A dialectical basis for consilience

in marine resource management.

Giles Edward Austen

B.Sc (Econ.) Hons. University of Zimbabwe.

Grad. Dip. Econometrics. London School of Economics and Political Science.

M.Env. (Economics and Policy). Griffith University.

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The following people and institutions contributed to the publication of work undertaken as part of this dissertation:

Giles Austen, UTAS, Tasmanian School of Business and Economics
Sarah Jennings, UTAS, Tasmanian School of Business and Economics
Jeffrey Dambacher, CSIRO, Computational Informatics, Hobart

Author details and their roles:

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Giles Austen was the primary author and Sarah Jennings and Jeffrey Dambacher assisted with refinement and presentation.

We the undersigned agree with the above stated "proportion of work undertaken" for each of the above published (or submitted) peer-reviewed manuscripts contributing to this dissertation.

Signed: ________________ ________________

Sarah Jennings
Supervisor
Tasmanian School of Business & Economics
University of Tasmania

David Adams
Head of School
Tasmanian School of Business & Economics
University of Tasmania

Date: ________________ ________________

I the undersigned agree with each of the above declarations.

Signed: ________________ Date: ________________

Giles Austen
Candidate
Tasmanian School of Business & Economics
University of Tasmania

Abstract

Contemporary management of renewable resources requires an interdisciplinary approach incorporating both the social and natural sciences. Within marine resource management, the requirement to incorporate biology and economics has led to the development of models in which the mathematics of both disciplines are combined. To improve the efficacy of using such models for sustaining the natural resource base and its services, managers have shifted focus from distinct biological populations towards their containing ecosystems. Recognising that ecosystems should be the focus of management has proven easier, however, than elucidating the practical manner in which they should be managed. This requires concurrence between disciplinary approaches; a consilience that we will pursue in a structured manner that avoids loose methodological eclecticism.

The way in which this consilience is sought depends on the ontological understanding of the nature of the systems being managed. Systems that are complex and contingent with emergent features and downward causality, will resist reductionist-determinist analysis and are better considered dialectically. This dissertation favours a non-reductionist dialectical form of consilience and demonstrates how the application of dialectical forms to the analysis of complex ecological systems facilitates the pursuit of ecosystem policy objectives. A generalised theoretical process of policy evolution is illustrated using fisheries management as an example, and a process of dialectical abstraction supported by qualitative modelling is suggested as a way of achieving the practical operationalisation of ecological management objectives. A process of dialectical abstraction permits the decomposition of the observed real world into units or subsystems, establishing appropriate boundaries of abstraction in order to consider relations within the abstraction and between the abstraction and the rest of the world. Qualitative modelling provides a tool for unpacking these abstractions, and for understanding their dynamics with respect to their likely response to perturbations or interventions.

The combination of dialectical abstraction and qualitative modelling provides the method in this dissertation to re-examine the traditional manner in which marine resources have been viewed economically. A series of analytical exercises are presented. The first examines the capital theoretic description of optimal resource use and the implications of the associated golden rule. The theoretically promised confluence of favourable biological, economic and social outcomes in neoclassical solutions for fisheries management is shown to be illusory. The second exercise considers a neoclassical market adjustment mechanism in the context of a stylised regional fishery ecosystem, in which the dialectic method, applied using a biological metaphor, reveals feedback cycles that explain unexpected policy outcomes, or contradiction. Finally, the link between apparently paradoxical results and insufficiently broad analytical focus is demonstrated through analysis of a socio-ecological meta system.

More broadly, the dialectic method employed in the dissertation is shown to allow for a structured pragmatic interdisciplinary consilience between reductionist-determinist approaches and those that are evolutionary and contingent. Furthermore the pivotal role of social considerations in ecological outcomes is emphasised with the fundamental tradeoff between competing social pressures of environmentalism and materialism revealed.

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Chapter 1

Introduction

For him as well as for her, there was no end. There was process: process was all. You could go in a promising direction or you could go wrong but you did not set out with the expectation of ever stopping anywhere. All responsibilities, all commitments thus understood took on substance and duration.

