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CHARACTERIZING ADAPTABLE SYSTEMS:
MOVING FROM SIMULATION MODELS TO ADAPTATION POLICY

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ABSTRACT: Developing a capacity for adaptation is an important component of policy development. This paper uses an agent-based model to conduct a large number of experiments. The model incorporates research into artificial life simulations and Holland's work with genetic algorithms and classifier systems. The research is based on the simulation platform, Complex Organization and Bifurcation Within Environmental Bounds, or COBWEB. COBWEB simulates how a system of autonomous agents adapts to variation and sudden changes in the resource base. COBWEB was set up as a generic system of agents in an environment, but can be configured to represent an ecosystem or a social system. In COBWEB, when the population is well adapted to its environment, an increase in resources is followed by an increase in population, which in turn is followed by decreasing resources, that is, the predator-prey pattern in ecology. In environmental change experiments conducted for this paper, the system was most sensitive to changes in the energy cost of activities, particularly movement, and the amount of energy available from resources. This was highlighted in two sets of experiments designed to mimic invasive species and the response of the system to climate change, expressed as a change in the length of seasons. COBWEB also allows for experiments with communication and memory. A series of experiments was conducted with very low rates of resource production, in other words, a resource scarcity. Without communication, all of the agents died out. With communication, the probability of survival for the whole population increased by 50 percent. The simulations highlighted the characteristics of a well-adapted system and the importance of threshold values, energy, communication and memory in adapting to variability and change. A system that is well-adapted to its current environmental variability is characterized by a balance between population and resources that is quite resilient to minor changes in various parameters that define its environment. However, at the margins, there are threshold values which, when crossed, produce more significant changes. This paper demonstrates the importance of energy and communication within a system, but it also raises questions as to the required speed at which society must develop innovative adaptive strategies to cope with environmental change.

Keywords: climate change, adaptation, COBWEB, model simulation, ecosystems, complexity, populations, resources, memory, communication, energy

1. Introduction

Socio-economic and ecological systems are subject to a wide variety of stresses, many of which are associated with the atmosphere. Although a great deal of political will is being expended on slowing down, halting or reversing various atmospheric changes, at least in one case - that of climate change - the international agreements recognize the need for adaptation to a different atmosphere. Most studies of adaptation in this context look at specific locations, specific impacts and the recommendation of specific measures to reduce vulnerability or the expected level of damage. While this is necessary to develop specific responses to specific impacts it does not explicitly address the question as to whether any system, be it ecological or social, is adaptable or how to encourage adaptability. Although we can provide scenarios of impacts that may occur within certain time periods in the next century, the uncertainties and the surprises that occur in any complex systems suggest that developing a capacity for adaptation is also an important component of policy.

One step to develop this capacity is to examine the properties of systems to discover those characteristics that are important in creating a capacity to adapt, regardless of the specific stress. Buz Holling, using induction, has characterized what he terms the adaptive cycle based on specific case studies of several ecosystems, resource management and social phenomena (Holling, 1986; Holling and Gunderson, 2002). The adaptive cycle emphasizes the importance of connectedness, resource potential, destructive events and reorganization. A second approach is to begin with systems theory itself, which might lead to an emphasis on redundancy, diversity and the clarity of communication. A third approach is to use a generic simulation model to conduct a large number of experiments, taking advantage of the speed available on most desktop computers. This approach underlies the research into artificial life simulations and Holland's work with genetic algorithms and classifier systems.

This paper builds upon this third approach to develop a characterization of adaptable systems. The advantage of this approach is that it can be used on its own or in conjunction with either of the other two approaches by providing a platform to test the importance of various characteristics in creating the capacity to adapt to change. The research is based on the simulation platform, Complex Organization and Bifurcation within Environmental Bounds or COBWEB for short. COBWEB is a robust simulation platform that simulates how a system of autonomous agents adapts to variation and sudden changes in the resource base. COBWEB can be set up as a generic system of agents or it can be configured to represent an ecosystem or a social system.

