Using inclusive wealth for dynamic analyses of sustainable development: Theory, reflection and application

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Abstract

The concept of inclusive wealth as an indicator of sustainable development has garnered increasing attention in academic and policy circles. Inclusive wealth is defined as the value-sum of a country's capital asset stocks, and the associated economic theory states that development is sustainable if this value-sum does not decline through time. This framework for conceptualizing sustainable development should have immediate appeal to the system dynamics community given the centrality of capital stocks, and it represents potential for reaching common ground with the economics community. This paper describes the inclusive wealth framework, highlights gaps in the current literature, as well as areas rife for future system dynamics research. To illustrate how one might apply the framework in a system dynamics case study, it uses water and energy infrastructure policy in the Kingdom of Saudi Arabia (KSA) as an example. Some preliminary results from the case study are presented and analyzed in the context of sustainable development. The paper concludes by discussing how the system dynamics community can embrace the theoretical advances of the inclusive wealth framework in their applied work on sustainable development.

Keywords: sustainable development, wealth, policy analysis, Saudi Arabia

Word count (sans figures, footnotes and references): 4,978

1. Introduction

1.1 What is Inclusive Wealth?

Inclusive wealth, a term coined by the UN in a recent report (UNU-IHDP, 2012), embodies the culmination of decades of research in welfare economics on the topic of sustainable development[1]. Inclusive wealth (henceforth simply wealth) is ultimately a measure of an economy's *productive base*, and it is tightly related to the concept of *intergenerational wellbeing*. Previous theoretical work (Dasgupta & Mäler, 2000; Hamilton & Clemens, 1999) showed that the determinants of intergenerational wellbeing are the multitude of *capital assets* in an economy, and furthermore that the weighted sum of the stocks of those assets is the criterion function of sustainable development. Thus the weights are the marginal contributions of the stocks to intergenerational wellbeing, also called the assets' *shadow prices*, and the weighted sum is the economy's wealth. Mathematically the framework can be shown with a few simple equations; let S be a vector of the capital stocks in an economy at time t (these include produced capital K, human capital L and natural capital N), V the value function for determining intergenerational wellbeing (in this formulation it is simply the discounted stream of future consumption), p_i the shadow price of capital asset i and W the total wealth of the economy.

$$S(t) = \langle K(t), L(t), N(t) \rangle$$

$$V(S(t),t) \equiv \int_t^\infty \left[U(C(S(t),\tau)) e^{-\delta(\tau - t)} \right] d\tau$$

$$p_K(S,t) = \frac{\partial V(S,t)}{\partial K(t)}$$

$$p_L(S,t) = \frac{\partial V(S,t)}{\partial L(t)}$$

$$p_N(S,t) = \frac{\partial V(S,t)}{\partial N(t)}$$

$$W(t) = p_K(t)K(t) + p_L(t)L(t) + p_N(t)N(t)$$

[1] This paper will not provide a comprehensive review of this research, but a few things of note are worth mentioning. Erik Lindahl, a Swedish economist in the early 20th century, was one of the first to theorize about sustainable development, stating that aggregate consumption must not surpass net national product (NNP) if an economy's wealth is not to decline (Lindahl, 1933). John Hartwick, a resource economist, later shifted the sustainability discussion from income to wealth, stating that investment in produced capital must offset any decline in nonrenewable resource stocks in order to achieve sustainable development (Hartwick, 1977). The World Bank (2006) built on Hartwick's rule by also including investments in human capital and damage caused by pollution in their calculation, calling the resultant sum adjusted net savings, or genuine savings. Negative genuine savings imply that total wealth is in decline, i.e. development is not sustainable. The World Bank (2011) eventually established their own criterion for sustainable development, called comprehensive wealth. There are some theoretical differences between inclusive and comprehensive wealth, but the general approach is the same.

The time derivative of W is the total investment (or disinvestment) in wealth at time t, holding shadow prices constant (Dasgupta, 2009). Thus it is the changes in the capital stocks that are central to determining the sustainability of a particular development path. If wealth is declining (i.e. time derivative is negative), development is not sustainable. The above formulation uses produced (K), human (L) and natural capital (N), but the literature is still evolving to answer what constitutes the capital assets of an economy. Nonetheless, it is generally accepted that most assets fall under the following categories:

- *Produced capital* – also called reproducible, manufactured, man-made or physical capital; includes the buildings, machines and technical equipment used in production
- *Natural capital* – includes the nonrenewable (oil, gas, minerals) and renewable (forests, fisheries, cropland) natural resources of an economy, as well as ecosystem services from which the economy benefits
- *Human capital* – measurable in a variety of ways, but captures the educational attainment, skills, core competencies and health of the total and working population
- *Social capital* – embodied in the institutions, rules, norms and culture of a society; it is also a measure of trust in personal and business relations
- *Knowledge capital* – the collection of technologies and information to which an economy, and its citizens, have access

All of these together comprise the productive base of a society, thus measuring and tracking their development through time is crucial to evaluating whether development is sustainable. Empirical work in wealth accounting has measured changes to produced, human and natural capital in various countries of the world (Arrow et al., 2012; UNU-IHDP, 2012), discussed in the next section. Social and knowledge capital are more difficult to quantify as stocks, though recent work has attempted to operationalize social capital from the standpoint of trust (Morrone et al., 2009), relationships (Ostrom & Ahn, 2009) and resilience (Hall & Lamont, 2013), as well as measure the benefit of increased access to certain types of knowledge capital (Jensen, 2007).

1.2 Previous work in wealth accounting

The 2012 Inclusive Wealth Report (IWR), authored by the United Nations University's International Human Dimension Program (UNU-IHDP, 2012), calculated wealth for 20 countries over the 1990-2008 time period. Details can be obtained from the methodological annex of the IWR.

It is important to note that the calculations do not use shadow prices. As the authors humbly point out, true calculation of an asset's shadow price – that is, its overall contribution to intergenerational wellbeing net of externalities, expectations, scarcity and non-market benefits (Arrow et al., 2012; Dasgupta, 2009) – is an elusive task in need of further research. Thus, where available the report uses market prices to value the stocks of capital, e.g. the capital stock of oil in a country is valued at the price it fetches in the international market. While admittedly a limitation for applying the theory, the results are nonetheless illustrative of the differential endowments and trajectories of wealth across the world.

Figure 1 shows the average annual growth rate for wealth per capita across the 20 countries. The per capita calculation is an interesting extension to wealth, since a population growing faster than wealth implies less available wealth for each person in the country. Arrow et al. (2012) discuss the nuances of including population growth in wealth estimates and how this affects the definition of sustainable development.