Ursula K. Le Guin, 'The Dispossessed', 1974

1. Motivation

The importance of marine resources as a source of protein and their significance in terms of economic and social relations, has for centuries seen them managed both by custom (Ruddle et al., 1992) and by regulation (O'Sullivan, 2004). Since the late nineteenth century, marine resource management has increasingly been informed by mathematical modelling of both the biological (Volterra, 1926) and economic (Warming, 1911) aspects of these resources, leading to combined bioeconomic models (for example Gordon, 1954, Scott, 1955), which continue to inform fisheries management today. The economic aspects of bioeconomic models are underpinned by mainstream, or neoclassical, economics[1] exemplified by the work of Clark (2010) who makes clear the importance of "economically rational individual decisions" to realising the sustainable use of resources (Clark, 2010: xi). However, despite over a century of development and use of such models, marine resource managers and policy makers continue to be surprised by management outcomes (Foley et al., 2011, Hilborn, 1992), which are often seen as paradox. At the same time concern has grown about an ongoing and widespread loss of marine biodiversity and habitats, and the consequent risks to the continued availability of marine resources (Worm et al., 2006, Young,

1 In this dissertation the terms mainstream, orthodox and neoclassical are used interchangeably to describe those schools of economics associated with a Newtonian paradigm and a reductionist-determinist method. This distinguishes these schools of thought from those associated with an evolutionary paradigm and a contingent method, which will be referred to as heterodox economics. The use of this classification is often quite unclear at the boundaries, as illustrated by Radzicki (2003), however, this distinction is considered to be sufficient for the purposes of this dissertation. Although, when considered from a heterodox perspective, the terms neoclassical and reductionist are often pejorative (Lawson, 2013), this is not the intention here.

2003) and the goods and services they provide. Even where the degree of this risk is questioned (Hilborn, 2007b), the potential for management and policy improvement is nonetheless acknowledged (Hilborn, 2007c).

While it is clear that the fugitive nature of fish and the opaqueness of the ecosystem that contains them, of which our understanding remains limited, pose challenges for fisheries managers (Garcia et al., 2003), we must additionally question the link between the reliance on reductionist-determinist methods and models and the apparent ongoing failure in policy effectiveness. There are also concerns that the extension of neoliberal[2] market relations to the management of natural resources more broadly has led both to the commodification of the environment and to the alienation of society from it (Foster, 2002). Furthermore, it is clear that as human populations and their productive activities grow, societies are discovering the limits in the capacity of global ecosystems, including marine systems, to support them and, as a consequence, are encountering the reality of a full world (Daly, 2005). This reality presents further challenges to the manner in which we consider and deal with natural resource management problems.

There is now broad recognition that problems occurring at the human-environmental nexus must be considered within a whole-systems context and that this requires an interdisciplinary approach (Taussik, 1998, Tavoni and Levin, 2014). Within the field of marine resource management, this recognition has resulted in the development of progressively more complex marine systems models (Bjørndal et al., 2004), their extension to support ecosystems perspectives (Plagányi, 2007b), and the integration of ecological, social and economic components at various scales and levels of complexity (Plagányi et al., 2014). Although attempting to address the complex nature of the system

2 The term neoliberal is used in this dissertation to describe a political economic system associated with the extremes of neoclassical economics that adheres to laissez-faire individualism, free markets and trade, strong private property rights and minimal state intervention and that has become the hegemonic political economic discourse globally (Harvey, 2007)

that they describe by widening the scope of the analysis, these models generally remain bounded by reductionist assumptions, whether implicit or explicit.

The economist Schumpeter (1986[1954]: 39) emphasised the requirement for pre-analytic vision, which is an act that establishes the boundaries for analysis, and which also circumscribes any future choice of boundary for subsequent abstraction and analysis. The art of abstraction lies in understanding the choices presented, and their implications, as issues are separated out for our analysis, thereby establishing their boundaries. In philosophical terms this describes the need for the analyst to understand that they take an ontological position, whether implicitly or explicitly (Bhaskar, 1997), which then extends to one of epistemology and to method.[3]

Neoclassical economics, the ontology for which is implicit rather than theorised, is defined by its orientation to a particular method (Lawson, 2006). This method is mathematical, reductionist and deductive, and is suited to the investigation of carefully defined closed systems described by closed causal sequences or functional relationships, where wholes are precisely comprised of parts that behave in a determinist manner. However, the method is less suited to the consideration of open systems in which emergence[4] at different levels causes the behaviour of a system to be evolutionary and contingent, that is a complex adaptive system. As examples of complex adaptive systems, ecosystems (Levin, 1998) and social systems (Lawson, 2006) present particular analytical problems that are suited to analysis using the neoclassical method only where sufficient boundary conditions are assumed to enclose the system, or an abstraction of it. The establishment of such conditions introduces tensions to the analytical boundaries that will, if not understood in terms of the often implicit conditions, eventually emerge as contradictions that appear to the analyst to be paradoxical.

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3 While the nature of these philosophical concepts is often impenetrable, for the purposes of this dissertation ontology is simply taken to be the nature of reality and epistemology to be how we approach and understand that reality in terms of method (Ollman, 2003).

4 Features in complex systems are emergent where they are unexplained by elements at lower system levels, that is there is downward causality (Axtell, 2007).

In an attempt to remove the appearance of paradox, the process of widening boundaries through their redefinition continues to transfer tensions to the boundary and may in fact worsen them, acting to increase the appearance paradox and their potential to surprise managers and policy makers.

