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What Can We Learn From Systems Based Approaches: From Systems Biology to Earth Systems Science?

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Abstract: Systems based approaches have been developed and applied in a broad range of disciplines. These cover a wide range of processes, structures and scales. Ludwig von Bertalanffy is often credited with establishing and developing 'general systems theory'. The ecosystem based approach to ecology developed by the Odum brothers (Eugene Pleasants and Howard Thomas) instigated approaches to understanding ecological systems that are still advancing within the frameworks of ecosystem services and ecological thermodynamics. West Churchman and Russel Ackoff were early pioneers in the field of operations research following on from techniques developed during the Second World War. Jay Forrester was also influenced by his work on feedback systems during the Second World War and went onto apply these engineering principles to management issues. In part due to limitations of 'hard' systems based approaches such as operations research and systems dynamics, Peter Checkland and others promoted 'soft' systems methodologies in the 1970s to take greater account of the social processes at the heart of complex situations. Social learning theory of Albert Bandura has been a key component of 'soft' system approaches. In the ecological domain it has been realized that social as well as ecological components of the system need to be considered. At the same time the ecosystem service framework has been widely utilized to help assess what benefits humans receive from the wider environment. 'Sustainability science' has been suggested as a new approach that can help scientists work with a wider set of stakeholders to address societal needs. At a smaller spatial scale significant advances at the sub-cellular and cellular scale by Hiroaki Kitano and colleagues in systems biology, has been enabled by rapid increases in the data and information available through genomic sequencing and high throughput assays. Just as with the birth of 'general systems theory' and cybernetics in the 1920-1950s there is a need to assess what can be learned from these often disparate systems based approaches and how we can work towards integrating our understanding and models from the sub-cellular level to the global scale. Here I suggest that diagramming, network theory combined with markup languages based on data and meta-data standards within an analytical-deliberative framework can lead to learning and greater integration across these disparate systems based approaches.

***Keywords**:* socio-ecological; systems biology; general system theory; ecosystem services; analytical-deliberative

1. INTRODUCTION

There is an increasing need to integrate our understanding and modelling over a wide range of spatial and temporal scales to help address complex societal and environmental situations we face. To achieve this we need to increase the level of societal relevant science that is carried out [Lubchenco 1998]. There has been a long term interest in systems based approaches to understanding ourselves and our interactions with our environments. Ludwig Von Bertalanffy is credited with making major advances in systems based approaches in the early twentieth century. 'General systems theory' was further developed by himself (biologist), Kenneth Boulding (economist), Ralph Gerard (biologist) and Anatol Rapoport (mathematician) to address what they saw as a requirement for a more integrated approach to solving societal problems. This led to the formation of the Society for General Systems Research in 1954, which later was renamed the International Society for Systems Science. The societies aim was to reduce the growing isolation of the specialization of disciplines. At this time West Churchman and Russel Ackoff wrote an early text book 'Introduction to Operations Research' [Churchman et al. 1957] that was based on applying scientific methods to understanding the operations of a system within an interdisciplinary framework. Jay Forrester led developments of system dynamics based on his experience in the Second World War resulting in the famous Limits of Growth study by his colleague Meadows [Meadows et al. 1972] and the release of the widely used graphical modelling software 'Stella' in the mid 1980s. In part due to limitations of 'hard' systems such as operations research and systems dynamics, Peter Checkland and colleagues developed 'soft' system approaches to counteract limitations associated with technical assessments [Checkland 1981]. Social learning theory of Albert Bandura has been a key component of 'soft' system approaches. In the ecological domain it has been realized that social as well as ecological components of a system need to be considered. At the same time the ecosystem service framework has been widely utilized to help assess what benefits humans receive from the wider environment. Sustainability science has recently emerged as a new approach that can help scientists work with a wider set of stakeholders to address societal needs. At a smaller spatial scale significant advances at the sub-cellular and cellular scale by Hiroaki Kitano and colleagues in systems biology, assisted by rapid increases in the data and information available through genomic sequencing and high throughput assays. At the other extreme in the 1980s and 90s the field of earth systems studies developed understanding and models at the regional and global scale of key biotic and abiotic processes to address large scale environmental issues such as climate change e.g. [Dorman and Sellers 1989]. The need for finer resolution earth system models led to the development of nested physical based global climate models for regional studies [Giorgi and Mearns 1991]. To make sense of various developments in systems based approaches over the past century I introduce each of the major branches of systems science, consider what we can learn from them to enable greater levels of integration from the sub-cellular to global scale. This is not an attempt to provide a single approach to the wide ranging and complex situations we face, but to help integrate our understanding and modelling within this series of frameworks.