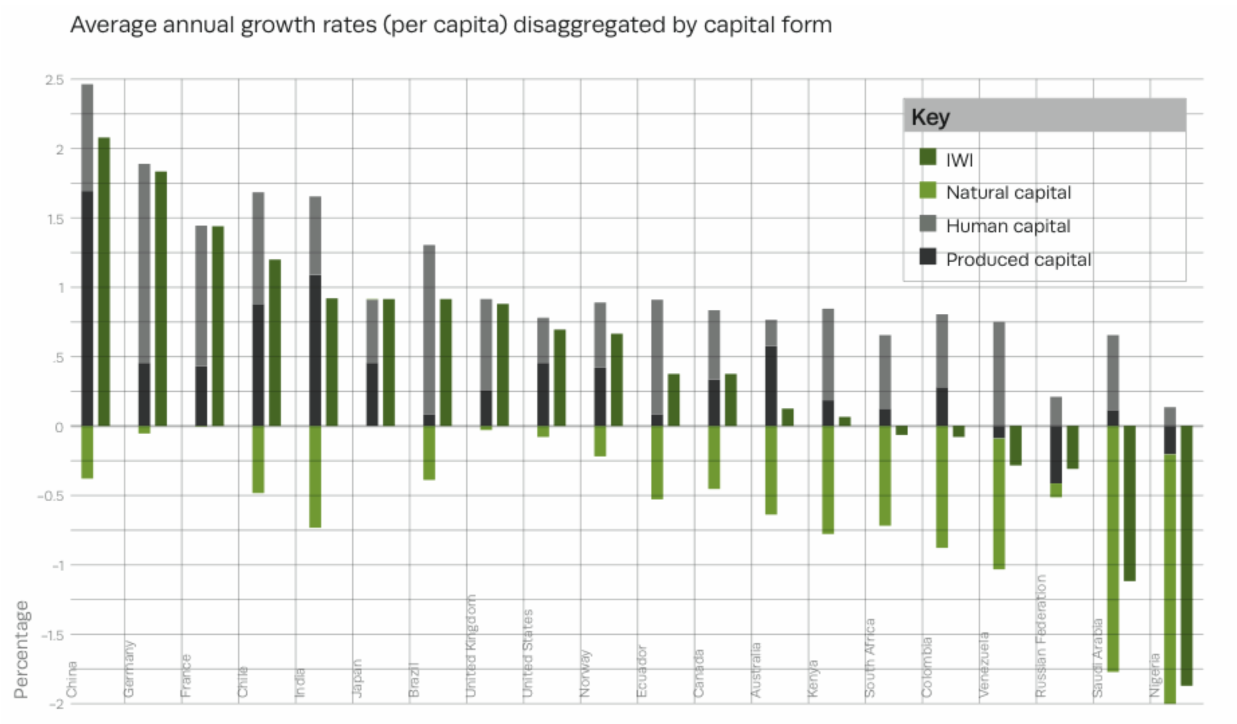

Figure 1: From p. 34 of the IWR (UNU-IHDP, 2012).

From the figure it is evident that composition of wealth varies across the developing and industrialized world. On the right are countries heavily dependent on natural capital (in particular fossil fuels), and thus high rates of extraction and population growth are leading to low or negative wealth growth rates. On the left are countries from Europe and North America with large amounts of human capital driving their economies[2]. Some notable exceptions, however, include countries like China and India, who have increased their wealth largely through rapid investment in produced capital, thus offsetting any declines in natural capital.

1.3 Addressing gaps in the literature with system dynamics

Empirical work in wealth accounting has advanced via measurement our understanding of sustainable development. However, a significant gap in the literature is that all work thus far has been *retrospective*, meaning that key questions concerning whether development *will be* sustainable in any of the countries analyzed remain unanswered. Projecting wealth, its constituent capitals and other policy-relevant metrics is a necessary component of any policy

[2] Since the wealth accounting draws boundaries around each country, it does not take into account the vast amount of natural capital transfers that occur from the developing to industrialized countries. Trade-adjusted, "virtual" capital accounts are discussed in Chapter 5 of the IWR, taking into account the resource depletion and pollution damages caused by country *X* consuming the resources produced in country *Y*.

analysis, particularly if one wants to evaluate and ultimately choose among different policy options. Therefore *prospective* assessments of wealth, its long-run trajectory, and sensitivity to policies implemented in the near-term represent a fruitful area for further research. Given that the trajectories of capital stocks – and importantly their interactions and feedback with one another – will dictate the evolution of wealth, system dynamics is an appropriate methodological approach for operationalizing inclusive wealth in a prospective framework.

Interestingly, Donella Meadows (1998) described in a report out of the Balaton Group[3] a potential dynamic framework for organizing analyses of sustainable development based on the "capitals" approach. Meadows, presumably speaking on behalf of the majority of the group, adopted the capitals approach of the economics community (largely being developed by the World Bank at the time) but offered some key additions. In particular, she organized the capitals into a triangular hierarchical framework based on the work of ecological economist Herman Daly (1973). Figure 2 depicts the hierarchy: natural capital is the ultimate means on which the economy and society depend; through science and technology natural capital can be converted into built (i.e. produced) or human capital, the intermediate means; through mechanisms of political economy the built and human capital can grow a society's social capital, the intermediate ends (human capital is included here as well since simply growing the stock of human capital can be conceived as an end in and of itself); finally through theology and ethics the social and human capital can cultivate increased wellbeing, the ultimate ends. While both Meadows and the inclusive wealth authors denote [intergenerational] wellbeing as the ultimate measure to be maximized, the hierarchical distinction made by Meadows implies that natural capital is the *sine qua non* of sustainable development.

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[3] The Balaton Group is a global network of researchers and practitioners in fields related to systems and sustainability. Dennis and Donella Meadows founded the organization in 1982 to review the state of the art in natural resource modeling and identify ways to advance the theory and practice of regional resource management. Website: http://www.balatongroup.org/