In the case of fisheries, increasing recognition of the importance of broader ecological (Garcia and Cochrane, 2005) and social (Urquhart et al., 2011) components of systems, and the shifting of management boundaries beyond those encompassing particular fish stocks, may fail to resolve the tensions in the system. In these circumstances reductionism leaves us with nowhere to go in the face of policy surprise or failure, other than increased complexity.

In what the philosopher Whitehead (1948 [1925]) describes as misplaced concreteness the neoclassical economic method confuses an abstraction of the system, even when broadened to reflect system complexity, with the actual system itself, that is the real system. It is not suggested here that the reductionist models described are necessarily understood as the real system, but rather that the understanding and acknowledgement of the real system they represent is lacking. That is, the problem is neither methodological nor epistemological but is ontological. In order to move contradiction from the boundary of the problem to its interior, where it becomes penetrable and loses the appearance of paradox, a broader analytic vision and a changed ontology are required.

2. Objectives

The overarching purpose of this dissertation is to challenge the mainstream neoclassical economic perspective of marine ecosystems, and more broadly of socio-ecological systems, by casting a dialectical lens upon selected aspects of policy and management.

The following specific research objectives assist in the dissertation meeting its overall purpose:

- To consider how an interdisciplinary[5] consilience can be achieved in the context of marine resource management within socio-ecological systems.
- To investigate the manner in which a dialectic method increases our understanding of the duality between orthodox fisheries management and ecosystem based approaches to fisheries management.
- To formally establish orthodox economic models within the dialectic in order to examine how the ecological qualitative modelling method of loop analysis[6] improves our understanding of these models within broader social and ecological contexts.
- To investigate how feedback dynamics within complex socio-ecological systems can affect our understanding of the results of policy and to consider whether paradox may be explained as penetrable contradiction when framed in dialectical terms and examined through a process of dialectical abstraction.

In achieving these objectives, we seek a consilience both within and between the concerned disciplines in a pragmatic manner that facilitates their methodological integration in policy formulation and management. While the act of labelling disciplines — for example: ecology, biology, sociology, economics — facilitates their analysis, it also objectifies them as separate things and to complete our understanding of complex adaptive systems they must again be brought together.

5While they hold specific meanings, the terms multidisciplinarity, interdisciplinarity and transdisciplinarity are often used interchangeably in the literature (Alvargonzález, 2011). In this dissertation our emphasis is upon a pragmatic means by which different disciplines may work in concert, for which any of these particular terms may apply. Aspects of our dialectic approach suggest the transcendence of traditional disciplinary boundaries, in a manner associated with the transdisciplinarity. We nevertheless adopt the commonly used term interdisciplinarity for the purposes of this dissertation.

6 Loop analysis is a qualitative modelling method that is both sympathetic to and coherent with the dialectic. It was initially described in Levins (1974) and further developed in Puccia and Levins (1985).

The concept of consilience as used in this dissertation refers to the bringing together of 'things' and the examination of how they interact and evolve together as distinct parts (Levins, 2008) within a whole, and is consistent with our dialectical approach that recognises the counterbalance of whole and part. It is also consistent with the term's first use to mean a 'jumping together' of classes of facts (Whewell, 1840: 230), and with what has been described as an embracing pluralism rather than the seeking of a monistic banner (Gould, 2004: 192). Moreover, philosophy here is no 'shrinking dominion' in the face of empiricism (Wilson, 1998: 10), a mere contemplation of the unknown, but is central to our analysis and, in terms of the particular heterodox position we adopt, not metaphysical but material and dialectic. This contrasts with a reductionist view of consilience which maintains the scientific hubris that everything is in essence quantifiable and expressible in terms of closed causal sequences (Wilson, 1998), something which can only hold in the absence of emergence, contingency and systems that behave in an evolutionary manner.

3. A note on method - ontology and dialectics

The term dialectic has held alternative meaning for different schools of philosophy and individual philosophers since first being described by Plato in the Socratic dialogues (Kenny, 2010). The Hegelian dialectic (Hegel, 2010 [1812-1816]) is idealised, determinist, and inconsistent with emergence and the possibility of contingent futures unfolding in an evolutionary manner. However, Engels (1935) and Georgescu-Roegen (1971) both describe a non-idealised contingent derivative of the Hegelian dialectic that recognises this possibility. This form of Hegelian dialectic is used in this dissertation, in which we describe and apply a methodological approach comprising dialectical abstraction (Levins, 2007), supported by the tool of loop analysis (Puccia and Levins, 1985), within a biological metaphor used in community ecology.

While Engels takes the ontological position of Hegel that all things are dialectical, Georgescu-Roegen (1971: 14), in his formative work for bioeconomics, contends that while some phenomena are dialectical others are non-dialectical, or 'arithmomorphic'. The central role of dialectical thinking in this dissertation makes it important to understand the dialectical ontology and to consider how it can provide a methodological path between the alternate ontologies of neoclassical and heterodox economics.

