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ANALYSIS

A quest for the economics of sustainability and the sustainability of economics

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Abstract

This paper briefly reviews key insights from natural resource and environmental economics, ecological economics and industrial ecology in an effort to identify the major contributions of these fields to the understanding and promotion of sustainable development. Each is based on overlapping worldviews, methods and tools. Their synthesis and extension–subsumed under the rubric of 'Natural Economics'–is suggested as a new thrust in environmental research, offering valuable guides to policy making. An early illustration of the application of natural economics in New Zealand is presented.

Keywords: Sustainable development; Resource economics; Environmental economics; Ecological economics; Industrial ecology; Natural economics

1. Introduction

Environmental issues are complex and to understand them requires interdisciplinary approaches (Funtowicz and Ravetz, 1993). Methods and insights from economics, biology, chemistry and physics are being applied, individually, and increasingly in combination to advance understanding of environmental issues (Ruth, 1993). From the last century of environmental research and application, a set of fundamental principles has emerged to guide future research and decision making. First, natural processes and human activities are subject to the self-enforcing, self-organizing and self-regulating laws of nature. As humans, we can reason and we can actively shape the biophysical and socioeconomic realms within which we make decisions; consequently our self-exacting laws and self-actualizing behaviour govern the accessibility of natural and developed resources. Second, we are appropriating ever larger stocks and flows of materials and energy, and this appropriation ever more aggressively alters the biophysical and socioeconomic environment. Sustainability requires us to assume a custodian's accountability for resources essential to meeting our needs, and a steward's responsibility for the resources required for meeting our wants.

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While the first of these insights concentrates on "natural laws", the second addresses the moral dimensions of human activity. The key to achieving sustainability is to understand both.

Efficiency and effectiveness are preconditions for any morally acceptable resource use—inefficiency and ineffectiveness imply waste. In turn, wasteful behaviour implies we fail as accountable custodians and responsible stewards. Since the concepts of efficiency and effectiveness fall within the purview of economics, concepts from economics are central when trying to understand and guide human activity. However, because modern economics concentrates more on efficiency than on effectiveness, and only addresses a subset of issues relevant to achieving sustainability, its approach and methods must be revised. To identify shortcomings and suggest changes, this paper first reviews (in Section 2) some of the contributions concepts from neoclassical economics have made to our understanding of resource extraction, and how the adverse environmental side effects of production and consumption can be included in economic decision making. These two areas of investigation take place, respectively, in resource economics and environmental economics. However, the main focus of Section 2 is on six challenges for modern economics if it is to promote sustainability by contributing to investment and policy decision making. Section 3 identifies contributions, from ecological economics and industrial ecology, to the understanding of human–environment interactions. The main focus here is on a set of broad strands of research and policy advice, generated over the last decades. The themes emerging from Sections 2 and 3 provide the basis for the synthesis presented in Section 4, where I return to basic insights for environmental research and decision making, before closing the paper with some guidance for environmental research and an illustration of an early application of natural economics in the New Zealand context.

2. Resource and environmental economics

2.1. Basic tenets and approaches

Thirty years ago, economist Robert Solow, in his lecture on "The Economics of Resources and the Resources of Economics", beautifully summarized and contributed to more than 50 years of theory about the optimal extraction of nonrenewable resources (Solow, 1974). Many of the insights available then, and since, trace back to articles by Lewis C. Gray (1913, 1914) and Harold Hotelling (1931). Their theoretical investigations identified conditions for inter-temporally optimal extraction of resources, and showed how changes in the value of resource stocks and the materials extracted from them must relate to the interest rate, which guides investment decisions in the economy.

The marginal cost of resource extraction, together with the opportunity cost of a unit of the resource in the ground, helps set the price for the resource and, for a given demand, determines extraction rates. As extraction proceeds, the opportunity cost of a unit of the resource rises. Ultimately, the optimal extraction path leads to depletion when price reaches a level where demand is choked off (Dasgupta and Heal, 1974).

Early efforts presented results under standard conditions of perfect knowledge about such things as technological conditions, resource endowments, perfectly operating markets and fixed preferences. Recent research has relaxed many of these assumptions and generated many variations around the themes identified in early works on the topic.