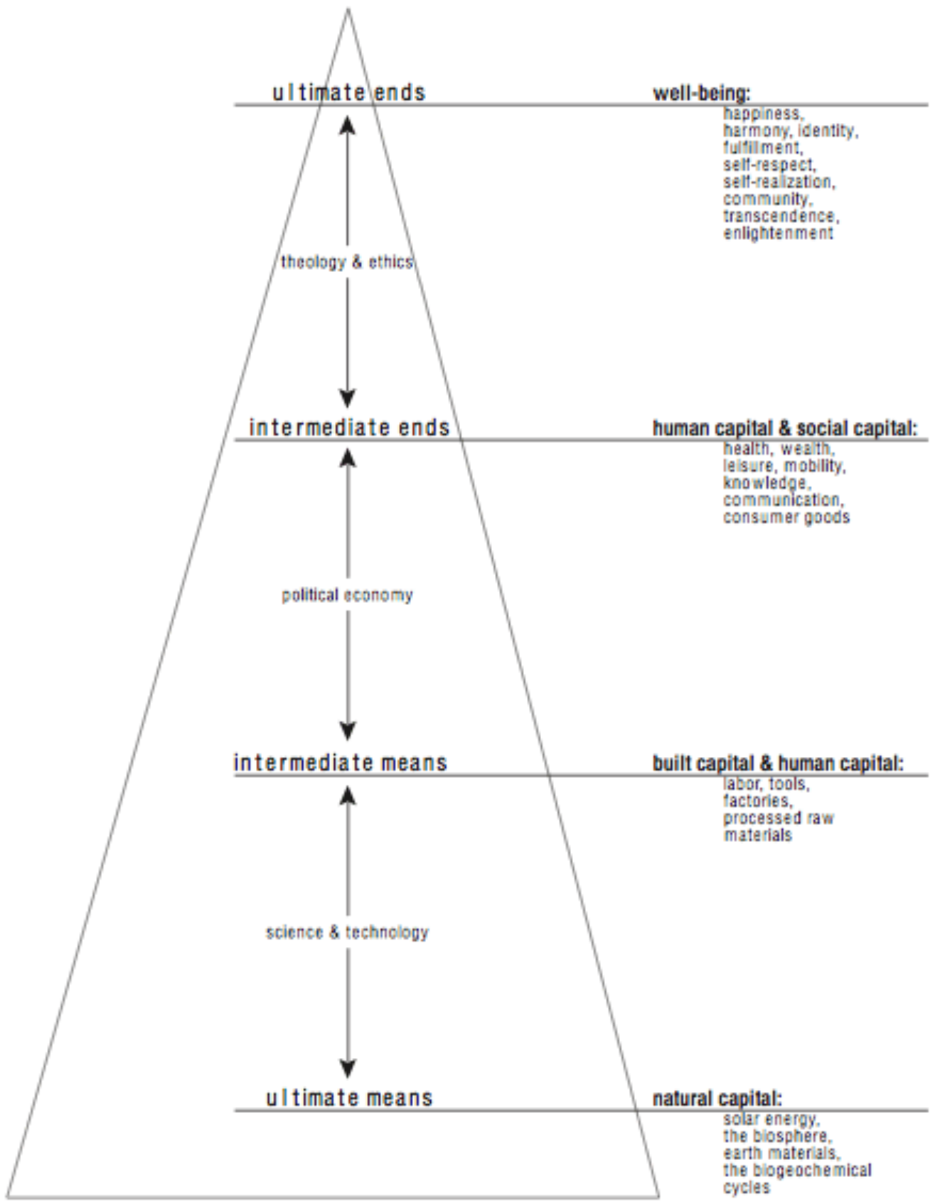

Figure 2: Hierarchical framework of the wealth/capitals approach to sustainable development (Meadows, 1998).

In addition to organizing the capitals hierarchically, Meadows commented on the need to organize the capitals as a dynamic system. In other words, the rates and accumulations of natural capital will impact the rates and accumulations of built capital, which in turn affect human and social capital based on how the built (or what she calls "industrial") capital is spent and/or invested. This systems view is largely absent from the inclusive wealth literature. Though the authors recognize that there are linkages among the capital stocks and that nonlinear dynamics could lead to tipping points or bifurcations in natural (and thus potentially socioeconomic) systems, the missing link still lies in the fact that forward-looking analysis has yet to be conducted.

2. Reflections on initial modeling attempts

I'd like to reflect briefly on some of my preliminary thoughts connecting inclusive wealth with system dynamics. Having developed academically with one foot in engineering and one foot in economics, I cannot resist trying to reconcile the theories of system dynamics and economics (particularly macroeconomics). To me, inclusive wealth represents the culmination of a very gradual understanding in the economics community that there is more to economic development than simply adding more capital (used here in its simplest sense) and labor inputs. The problem of how to manage declining natural resource stocks has a longer history of attention (Hartwick, 1977; Hotelling, 1931), but the broader concerns of natural capital erosion (e.g. climate change, water scarcity, nutrient overloading, etc.) are only recently being brought to the fore of economic modeling. On the other hand, I would argue that the system dynamics community (to the extent that the entire community consists of "systems thinkers") has long understood the "inconvenient" variables of economic development and their relation to long-term development. The methodological hump that the system dynamics community needed to get over – at least to be taken seriously by the economics community – was empirically grounding their models. Again, I would argue that the system dynamics community has made major strides in this regard over the years. Figure 3 outlines a notional view of the progression of these two literatures. While the factors emphasized in modeling are different, I think the literatures are more or less converging on how to tackle problems of sustainable development. Shilling (2003) made a similar observation at the 21st System Dynamics Conference and others have written extensively on the overlap of the fields (e.g. Radzicki, 2011).

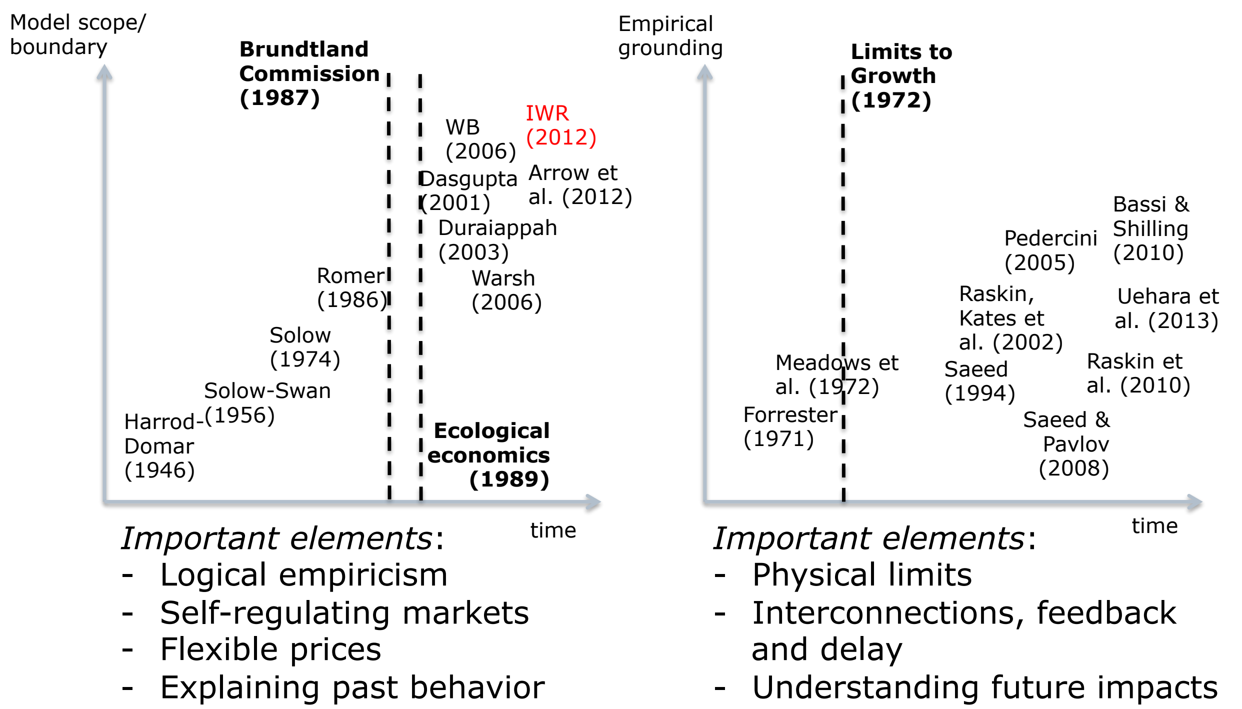

Figure 3: A tale of two complementary [sustainable] development literatures: macroeconomics (left) and system dynamics (right). Reference placement in the 2D space is notional.