The neoclassical reductionist method implies an ontology where every 'thing' can be viewed as a closed causal sequence or functional relationship, such that a subset of events in a system, the independent variables, describe the causal relations of their complement, the dependent variables. In contrast to this implicit neoclassical ontology, a suggested ontology for heterodox economics is explicit and described as one of 'openness, process and internal relationality' (Lawson, 2006: 498), in terms of which social phenomena are differentiated from natural phenomena. This heterodox ontology considers natural phenomena non-dialectically in terms of the closed causal sequences that are not, as a rule, considered relevant in the social sciences. On the other hand, the ontology defines social phenomena in terms of internal relations, which are central to dialectical thinking and which describe the manner in which a thing incorporates within itself its relations with all other parts, including the whole (Ollman, 1993), so that each thing is wholly defined by its relations.

Heterodox ontology, therefore, implies that things may be dialectic or non-dialectic, which is a duality that reflects Georgescu-Roegen's (1971) description of two classes of thing. By contrast, Ollman (2003), whose exposition of the dialectic is consistent with that of Engels, suggests that an acceptance of internal relativity of social phenomena, when taken together with the position that social things are related to natural things, necessarily means that all things are internally related and therefore that all things are dialectical, a wholly dialectical ontology. Viewed epistemologically, however, the duality within the heterodox ontology is consistent with this wholly dialectical ontology. This suggests that the heterodox duality, which we will refer to in this dissertation as quasi-dialectic, can provide an important device for moving reductionist constructs, which bring essential understanding of system detail (Lewontin and Levins, 2007a), from a closed- to an open-system conceptualisation.

The three ontological viewpoints described here — neoclassical, quasi-dialectical and dialectical — can be shown to encompass one another. The quasi-dialectic ontology incorporates the reductionist phenomena, described as arithmomorphic, which neoclassical reductionism regards as universal. It also incorporates dialectical phenomena which are defined by internal relations and emergence. In turn the quasi-dialectic is epistemologically consistent with a wholly dialectic ontology, which describes the ubiquity of internal relations, since the method of dialectical abstraction allows for the specification of particular abstractions in which closed causal sequences exist.

At an epistemological level, and methodologically, these ontological differences may be set aside since, from a wholly dialectical viewpoint, the tensions and contradictions arising from any assumptions made in establishing the frame of any abstraction, including those assumptions required to ensure reductionist validity, will be resolved in the process of the historical development that marks the evolutionary change of the dialectic. This setting aside of differences is important for achieving the interdisciplinarity and the consilience sought for ecological economics (Costanza, 2009), and also sought in this dissertation.

4. Contribution of the dissertation

This dissertation applies a method of dialectical abstraction to an area of economic policy where the effects of management have substantial long term and often irreversible impacts on human and natural systems. The management of marine resources is an area of increasingly interdisciplinary research, policy development and implementation, and the successful consilience of ontologically disparate disciplines must be pragmatic in order to accommodate both reductionist-determinist and dialectical thinking. We show that this can be achieved epistemologically in a structured way that does not lead to the problems associated with methodological pluralism where the approach degenerates into eclecticism and irrelevance (Spash, 2012).

We start from a belief that, since ontological differences are not easily resolved even within a single sub-discipline, including heterodox economics (Fullbrook, 2008), any hope of overall ontological unity is fanciful. It follows that the ability to set aside these differences is important for achieving the interdisciplinarity that is essential to the successful management of marine systems. A pragmatic approach to the issues confronting marine management, however, must recognise the value in the existing investments in models and policy frameworks. As the boundaries of management are necessarily expanded, we take the view that what is needed is both a deeper mathematical understanding and a philosophical view that avoids the fallacy of misplaced concreteness. It is our contention that the natural dialectical form described by Engels (1935)[7], and which has been applied in the consideration of ecological crises (Foster, 2008), provides an appropriate philosophical position for this purpose. We also take the view that for this to be achieved, the praxis of the dialectic must shift from that of revolutionary change (Feenberg, 2014) to a pragmatic transformation of management.

In this dissertation we demonstrate how contradiction and paradox within marine policy may be addressed in moving from a reductionist neoclassical position to one that is fully dialectic by means of the quasi-dialectic position described in section 3 of this chapter. It is our view that this approach allows for an interdisciplinarity without requiring the impossibility of ontological unity. Disciplines that pursue a reductionist-determinist approach, including neoclassical economics and elements of biological science, can do so without causing practical concern for non-reductionist disciplines since, if they never encounter dialectically anticipated contradiction in the boundaries of their analytical frame, there is no harm. On the other hand, if they do encounter contradiction, then this

7 The contingent form of the Hegelian dialectic described by Engels is simply referred to in this dissertation as 'the dialectic'.

may either be explained dialectically, in which case a quasi-dialectic or dialectic position may be adopted, or the problem may be reframed so that the contradiction is set aside. It is our view that will not be of concern to the dialectician if it is accepted that identifying the contradiction is in itself of value to informing discourse.