2. The COBWEB Simulation Platform

The COBWEB software platform and variables have been described in Bass et al. (2002), Suh et al. (2004) and Bass and Chan (2004). COBWEB offers many unique features as a simulation model:

1. It allows for multiple resources, each with its own variability;
2. Environmental change can be introduced suddenly at any point in the program;
3. The agents are classified according to the similarities in their genetic code;
4. It allows for resource preferences amongst the agents;
5. At any point in a simulation, the user can alter the quantity and location of resources, agents and barriers;
6. The agents can exhibit both biological and social behaviours; and
7. The software is both flexible and portable.

COBWEB is implemented in Java to provide flexibility and portability. It consists of a two-dimensional multiple resource environment, autonomous agents and barriers to movement. The resource growth is simulated with a cellular automata algorithm. The grid size is flexible and the user can choose either hard boundaries, (an agent hits the boundary is turned around), or wrap around boundaries (an agent hits a boundary and emerges on the opposite side of the grid). The agents are genetic algorithms, a software representation of genetic code consisting of a string of 1's and 0's that determines behaviour at every time step. It is essentially a map or computer program that associates an input with a specific output. The string is randomly assigned at the beginning of a simulation, but changes to the code occur in offspring through mutation and breeding. Other behaviours are available that are initialized at the start of the simulation. For example, each agent has a distinct probability that it will share information with another agent or whether or not it will mate with another agent. Each agent is also assigned a resource preference at random, which can be used to assign an agent more energy from the preferred resource than from other resources.

The genetic code determines what action the agent takes in the environment. In the current version of COBWEB these actions are restricted to turning left or right, moving forward, consuming resources, and clustering together with other agents. The agent also has additional code that is not genetically determined but consists of information about the environment and information communicated by other agents. If the strategy represented by the genetic array and non-genetic information does not lead to sufficient accumulation of energy, the agent and its strategy is eliminated from the environment. If sufficient energy is accumulated, the agent can reproduce, thereby copying its strategy or recreating a strategy that has been eliminated from the system.

The genetic code or strategy and the resource preference or agent type are randomly assigned at initialization. It is important to note that the strategies and the agent types are not connected in the model. Different agent types could in principle have similar strategies, and multiple strategies can emerge within the same agent type. Using a scheme developed for characterizing variations in soil composition (Hu et al., 2004), COBWEB colours the agents based using a red-green-blue spectrum, with one red, green and blue agent acting as three genetic markers. The other agents receive a colour based on their similarity to these three markers with similar agents receiving different shades of the same colour (see Figure 1).

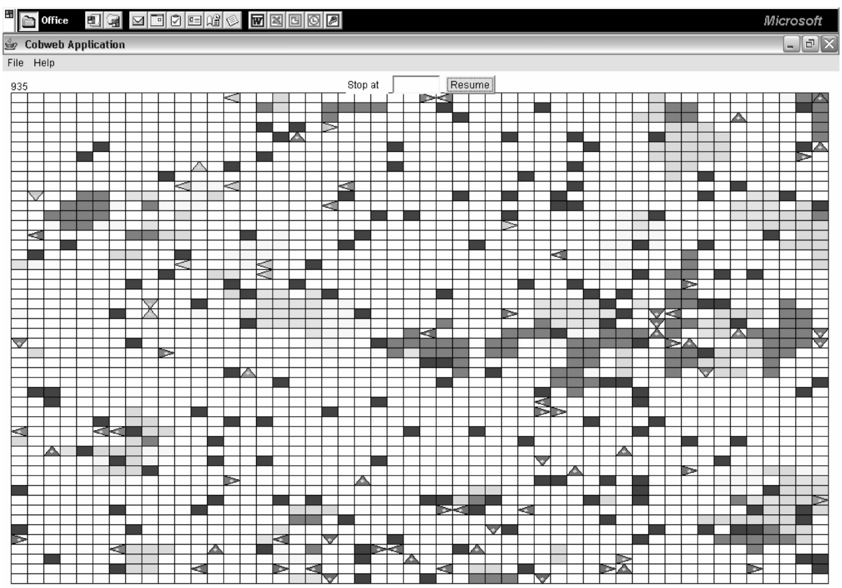

FIGURE 1

A COBWEB simulation in which the agents are triangles, resources are grey squares and stones are black squares.