Armed with the tools of inclusive wealth and system dynamics, I must admit that I then fell into the seductive trap of *modeling the system, not the problem*. I saw inclusive wealth as an entry point into revisiting the structure of the World models – in particular expanding the set of capital stocks to include more than just industrial capital – but targeted instead for national analyses. Model boundary issues notwithstanding (there is, after all, the issue of capital flows across country borders), I thought merging these bodies of work could lead to country-specific policy prescriptions, in contrast to broad global strategies. As a researcher for the Center for Complex Engineering Systems (CCES)[4], my initial thought was to study development issues in the Kingdom of Saudi Arabia (KSA). It quickly became clear, however, that by focusing on all of the capital management issues at once (and trying to model their numerous interdependencies) I was either going to become inundated with complexity or end up providing watered-down policy conclusions based on spurious model structure, or both. I realized that I needed to focus my efforts on one aspect of sustainable development in Saudi Arabia, which meant defining the specific problem I wanted to address, and consequently modeling only a subset of the capital asset stocks that comprise the productive base.

3. Applying the inclusive wealth framework

In focusing my wealth-system dynamics modeling I zeroed in on the infrastructure and economic challenges of managing the water-energy nexus in KSA.

3.1 Water and energy infrastructure systems in Saudi Arabia

In recent years, KSA has seen annual growth in population of 2-3% and GDP of 6-7%. These trends have led to an even faster growth rate in the consumption of goods and services, including potable water, energy and transportation services, among others. This consumption growth is explained not only by socioeconomic trends, but also by the subsidization of water and energy to farmers, industry and the public at large. Thus not surprisingly, demands for the infrastructure that provide water and energy are also growing rapidly.

While KSA currently possesses the financial resources to facilitate such a broad infrastructure rollout, a major question surrounds the extent to which these new infrastructures will diminish the valuable natural capital base on which the KSA economy heavily depends, impacting sustainable development. This base consists almost entirely of fossil resources, including aquifer water, oil and natural gas. The agricultural sector, which has grown considerably since food security policies were enacted following the 1970s energy crises (FAO, 1997, 2009), consumes nearly 90% of the yearly water supply, the bulk of which comes from groundwater abstraction. Measurements indicate that water levels in key aquifers have dropped by dozens of meters, and there is substantial concern and uncertainty surrounding the amount of usable water remaining (Abderrahman, 2006; Al-Ibrahim, 1991; Kalbus et al., 2011). What is nonetheless certain is that

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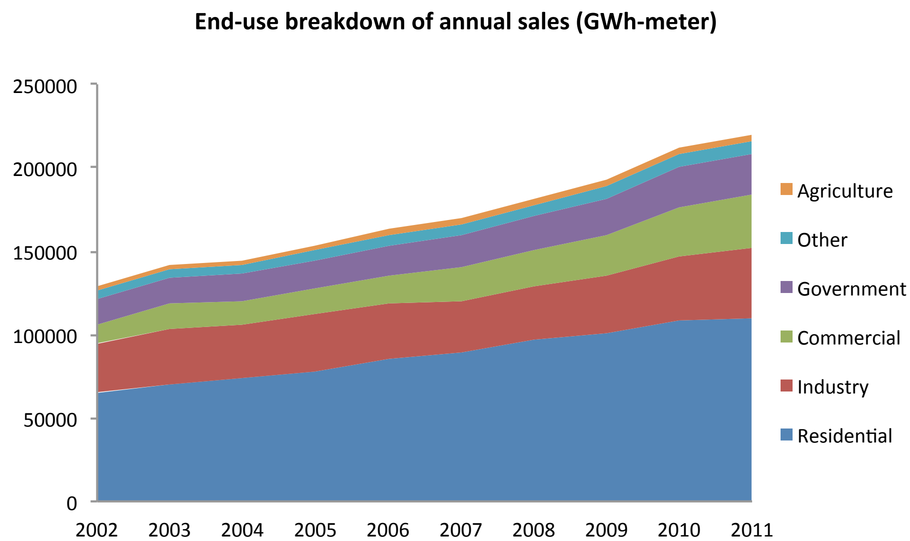
[4] CCES is a joint research venture between MIT, housed in the Engineering Systems Division, and the King Abdulaziz City for Science & Technology (KACST) in Riyadh, Saudi Arabia. The center has many projects but nearly all are concerned with long-term infrastructure investments in increasingly interlinked systems as well as the corresponding policy decisions to be made under uncertainty. Website: http://www.cces-kacst-mit.org/

a declining water table will require increased desalination investment, an energy-intensive water supply option.

At the same time, residential and industrial demand for energy has led to precipitous increases in both primary energy production and electricity generation capacity independently of the water sector's growing demand for energy. In the past ten years alone, generation capacity has nearly doubled from roughly 28 GW in 2002 to 54 GW in 2012 (SEC, 2013). Peak power demand, however, is expected to nearly triple over the next 20 years (ECRA, 2009), requiring additional capacity rollout. The subsidized energy prices have served an important economic development goal, as foreign direct investment in KSA has increased considerably, but they also encourage inefficient use of resources in an electricity system that currently runs entirely on oil and natural gas (approximately 50% each). This growing domestic consumption represents a serious economic challenge to KSA, a country where oil exports contribute more than 65% to GDP[5] (Al-Ahmed, 2012). The following figures illustrate some of these reference modes.



[5] According to the CIA (2013), the petroleum sector in KSA accounts for roughly 80% of budget revenues, 45% of GDP, and 90% of export earnings.