In our application of dialectical abstraction to the nexus of human and environmental systems, we use loop analysis. Loop analysis is a method of qualitative modelling that describes and analyses the relations and feedbacks between components of a system. It is presented in the form of a sign directed graph, or signed digraph, and can be used to determine system's stability and its movement between states of equilibrium. It is particularly concerned with the contingent impact of feedbacks upon a system and, as such, is well suited to the analysis of complex adaptive systems. Its close association with community ecology means that it has been widely applied in the consideration of ecological problems (Dambacher et al., 1999, Zavaleta and Rossignol, 2004), including those associated with marine systems (Carey et al., 2013, Espinoza-Tenorio et al., 2010, Marzloff et al., 2011, Metcalf, 2010, Metcalf et al., 2008, Raymond et al., 2011). The method has been used in sociological applications (Dinno, 2007) and also in supporting interdisciplinary work at the interface of human and ecological systems (Dambacher et al., 2015, Espinoza-Tenorio et al., 2010, Metcalf et al., 2014, Rochet et al., 2010). However, the use of loop analysis to specifically evaluate the economic dimensions of these systems is limited (Dambacher et al., 2009, Ortiz and Levins, 2011) and it has not been applied to a formal economic analysis.

The mathematical method underpinning loop analysis is not unknown to economic analyses, indeed Samuelson (1947) describes the use of such a qualitative calculus in economics, emphasising that the establishing of appropriate signed relationships, and understanding the relative importance of such effects, need not depend on the possession of relevant quantitative knowledge[8]. While there

8 Rather, Samuelson held that a measure of economists worth lay in their ability to exercise judgement in matters where quantitative information was lacking.

has been subsequent development in the application of this non-parametric analytical method (Hale et al., 1999a) it has not achieved the same traction within economics that it has in ecology. The reason for this may be that the analysis to date has been largely neoclassical in nature and so misses out on the coherent qualities the method enjoys with the dialectic, a notable example of which is the unitary nature of quality and quantity. In this dissertation the validity of loop analysis for the economic aspects of marine ecological systems is established through demonstrating its ability to correctly represent standard orthodox economic forms, following which these forms are transformed in terms of the dialectic, and their usefulness is seen in identifying and explaining contradictions.

5. Outline of the dissertation

The main body of the dissertation consists of four chapters presented in the form of independent but related papers. Chapter 2 demonstrates how the pragmatic application of dialectical forms to the analysis of complex ecological systems facilitates the interdisciplinary pursuit of ecosystem policy objectives for common-pool resources. A generalised theoretical process of management policy evolution is illustrated using a fisheries management example, and the way in which a process of dialectical abstraction supported by loop analysis can be used to support the operationalisation of ecological management objectives, is described. This combination of dialectical abstraction and loop analysis provides a heterodox economic perspective in challenging the conventional neoclassical economic view of marine resources, and is described as the 'dialectical method' in the dissertation.

Chapters 3, 4 and 5 present three analytical exercises, each of which utilises a fully dialectic ontology. In the first two exercises system abstractions are formally grounded in standard neoclassical functional forms, and our dialectical method is used to reveal the underlying relations.

The third exercise describes a meta system and locates alternate neoclassical and heterodox pre-analytic visions within it. Specifically:

- Chapter 3 begins with the neoclassical growth model and the associated golden rule, which underpins much of contemporary fisheries management, and uses the dialectical method to reduce it in order to show how a theoretically promised confluence of favourable biological, economic and social outcomes in neoclassical solutions for fisheries is illusory. The required commodification of the fish, including the species, and accompanying oceanic commons enclosures result in contradictions that cannot be understood within the neoclassical economic paradigm. The dialectical method exposes the source and mechanism of the contradictions providing an alternative basis for discourse on the fishery and the commons.
- The research presented in Chapter 4 applies the method of abstraction and loop analysis to consider the efficacy of ecological policy for improving resource viability in a regional-level marine socio-ecological system and how this might appear differently when considered from alternative biological, social, or economic perspectives. Starting from a neoclassical competitive market adjustment mechanism applied to a fishery, a broadening of analytical vision through the application of a biological metaphor and the dialectic method, reveals feedback cycles that potentially explain unexpected policy outcomes, or contradiction. The importance of the tradeoff between environmentalism and materialism to the determination of outcomes is described, and the implications that this holds for the management of complex adaptive socio-ecological systems is considered.
- Chapter 5 defines a broad socio-ecological meta system that is consistent with the manner in which neoclassical economics considers human-environmental problems in general, and those commonly posed by the management of marine resources in particular. The dialectical method is used to demonstrate how this system's response to perturbation may be understood

