



ARTICLE

Uncertainty, innovation, and dynamic sustainable development

Lenore Newman

School of Environment and Sustainability, Royal Roads University, 2005 Sooke Road, Victoria, B.C., Canada V9B 5Y2
(email: lenore.newman@royalroads.ca)

Sustainable development is a rich concept that has helped shape the discussion of human society's interaction with the biosphere. However, the term "sustainable development" is contentious, and some dismiss it outright as an oxymoron. The seemingly contradictory "sustainable" and "development" can be reconciled by accepting that due to two factors, the inherent complexity and uncertainty of human and natural systems, and the ability of human society to innovate, sustainable development must be dynamic. It must be an ongoing process, not a goal. A sustainable society must constantly evaluate its relationship with nature as it adopts new innovations and encounters unexpected events. The role of feedback and suitable application of the precautionary principle are key elements of a dynamic sustainable development process. The example of nuclear waste management in Canada demonstrates the beginning of such a process.

KEYWORDS: sustainable development, human-environment relationship, human impact, innovations, appropriate technology, human ecology, waste management, radioactive wastes

Introduction

Since being defined by the Brundtland Commission as behavior that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987), the concept of sustainable development has continued to evolve. There are now hundreds of definitions for "sustainable development" (Dale, 2001), a term that several observers contend is problematic. Certainly some of these definitions are no longer mutually compatible, yet this ongoing debate can be seen as an evolution rather than an argument.

William Rees, co-developer of ecological footprint analysis, argues that a prerequisite to formulating sustainable policies is to develop a satisfactory working definition of the concept (Rees, 1989). However when dealing with complex systems such as human societies and ecological regimes, meaningful global definitions are not always possible or useful. The Brundtland Commission's definition was left purposefully vague to allow various shareholders to work toward common ground. The resulting controversy, according to some observers, has created a constructive dialogue (see, e.g., Dale, 2001).

Though some protagonists argue that the very term is an oxymoron (Livingston, 1994), another possibility is that the perceived incompatibility in the terms "sustainable" and "development" is an artifact of a worldview based on equilibrium. However, from the perspective of complex adaptive

systems theory, human societies are dynamic, open systems far from equilibrium and must evolve and adapt to survive. Development does not need to refer to mindless growth; it can also manifest itself as adaptation. Such adaptation can be sustainable over very long time scales, as is demonstrated by the biosphere, which has grown more diverse, extensive, and complex over the last several billion years.

Embracing dynamic sustainable development comes at a price, as the concept of a stable equilibrium state for human society disappears. This occurs for two reasons: complex adaptive systems are inherently unpredictable, and innovation constantly changes our impact upon the biosphere (Newman & Dale, 2005). Innovation and uncertainty ensure that a dynamically sustainable society must prepare for the unexpected.

From Goal to Process

Numerous recent publications support the shift from a goal-oriented to a process-oriented sustainable development. As C. S. Holling (2001) argues,

Sustainability is the capacity to create, test, and maintain adaptive capability. Development is the process of creating, testing, and maintaining opportunity. The phrase that combines the two, "sustainable development" thus refers to the goal of

fostering adaptive capabilities and creating opportunities. It is therefore not an oxymoron but a term that describes a logical partnership.

Such an approach is a shift from a command-and-control model to a self-organizational model of dynamic sustainable development. This type of model is more likely to succeed if it can emerge organically from unsustainable behavior in manageable steps. Norms cannot be imposed in advance (Robinson, 2003), but emerge as part of an adaptation process. Instead of being a final objective, sustainable development has to be understood as a continuous process of change (Jokinen et al., 1998); a potentially fruitful approach is to treat it as an evolution (Rammel & Van den Bergh, 2003).

Treating sustainable development as a process creates the need for an indefinite program of monitoring and adjustment, with every successful adaptation only a temporary "solution" to changing selective conditions (Rammel & Van den Bergh, 2003). In short, sustainable development is a moving target (Salwasser, 1993). In some cases, the time spans involved are long to the point of being indefinite. The two factors earlier mentioned - the inherent unpredictability of complex adaptive systems, and the changes brought about by human innovation - necessitate certain requirements of what I call dynamic sustainable development.