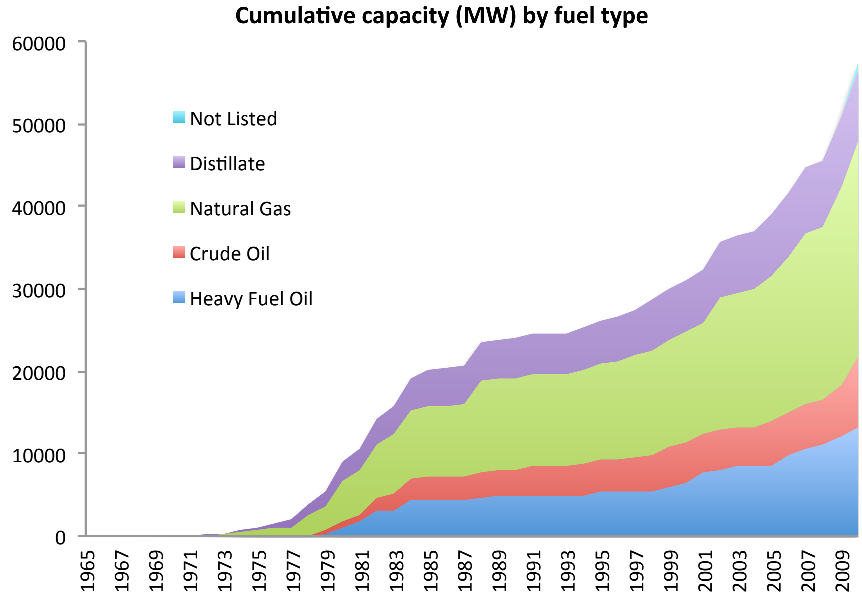
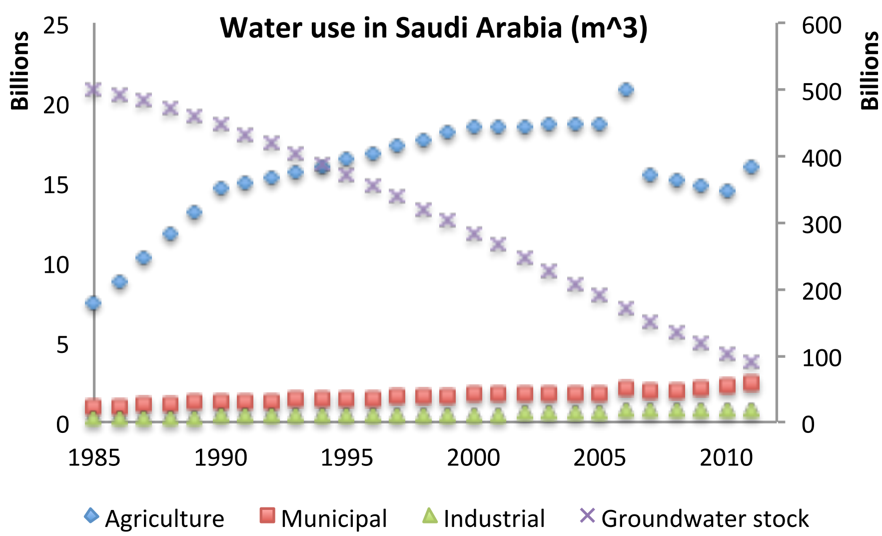


Figure 4: Electricity demand (top figure) in KSA is driven largely by residential (approx. 50%), where air conditioning loads represent 70% of that demand. Electricity supply (bottom figure) is fueled entirely by oil, its derivatives and natural gas. Sources: (ECRA, 2012; SEC, 2013)



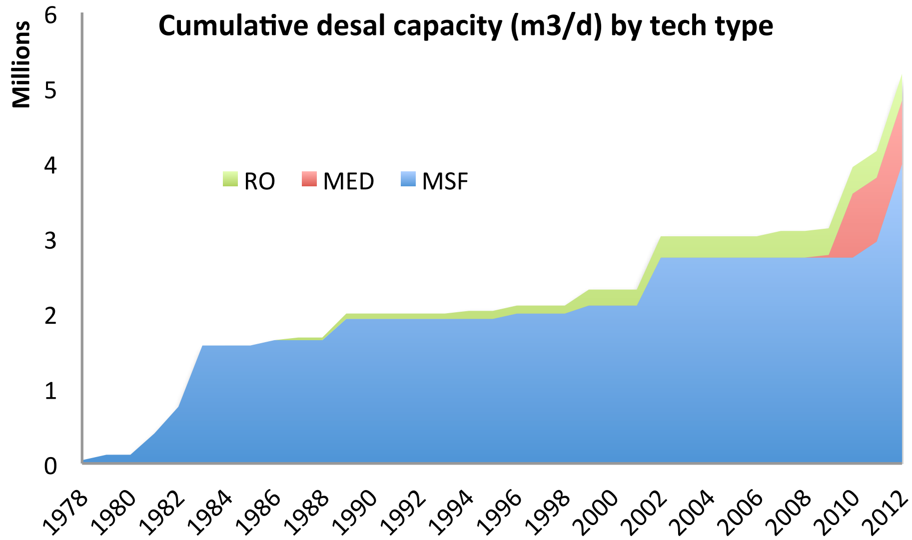


Figure 5: The vast majority of water demand (top figure) in KSA comes from the agricultural sector, which has depleted aquifer stocks rapidly. Water is increasingly being supplied by desalination (bottom figure), though this is now largely for the municipal sector. Sources: (Al-Turbak, 2012; GWI, 2013; MoWE, 2012)

To summarize in the context of inclusive wealth, this case presents a problem of natural capital management mediated by produced capital decisions, namely the technologies and policies associated with the water and electricity infrastructures. Recent studies have indicated that, based on the electricity reference modes alone, Saudi Arabia could become a net oil *importer* some time in the next 2-3 decades (Al-Ahmed, 2012; Lahn & Stevens, 2011), which has enormous sustainable development implications for the kingdom.

3.2 Model development

A useful starting point for any system dynamics modeling effort is the set of system archetypes that the community has codified over the years (see Braun, 2002; Senge, 1990). After collecting the data and doing some preliminary causal mapping, it became clear that the water-energy nexus challenge in KSA is an instantiation of the *Attractiveness Principle*, a system archetype that is essentially the convolution of two *Limits to Growth* archetypes (Senge, 1994). In other words, there are two or more slowing actions that combine to balance a reinforcing growth process. Depending on the nature of the delays in the system, multiple behavior modes can ensue. Figure 6 depicts the system. The variables are also presented using the Drivers-Pressures-State-Impact-Response (DPSIR) framework, since DPSIR is another popular approach to conceptualizing sustainable development problems (I also add in a second reinforcing loop to show the potential impact that renewable energy investment can have on managing natural capital stocks).

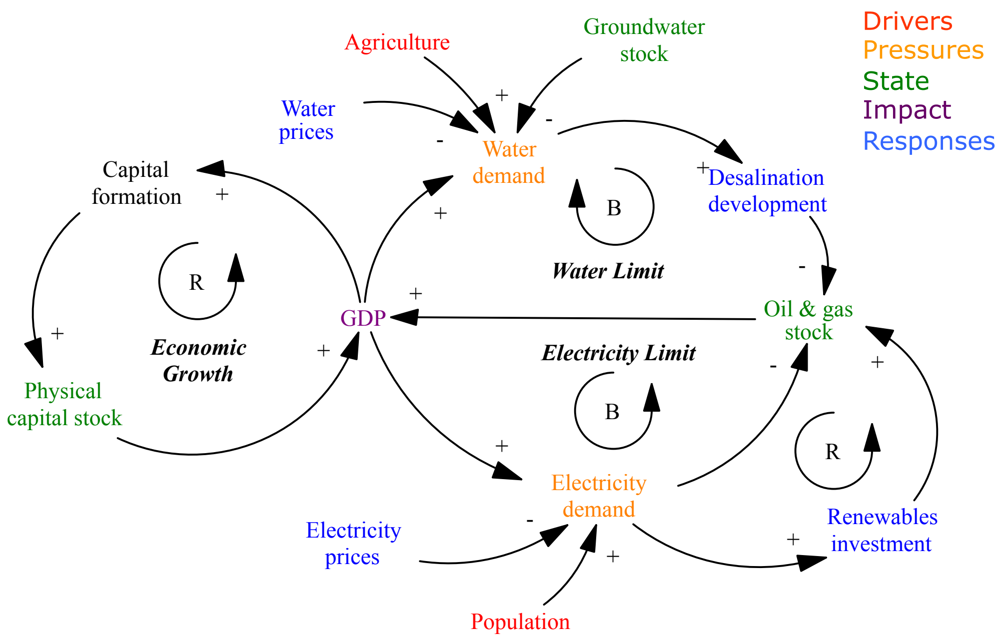


Figure 6: Causal loop diagram depicting the sustainable development challenge at the intersection of water and energy in Saudi Arabia. Based on the *Attractiveness Principle* system archetype.