in terms of feedbacks and both direct and indirect effects. Apparently paradoxical results for both human and ecological variables are shown to arise from the insufficiently broad analytical focus that arises from the neoclassical paradigm. Alternate parameterisations of the system representing both neoclassical and heterodox ontologies are examined to demonstrate how the appearance of contradiction differs between them. The fundamental tradeoff within the system described is again shown to reduce to one between the competing social pressures of environmentalism and materialism, and the particular importance of the way in which environmentalism acts on the system for achieving positive ecological outcomes is shown. The importance of the social relations to ecological outcomes is emphasised and questions of sustainability and degrowth are also raised.

Finally, overall results are briefly discussed and conclusions are drawn in Chapter 6.

Chapter 2

Turning a dialectical lens to policy in ecosystem management.

1. Introduction.

There is a clear paradigmatic duality within contemporary science (Hollingsworth and Muller, 2008), that has for some time been reflected in theoretical developments in both economics (Hamilton, 1953) and the natural sciences (Levins and Lewontin, 1985). The roots of this duality lie in the philosophical differences between a Newtonian mechanistic pre-analytic vision, which informs the dominant reductionist science, and an evolutionary pre-analytic vision that is strongly influenced by the philosophy of Hegel. The latter, which found expression in both the theory of Darwin (2009 [1859]) and the dialectical epistemology of Marx (1990 [1867]), employs a biological metaphor and offers particular insight into issues of systems complexity — including those posed by the management of common-pool resources such as fisheries — that are both contained within and help to define ecosystems. While an ecosystem is the basic theoretical unit of ecology, encompassing all of the biotic and abiotic features required for survival (Odum, 1953), it exemplifies a complex adaptive system (Levin, 1998) with ambiguous conceptual boundaries (O'Neill et al., 1986).

In the face of system complexity, a reductionist approach must inevitably resort to increasingly impenetrable concepts, leading to erroneous suggestions that all science is measurement (Georgescu-Roegen, 1971). This trend has not gone unchallenged, and Solow (2005), for example, dismisses any correlation between the complexity of economic models and their scientific value. Similarly, in ecology, O’Neil (2001) questions the development of arcane mathematical models that, he asserts, are of more utility to the intellectual curiosity of mathematicians than they are in informing biologists.

Marshall's (1961 [1890]: 14) view of biology as the 'Mecca of the economist', ignored by later marginalist neoclassical economists, has found expression in a rich body of heterodox economic thought around the evolutionary paradigm, including ecological economics. Costanza (2009) describes ecological economics as a consilient science, seeking a balanced pluralism of the sciences and the humanities in its integrated approach to the complexity of ecosystems. The consilience envisaged in this dissertation recognises the complex nature of ecosystems arguing that they must be understood through a biological metaphor and evolutionary paradigm, without discarding the epistemological value of reduction (Lewontin and Levins, 2007a). Any ontological commitment to reductionism, as envisaged in the theoretical synthesis proposed as consilience by the biologist E.O. Wilson (1998), is rejected. This paper argues that Wilson's reductionist synthesis fails to properly account for emergence within complex adaptive systems and consequently for their ongoing evolution, an end to which the dialectics of Hegelian philosophy may be successfully applied. The ontological understanding provided by the dialectic, supported by the methodological usefulness of reductionism, is the basis for the consilience that is required and is what is proposed here.

The method of abstraction within the Hegelian dialectical form (Ollman, 2003) provides a mechanism whereby the contribution of reductionist analysis can be incorporated in our understanding of complexity, thereby establishing the basis for a broad consilience within ecological economics. The manner of this consilience is through a process of sublation which, in its Hegelian sense, describes the assimilation by a larger entity of a smaller one, or dialectically the negation of an element in a manner that it is, in part, preserved in a synthesis. In this way a position — for example an environmental, economic, or social policy — is arrived at along a path of former positions that are not discarded but subsumed within the present position, where they are preserved. Continuing to consider the example of policy, while a final position or truth is envisaged within the idealism of Hegel, policy development is conventionally analysed as a cyclical process (Howlett and Ramesh, 2003) in which positions of finality are not achieved, but rather where policy continues to evolve. This is consistent with contingent forms of the Hegelian dialectic, including those described by Engels (1935) and Georgescu-Roegen (1971), in which the truth is never realised but where the dialectic rather represents an ongoing unfolding process.