Since the oil price shocks of the 1970s, much effort has gone into empirical testing of the Hotelling model. Evidence that it adequately describes resource extraction paths is mixed (Smith, 1981; Farrow, 1985), and the logical underpinning of such testing has shown to be misguided at best (Norgaard, 1990).

A separate strand of research in economics has concentrated on the environmental damage arising from production and consumption, and how costs associated with this damage may be incorporated into the prices of the goods and services bought by households, firms and government. Environmental economics concentrates on such internalization of externalities and traces its basic insights back to the works by Arthur Cecil Pigou (1932) and Ronald Coase (1960). It finds modern applications in the design of sulfur trading systems to combat acid rain, tradable permits in fisheries management, carbon taxes to reduce emissions of greenhouse gases and other market-based instruments that use the price mechanism to discourage socially undesirable repercussions of economic activity and encourage desirable actions.

Even though internalization of externalities through market-based mechanisms remains a popular theme among economists, market-based approaches to resource and environmental problems are often greeted with deep skepticism by those having to balance economic efficiency with issues of effectiveness, fairness and justice.

Notwithstanding problems of empirical dubiousness, logical inconsistencies and political infeasibilities, insights from traditional natural resource and environmental economics have shaped our understanding of how humans may make better use of the environment. They have highlighted how technology shapes extraction decisions through time, how decisions today affect the welfare of future generations and how the market coordinates decisions of myriad households and firms within and across countries. In so doing, these insights provide an important starting point from which to address issues of sustainability.

2.2. Six challenges to traditional resource and environmental economics

Many graduate curricula and professional journals are filled with variations on the same themes of basic natural resource and environmental economics, and careers are built by pursuing inquiry within one of these areas as if it were separate from the other or divorced from broader social, institutional and ecosystem contexts. However, if economics is to be a serious force in shaping the debate about sustainability, it must meet at least the following six challenges:

1. *Integration of Resource and Environmental Economics:* Resource extraction has an immediate impact on the local and global environment, as is clearly demonstrated by the mining of ores or extraction of hydrocarbons. Conversely, limits on the environment's capacity to absorb and assimilate waste can constrain resource extraction—a good example is the effect of eutrophication on the population growth, and therefore catch, of fish.

   Continuing to conceptually separate analyses of resource extraction from issues of environmental harm will, at best, provide partial answers to questions asked by society; moreover, it may literally (as well as mathematically) encourage locally optimal strategies at the expense of globally optimal ones.
2. *Consistency with Physical and Biological Principles:* Few economics textbooks teach undergraduates or graduates that materials and energy are essential inputs into any production process; instead, most include models that deal only with labour and capital, explore implications of different degrees of substitutability of one for the other and identify the implications of substitutability for optimal output. They then proceed as if materials and energy could be treated in the same way, and as if production only entailed desired output. While many individual production processes could in principle be carried out with no, or almost no labour, or alternatively with no, or almost no capital, clearly they all require materials and energy. For example, to make a ton of iron requires at least a ton of materials plus considerable energy to remove oxygen and impurities from the iron oxides in those materials; moreover, the process leads to the generation of waste materials and waste heat. No amount of capital or labour can overcome these physical (thermodynamically determined) requirements for materials and energy nor prevent the generation of wastes, yet conventional economic descriptions of production processes ignore those physical constraints (Amir, 1991; Ruth, 2005). To provide meaningful tools for investigating sustainability, economics must be consistent with physical reality. Resource and environmental economics are similarly naïve when representing ecological processes, ranging from the representation of carrying capacities, to ideas about climatic variability in space and time, or to dispersion of pollutants in air, water and soils. I will return to some of these examples in the closing section of this paper.
3. *Development of a Systems Perspective:* It is frequently argued that while physical constraints may operate at the process level, capital accumulation and technology substitution in the larger economy may help decouple economic processes from environmental constraints. For example, Robert Solow (1974, p. 2) makes the distinction between reproducible capital, such as a printing press or building, and non-reproducible capital, such as a pool of oil

or vein of iron, and argues that "[t]he only difference is that the natural resource is not reproducible", without recognizing that human-made capital will not be reproducible either, once the natural resources are gone. Such partial systems analysis can lead to theories that are meaningless from a broader systems perspective.