Uncertainty and Dynamic Sustainable Development

Complexity is the defining feature of our highly heterogeneous modern society. Human society is very non-ergodic. Ergodicity is the tendency of a system to move towards equilibrium, maximizing entropy and minimizing free energy. Human societies do not settle down into stable patterns for long. They constantly innovate, grow, and change, posing a challenge for those trying to adjust our interactions with the biosphere.

Though we might wish to design a perfect and stable society, history suggests such experiments end in failure. Sustainable development models must therefore be flexible enough to mitigate the ecological effects of a non-ergodic society. Theories based upon a complex systems approach are appropriate for the study of human society and its interaction with the biosphere for several reasons. First, complexity deals with the links between things. Second, it is neither reductionist nor holistic, but combines elements of both, necessary for multi-scale systems. Finally, the science of complexity deals with systems composed of varied elements connected in non-linear ways, a state that is certainly found within human societies.

Complex adaptive systems are far more than a collection of elements; they are bound together by the flow of energy, matter, and information. This flow is often two-way, forming feedback loops within the complex system. Achieving a sustainable society is fundamentally a question of observing and responding to feedback. Feedback loops form the nervous systems of complex adaptive systems, allowing the flow of information among elements and between the system and the environment. Feedback is a process in which a change in an element alters other elements, which in turn affect the original element (Jervis, 1997). Feedback is an iterative process, and is a fundamental part of what makes a system both complex and adaptive.

Complex systems generate both positive and negative feedback. Negative feedback loops are those which moderate a

system, damping out change; this process, however, does not always lead to stability. Too much negative feedback can cause a system to become stagnant and unable to adapt to suddenly changing situations. A system composed only of negative feedbacks will become out of step with its surrounding environment and perish.

In order to thrive, systems must also contain positive feedback, defined as feedback which reinforces a change or trend. As environmentalists we tend to shrink from positive feedback, as it evokes thoughts of runaway growth. However, positive feedback is what allows our societies to respond quickly enough to adapt to changing conditions. Sadly, positive feedback introduces an insurmountable uncertainty into our system that is best described as a sensitive dependence on initial conditions. This phenomenon is also called the "butterfly effect," a term coined by Lorenz in a 1972 talk titled, *Predictability: Does the Flap of a Butterfly's Wings in Brazil Set Off a Tornado in Texas?* (Lorenz, 1993). Positive feedback can reinforce a small event again and again until it becomes a system-wide phenomenon.

Positive feedback loops allow accidents of history to get magnified in outcome (Waldrop, 1992). If negative feedback loops hold a system stable, positive feedback loops allow systems to explore their environment and follow new development paths. As they magnify random small variations, positive feedback loops add an element of surprise to the system's behavior. This leads to the results of many small actions being unintended and unpredictable from the initial conditions (Jervis, 1997).

The existence of positive feedback and sensitive dependence on initial conditions within society has profound consequences for sustainable development. As we can never trust our predictions of the future entirely, there can be no perfect model of a permanent sustainable society. Instead, we must monitor feedback loops carefully and continually adjust our models and our actions accordingly. Systems theorists sometimes refer to this inherent unpredictability as "strong uncertainty," in the sense that not only are we unable to predict the consequences of events, we are unable to determine which events will lead to future change (Spash, 2002).

The effects of feedback are well illustrated by the collapse of the cod fishery in Newfoundland. Once the largest cod stock in the world, the Newfoundland stock supported a viable commercial fishery for over three hundred years. However, the stock was destroyed in only two decades and has yet to recover (EEA, 2001). During the 1970s and 1980s, the Canadian Department of Fisheries and Oceans ignored negative feedback from two important sources: its own research scientists and the inshore fishers who were directly observing the cod's decline (EEA, 2001). The fishers, for instance, noticed that the fish were becoming fewer and smaller and tried to communicate this information to the scientists at the DFO. They were ignored and dismissed. This is negative feedback, as in a perfect world their knowledge would have led to a change in fish catch limits, stabilizing the stock. At the same time, a positive feedback mechanism was in play. The large offshore fishing fleet was upgrading its technology, and this contributed to the pattern of stock depletion. As fish become scarcer, fishers were encouraged to invest still larger sums to ensure that the quota was being caught. In effect, the fleet was working harder to achieve the same result, but the catches were remaining constant, presenting the illusion of a stable stock. This cycle of

increasing pressure upon the stock continued right until the eventual collapse. Once it became clear the cod stocks were declining, corrective action occurred only slowly due to another set of negative feedbacks. The DFO feared the social and political effects of drastically reducing the fishery, and accordingly moderated their response (EEA, 2001). Positive feedback drove the stock's destruction and negative feedback inhibited the imposition of fishing curbs—a worst-case scenario for sustainable management.