As mentioned in the previous section, this case study is essentially a natural capital management problem mediated by infrastructure decisions. The reinforcing economic growth process is balanced by growing domestic consumption of oil & natural gas stocks that fuel the electricity and water infrastructures of the kingdom. Decision variables linked to the technology and policies governing the two infrastructures exist to dampen the balancing loops; Meadows (1998) calls these "leverage points". Figure 7 expands on Figure 6 to include more variables, causal detail and feedback loops.

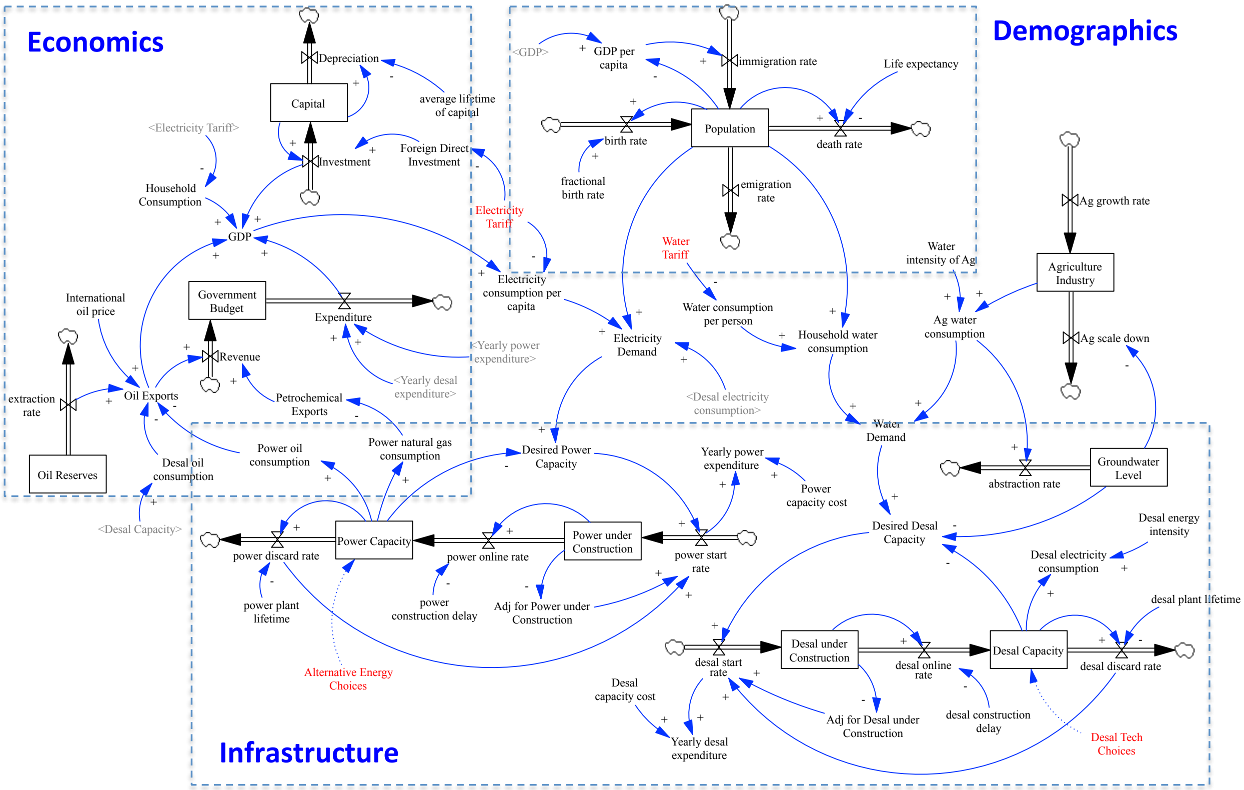


Figure 7: Qualitative model with expanded causal detail. There are essentially three modules that interact to affect sustainable development outcomes. Leverage points are highlighted in red.

Technologies relating to desalination and alternative energy, as well as policies geared toward addressing subsidies and the water-intensive agricultural sector, comprise the set of infrastructure systems that will eventually be evaluated in the case. These interventions will be evaluated based on the trajectories of relevant capital stocks (physical and natural capital), wealth and socioeconomic performance measures pertinent to the case (e.g. GDP, water/electricity prices). Sources of uncertainty include those pertaining to resource availability, baseline demand for water/energy, infrastructure delays, and oil price changes, among others. Simulations run from 2000-2050, with 2000-2011 as the calibration period. This time horizon was selected to include at least one investment cycle (15-25 years) as well as potential aftereffects.

3.3 Preliminary results and insights

The results presented in this section come from a "reduced form" version of Figure 7. In other words, the simulation model does not currently include all of the endogenous detail of the qualitative model, nor has it been fully calibrated yet. Still, some interesting insights emerge. Figure 8 displays oil consumption in the power and water sectors, and the subsequent impact on oil revenue and GDP under three scenarios. The scenarios differ according to long-term growth in population and the non-oil economy. Electricity demand is regressed on population and GDP, so it's no surprise that the higher growth scenarios lead to more power capacity expansion, and thus more oil consumed. The oil consumed for desalination is a little more nuanced, as it's driven by the extent to which municipal, industrial and agriculture water demands grow, and how much of that growth is met by desalination (recall that groundwater in the kingdom is rapidly approaching depletion).