2. REVIEW OF SYSTEMS BASED APPROACHES

2.1 General system theory, ecosystems, systems biology, operations research and system dynamics: Outline and main characteristics

The origins of systems thinking in the 20th century are associated with the 'organismic biologists' who started to consider organisms in their entirety, one of these was Ludwig von Bertalanffy who argued that these ideas about organisms could be applied to all systems. Ludwig von Bertalanffy developed systems based approaches in the 1920s [Von Bertalanffy 1969] were system was defined as "entities composed of interacting parts" [Marin 1997]. This was based on the idea it was not enough to study just the individual components of a system which was the prevalent reductionist approach at the time. "General systems theory is a name which has come into use to describe a level of theoretical model-building which lies somewhere between the highly generalized constructions of pure mathematics and the specific theories of the specialized disciplines" [Boulding 1956]. Boulding [1956] emphasized the hierarchical nature of the 'general systems theory' with nine levels starting from simple static structures to open systems e.g. a cell (level 4) all the way to individual humans (level 7) and society (level 8). At the time of writing his paper General Systems Theory: The Skeleton of Science he suggested we had adequate theoretical models up to the fourth level (i.e. an individual cell) and little beyond this and at all levels empirical knowledge was lacking [Boulding 1956]. The idea behind this pivotal paper was to provide a framework of systems to enable particular disciplines to add substance in an orderly and coherent manner. This 'general system theory' was advanced by James Miller in his book Living Systems [Miller J.G. 1978] and then updated again in 1992 [Miller Jessie L. and Miller 1992].

Arthur Clapham in the 1930s conceived the term 'ecosystem' to describe the biological and physical components of a system considered together as a unit and was first used in a paper (1935) by his colleague Arthur. G. Tansley [Willis 1997]. In 1953 Eugene P. Odum published the first edition of Fundamentals of Ecology [Odum E.P. 1953]. In this influential textbook his brother wrote a chapter on energetics, introducing energy circuit language which he later developed into energy system language [Odum H. T. 1972]. The importance of thermodynamics to provide a common currency for analysing systems led to the use of emergy and exergy concepts. Building on the research of the Odum brothers, Jorgensen and colleagues have recently summarized what are the fundamental properties of ecosystems: 1) they are open systems, 2) it is impossible to accurately predict their complex behavior, 3) ecosystems have network connectivity that leads to emergent properties, 4) they are hierarchical leading to the need to understand the interactions with the above and below levels, 5) ecosystems grow and develop and 6) they have complex responses to disturbance [Jorgensen et al. 2007].

The Second World War provided stimulus for developing systems based approaches. Around this time the discipline of cybernetics arose from a background in engineering, with a key early publication being Norbert Wiener's 'Communication and Control in Man and Machine' [Wiener 1948] in which feedback mechanisms were shown to play a key role in all aspects of our lives. Operations research emerged from activities in the Second World War demonstrating the benefits of using mathematical approaches to solving complex organizational problems [Churchman et al. 1957]. This led to the rapid development of a new interdisciplinary field that included mathematicians along with management scientists. Alongside a vibrant practitioner community, the academic community gained in size around the world between the 1940s and 1970s. Also emerging from the Second World War was Jay Forrester who whilst based at MIT had personal experience of the use of weapons systems on a USA naval ship. In the mid 1950s Forrester moved from engineering to the newly formed Sloan management faculty at MIT. He started applying his systems dynamics approaches to a broader range of problems leading to a series of influential books on systems dynamics [Forrester 1961, 1969]. Leading to the famous study 'Limits of growth' for the Club of Rome by Meadows et al. [1972]. Key aspects of system dynamics compared to other less quantitative studies is that you are able to set down all the internal consistencies and to see the result of complex feedbacks. In two recent papers, Jay Forrester reviewed the first 50 years of systems dynamics [Forrester 2007b] and then looked ahead to the next 50 years [Forrester 2007a]. He sets out the requirements for high quality systems dynamics studies, these include: setting out the short comings that the study will address and display the causes in a compact model structure, the model is completely endogenous (i.e. no external time series driving it), the model can be generic and fits to the wider class of systems, it produces recommendations that the author can defend and enables discussion how these recommendations differ to existing policies. Systems dynamics based approaches have been widely used and one example is in crop modelling were recent use of these approaches have led the authors to call for greater integration with system biology approaches [Yin and Struik 2008].