4. *Acknowledgment of Legacy Effects:* Human-made capital is rarely as malleable as economics assumes—labour is rarely as mobile, physical and institutional infrastructures are lumpy and change only slowly, and ecosystem goods and services are locally concentrated. All are characterized by age structures (capital vintages, demographics, successional stages, etc.) that fundamentally determine how, when, and where capital, labour, and environmental goods and services can be used.

   To promote sustainability requires keen attention to the patterns and processes of using capital, labour, infrastructure, and goods and services from the natural environment. It is the patterns and processes into which we are locked, and our choice of means to break out of them, that determine the extent to which human-environment interactions are, or can become, sustainable.
5. *Recognition of Interdependencies of Allocation, Distribution and Scale:* Economics has focused on issues of optimal allocation and has moved issues of distribution and scale to its sidelines. For economic decisions to contribute to economic, environmental and social sustainability, they must also be sensitive to those issues and recognize their interrelationships. While optimal allocation implies efficiency, the issues of distribution and scale call for measures of effectiveness.
6. *Demonstration of Policy Relevance:* Economics has prided itself on the mathematical sophistication of its models and the range of empirical analysis found within its domain. While both are key to any rigorous academic discipline, it is increasingly obvious that for economics to make a difference in real-world decision making, it will not be sufficient to arrive at the end of an eloquent mathematical derivation or extensive econometric analysis and point to its potential policy relevance. Instead, it is the decision makers and other stakeholders who can and must judge the relevance of an economic analysis. Getting stakeholders to rally around economic insights will require more transparency and critical assessment of underlying model assumptions; it will challenge economics to interface more actively with other disciplines and to consider not just the efficiency of proposed solutions, but also their effectiveness.

Historically, much of economics has dealt with issues of relatively low complexity, such as the optimal extraction of a mineral or the internalization of an externality; moreover, much of the analysis was static or equilibrium-focused. Consequently, there was neither a perceived need nor room for the inclusion of a wide range of information—some of which is held by members of other disciplines, and some by stakeholders elsewhere in society. Not surprisingly, the economics discipline was (and still is) largely engaged in a monologue and a unidirectional information exchange with the rest of society.

An alternative world view posits that as the complexity of the issues under investigation increases and the spatial and temporal reach of the problems (and solutions) increases, it becomes increasingly relevant to draw on stakeholder knowledge. Stakeholder involvement can then also help bridge the gap between research and implementation (Cohen, 1997; Costanza and Ruth, 1998) and reduce the frustration of economists who complain that their voices are not heard.

In closing this section, let me outline a mind-set that may promote an economics of sustainability and the sustainability of economics. First, academia has increasingly emphasized the use of discipline-specific knowledge in interdisciplinary research, but for economics this was often an unidirectional relationship. Thus, economics was a valuable contributor, but did not substantially change its own mind-set in response to needs for better interdisciplinary models.

Second, much of modern economics ignores spatial considerations and remains equilibrium-oriented. In contrast, ecologists tell us about the importance of concentrating on processes that occur across temporal and spatial hierarchies. Much must be done to economic models to reflect adequately the qualitative differences in system performance apparent at these different hierarchical levels.

Third, much of modern economics is basic and context free—the infamous "physics of the social sciences". History and culture matter to outcomes; they should matter to economics as well. At the turn of the 19th century, Alfred Marshall called for economics, in its later stages of development, to be guided by biological principles instead of treating the world like a mechanistic system (Marshall, 1898). The time may be right to follow his call.

Conversely, should economics continue along the path it has followed throughout much of the last century, it will not only risk failing to contribute to the sustainability debate, but may itself not be sustainable. A society faced with allocating scarce resources to meet its needs may eventually decide to allocate fewer resources to the discipline that claimed to study the best use of scarce resources but failed to deliver its promised valuable insights. Without an economics of sustainability, there may be no sustainability of economics.

3. Ecological economics and industrial ecology

Ecological economics and industrial ecology developed partly to address the need for biophysical reality in the analysis of human–environment interactions. Ecological economics is based on the tenet that all economic activity must be regarded as a subset of the ecosystem in which the economy is embedded and on which it depends. Of specific concern are the limits of ecosystems to handling human impacts and of the possibilities for human systems to maintain or increase quality of life.