COBWEB was not developed in a vacuum. It was meant to represent a complex system that builds on the work of Holling (creative destruction, reorganization and the presence of multiple attractors), Holland (recombination of genetic code to produce new strategies), and Hansell et al. (bifurcation, semi-stability and sudden change) (Hansell et al., 1997; Holland, 1995; Hollling, 1986). It was assumed that if COBWEB was built as a system of autonomous agents, making their own decisions, these properties of a complex system discussed by Holland (1995), Holling (1986) and Hansell et al. (1997) would emerge in various experiments. To some extent, COBWEB has been extraordinarily successful, both in representing complexity and in illustrating adaptation. As with most projects of this sort, every new set of experiments, every new user and with every new version (Version 2.4b is available and Version 3.1 is under development) raises new questions and uncovers new limitations.

3. What Was Learned: Population and Resources

In COBWEB, when the population is well adapted to its environment, an increase in resources is followed by an increase in population, which in turn is followed by decreasing resources, i.e. the predator-prey pattern in ecology. Within this pattern, a maximum and minimum value emerges for the population, resources and energy stored by the agents. Typically, the system goes through a period of large oscillations in resources and population before settling into this stable state (see Figure 2). However, there are several nuances in this state that are quite revealing.

The range of variation within a maximum and minimum value, suggesting a system that is well-adapted to its current environmental variability, is characterized by an optimum number of agents to maintain stability. Within this optimum, one or two dominant strategies tend to emerge quite rapidly, and are typically confined to one type of agent as defined by the resource preference. In many experiments, other strategies will emerge over time, challenging the dominant strategies and sometimes remaining in the system, yet the overall predatory-prey pattern, with its minimum and maximum population and resources remains in place with little variation.

In space, the story is quite different. Based on the movement of the agents, the strategies seem to fall into three categories: remain in one place, traverse long distances and movement with a range defined by the cluster of agents. Stable spatial clusters emerge, and if there are multiple strategies, they are

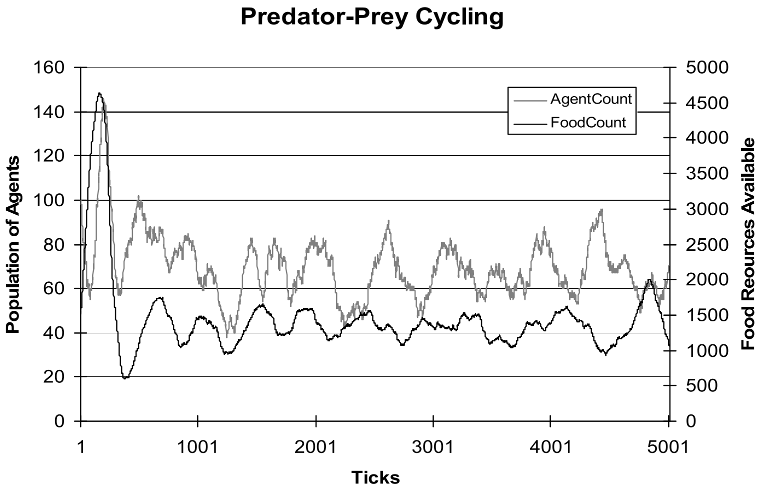

FIGURE 2

Output illustrating relationship between population and resources that characterizes a system that is well-adapted to current environment.

often located in different parts of the grid. The spatial patterns do not last and typically change between 500 and 1000 time steps. Sometimes these patterns follow the emergence of new resources, but at other times clusters will emerge away from the largest resource concentrations.

As expected though, even within this stable state, surprise and bifurcation is possible. Each agent type of COBWEB is associated with about 18 parameters. The stable state is quite robust to changing these parameters within a well-defined window. Depending on the initial set-up, there are threshold values for several parameters, that when crossed, will produce a different result. Often, crossing the threshold would lead to the elimination of all agents or the reemergence of a new population and new stable state. Surprise occurred within a simulation with the emergence of semi-stable attractors, that is, an apparently stable state that undergoes a sudden and dramatic change without any external intervention (i.e., a change in the environment).