Nuclear Waste Management and Complexity

The mismanagement of the Newfoundland cod stock is a good example of the problems that can result from incorrect actions. However, trouble can also arise when no action is taken and problems are allowed to accumulate. The lack of long-term management of nuclear waste is such a problem. This very complex issue involves both ecological and social systems on an unprecedented time frame.

In Canada, there are roughly 1.7 million used nuclear fuel rods from power generating stations in three provinces. To date, used fuel has been stored on-site, in cooling pools and in concrete bunkers. This waste will remain dangerous to human and ecosystem health for tens of thousands of years, posing a managerial problem on an immense scale. Many complex questions arise: Should waste be stored at reactor sites, or undergo the difficult process of being moved to locations far from population centers (where it might be neglected)? Should we place the waste beyond the reach of future generations, or do we include a level of accessibility in case a better method of disposal is developed? How can we communicate to future generations the danger this waste poses? These issues, combined with strong public feelings, make nuclear waste management a bellwether for dealing with complexity and uncertainty. Nuclear waste disposal presents vague and poorly defined social and ecological feedback loops.

Managing such a complex process successfully will require the development of new tools. First, plans must be ongoing and iterative, subject to adjustment. Ecological footprint analysis can provide a starting point for this purpose as it relies on quantitative data to provide a “snapshot” of how sustainable a society is at a particular time (Wackernagel & Rees, 1996). However, as this tool only provides an idea of present conditions, more work must be done to extend this process into the future. As an example of such a combination of visioning and measurement, the Natural Step process, developed by cancer researcher Karl-Henrick Robert to take advantage of the power of iterative analysis, has been widely used by both corporations and municipalities to map out a route to more sustainable behavior (Natrass & Altomare, 1999). The application of the Natural Step involves four core processes that build on each other to provide a course of action that leads toward a state of higher sustainability. The procedure is therefore a creature of feedback—it can be applied again and again, taking the user group to higher and higher levels. The steps are outlined below:

Understand the principles of sustainability.

Locate unsustainable processes and determine the gain in changing them.

Form a vision of how to change them by “backcasting” from the final goal.

Identify a series of paths leading to that goal, and then *pick* a path.

The process of “backcasting” is one of the key innovations of the Natural Step. Selecting a goal and imagining how to get there works better than adapting to prediction when the problem is complex, when the changes needed are major, and when trends and externalities play a role in the problem (Natrass & Altomare, 1999). In the case of nuclear waste, this process involves understanding the need to manage this waste, evaluating the sustainability of current practices, determining what the desirable goal of nuclear waste management might be, and identifying the steps necessary to reach that goal.

Innovation and Dynamic Sustainability

Humans must innovate to survive. The physical human is strangely and woefully unequipped to survive in the wild, and we rely extensively on technology to compensate for our lack of physical preparedness (Debray, 1997). Innovation, however, is not just technological; it can take several forms. Technical ingenuity creates new technology, but social ingenuity reforms old institutions and social arrangements into new ones (Homer-Dixon, 2000).

Innovation within a complex society occurs on many scales. At the smaller scale, we see incremental innovations, small refinements that occur relatively continuously. At a larger scale, there are radical innovations, very significant shifts in existent technologies and social structures. These are not predictable and may happen at any time. Lastly, there are systematic innovations that create entire new fields (Pereira, 1994). They cannot be predicted, and their occurrence radically reshapes society. These innovations can be thought of as “gateway events” and they can lead to rapid change (Rihani, 2000). Such sudden shifts can provide new technologies to protect ecosystems, can shift use from one resource base to another, and can also increase our impact on ecosystems in new and unexpected ways. We desperately need to sharpen our *a priori* understanding of what effect an innovation might have.