One strand of ecological economics research points to the many valuable contributions that ecosystems make to the economy by providing goods (e.g., timber, fur, fish, etc.) and services (e.g., waste absorption, pollination, etc.). Because there are no markets for many of these goods and services, economic inefficiencies and misallocations result (Costanza et al., 1997). Pricing ecosystem goods and services would more appropriately reflect their contribution to the economy. In the absence of markets, monetary values are derived through contingent valuation studies (Bateman and Willis, 1999) or by imputing values from other ecosystem goods and services for which markets exist. Estimates of monetary values of non-marketed ecosystem goods and services are then used to suggest mechanisms and policies to collect revenue from use, provide incentives for efficient use, or compensate for loss of ecosystem goods and services.

This "instrumentalist" approach has received much attention amongst researchers and policy makers because it is conceptually appealing, complements existing economic approaches and provides easily interpreted, quantitative results. However, the valuation of ecosystem goods and services is often plagued with its own empirical and conceptual problems (Toman, 1998; Turner et al., 1998). Many data issues arise from the complexity of ecosystem processes, often making it necessary to use data from one site for another, or extrapolating from limited observations to larger spatial or temporal scales. Selection biases often creep into ecosystem valuation studies because these studies focus on the goods and services we appreciate (such as the existence of wetlands for storm water control, water purification and maintenance of biodiversity), and not on those that we do not like (such as adverse health impacts prompted by the presence of breeding grounds for vectors and the diseases they carry). Most importantly, the valuation is similar to the traditional economic approach, which is based on the concept of marginal value—the value of an extra unit of a good or service. This makes sense when the goods or services are far from their limits, but not if the integrity of ecosystems is at issue. Thus, calculating the value of losing another hectare of forest or wetland from averaged or interpolated data makes little sense if we are left with little of these systems and if we do not know were ecological thresholds are.

The instrumentalist approach has turned to bite ecological economists and in many cases well-intended valuation approaches have opened the field to undue criticism. Pursuing this research further, and extending it to ever more ecosystem goods and services is not likely to help resolve current conflicts surrounding resource use and allocation (Sagoff, 2004).

Industrial ecology has been guided by the quest for production and consumption processes that minimize waste generation and, thus, environmental impact. It is largely driven by engineering approaches to increase material and energy efficiencies of specific processes, and by a systems perspective that calls for shortening or creatively combining process chains so that undesired intermediate products can be avoided or used elsewhere in the system. Most research so far has concentrated on accounting tools to trace material and energy flows, to provide life cycle assessments of products and to guide investments and policies to minimize adverse environmental impact.

Comparatively little research is carried out within industrial ecology on consumption processes, yet it is here where many decisions on total systems impact are made—if consumption expands faster than efficiency improvements, then total environmental impacts will rise (Waggoner and Ausubel, 2002). Efficient resource use is a necessary, though not sufficient condition, for sustainable material and energy use and only one of several preconditions for sustainable development. A better understanding of consumption requires a larger systems context; one in which socioeconomic (behavioural), biophysical and engineering insights are combined.

4. Natural economics

Returning to my opening comments about the fundamental insights emerging from past environmental research and decision making, and incorporating lessons from ecological economics and industrial ecology, I wish to identify four major themes for a natural economics, each following in part from the previous:

1. *Building on Concepts from Nature:* Natural processes perform a tricky balancing act between competition, cooperation and coordination on the one hand, and elimination on the other hand. Individual species do this when filling the niches opened, or left open, by others. For species to adjust, individuals must have opportunities to deviate from the norm. Deviations from the norm are essential for exploring alternative, more efficient and effective means of utilizing resources and maintaining or increasing population sizes. Not only must failure be allowed, but the willingness of individuals to embark on paths that lead to failure must be encouraged if sustainable development is to occur. But in the end, nature cares about the community not the individual—those who are not fit for a given environment will have reduced reproductive success or be eliminated from the system.