The link between an evolutionary science, suited to the analysis of complex adaptive systems and dialectics, is well established. Georgescu-Roegen (1971), whose bioeconomic challenge to mainstream economic paradigms laid the foundation for ecological economics, advocates a contingent dialectical analytic method, based on that of Hegel, in the consideration of qualitative concepts that do not readily lend themselves to quantitative description. More recently the natural dialectic form due to Engels has been applied in understanding the ecological consequences of the economic and social relations of capitalism (Foster, 2000)

This paper describes the utility to disciplinary consilience of Georgescu-Roegen's (1971) conceptualisation of phenomena as either arithmomorphic — those which lend themselves only to quantification and reduction — or dialectical, or both. This peculiar conception provides a pragmatic and structured basis for interdisciplinary policy formulation that avoids the identified problems of loose eclecticism in pluralist methodological approaches (Spash, 2012). To distinguish it from wholly dialectic forms, such as that described by Engels, this arithmomorphic-dialectic duality is described in this dissertation as quasi-dialectical, and the specific meanings of arithmomorphic and dialectic within it are described in section 2.1 of this paper.

We demonstrate the practical value of Georgescu-Roegen's quasi-dialectic formulation in the analysis of complex ecological systems, where abstractions formulated in terms of a mechanical metaphor and reductionist method coexist with those where emergence means that the explicit application of a biological metaphor and dialectical analyses are unavoidable if deepening contradiction is to be avoided. This is shown to facilitate the practical pursuit of ecosystem objectives for common-pool resources in an interdisciplinary context where a dialectic ontology may not be ubiquitous. A process of policy evolution is described diagrammatically and illustrated through an example drawn from fisheries management. In the practical operationalisation of ecosystems policy, the paper considers how tolerances to uncertainty, and failure within alternative contexts of dialectical abstraction, relate to adaptive management and the manner in which management can be supported by loop analysis, a qualitative modelling tool.

2. Definitions

2.1. Complex Adaptive Systems

A mechanistic view of a system can be considered in terms of the reduction of wholes into parts and their subsequent reformulation into wholes. For example, a clock is composed of springs, weights and wheels; parts that, once disassembled, can be used to reform the clock, or the real whole, provided that one understands both the function of each component and the way in which they interrelate. This describes a process of reductionism, where reductionist approaches are those which adopt a mechanical view of part-whole relations, working from the principle that defining parts and their interrelations is sufficient to define the whole. This principle is necessarily deterministic[9], that is it is consistent with a view that all events have prior cause, and that for any given state at a point in time, there is only one possible future state (Iannone, 2001). The clock can only be successfully assembled in one way and while there is still potential for the unexpected to occur, for example the spring that breaks during assembly, there is nevertheless an unambiguous relationship between the parts and the whole of the clock that is suited to description using a mechanical metaphor. This is

9 In considering the relationship between reductionism and determinism, the uncertainty resulting from stochasticity should not be confused with the indeterminacy caused by emergence and evolutionary processes. A stochastic event may be regarded as indeterminate to the extent that its outcome is not absolutely certain, however truly indeterminate events are acausal and, by their very nature, cannot be predicted ((Zernicka-goetz, 2010)) When describing events as deterministic in this dissertation we mean all events other than those that are acausal in this manner.

not universally true of systems, and complex adaptive systems, including ecosystems, resist description in such a manner.

For our purposes the term ‘complex adaptive system’ is used to describe systems that are consistent with an evolutionary biological metaphor and which exhibit features associated with emergence and indeterminacy. Difficulties arise because the non deterministic and non linear nature of complex adaptive systems makes the prediction of their future behaviours, on the basis of their past behaviours, non-viable. This means that the behaviour of complex adaptive systems cannot be captured by the methods of reductionist analysis. However, abstractions may be drawn from complex adaptive systems, or from selected subsystems, under assumed conditions such that they are consistent with a mechanical metaphor and so are suitable for reductionist consideration.

2.2. Dialectical Methods

Dialectics is a philosophical method based on change through the conflict of opposing forces or ideas (Kenny, 2010). A dialectical lens reveals conflict and contradiction as inherent features of reality that provide evolutionary momentum to phenomena and their analyses. The principle of non-contradiction, which states that a thing cannot simultaneously be and not be (Hamilton, 1860: 59), is a central principle in logic that does not hold for dialectical concepts and a dialectical concept can simultaneously encompass both itself and its opposite (Séve, 2008); that is A can contain non-A.

The dialectic asserts the unity of quantity and quality, the force of abstraction in analysis, and both the non-deterministic and continuous nature of change (Ollman, 2003). It describes a triadic reasoning expressed as the self-propelling process of position, negation and negation-of-the-negation (Kovel, 2008), with an emphasis on the qualitative-quantitative nature of change (Séve, 2008). Engels (1935: 138) provides a simple example of this dialectical process, drawn from the natural world: a grain seed is planted, the seed is negated as the plant emerges, and as the plant then dies it turns to an increased quantity of the seed in a negation of the negation. Qualitative and quantitative change are inextricably linked through this process, and may be understood as the phase transitions or threshold effects in ecological, economic and social systems (Scheffer et al., 2002) that are critical in our understanding of any system.

