forecast (see earlier discussion on change in IW estimates for rationale of why this has occurred). Such an analysis is useful because it confirms that aggregate changes in society can mask major losses or gains for particular sectors.

**Accounting for Price Changes: Capital Gains and the Drift Term**

When assessing IW between two points in time, changes in both the quantities and the prices need to be considered. Although changes in stock quantities, not prices, are used in determining whether IW is being maintained, two sources of price changes need to be identified when considering how prices should be treated: internal and external to the region of analysis. Internal price changes assume that the region under investigation is large and “powerful” and determines all its shadow prices; therefore, changes in shadow price are regarded as internal, or related to capital gains. External price changes assume a small region with little influence over changes in prices due to the “global” markets in which the stocks are
We propose two practical approaches to implementing a discrete measure of time-dependent IW for a small region. The first is negating the impact of price change by using an average/constant price for the two years, as done in this exemplar model. This negates both internal and external price changes. The change in IW is then given by \( V_T - V_0 = \sum p_i[K_{it} - K_{i0}] \) (Equation 2). The second approach assumes all price changes are external, that the region under investigation has little influence over changes in prices. All changes in price are attributed to external impacts, are therefore considered the drift term, and are included in the estimates (i.e., \( V_T - V_0 = \sum [p_f K_{iT} - p_o K_{i0}] \)).

Alternatively, we could assume that the region under investigation is large and “powerful” and determines all shadow prices. Therefore, all shadow price changes are regarded as internal, or related to capital gains, and are deducted from the IW estimate (i.e., \( V_T - V_0 = \sum [p_f K_{iT} - p_o K_{i0}] - \int \left[ \sum \frac{dp_i}{dt} K_{i0} \right] dt \)).

For our trial, we used the first, small-region approach. However, to test the significance and importance of the assumptions held under this procedure, we implemented all three of the above approaches to discrete measures of three stocks: dairy cattle, sheep, and beef cattle, as they relate to dairy production and processing and to dryland agriculture under the BAU scenario. All data were derived from available statistics using market prices and quantities per farm. Although these methods are at the extremes, they are useful in determining the sensitivity of IW estimates to alternate approaches (constructions) of the region under investigation. The legitimacy of estimating capital gains and a drift term on shadow prices, renewable capital stocks, and moveable capital stocks was not addressed in this analysis.

Depending on the method used, the trend and the magnitude of change in IW between 1991 and 2001 can vary for some stocks (Figure 4). For beef cattle, assuming all price change is due to capital gains resulted in an estimated increase in IW, whereas the other methods suggested a reduction in IW. This is because the capital gains for beef were estimated to be negative, and were therefore added, rather than deducted, from IW. The constant prices and drift-term methods yielded similar results in trend and contribution of components stocks (i.e., sheep, beef, and dairy cattle), which is appropriate as they are both considered suitable for small open regional analysis. This result raises concern about the legitimacy of deducting capital gains components from small open regions with highly moveable capital stocks (e.g., cattle) and about the data available to estimate this impact accurately.

**Issues to Consider in Using IW as a Policy Tool**

Our implementation of IW has raised theoretical and methodological issues and some practical hurdles. We discuss them here with some suggestions for how they might be addressed in a full-scale implementation of IW. Fundamentally, the definitions of sustainability, and the construction of measures to assess whether we are acting sustainably or otherwise, are contested territory among scholars, as is highlighted in survey treatments such as Neumayer (2004; 2010) and Pezzey & Toman (2002; 2005). Furthermore, the fundamental subjectivity of sustainability concepts and measures is emphasized by Gasparatos (2010) and Vatn (2005; 2009). The recent report of the Commission on the Measure of Economic Performance and Social Progress (Stiglitz et al. 2009) makes plain the difficulty of settling on one overarching headline indicator, as opposed to taking a “dashboard” approach. Hanley et al. (1999) demonstrate the conflicting diagnoses that emerge from various indicators, including Genuine Savings, the Ecological Footprint, and the Genuine Progress Indicator. However, IW has attained international interest through the UNU-IHDP & UNEP (2012) report *Measuring Progress Toward Sustainability*, ensuring that the issues raised here have direct policy application, as well as academic merit. These valid concerns
and disagreements notwithstanding, we believe wealth, defined inclusively as per IW, represents a meaningful and robust measure of aggregate sustainability that can be applied at multiple scales and used to meaningfully assess tradeoffs between alternative development/management options. It has been employed in various contexts, including by Lange (2004) in the context of comparing national reinvestment rules aimed at turning resource deposits into sustainable income streams. More ambitiously, Arrow et al. (2004) and Ehrlich & Goulder (2007) indicate that, in terms of consumption flows, the composition is the stronger driver of unsustainability in a number of countries than is the volume (relative to investment back into improving/increasing the stock of valuable assets). Randall (2008), meanwhile, counsels a hybrid approach of savings/wealth-based analysis (not including resilience as per Walker et al. 2010 and this article) and resource-specific biophysical indicators where concerns are raised around legitimacy of “critical capital stocks” and their significance to global functioning ecosystems. Incorporating (changes in) resilience into wealth measures is a potentially significant step in improving the sustainability interpretation provided by such measures.