Detecting gateway events is difficult, as it is hard to identify signals of massive change early enough (Levin et al., 1998). While there is no real way to predict gateway events, we can increase the chance that we will be able to take advantage of them when they occur. In the case of nuclear waste management, we might consider making certain that the material remains accessible in case better disposal technologies arise in the future.

Incorporating innovation into a model of sustainable development is difficult. Though technology can be seen as an “adaptive answer” to problems (Rammel & Van den Bergh, 2003), there is a fundamental disconnect between the world of the information society and the groundings of sustainable development. These two systems of social organization are often presented as mutually exclusive due to differing values held by the actors involved (Jokinen et al., 1998). Even if we can surmount this chasm, there is inherent uncertainty in the process of innovation (Buenstorf, 2000). Innovations can give rise to new needs, but they introduce variation and learning that is essential to the exploration and development of new possibilities (Vollenbroek, 2002). Some of our problems require systems innovations that will enable the fulfillment of needs in an entirely new manner, yet planning is difficult when resources

and concepts that are useful to us today might be of no use in the future, and resources and concepts that we do not presently value may be essential to humans living in the future (Gowdy, 1994).

Precaution in an Uncertain World

One method used to mitigate the uncertain effect of new innovations is to evaluate them according to the precautionary principle. However, the very complexity that makes the precautionary principle desirable also makes it contentious and hard to define. The origin of the precautionary principle concept is often credited to the German notion of *Vorsorgeprinzip*, or foresight planning, which began to receive attention in the 1970s (Morris, 2000). The concept has evolved over time, and what began as a “measure” shifted to an “approach” and finally to a “principle” (Adams, 2002).

The Rio Declaration urges the use of the precautionary principle. Principle 15 states that where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing cost-effective measures to prevent environmental degradation (Morris, 2000). A stronger definition, known as the “Wingspread definition,” emerged from a 1998 conference. The Wingspread definition of the precautionary principle states that when an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause-and-effect relationships are not fully established (Raffensperger, 2002).

Intuitively, the precautionary principle is straightforward, (Adams, 2002; Saltelli & Funtowicz, 2005). The general idea is to avoid serious and irreversible damage (Som et al., 2004). As Raffensperger (2003) states, the precautionary principle can be used to prevent, not just redress, harm. What is simple to describe, however, is not necessarily simple to put into use. Critics say the precautionary principle is ill defined, unscientific, and ideological. Some commentators argue that universal application of the precautionary principle would rule out any action, including doing nothing (Sunstein, 2002). It is also argued that the precautionary principle inhibits innovation and the creation of better substitutes (Goldstein & Carruth, 2005). These concerns must be addressed before the precautionary principle can be applied practically. Innovation is critical to human health and welfare. The optimal balance between precautionary principle proponents and their critics would be to develop a method of screening inventive adaptations that does not cripple innovation, but does limit potential harm. Such an approach might proceed as follows:

- A brief application of the precautionary principle is needed for trivial innovation similar to other innovations with only local effect. As an example, imagine that someone develops a slightly better corkscrew. It is unlikely such a refinement will have serious consequences, and therefore the precautionary principle might consist simply of testing to ensure the product does not cause injury.
- A much more thorough application of the precautionary principle is needed when a clear risk can be imagined. For example, genetically modified organisms that contain genetic material from serious allergens such as peanuts and shellfish should be carefully studied before being used in food products.
- We must accept that some breakthrough technologies will have unpredictable effects, and develop our ability to cope reactively with problems accordingly. As an example, the development of chlorofluorocarbon-based refrigerants allowed a revolution in cooling and food storage that saved many lives and greatly improved human health. The technology to understand the risk that these compounds posed to the ozone layer did not exist until much later, and thus what mattered was not our ability to apply a precautionary principle, but our ability to react quickly and effectively to an unforeseen problem.

It is necessary to begin by asking, “to what sort of hazards does the precautionary principle apply?” What level of evidence should be required for its use, and what kinds of preventive measures should be invoked? In the first instance, there must be some evidence that a hazard exists if the precautionary principle is not to lead to efforts to rule out any action (Sandin et al., 2002). If the precautionary principle is not to stifle progress, it should be coherent, use known information and theories, have explanatory power, and possess simplicity (Resnik, 2003). Low complexity solutions should be preferred to high complexity solutions, if the precautionary principle is to avoid simply creating further problems (Som et al., 2004).