In the environmental change experiments, the system was most sensitive to changes in the energy cost of activities, particularly movement, and the amount of energy available from resources. This was highlighted in two sets of experiments designed to mimic invasive species and the response of the system to climate change, expressed as a change in the length of seasons. In simulating an invasion by an external set of agents, the invasion was only successful if the invaders required less energy to move or could extract more energy from resources. To achieve a 100 percent success rate, it was necessary to increase the total amount of energy in the system either through the existing mix of resources or through adding a new resource.

Climate change was represented by a change in the growth rates of the resources with higher growth rates representing the wet or growing season. In these experiments, the system had the most difficulty in adapting to a change that both altered the length the wet/growing season and the dry/winter season. When the wet/dry season was lengthened/shortened, the population expanded to match the increase in resources. Occasionally, with a longer wet season, the system maladapted to the change as the population consumed all of the resources too quickly and subsequently died out. In the opposite experiment, the population would often die out, even if the rate of resource growth during the dry season was marginally less than in the wet season.

4. What Was Learned: Social Factors

COBWEB allows for experiments with communication and memory. Although these characteristics may be found to some extent in an ecological context, they are more frequently associated with human systems. Communication means that an agent transfers information from its communication buffer into another agent's buffer. The memory is where the agents store information about the environment at each time step. In both cases, this new information is a string of 1's and 0's so that it can be added to the genetic code, thus combining nature and nurture. The initial experiments with memory indicated that the new information did indeed alter the behaviour of an agent, i.e. the agent modified its strategy.

Further experiments were conducted on individual agents and on the system as a whole. In the first set of experiments, we tracked an individual agent. Increased success was measured by the probability of survival and having descendants and the length of survival and the number of descendents. Adding memory and communication led to an equal or slightly higher probability of increasing life spans and having descendants. What was more remarkable is that when an agent with memory and/or communication did survive and reproduce, they were prone to live longer and have far more descendants than an agent without memory or communication.

In testing the impact on the system, we examined both the number of agents and the energy in the system as we varied the size of the memory and the communication buffer. Increasing the amount of information that could be communicated resulted in a larger population, but it was confined to one agent type and resulted in the reduction of the average energy per agent, a reduction that grew larger as the communication buffer was increased in size.

A series of experiments was conducted with very low rates of resource production, in other words, a resource scarcity. Without communication, all of the agents died out. With communication, the probability of survival for the whole population increased to 50 percent. The probability increased by 10 percent with linear increases in the communication buffer. Increasing the size of the memory led to a larger agent population, again confined to one type. With further increases in size, multiple types of agents survived, eventually resulting in the survival of all four types, but the overall population decreased below the baseline.

The most recent iteration of Version 2 includes a Prisoner's Dilemma option. When two agents meet, they have the option of cooperating and sharing energy resources or trying to steal energy resources. Although this requires a great deal more testing, the initial simulation runs with this option suggested that cooperation pays off, as the cheaters did not survive. Part of the reason might have been that the cooperators would remember an agent that had cheated them in the past and would be unlikely to have any further contact with that agent. However, these initial experiments had a very low probability of asexual reproduction. Hence, cheaters could only mate with other cheaters, but this may have been hampered by the constant efforts to steal energy. When the probability of asexual reproduction was increased, the cheaters were far more successful and could out-compete the cooperators.

5. Comparison with other Hypotheses of Adaptation

COBWEB has not been used to replicate other hypotheses of adaptation, and a comparison with the broad range of thinking across a myriad of disciplines is beyond the scope of this paper. However, there are correspondences with Holling's adaptive cycle, Scheffer's work on shallow lakes (Scheffer, 1998) and Byers and Hansell (1996) ideas on semi-stability. Although these works were all targeted towards ecological adaptation, Holling and Gunderson (2002) have expanded the discussion to a broad range of social systems.

Holling and others have developed a theory of adaptation that does not characterize adaptive systems so much as it describes the dynamic of adaptation. Usually represented as a figure 8 diagram, Holling proposed that many complex systems exhibit a similar pattern beginning with rapid growth, stability, creative destruction and reorganization. The first stage allows the early opportunists (the r species in ecology) to take advantage of a new situation. Their success paves the way for other participants (the k species in ecology) who create a stable, if not resilient system, but a system that is based on tightly connected networks and resources that are bound up within the system and not readily accessible. The period of creative destruction, forest fires or pest outbreaks in ecology, are a necessary part of the adaptive cycle as they create space for new organisms or experiments, and lead to a system that is better adapted to a change in the environment. These new experiments are the period of reorganization as the system prepares to begin for the early opportunists. This period of reorganization determines whether a similar system reappears or something different, and perhaps unexpected, emerges in its place.