   If natural processes do indeed favour the long-term viability of populations and communities over the short-term gain of individuals, and if we must ultimately follow principles similar to those ensuring sustainability in nature, then this has far-reaching implications for the economic, legal, and ethical underpinnings of society. For example, profitability for individuals and the ability to seek out profitable strategies must be encouraged in ways that yield net benefits both for the individual and for society. Thus, legal systems must effectively penalise individuals who use resources at the expense of others, and tax codes must encourage entrepreneurial risk-taking without allowing the entrepreneur to transfer the cost of any failure to society.
2. *The Roles of Efficiency and Effectiveness in Decision Making:* Efficiency and effectiveness are important guides for decision-making. Efficiency requires the highest productivity per unit of a resource; and effectiveness requires the highest utility from what is used. Systems that are highly efficient are not necessarily also effective—they often reduce redundancies for purposes of cost savings, and as a consequence become brittle and unstable and may collapse when faced by unanticipated changes in their environment. Historically, decision makers have tried to maintain highly efficient systems by controlling the environment in which they operate. A prominent example is monocultures, which are prone to massive pest outbreaks. To avoid the collapse of monocultures, typically has meant strictly controlling physical, chemical and biological conditions by irrigation and by using fertilizers and pesticides. As the cost of, and limits to, environmental control become increasingly apparent, the focus of agricultural research has returned to the crops, attempting through breeding and genetic engineering to make them more efficient in variable environments. However, as the wider effects of genetic engineering become apparent, societal acceptance becomes a major stumbling block for modern agriculture. With increased societal concerns about the impacts of new crops, attention increasingly focuses on the socioeconomic envir-

onment within which food production and consumption take place.

3. *The Need for Adaptive and Anticipatory Management:* Because biophysical, technological and socioeconomic environmental conditions always change, and because we typically lack all the information needed to identify the best management decisions, some researchers and practitioners have called for an iterative process of data collection, interpretation and adjustments of management decisions as we learn more about system behaviors. This adaptive management has been promoted, for example, for water resource management and fisheries and wildlife management (Gilmour et al., 1999; Gunderson, 1999; Johnson, 1999; Lee, 1999; Pinkerton, 1999). The underlying management paradigm is a co-evolutionary world view that recognizes that natural systems and human systems adjust to each other's behavior. It does look forward, recognizing that uncertainties increase as time horizons and spatial scales increase, and it emphasizes the need for adjustments as hitherto unknown system features and behaviors are revealed.

   However, some systems are characterized by long temporal and spatial lags between actions and system response as well as high degrees of complexity and irreversibility. These cases are often of interest to ecological economists and industrial ecologists and they pose a major challenge to sustainable development. In such cases, adaptive management may not be the best approach. For example, for industrial or infrastructure systems, investments are lumpy and turnover rates are low. Waiting until the ramifications of decisions are known before new decisions are made is often impossible. Instead, management must anticipate the future—it must look forward. Actions must be taken well before likely future environmental conditions are known and must be chosen so they are robust under a wide range of possible futures. Since humans can explore theoretically and with scaled experiments various potential futures, we are in a different position from nature, where "management" follows a trial-and-error, "adaptive" approach.

   Examples where current management is clearly not anticipatory range from land use planning to infrastructure design. Expansion of suburban developments along steep slopes, without natural buffers to surrounding ecosystems, into wetlands and along coasts often disregards available knowledge about the long-term potential for soil erosion, the spread of wildfires and flooding, all of which may be exacerbated by the presence of human settlements. Insurance premiums are based on historical risk, rarely take into account the changes in risk that those settlements are likely to induce, and therefore subsidize unsustainable land use patterns. Similarly, infrastructures are designed to withstand one-hundred-year floods which are events that have the probability of occurring once in a hundred years. Since climate change affects both the frequency and severity of extreme weather events, what is considered a one-hundred year flood may by the end of this century occur on average every ten years. Many infrastructures planned and built today will likely still be in use by then, but they are designed with static definitions of a one-hundred-year flood, and will be woefully inadequate to provide services. What is deemed cost efficient from today's perspective will likely be ineffective in the long term. Consequently, adapting to climate change will mean costly replacements and retrofits that could have been avoided had some basic understanding of possible climate futures been taken into account (Kirshen et al., 2004).