Tickner & Geiser (2004) point out that an important proviso is needed if the precautionary principle is to be practical and workable. Many framings of the precautionary principle call for preventative action and reversing the burden of proof. These measures need to be coupled with alternatives assessment in order to be proactive. This recommendation leads to a focus on solutions rather than problems and can stimulate innovation. Alternatives assessment can also allow an avenue for public participation, as we will see in the following discussion of nuclear waste management. To summarize:

- The strength of the precautionary principle applied should reflect the scale of the innovation in question.
- A discussion of alternatives should be a part of a precautionary principle process.
- The precautionary principle should focus on known risks, with the understanding that unknown risks might exist.
- It must be understood that no precautionary principle short of disallowing any action will be 100% effective in preventing problems, as our society and ecosystems are inherently unpredictable. We must therefore develop our ability to respond to such problems as they arise.

Uncertainty and Resilience

Complex systems are filled with uncertainty, and no amount of precaution will eliminate all risks. We therefore need to build system resilience, which Holling (1976) defines as the ability of a system to persist by absorbing change. Several factors influence a system’s resilience. These include its latitude, or the maximum amount of stress that it can absorb without changing to a new state, its ability to resist change, and its precariousness or fragility (Walker et al., 2004). The more resilient an ecosystem or society is, the better it will be at responding and adapting to unpredictable changes.

There are several ways we can increase system resilience. In the first instance, we can increase resilience by ensuring that as we undertake a course of action we leave room

for alternatives. Preventative measures should allow for more flexibility in the future (Gollier et al., 2000). Especially in cases of irreversibility, options should be kept open (Arrow & Fisher, 1974). We can expand resilience by increasing a system's buffering capacity, by managing for processes at multiple scales, and by nurturing sources of renewal (Gunderson, 2000). Allowing cross-scale communication can be particularly important, as information presented by the inshore Newfoundland fishers demonstrates (although it was ultimately ignored by the government). Moving information across scales is difficult, but it is critical to resilience (Peterson, 2000).

In his detailed study of historical social collapses, the geographer Jared Diamond (2005) highlights several points of failure: failure to anticipate problems, failure to perceive the problems once they exist, failure to act on problems, and finally failure of an action to solve a problem. The precautionary principle can mitigate the earlier stages of this progression, but how do we successfully manage the entire spectrum of proactive and reactive responses? Diamond argues that important components of resilience are a willingness to engage in long-term planning and an openness to reconsider core values.

Precaution, Uncertainty, Resilience, and Nuclear Waste

Nuclear waste management presents a poignant example of a case that mandates action despite extremely uncertain information and future scenarios. Canada is currently deciding how to manage its existing high-level nuclear waste. During the fall of 2004 and the spring of 2005 I participated in the organization of three electronic dialogues on nuclear waste disposal with the goal of engaging the Canadian public.¹ The dialogues were conducted for the Nuclear Waste Management Organization (NWMO) of Canada, an entity established under the Nuclear Fuel Waste Act to study various options for managing the country's used nuclear fuel. Three provinces (Ontario, Quebec, and New Brunswick) currently produce such waste, which poses a very long-term hazard to both human health and natural ecosystems. The organization has been charged to:

- Establish an Advisory Council that will make public its comments on the study by the waste management organization and other reports.
- Submit to the Minister of Natural Resources, within three years of the legislation coming into force, proposed approaches for the management of used nuclear fuel, along with Advisory Council comments and a recommended approach (NWMO, 2005).

The NWMO focus on public involvement stems in part from the failure of the earlier Canadian Nuclear Waste Management Program (CNWMP) to finalize a waste management process. Begun in 1978, the CNWMP concluded in its final report, released in 1998, that broad public support for the proposed disposal measures had not been demonstrated (CEAP, 1998).

¹ These electronic dialogues were created by Ann Dale of Royal Roads University in British Columbia.

The dialogues were held to engage the public in a discussion of the NWMO Assessment Framework, of the general risk and uncertainty of nuclear waste disposal and management, and of the decision-making processes most applicable under such conditions of risk and uncertainty. The goal was to provide a neutral space where discussion of a contentious and complicated public policy issue could take place. The dialogues were also designed with an educational role in mind, to further public engagement with sustainable development issues in which the science is often uncertain, the needed information is incomplete, and the time frames transcend successive generations (Newman & Dale, 2005).