At initialization, COBWEB resembles the first stage of the adaptive cycle, and in most cases reaches the stable stage before 1000 time steps, a time step being defined as that interval when every agent makes one move. At smaller spatial scales, this type of process appears to occur in a manner not altogether different than described in Holling et al. (2002). Pockets on the COBWEB grid appear to reach a stable state that may last for 500 to 2000 time steps, only to collapse, followed by a reorganization of the resource base and the mobile agents. At smaller time scales, new strategies are often being introduced, but at this point these temporal changes have not been linked with the spatial changes. Although COBWEB can be set up to introduce a wide-spread environmental change, these changes have not been devastating enough to represent creative destruction as that was not the objective of the experiments.

COBWEB does reflect the findings of Scheffer (1998) and Hansell et al. (1997). As reported above, the long-term pattern often exists within a well-defined boundary of parameter values, and this solution is quite resilient to incremental change. Yet these changes led to the discovery of threshold values, beyond which, the system would flip to a different state or attractor, similar to Scheffer's discussion of shallow lakes. However, these simulations were run in a statistical not dynamic mode, i.e. the changes were made at initialization, in a large number of experiments (Bass et al., 2002; Suh and Bass, 2004).

Over the long term, the temporal predator-prey pattern that characterizes the balance between resources and population will collapse quite suddenly and quite surprisingly, suggesting the presence of a semi-stable attractor, a state that appears stable but is imperceptibly shifting to another state or a bifurcation point (Hansell et al. (1997); Bass et al., 1998). As COBWEB is not based on either a set of nonlinear differential equations or an iterated function system, it is not possible to test for semi-stable attractors in a formal manner.

If the emergence of a semi-stable attractor is interpreted as a destructive event, we find some correspondence to Holling's adaptive cycle. In many cases the system died out or the new state or attractor consisted solely of the resources. However, in a few cases, a small group of mobile agents survived and were able to reestablish the population or accumulated and conserved enough energy to survive at significantly reduced numbers. The fact that the changes in space occur at short frequencies, and the collapse of a semi-stable attractor occurs at much longer frequencies also indicate a correspondence with Holling and Gunderson's suggestion that these cycles occur at multiple scales and have a spatial structure (Holling and Gunderson, 2002). The newer versions of COBWEB will provide a better platform for testing hypotheses of adaptation across a broad range of systems.

The development of COBWEB is itself an adaptive process and has followed a dynamic that very much resembles Holling's adaptive cycle. It began with a rush of ideas as this was a new ground for Adaptation and Impact Research Group research, corresponding to the shift from phase 4 to phase 1. The first version was ready in 1999 and was used as a research tool while the code was altered in minor ways to provide a more realistic simulation. This was stage

2, the stable stage. At some point, the research team realized that we could not proceed in this manner without a major revision of the software, phase 3 and the revision itself, which led to something different and a new research cycle. This has occurred three times, but is deemed to be a necessary component of the development of COBWEB, allowing us to cope with new challenges from the research and policy communities.

6. Important Characteristics of Adaptable Systems

The simulations highlighted the characteristics of a well-adapted system and the importance of threshold values, energy, communication and memory in adapting to variability and change. A system that is well-adapted to its current environmental variability is characterized by a balance between population and resources that is quite resilient to minor changes in various parameters that define its environment. However, at the margins, there are threshold values which when crossed, produce more significant changes. Adaptation to change was far more likely to be successful if the available energy was increased or remained constant.

Both communication and memory increased an agent's life span and the number of descendents. At a system-wide scale communication between agents enhanced the rate of survival for the whole population under a relative scarcity, albeit for only one type of agent. Memory (i.e. storage of environmental information) also enhanced system-wide survival of the agents, particulary the survival of multiple agents. The Prisoner's Dilemma option suggests a further role for communication and memory. In a system that favoured collaboration, cheaters did not prosper.