4. *The Need for Holistic Impact Assessments:* One way to think about system interventions is with respect to their reach and complexity (Fig. 1).

		Complexity	
		Low	High
Reach	Short	**Example:** Hair Cut	**Example:** Open Heart Surgery
	Long	**Example:** Land Development	**Example:** Use of CFCs

Fig. 1. Schematic of system interventions (adapted from Bullard, 1988).

Simple interventions with a short (geographic or temporal) reach affect only a few individuals and they have immediate or rapid effects. The larger the complexity and the longer the reach, the more important it is to broaden one's view to avoid being taken unawares by challenges that lie outside the narrow focus of technical interests and expertise. For example, cloud seeding to influence precipitation, or deliberate injection of aerosols to influence global climate, may work very well from an engineering perspective, and may even be highly cost effective, but are likely to be opposed if there are sentiments, legal/liability issues and institutional constraints that are ignored at the outset. In short, an engineering or economic solution that is blind to ethical, moral, emotional, legal or institutional constraints is not a real solution. However, these constraints have frequently served as excuses for engineers and economists to remain busy while blaming others for failing to solve the problem.

Ensuring that stakeholders from the public, private, non-profit and academic communities constructively seek and implement sustainable solutions may require an assessment of impacts of system interventions that is grounded in natural economics. Such an assessment should include:

(a) a statement of the purpose, objective and goals for a proposed change;
(b) a system and subsystem description appropriate for the analysis, including information about interrelationships among system components, interdependencies between the system of interest and its surroundings and information on material and energy flows across temporal and spatial scales;
(c) a set of objective functions that include the needs and desires of the identified stakeholders;
(d) the limits and balances that constrain and enhance the analysis and determine the boundaries of the solution space; and
(e) an assessment of the effects of the proposed changes on all significant stakeholders, and a means to reconcile differences among the criteria applied to those stakeholders when they evaluate proposed changes.

Many current procedures for impact assessment, as well as deliberative processes for conflict resolution and large-scale, dynamic modeling of system change meet some of these requirements. Few, if any, integrated assessments are "holistic" enough to foster sustainable development. Where integrated assessments have been carried out, they have frequently served key roles in policy analysis. Policy analysis here is understood as an effort to find possible system inputs to achieve desired outcomes. It differs from both path analysis, which describes likely system output given some system input and structure, and from system design, which attempts to find system structures and inputs to achieve desired output. Typically, the degrees of freedom in carrying out system design are significantly larger than for path or policy analysis, where either input and structure or output and structure are assumed as given. System design requires establishment of "desired outputs" and criteria for judging appropriate (sustainable) structure and input choice. To develop and select system designs that are sustainable will require a natural economics—one that builds on fundamental insights from the natural sciences for sustainable system behaviour and, on the basis of these insights, establishes the economic, legal, institutional and ethical basis for humans to interact with their environment.

5. Ecological economics, industrial ecology and the emergence of natural economics in New Zealand

Path and policy analyses, broadly defined, are key features of natural resource and environmental economics, ecological economics and industrial ecology. They lie at the heart of most major environmental policy efforts to date, beginning with descriptions of system behavior and ending with an identification of intervention mechanisms that tweak system inputs to achieve desired outcomes. For example, the processes that generate sulfur emissions into the atmosphere and the chemical reactions of sulfur in the environment can be identified and described. So too can the market mechanisms, such as tradable permits, which can be used to limit sulfur emissions and provide incentives to reduce the loss of environmental goods and services and the associated economic damage. Markets and regulatory frameworks focus on one level of system organization (an industry or pollutant) with desired impacts on another level (choices of individual fuels and technologies by the firm), but they usually do so without explicitly considering unique and potentially important features that guide the behaviors at those other levels. As a result, policies frequently have multiple unintended and often perverse consequences (Ruth et al., 2004).