Cybernetics and 'general system theory' provided inspiration for the recent rapid emergence of systems biology [Kitano 2002]. Systems biology signaled a shift from understanding and modelling single genes and proteins to a greater focus on a system's structure and dynamics. This has brought the '–omics' and computational sciences closer together. A key step is understanding the network structure which enables the dynamics of complex networks to be understood and modelled [Kitano 2002]. This has resulted in advances in mark up languages [Hucka et al. 2003] and more recently graphical notation [Le Novere et al. 2009] to enable the sharing of understanding and model structures. At the same time of increased interest in system biology, there has been an explosion in studies that aim to understand larger scale ecosystems in a more holistic manner. In 2005, the global scale Millennium Ecosystem Service Assessment was published [Millenium Ecosystem Assessment 2005], with assessments of the science required to assess the functions, services and benefits that humans gain from ecosystems set out more recently [Carpenter et al. 2009]. A characteristic of this growth in ecosystem service science has been the need to conduct more holistic studies and to consider the trade-offs between individual functions and services [Bennett et al. 2009].

2.2 General system theory, ecosystems, systems biology, operations research and system dynamics: What these approaches offer and synergies with other systems based approaches

These approaches have highlighted the need to consider the full breadth of the system under study, the interactions and feedbacks internally and externally, the benefit of using diagramming, network structures and related quantitative model structures to set down the components of the system understudy and the need to be fully aware of what exactly the purpose and aims of the study are.

2.3 Soft systems methodologies, social learning, socio-ecological systems and sustainability science: Outline and main characteristics

The preceding group of systems based approaches can be classed as 'hard', since their focus is on goal seeking [Checkland 1985]. In the 1970s the field of operational research faced a serious loss of confidence. There were a number of reasons for this including poor delivery of solutions to real problems and from being a very broad discipline [Corbett and Vanwassenhove 1993]. In the UK, Peter Checkland and colleagues promoted an alternative to these complex mathematical based operational research solutions in the form of soft systems methodology that could be used alongside more technical approaches [Checkland 1981]. This was combined with the realization that the most difficult aspect of any study was establishing what the exact question to answer was. More recently the approaches of 'critical systems thinking' [Flood 1990] and 'critical systems heuristics' [Ulrich 2003] have stressed the need for reflective professional practice and a focus on the judgments made about the boundaries of a study. Social learning theory of Albert Bandura [1977] has been a key component of 'soft' system approaches. Systems methodologies that embrace social learning are increasingly being applied to better understand how land and catchments can be managed and how the situation of managing complex systems can be improved [Collins et al. 2007].

In the field of ecology, Holling [1973] first introduced the concept of resilience of biophysical and social systems, highlighting that there was a need to understand how resilient social and biophysical systems were to disturbance. A socio-ecological system is defined as encompassing ecological and societal subsystems in mutual interaction. Gallopin et al. [2001] suggested that socio-ecological systems are the natural unit of study for sustainable development research, this is because socio-ecological systems are complex and have a large number of non-linear processes which vary across scales. Complex systems are characterized by: variables that can be conceptually portioned into classes and subclasses, the presence of relatively separable subsystems that function on their own but also influence each other and that they are greater than the sum of the parts [Ostrom 2007]. Through studying complex coupled socio-ecological systems there needs to be more emphasis on the dynamics of vulnerability, resilience and adaptability compared to earlier emphases on control, stability and risk [Young et al. 2006]. Increasingly there are linkages to earth system science through the process of globalization leading to greater connectedness, speed and scale of socio-ecological systems [Young et al. 2006]. A recent survey of 36 quantitative models (published paper between 2003 and 2008) that integrated social and ecological concepts identified the need for a greater range of approaches to quantify human values and ways to evaluate integrated socio-ecological models [Cooke et al. 2009].