Despite its contested theoretical standing, IW has been adopted by the United Nations as a potential measure for long-term national sustainability (UNU-IHDP & UNEP, 2012). As such, this article further refines the application of IW by resolving five methodological and practical issues, as discussed below.

Identification of Stocks
The use of a production-systems framework to identify critical capital stocks, based on identified important flows, proves to be useful and workable. The difficult step was to assemble the “right” group of stakeholders, including those who live outside the region. This also relates to the issue of deriving different sectoral IW estimates to address intragenerational equity issues.

Lack of a Methodology and Data for Estimating Shadow Prices
Different approaches to shadow pricing yield different results, and no single method adequately addresses the complex value a shadow price aims to portray. There are no direct data for real, social values ascribed to capital stocks, and prices need to be inferred from various sources. For this exemplar model, we used a single estimate derived from either market or benefit-transfer approaches. However, even these price estimates are subject to substantial uncertainties. An acceptable and credible way to estimate shadow prices is a key requirement for the IW approach to become generally useful. An appropriate way might be to use several different price estimates, bounding the shadow price and iterating toward an acceptable value. Whether this results in repeatable and acceptable estimates will determine if change in IW is a useful, practical tool for assessing sustainability.

Sensitivity of Shadow Prices to Forecasts of the Future
Our trial results clearly illustrate the sensitivity of IW to expectations of the future. To address this sensitivity, we suggest that any analysis of IW needs to incorporate multiple forecasts. A remaining research issue is a rigorous way of choosing forecasts that will prove acceptable to all involved and that will enable assessment of the estimates’ sensitivity to future uncertainties.

Sectoral Bias: The Equity Issue Uncovered
The IW technique assesses intragenerational equity under a policy-analysis scenario. We provided one approach, the “sector analysis,” as sectoral distinctions are important for policy makers. Our analyses show that average aggregate assessments of IW, particularly for proposed policy developments, do not make explicit substantial differences in winners and losers within different groups in society. In other words, the method does not fully expose intragenerational equity concerns. We have presented a crude approach for adjusting aggregate shadow prices to reflect those of a particular sector, but how to best do this requires further consideration. Additionally, the question of intergenerational equity is captured in IW through the nondeclining wealth rule. This assumes the use of discount rates, which is controversial in some circles and does not take into account broader equity issues such as justice and freedom (see Goulder & Stavins, 2002).

Incorporating Risk
We applied the theoretical approach for incorporating resilience developed in Walker et al. (2010). Our results suggest that resilience and threshold effects can be important in an assessment of IW and need to be included in the analysis. A practical limitation is the ability to identify which stocks have, or are likely to have, threshold effects, where the thresholds might be, and how to assess the value of the stock in its alternative states. These issues can be dealt with in a probabilistic way, as is done in this article. Incorporating estimates of such probabilities is a significant advance over not considering resilience at all. This approach directly addresses “specified resilience;” however, it does not address...
the issue of “general resilience,” which refers to a system’s vulnerability to all threats known and unknown.

Conclusion

In theory, the IW framework uses a single philosophical perspective (based in the economics discipline) to assess a region’s sustainability. In practice, the framework may not address the full criteria necessary for a sustainability assessment. Other philosophical perspectives raise, for example, the importance of intragenerational equity, justice, and freedom. Additionally, a substantial practical problem with the framework is estimating the shadow price of goods and services.

Based on this trial implementation of IW, we have suggested how full-scale IW assessments can overcome some methodological issues and hurdles and highlighted where outstanding theoretical issues need to be resolved. While precise, universally acceptable estimates of IW are impossible in practice, we nevertheless believe that IW is a valuable addition to the policy-making toolkit as it does more than assess the costs and benefits of policy options; it assesses their sustainability. We can only wonder what decisions could have been made over the last 30 years if policy makers were able to test the sustainability of proposals as well as their economic efficiency.

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