The process was similar for each of the three dialogues. Before each session, we posted on the e-dialogue website illustrative background material that was chosen to be informative, fair, and balanced. All three dialogues are available at www.e-researchagenda.ca, and a summary report was prepared for the NWMO.

The three dialogues introduced several new points and reiterated others for political decision makers. There was widespread consensus among both the experts and the panelists that the worst decision would be to take no decision, despite the risk and uncertainty. In the spirit of alternatives assessment, participants discussed the merits and detractions of several proposed solutions. Many participants believed that adaptability should be strengthened to include ongoing improvement, innovation, and research and development, a result that reinforces the above discussion on resilience. The public wanted to ensure maintenance of capacity to adapt to and to benefit from changing cognition. The framework should provide flexibility to future generations to "support improved management options" and changes in decisions, and not place constraining burdens or obligations on future generations.

More importantly, although the federal government mandated the NWMO to focus exclusively on the management of used nuclear fuel, an ardent public desire emerged, especially among younger Canadians, to see this issue linked to nuclear waste production. From a systems perspective, it was viewed as problematic to separate the human demand for, and use of, energy from the management of spent fuel. This result mirrors the previously discussed need to connect across scales.

We feel the issues raised during these discussions represent a successful and diverse engagement with the audience that has enriched the NWMO decision process. It was particularly interesting to see how the dialogues encouraged participants to challenge the assessment framework and to suggest more holistic approaches for the management of used nuclear fuel. The preliminary report from the NWMO to the Canadian government reflects these concerns, and calls for the waste to be buried but left accessible for at least several hundred years (NWMO, 2005). The alternatives assessment undertaken here resembles the Natural Step process. The problem was acknowledged, a goal set, and a selection of paths considered. In this case, the process will be ongoing for thousands of years, and the progress to date is only the barest beginning of a very complex management problem.

The NWMO process has precedent in the Berger Inquiry into pipeline development in Canada's North. Parliament established this inquiry early in 1974 to review plans to build an oil and gas pipeline in the Mackenzie Valley. This wide-ranging process evaluated social, environmental, and economic impacts of the prospective facility. The inquiry had

great flexibility, with permission to gather testimony at hearings throughout the country. Hearings were held in all communities along the proposed route. The inquiry concluded that no pipelines should be built in the Northern Yukon, and that the building of a pipeline in the Mackenzie Valley should be delayed. Key issues included the great risk to the fragile Arctic environment, the smaller-than-promoted size of economic benefits, and the opposition of the local population (O'Malley, 1976).

The Berger Inquiry and the NWMO represent flexible, open, and responsive approaches to complex issues. The mismanagement of the Eastern Cod fishery, particularly the exclusion of the views of local fishers, stands in stark contrast, suggesting that inclusion of public knowledge is crucial to a dynamic approach to sustainable development.

Conclusion

One of the goals of any approach to pursuing sustainable development is to ensure that future generations have ample options (Tonn, 2004). A dynamic approach that manages uncertainty as an ongoing process could maintain our future options. Dynamic sustainable development is largely about balance; embracing precaution will be most effective when paired with alternatives assessment. Innovation needs to be coupled with resilience building.

The NWMO has begun a process designed to address a very complex, very long-term problem in a manner that respects many of the issues addressed in this paper. The organization recognized the problem and realized that the status quo was not sustainable, even if the results of any recommended action would be intrinsically uncertain. The NWMO embraced the precautionary principle in their decision making process (NWMO, 2005), but acknowledged the need for alternatives assessment. As part of this process, the organization engaged the public and this helped to bring together the issue's social and technical dimensions. In the subsequent report, the NWMO responded to calls for resilience by recommending a course of action that would leave room for future technical innovation and allow for monitoring, thus providing important feedback. However, it remains to be seen whether Canadian governments will progress to a multi-scale conversation that connects waste management with waste production, an important step in linking feedback loops.