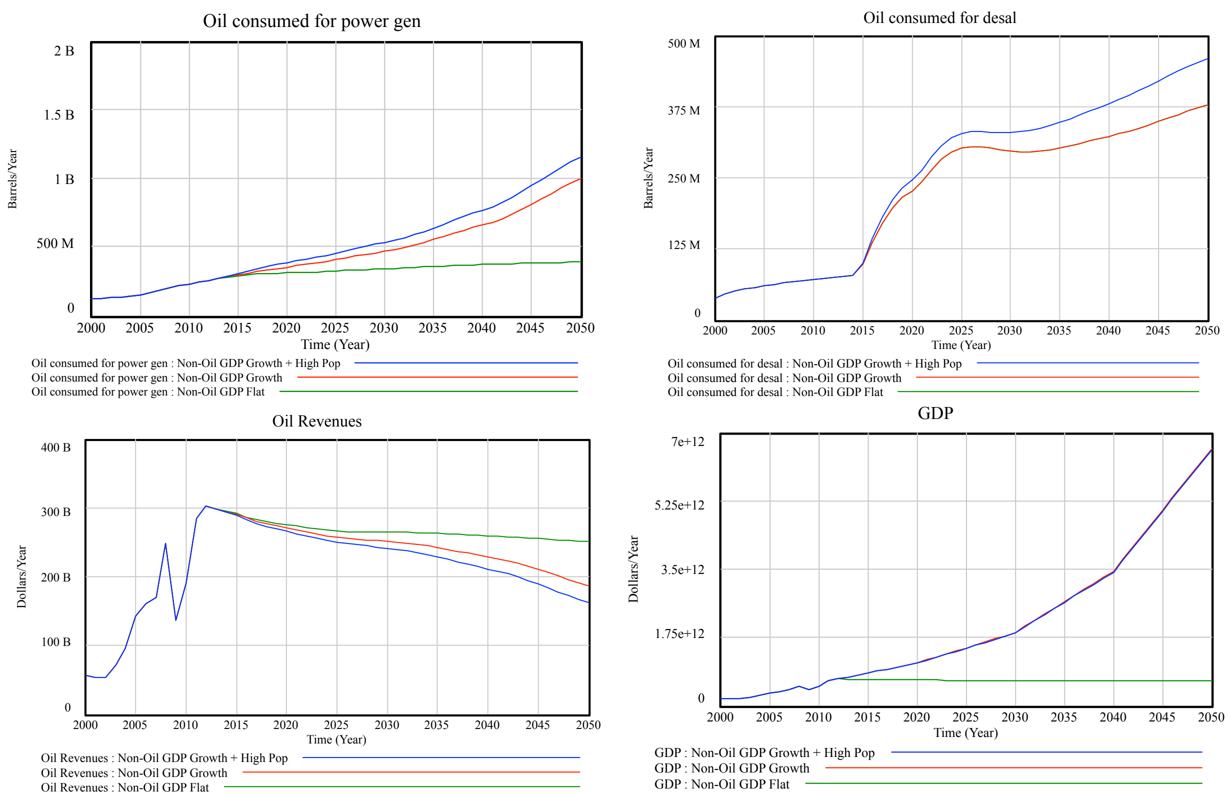


Figure 8: Sample results from preliminary simulation model for three scenarios: (1) no growth in non-oil GDP (2) high growth in non-oil GDP (3) high growth in non-oil GDP and population. Graphs include oil consumed in the power and water (desal) sectors, as well as the effect on oil revenues and GDP.

The model currently assumes that oil-fired plants meet 50% of the power sector's needs, and that desalination is not used to meet any of agriculture's demand. Clearly, these parametric and structural assumptions will need to be varied in future work, as they'll have a large impact on final results. For instance, the share of oil consumed in the water sector versus power will grow quite a bit if agriculture water is assumed to be met via desal, even in some small proportion. Similarly, a natural gas-constrained future may require that more than 50% of the power sector's needs be met via oil.

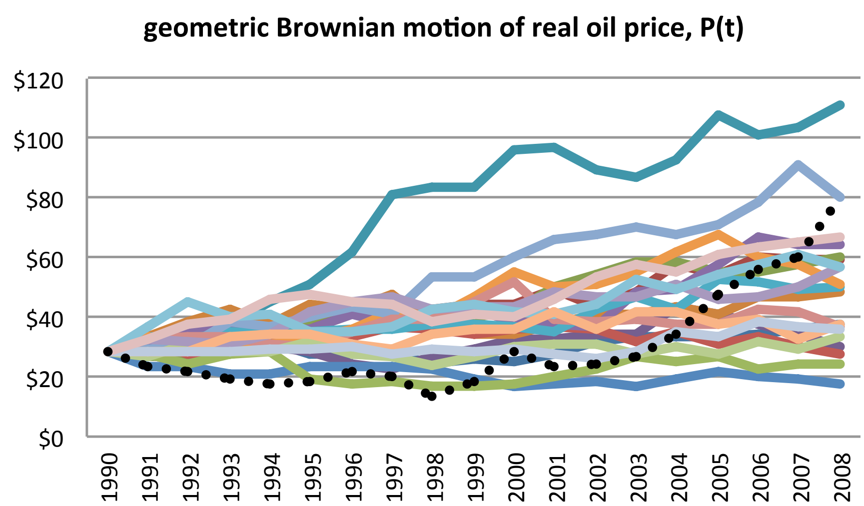
While "scenario tests", such as the ones described above, may lead to diverse outcomes, there are more fundamental issues that need to be addressed first in the model, and they have to do with closing feedback loops. The first issue has to do with non-oil GDP growth. Non-oil GDP, as defined by the Saudi Arabian Monetary Agency (SAMA), is all of the economic activity not generated by exporting oil (SAMA, 2012). In other words, it's everything minus oil export revenues. However, many of the products produced in the non-oil sector nonetheless require oil (or gas) as an input feedstock. Petrochemical production, a rapidly growing industry in Saudi Arabia, is a perfect example. Thus, the level of domestic oil consumption should feedback to the non-oil GDP sector in order to provide a balancing effect on economic growth, new capacity expansion and thus oil consumed domestically. The second issue has to do with modeling the feedback between groundwater depletion, water demand and therefore desalination capacity expansion. Right now the model simply uses exogenous time series of municipal, industrial and agriculture water consumption to drive the dynamics, but in reality the perceived level of groundwater remaining will moderate these demands. Groundwater perceptions will similarly guide desal decisions. In the language of inclusive wealth, the remaining level of groundwater represents a scarce and therefore very valuable source of natural capital. The decision rules moderating its use could have very different effects on the other valuable stocks of natural capital, oil and gas, as well as economic impacts. The final issue involves adding detail related to infrastructure technology and policy choice, as these produced capital decisions will also guide how the natural capital is managed over time and the subsequent economic impacts.

4. General avenues for future research

I've described thus far the inclusive wealth framework, including some of my preliminary attempts at modeling and analysis using system dynamics. There is certainly more work for me to do in the case I outlined above, but I want to use this section to suggest some potential avenues of future research for system dynamics researchers interested in applying the inclusive wealth framework to their sustainable development work.

4.1 Handling future uncertainty

Any model of wealth, concerning a subset of the capital asset stocks or all of them together, will need to grapple with the impact that future uncertainty can have on model results. This is something very familiar to the system dynamics community, where uncertainty can be evaluated through either parametric changes to model constants or through the introduction of process noise. However, for the economists developing the inclusive wealth theory, the handling of future uncertainty is discussed only briefly. As an illustration, I recalculated the oil wealth of Saudi Arabia between 1990 to 2008 using 20 different oil price trajectories that could have unfolded but didn't. To do so I used a simple Geometric Brownian motion (GBM) process not unlike the pink noise processes commonly found in system dynamics models. The results are striking as they show the sensitivity of final wealth (in 2008) to uncertain parameters and processes (Figure 9).