Great strides have been made by ecological economists and industrial ecologists to advance path and policy analysis in efforts to ultimately address the larger challenges of system design. In New Zealand, for example, work by John Peet laid many valuable foundations, ranging from the physical analysis of energy use to ethics-based indicator development for sustainable development (e.g., Peet, 1992; Peet and Bossel, 2000). The establishment of the New Zealand Centre for Ecological Economics helped institutionalize policy analysis based on ecological economics, and began to stimulate research into national environmental accounting, ecological footprints, the sustainability of cities and the development of indicators to measure progress towards sustainability, using a wide range of methodologies commonly found in ecological economics and industrial ecology (for an overview refer to: http://www.nzcee.org.nz). The limitations of narrowly defined optimal resource use have been recognized and replaced with stakeholder-guided explorations of the dynamics of complex human-environment systems that acknowledge processes that occur at different temporal scales and system hierarchies.

One recent example of stakeholder-guided research that merges concepts and tools from ecological economics and industrial ecology is the Climate's Long-term Impacts on New Zealand Infrastructure (CLINZI) project. CLINZI explores opportunities and constraints on custodian and stewardship responsibilities at the local level, but within larger regional and global social, economic, technological and environmental changes, and with an eye towards short-, medium-and long-term implications of investment and policy decisions (Jollands et al., 2005). In CLINZI, a wide range of alternative projections of local climatic conditions are used to assess the performance of the major "hard" and "soft" infrastructures (ie, the "built" and "institutional" environment) under different assumptions about population and technological change. Special attention is paid to water, energy, transport and public health issues on which the welfare of the region depends. The assessments are guided by interactions with regional stakeholders who provide inputs into the assessment process, interpret results on the basis of multiple criteria and translate those results into investment and policy actions that affect infrastructure performance.

Preliminary results of the CLINZI project suggest climate change by itself has minor impacts on regional infrastructure, economy and society. Nevertheless, climate change can have profound implications for planning, investment and policy making because it reinforces and adds to system stresses already occurring at multiple spatial and temporal scales, such as changes in population size and effluence, all of which combine to influence regional infrastructure performance.

While much infrastructure planning recognises projected socioeconomic changes, it assumes environmental, especially climate conditions, to be stationary within the design life of infrastructures and the mandates of the institutions that govern them. Vulnerabilities to uncertain, often disregarded, environmental change may be reduced through environmental investments and policies that target individual system aspects such as bottlenecks in the transport network, or that focus on system interconnections such as when flooding compromises electricity distribution through its effects on underground cables and transformers. Many of these interventions incorporate redundancies—i.e., they promote effective resource use rather than narrowly defined efficiency. Among the investments and policies that most promote resilience are those that build responsive and proactive institutions. For example, Environment Waikato, the regional environmental planning agency and key participant in CLINZI, is regularly and actively involved with its local and national partners in cross-sector communication and assessment to build competencies that help the region think and plan ahead. Arguably, the costs of such system-design-oriented activities are small compared with the benefits associated with the consensus they generate across infrastructures and institutions, and the ground they lay for effective implementation of technologies and policies.

6. Conclusions

At the beginning of the 21st century we are witnessing the confluence of major developments in the natural, engineering and social sciences in profound challenges associated with the sustainability of the human endeavor. Insights from various academic disciplines are graduating from their use by analogy to shaping methods and analyses across a wide range of applications. Heightened attention is being paid to the processes that connect across system hierarchies, across space and through time. The lessons being learned when choosing a systems perspective gradually influence the interactions of science and society, and the choice of investments and policies. Expert-based, efficiency-driven advice on cause–effect relationships is enriched, and increasingly supplanted by adaptive and anticipatory management that is systems-oriented and informed by stakeholders.

Natural economics lies at the heart of these developments, emphasizing that humans have responsibilities as custodians and stewards, and highlighting the role of self-organizing and self-regulating laws of nature, the complexities, uncertainties and risks associated with alternative management approaches and the opportunities for sustainable development when investment and policy choices are guided by effectiveness rather than narrow definitions of efficiency. Recent pilot projects in New Zealand and elsewhere vividly illustrate these opportunities at local levels and beyond. In this paper I have traced these recent developments to natural and resource economics, ecological economics and industrial ecology. During the next decades of research we must expand our theories, develop new analytic tools to assess the impacts of holistic natural economics, advance methods for creative dialogue about complexities, uncertainties and risks, and conduct case studies to further substantiate (or refute) the lessons learned to date.

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