The experiments on memory and communication and some limited work on barriers to reproduction, suggest that one other characteristic of an adaptable system is an environment that rapidly fosters experimentation with new ideas that match the speed of environmental variation and change. These new strategies occur through mutation in asexual breeding, genetic crossover in sexual breeding, through communication and through memory. The exact balance of these four determinants of new strategies has not yet been discovered and will require further research.

The emergence of bifurcation points or semi-stable attractors also indicates that the trajectory of a complex system can move in surprising ways, without warning. In many cases, the agents were not able to adapt to this change indicating that what appears to be a successful adjustment in the short term may have other unintended and unpredictable consequences.

7. Conclusions - Translating Theory into Policy

Do the COBWEB simulations provide any insight into future policy, geared towards increasing adaptability? In an obvious sense, the answer is yes. It highlights the importance of energy, both in terms of what is available and in terms of required energy costs or expenditures. Thus an increase in the cost of energy resources, without widely available alternatives, may increase the difficulty of maintaining our current standard of living.

The role of communication and memory were important in adapting to changes in the availability of energy. Memory, which is the storage of new information collected directly from the environment, alters an agent's strategy. This is akin to creating a new forecast as to the best location for new resources. The anticipatory nature of the memory has been discussed in Bass et al. (2002), but it suggests an important role for monitoring and the capacity for using new information.

Communication occurs through electronic infrastructure, but COBWEB emphasizes the importance of face-to-face contact, which could just as easily be interpreted as a high degree of social capital. Social capital has been linked to the capacity of communities to adapt to economic changes at different scales.

However, there are other aspects to COBWEB that are more intriguing for the policy of adaptation. Burton (2004) suggested that promoting an adaptation policy agenda is plagued by a lack of a measuring instrument, equivalent to greenhouse gas emissions for the mitigation camp. He suggests insurance losses due to weather as it would be an easily understood measure. Insurance losses provide some indication of societal vulnerability but is only a proxy for characterizing the adaptive capacity of any system.

Developing an index or indices may be important not only for measuring performance, but to provide an early warning with regards to a bifurcation in the system trajectory or a semi-stable attractor. Hansell et al. (1997) suggest a method for using an index to predict a change in system trajectory, but the method requires a long time series of data for which insurance losses may not be adequate. COBWEB suggests that an index based on energy or the relationship between population and energy is a suitable index of adaptability. Beer (1975) proposes how this information could be collected on real time at a suitable temporal scale to develop the capacity to predict change and suggests an alternative method based on the use of simulation models which is in line with Holling (1986) and the detection of a semi-stable attractor (Byers and Hansell, 1996).

Perhaps the most challenging aspect of COBWEB for policy, particularly geared towards increasing adaptability, is the rapid emergence and testing of new strategies. Discussions on how to foster this type of experimentation are usually confined to institutions (exceptions include the work of Stafford Beer (1975) and Charles Leadbeater (1999)) due the widespread cultural change that is required for success. It is difficult enough to implement within an institution, let alone within society as a whole, although Beer was involved in the design of a system in Chile that involved real-time monitoring of industrial output and citizen participation in political decisions through electronic communication. Unfortunately, this experiment was cut short by the overthrow of the government through a military coup in 1973.

What would be required to develop and test new ideas at a pace analogous to that in COBWEB or at a pace sufficient to match environmental variability and change? A growing body of literature has linked the emergence of creative solutions to an environment of collaboration, which in turn is a result of investments in building up social capital, both in the community and in industry. Michael Porter has written extensively the development of industrial clusters, competitive and complementary activities located within a small geographic range that allows for frequent personal contact. Similar proposals have been made, and experiments have been conducted, to create artist clusters in communities, but even investing in something as small as parent-child drop-in centres can lead to establishment of social networks and increased social capital in a community. The Prisoner's Dilemma experiments in COBWEB suggest that when the barriers to collaboration are lowered, collaboration does occur and the collaborators are more successful in adapting to the environment.