Throughout the public consultations, members of the public have asked why Canada's nuclear waste exists in the first place and whether the current dilemma could have been prevented. If the founders of the Canadian civilian atomic power program had applied the precautionary principle to the development of nuclear energy, they might have determined that the waste from these facilities posed serious, but poorly understood, risks that were not technologically resolvable, and that alternative sources of electricity were available at the time. However, even the most diligent application of dynamic sustainable development will never create an entirely proactive society. The interaction between human societies and biological ecosystems will occasionally generate surprising threats to sustainability, and these situations must be managed reactively. Inherent uncertainty always exists, and innovation can act as a double-edged sword, both straining the biosphere and simultaneously creating new ways to achieve sustainability. A society with sufficient diversity and resilience will be able to

adapt to such surprises. As the concept of sustainable development evolves, a combination of proactive and reactive management should prove central to sustaining societies in the face of change.

Acknowledgement

I would like to thank Dr. Ann Dale for her insight into these issues.

References

- Adams, M. 2002. The Precautionary Principle and the Rhetoric Behind It. *Journal of Risk Research* 5(4): 301-316.
- Arrow, K. & Fisher, A. 1974. Environmental Preservation, Uncertainty, and Irreversibility. *Quarterly Journal of Economics* 88: 312-319.
- Buenstorf, G. 2000. Self-Organization and Sustainability: Energetics of Evolution and Implication for Ecological Economics. *Ecological Economics* 33: 119-134.
- Brundtland, G. 1987. *Our Common Future: World Commission on Environment and Development*. New York: Oxford University Press.
- CEAP, Canadian Environmental Assessment Panel. 1998. *Nuclear Fuel Waste Management and Disposal Concept*. Ottawa: Canadian Environmental Assessment Agency.
- Dale, A. 2001. *At the Edge: Sustainable Development in the 21st Century*. Vancouver: UBC Press.
- Debray, R. 1997. *Transmitting Culture*. New York: Columbia University Press.
- Diamond, J. 2005. *Collapse: How Societies Choose to Fail or Succeed*. New York: Viking Press.
- EEA, European Environmental Agency. 2001. Late Lessons from Early Warnings: The Precautionary Principle, 1896-2000. http://reports.eea.eu.int/environmental_issue_report_2001_22/en. June 2005.
- Goldstein, B. & Carruth, R. 2005. Implications of the Precautionary Principle: Is it a Threat to Science? *Human and Ecological Risk Assessment* 11: 209-219.
- Gollier, C., Jullien, B., & Treich, N. 2000. Scientific Progress and Irreversibility: An Economic Interpretation of the Precautionary Principle. *Journal of Public Economics* 75: 229-253.
- Gowdy, J. 1994. The Social Context of Natural Capital: The Social Limits to Sustainable Development. *International Journal Social Economics* 21(8): 43-55.
- Gunderson, L. 2000. Ecological Resilience: In Theory and Application. *Annual Review of Ecological Systems* 31: 425-439.
- Holling, C.S. 2001. Understanding the Complexity of Economic, Ecological, and Social Systems. *Ecosystems* 4: 390-405.
- Holling, C.S. 1976. Resilience and Stability of Ecosystems. In E. Jantsch & C. Waddington (Eds.), *Evolution and Consciousness: Human Systems in Transition* pp. 73-92. Reading, MA: Addison Wesley Publishing.
- Homer-Dixon, T. 2000. *The Ingenuity Gap*. New York: Alfred A. Knopf.
- Jervis, R. 1997. *System Effects: Complexity in Political and Social Life*. Princeton, NJ: Princeton University Press.
- Jokinen, P., Malaska, P., & Kaivo-Oja, J. 1998. The Environment in an Information Society: A Transition Stage Towards More Sustainable Development. *Futures* 30(4): 485-498.
- Levin, S., Barrett, S., Aniyar, S., Baumol, W., Bliss, C., Bolin, B., Dasgupta, P., Ehrlich, P., Folke, C., Gren, I., Holling, C.S., Jansson, A., Jansson, B., Maler, K., Martin, D., Perrings, C., & Sheshinski, E. 1998. Resilience in Natural and Socioeconomic Systems. *Environment and Development Economics* 3: 221-262.
- Livingston, J. 1994. Sustainability and the Future. In D. Bell, R. Keil, & G. Wekerle (Eds.), *Human Society and the Natural World: Perspectives on Sustainable Futures*, pp. 4-7. Toronto: York University.
- Lorentz, E.N. 1993. *The Essence of Chaos*. Seattle: University of Washington Press.
- Morris, J. 2000. Defining the Precautionary Principle. In J. Morris (Ed.), *Rethinking Risk and the Precautionary Principle*, pp. 1-14. Oxford: Butterworth-Heinemann.
- Natress, B., & Altomare, M. 1999. *The Natural Step for Business: Wealth, Ecology, and the Evolutionary Corporation*, Gabriola Island, BC: New Society Publishers.
- Newman, L., & Dale, A. 2005. Network structure, diversity, and proactive resilience building: a response to Tompkins and Adger. *Ecology and Society* 10(1): r2. [online] URL: <http://www.ecologyandsociety.org/vol10/iss1/resp2/>.
- NWMO, Nuclear Waste Management Organization. Nuclear Waste Management Organization. 2005. <http://www.nwmo.ca/>. June 2005.
- O'Malley, M. 1976. *The Past and Future Land: An Account of the Berger Inquiry into the Mackenzie Valley Pipeline*. Toronto: Peter Martin Associates.
- Peterson, G. 2000. Political Ecology and Ecological Resilience: An Integration of Human and Ecological Dynamics. *Ecological Economics* 35: 323-336.