Sustainability science has arisen from a realization that to meet the challenges we face we need to take a different approach to our science (methods, structures and content): 1) to span a wider range of spatial scales, 2) account for temporal inertia, 3) handle functional complexity that arises from multiple stressors, and 4) a greater recognition of what makes science useable by society and other scientists. An important step forward is for "research itself must be focused on the character of nature-society interactions, on our ability to guide those interactions along sustainable trajectories, and on ways of promoting the social learning that will be necessary to navigate the transition to sustainability" [Kates et al. 2001].

2.4. Soft systems methodologies, social learning, socio-ecological systems and sustainability science: What these approaches offer and synergies with other systems based approaches

These approaches have highlighted that there is a need to think critically about the boundary judgments to any study, there is a need to balance 'hard' quantitative approaches with 'soft' approaches to ensure that you are asking the correct question. In natural resource issues there is a need to consider the social as well as the ecological system understudy, the resilience of the system under study and the trade-offs between different ecosystem functions and services is consider in the decision making process.

3. POTENTIAL FOR MORE INTEGRATIVE SYSTEMS BASED STUDIES

There are increasing calls for scientists, regulators and policy makers to adopt more integrated and holistic approaches to understanding how we manage systems from the local to global scales. Recent papers have highlighted the need for more integrated approaches e.g. [Ison et al. 2007, Liu et al. 2007, Macleod et al. 2007, McIntosh et al. 2005, Pahl-Wostl et al. 2007]. These draw on a variety of perspectives and approaches such as soft systems approaches [Checkland 1981], the advent of post-normal science [Funtowicz and Ravetz 1992, Lubchenco 1998], social framing of risk [Wynne 1992], participatory rural appraisal [Chambers 1994], participatory learning [Pretty 1995], ecosystem resilience [Holling C. S. and Meffe 1996, Scheffer et al. 2001] and social network analysis [Borgatti et al. 2009]. It is increasingly realized that a mixture of 'hard' and 'soft' approaches are required to address natural resource management questions [Pahl-Wostl 2007].

Potential for linking current systems based approaches to lead to greater levels of scientific interoperability come from two main areas and I would like to explore these in the workshop:

1) Systems modelling approaches from systems biology to earth systems science include approaches that range from qualitative network models to quantitative process/kinetics based approaches. It is the network models that have the potential to link systems biology, socio-ecological systems and earth systems science. Advances in network theory and analysis have been recently reviewed by Borgati *et al*., [Borgatti et al. 2009]. There has been growing interest in the application of network analysis in the analysis of scientific interactions [Borner et al. 2004].
2) To increase the sharing of data between individual projects and between disciplines requires the establishment of data and meta-data models. Key to the implementation of these have been advances in markup languages e.g. system biology markup language (SBML) [Hucka et al. 2003] systems biology graphical notation [Le Novere et al. 2009], waterML [Horsburgh et al. 2009] and earth systems markup language [Ramachandran et al. 2004]. What is required are ways to link across these individual standards so that individual communities of scientists can link their understanding and models.

4. CONCLUSIONS

Advances in a wide range of systems focused disciplines have increased our ability understand and model socio-ecological systems from the sub-cellular to global scale. These can be classed as 'hard' and 'soft' approaches and both are required when you are studying systems across multiple spatial and organizational levels. Here I suggest that diagramming, network theory combined with markup languages based on data and meta-data standards within an analytical-deliberative framework can lead to learning and greater integration across these disparate systems based approaches. I am not suggesting that one approach or framework will address all situations, but highlighting the commonalities that will enable us to integrate across situations and scales, which is required for increased scientific interoperability.

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