Charles Leadbeater (1999) also discusses the need to rethink the way in which we create, store, pay for and disseminate knowledge if we are to increase the rate of innovation and experimentation. Most of our societies have a very centralized and hierarchical means of producing and distributing knowledge, particularly specialized knowledge. In COBWEB, knowledge is extremely decentralized, allowing for frequent experimentation of new strategies. A more decentralized means of creating and spreading knowledge will expose us to more diverse ideas, competition between ideas and a higher rate of innovation. Although the Internet can act as a high-speed dissemination conduit, achieving a level of innovation analogous to what can occur within COBWEB will require rethinking the way in which we fund research, the role of universities and the pre-university education system.

Policies around energy, social capital, communication infrastructure and information are not novel, but on the energy side, it may require a broader exploration of how different the future should look from the past, as the adaptations to energy shortages often produced a smaller population, and perhaps new behaviours. The other policies are more problematic in that we do not have consensus on the value of communication, social capital and information. Outside of funding the construction of communication infrastructure, programs that build social capital or provide more information are frequently subject to funding cuts or, at the discussion phase, may be the first elements discarded from a discussion on new policy.

The crux of the issue was outlined by Charles Leadbeater (1999) in his book *Living on Thin Air.* We are living on a 15th century attractor with respect to financial accounting. We still live in the world of Luca Paccioli, a Franciscan monk and mathematician who created double-entry book-keeping, or the debit and credit that is the heart of financial accounting, an attractor that has proved quite stable. Yet all of those assets that might be labelled broadly as information are not recorded in this system; they were not valued by Professor Paccioli and we still find it extremely difficult to put value on those things that appear important, if not critical, to creating an adaptable system.

8. References

Bass, B. and Chan, E. (2004) Complex Organization and Bifurcation Within Environmental Bounds (COBWEB): An agent-based approach to simulating adaptation. *Environmental Informatics Archives,* 4

Bass, B., Hill, J. and Suh, N. (2002). Simulating adaptation to environmental change: Complexity and Organized Behaviour Within Environmental Bounds (COBWEB). *J. CASYS,* 13, 21-33.

Bass, B., Byers, R.T. and Lister, N.-M. (1998). Integrating research on ecohydrology and land use change with land use management. *Hydrological Processes,* 12, 2217-2233.

Beer. S. (1975) *Platform for Change.* Chichsester, UK: John Wiley & Sons.

Burton, I. (2004) Climate Change and the Adaptation Deficit. Paper presented to the *International Conference on Adaptation Science, Management and Policy Options,* Yunnan, China, May 17-19 2004.

Byers, R.E. and Hansell, R.I.C. (1996) Implications of semi-stable attractors for ecological modelling. *Ecol. Modelling,* 89, 59-65.

Hansell, R.I.C., Craine, I.T. and Byers, R.E. (1997). Predicting change in non-linear systems. *Journal of Environmental Management,* 46, 175-190.

Holland, J. (1995) *Hidden Order: How Adaptation Builds Complexity.* Reading, MA: Addison-Wesley.

Holling, C.S. (1986). The resilience of terrestrial ecosystems: local surprise and global change. In Clark, W.C. and Munn, R.E. (eds.) Sustainable Development of the Biosphere. IIASA, Cambridge University Press, 292-317.

Holling, C.S. and Gunderson, L.H. (2002) Resilience and Adaptive Cycles, in Gunderson LH and Holling CS (eds.) *Panarchy Understanding Transformations in Human and Natural Systems.* Washington, D.C.: Island Press, pg 25 – 62.

Holling, C.S., Gunderson, L.H. and Peterson, G.D.(2002) Sustainability and Panarchies, in Gunderson LH and Holling CS (eds.) *Panarchy Understanding Transformations in Human and Natural Systems.* Washington, D.C.: Island Press, pg 63-102.

Hu, Z., Bass, B., Chan, C. and Huang, G, (2004) An Innovative Approach for Visualization of Subsurface Soil Properties. *Canadian Journal of Soil Science* (in press)

Leadbeater. C. (1999) *Living on Thin Air: The New Economy.* London, UK: Penguin Books.

Scheffer, M. (1998) *The Ecology of Shallow Lakes.* London, UK: Chapman & Hall.

Suh, N., Bass, B., Chan, E. and Toller, N. (2004). Emergent computation and modelling: Complex Organization and Bifurcation Within Environmental Bounds (COBWEB). *Jnl of Environmental Informatics,* 3:1, (in press).