- Pereira, P. 1994. New Technologies: Opportunities and Threats. In J. Salomon, F. Sagasti, & C. Sachs-Jeantet (Eds.), *The Uncertain Quest: Science, Technology, and Development*. 448-462. Tokyo: United Nations University Press.
- Raffensperger, C. 2003. Constitutional Experiments: Protecting the Environment and Future Generations. *Conservation Biology* 17(6): 1587-1488.
- Raffensperger, C. 2002. Precaution and Security: The Labyrinthine Challenge. *Whole Earth* 109: 34-37.
- Rammel, C. & Van Den Berg, J. 2003. Evolutionary Policies for Sustainable Development. *Ecological Economics* 47: 121-133.
- Rees, W. 1989. *Planning for Sustainable Development: A Resource Book*. Vancouver, BC: University of British Columbia Centre for Human Settlements.
- Resnik, D. 2003. Is the Precautionary Principle Unscientific? *Studies in the History and Philosophy of Biological and Biomedical Sciences* 34: 329-344.
- Rihani, S. 2002. *Complex Systems Theory and Development Practice*. London: Zed Books.
- Robinson, J. 2003. Future Subjunctive: Backcasting as Social Learning. *Futures* 35:839-856.
- Saltelli, A. & Funtowicz, S. 2005. The Precautionary Principle: Implications for Risk Management Strategies. *Human and Ecological Risk Management* 11: 69-83.
- Salwasser, H. 1993. Sustainability Needs More than Better Science. *Ecological Applications* 3(4): 587-589.
- Sandin, P., Peterson, M., Hansson, S., Ruden, C., & Juthe, A. 2002. Five Charges Against the Precautionary Principle. *Journal of Risk Research* 5(4): 287-299.
- Som, C., Hilty, L., & Ruddy, T. 2004. The Precautionary Principle in the Information Society. *Human and Ecological Risk Assessment* 10: 787-799.
- Spash, C. 2002. *Greenhouse Economics: Values and Ethics*. New York: Routledge.
- Sunstein, C. 2002. The Paralyzing Principle. *Regulation* 25(4): 32-37.
- Tickner, J. & Geiser, K. 2004. The Precautionary Principle: Stimulus for Solutions and Alternatives-Based Environmental Policy. *Environmental Impact Assessment Review* 24: 801-824.
- Tonn, B. 2004. Integrated 1000-year planning. *Futures* 36: 91-109.
- Vollenbroek, F. 2002. Sustainable Development and the Challenge of Innovation. *Journal of Cleaner Production* 10: 215-223.
- Wackernagel, M. & Rees, W. 1996. *Our Ecological Footprint: Reducing Human Impact on the Earth*. Gabriola Island, BC: New Society Publishers.
- Waldrop, M. 1992. *Complexity: The Emerging Science at the Edge of Order and Chaos*. New York: Simon and Schuster.
- Walker, B., Holling, C., Carpenter, S., & Kinzig, A. 2004. Resilience, Adaptability, and Transformability in Social-Ecological Systems. *Ecology and Society* 9(2): 5. [online] <http://www.ecologyandsociety.org/vol9/iss2/art5/>.