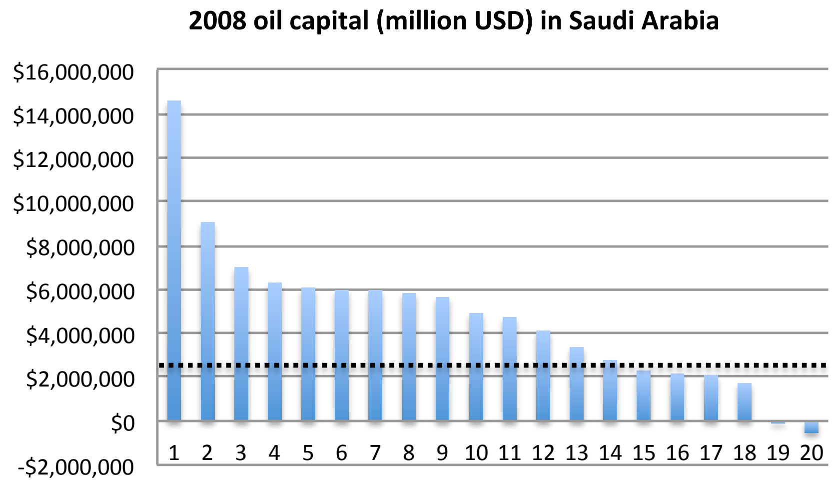


Figure 9: Top figure shows 20 different realizations of the oil price that could have occurred between 1990 and 2008; bottom figure shows the implication for 2008 oil wealth in Saudi Arabia (black dotted lines are what actually happened).

As I indicated when introducing the inclusive wealth literature, all work thus far has been retrospective. If inclusive wealth is to be operationalized into a forward-looking policy analysis framework, rigorous uncertainty evaluation will need to be included. There are a number of scenario planning approaches that have been integrated into system dynamics models that go beyond simply parametric changes and process noise to include future regime shifts or discontinuities (Lempert et al., 2003; Pruyt, 2007). Such approaches might be the best starting point for applying inclusive wealth into dynamic models.

4.2 The dynamics of shadow prices

Shadow prices are at the core of the inclusive wealth theory. They provide the mapping from capital stock movements to changes in intergenerational wellbeing. The elegance of the shadow price formulation, however, is also its shortcoming: the shadow price of each capital asset captures, in theory, the marginal contribution of each asset to intergenerational wellbeing, but to do so requires that the analysis consider everything that happens (or can happen) in the future (Smulders, 2012). Even a remarkably comprehensive scenario analysis, as discussed in the previous section, cannot anticipate every potential future state of the world. The inclusive wealth authors rightfully admit that shadow price estimation is an area for significant future work[6].

While true shadow price estimation is likely a will-o'-the-wisp, the system dynamics community can nonetheless add value by characterizing shadow price dynamics in simple models. For example, the World models could be adapted in this regard: as the stock of pollution grows, the marginal [shadow] value of industrial capital declines (unless its being used to control pollution); as the stock of natural resources declines, the shadow price goes up to reflect the pending scarcity. These exercises are not trivial. They require functional forms for the shadow price

[6] It is worth noting that any economic analysis that tries to price in externalities to a good or service is also trying to better estimate the shadow price. There is of course a large environmental economics literature dedicated to this pursuit. What has gotten considerably less academic attention is the estimation of shadow prices given pending scarcity of the good or service (e.g. fossil fuels or water) and benefits to the good or service not captured in the market (e.g. clean air derived from forest filtration).

dynamics (e.g. linear or exponential decline in the value of industrial capital as pollution grows) and an intergenerational wellbeing value function[7] (selection of this value function will in turn affect the shadow price dynamics). Furthermore, both exercises are at risk of being impacted by modeler subjectivity.

Shadow prices lead to self-regulating systems to the extent that their value is captured in the market. Thus, without pollution taxes for example, the lower value of industrial capital will not be captured in the market, and therefore growth of that capital stock will not slow. This is why it's important to keep shadow prices and market prices distinct (if all costs and benefits to intergenerational wellbeing were captured in the market, they would converge). Still, in simple applications like the World models (and more complex ones eventually), the ability to model the trajectories of shadow prices through time would be an informative policy analysis tool, and therefore a useful contribution to the inclusive wealth literature.

4.3 Framing case studies using inclusive wealth

I've alluded to this several times, but I see the inclusive wealth approach to sustainable development as an opportune platform for system dynamicists to make inroads with economists working on the same problems. There's a long history of the economics profession being skeptical of system dynamics models (the critiques following publication of the *Limits to Growth* are obvious examples), but as I tried to capture in Figure 3 I think time has permitted more conceptual and methodological convergence, at least in the context of sustainable development. Consolidating interdisciplinary research efforts in this regard may then simply be an issue of language and framing. I tried to do this in Section 3, framing Saudi Arabia's water-energy nexus as a problem of interconnected natural capital management, where outcomes are mediated by produced capital decisions. It's an imperfect start to be sure, but if future work in system dynamics adheres to the same framework, then it may provide the critical mass necessary to capture the attention of the economists who I believe are still constricted to a narrow set of modeling tools and approaches. Luckily, many of the economists involved with the inclusive wealth effort are so-called ecological economists, a minority community of the larger profession with whom system dynamicists have already had documented success in research collaborations (Uehara et al., 2013).

5. Conclusions

This paper introduced the inclusive wealth framework of sustainable development, and documented some preliminary efforts of the author to operationalize the framework in applied system dynamics models. Inclusive wealth, while a powerful and comprehensive vehicle for sustainable development analyses, has not yet been translated into a policy analytic framework for long-term evaluation of near-term policies. Relatedly, handling future uncertainty and shadow prices have not yet been adequately explored in the literature. All of these gaps represent opportunity for system dynamics researchers.

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[7] Inclusive wealth theory uses the discounted stream of the utility of future consumption for their value function (see Section 1.1), but given the inherent subjectivity in any [functional] definition of intergenerational wellbeing a diverse set of value functions could be justified.

That said, it's possible that many system dynamicists will look at inclusive wealth and conclude that they're not really advancing anything novel or interesting. After all, system dynamicists concerned with problems of sustainable development have known for a long time that stocks, their turnover and coverage times, and associated inertia are what govern socioeconomic systems. The major advance, I think, comes from the fact that through inclusive wealth the economics community – at least those from the UN and World Bank – are starting to embrace a systems view. This has two significant implications. One, multiple disciplines and backgrounds are now part of the economic planning discussion, where in the past it was primarily economists who had the ear of decision makers. The broad view of what constitutes the productive base of a society permits inroads for subject matter experts not part of traditional economic disciplines. Two, the methodological toolkit of welfare economics must necessarily expand to embrace the complexity of capital stocks, their interactions and feedback, as well as the long-term effect of their trajectories on policy-relevant measures. To the extent that system dynamicists are willing to work with and learn from welfare economists, both communities may reap intellectual rewards. And more importantly, we may actually start solving the pressing problems of sustainable development that are only going to get more challenging as time goes on.

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