Hegel (2010 [1812-1816]) argues that independently of the whole, parts are not parts, likewise independently of the parts, a whole is not the whole. Part and whole form a single relationship in a dialectal unity of opposites. The nature of part-whole relations is considered through the dialectical use of abstraction, a process that establishes boundaries, units and their interrelationships. Ollman (2003) describes the role of abstraction — which dialectically is both a construct and a process — within the dialectical method as one in which we move from the real world we observe and decompose into mental units, or abstractions, for our consideration, following which we can reconstitute it as a mental whole. This reconstituted whole remains an abstraction, but one in which relations between things are more clearly revealed and from which parts and wholes can be usefully analysed.

Taking the case of ecosystems, Holling et al. (2002) present a form of complexity in which biotic and abiotic ecosystem components are described over spatial scales ranging from centimetres to thousands of kilometres, and timescales from minutes to millennia. Ecosystem components may include biophysical processes within plants and animals at small and fast scales, interspecies competition at medium scales and time periods, and climatic and geological processes which operate at planet-wide scales and in geological time periods. While the ecosystems these components are a part of clearly exist, they can be viewed only in terms of various abstractions based on scale and purpose. For instance, a fast breeding malarial mosquito population may be controlled though insecticide spraying, however any reduction in the incidence of malaria may be offset by immediate increases in mosquito life expectancy (Dambacher et al., 2005), by medium term increased resistance to antimalarial drugs provided to human populations (Janssen and

Martens, 1997), and by long term increases in the viable range of mosquitoes due to climate change (IPCC, 2007a). While we can move between such abstractions to better understand the ecosystem, the real whole of the system will elude us.

Indeed the very concept of an ecosystem is problematic. Whether considered from the perspective of species or from the perspective of function (O'Neill et al., 1986), the ecosystem concept itself utilises a mechanical metaphor that is unsuitable for describing the ecological understanding of systems operating far from equilibrium (O'Neill, 2001). For example, highly ordered biological life occurs at the expense of the ecosystem it forms a part of, and interacts with, in a thermodynamic evolution (Schneider and Kay, 1994). This cannot be explained within a mechanical metaphor, so that the practical credibility of the ecosystem concept depends upon its ability to embrace both mechanical and biological metaphors, which the quasi-dialectic and the process of dialectic abstraction allow for.

Georgescu-Roegen (1971) asserts that many phenomena, which he describes as arithmomorphic, are distinct, measurable, and follow the principle of non-contradiction; while other phenomena are dialectical, lacking distinct boundaries, their boundaries instead being penumbra shared with their opposites. The existence of biological life is an example of such a dialectical concept: there is that which is clearly dead, that which is clearly alive, and between these a problematic intersection of uncertainty where both qualitative and quantitative methods enter the fray (Davey, 2011). In recognising this Georgescu-Roegen does not disregard the value of mathematical reduction, but instead seeks to restore the balance between Pascal's (1995 [1670]) *l'espirit de finesse* and *l'esprit géométrie,* that has been lost from reductionist analysis. This quasi-dialectic form embraces reductionist methods, but does not attest to their sufficiency, rather their role is understood to be one of validating the propositions arising from dialectical analysis. While this view is ontologically inconsistent with the position of Hegel that everything is dialectical, it is consistent with the epistemology of alternate dialectic abstractions, which may be constructed to be either arithmomorphic or dialectical.

In order to advance toward a more complete understanding of any complex problem, multiple abstractions must be considered: both reduced parts and those that might be regarded as encompassing some concept of a systemic whole. Consideration of multiple abstractions ensures that the process of reducing complexity does not lead to a loss of sight of the real whole, a dialectical method which has been described as continuously asking where the rest of the world lies in relation to any particular abstraction (Levins, 2007: 153). In this manner the set of all abstractions better approximates reality, and, when applied to the problem of theory and knowledge, results in an improved understanding of this real whole.

It is argued here that where there is contradiction, such as exists between policies relating to sustainable ecosystem objectives and those designed to optimally manage individual resource stocks, the way forward is not one of compromise, but rather that a pragmatic transformation is required. The different foci, for example those of the ecosystem and the resource, must be transformed into distinct abstractions within the larger abstraction of the whole. The solution to policy restructuring can then be found as an unfolding process of change and dialectical abstraction, where the parts of what is negated are absorbed, or sublated, into something new, that is itself then negated as new sources of contradiction arise. This then describes policy as a process of continuous evolution.

3. The evolution of policy for common-pool resource management

Policy solutions to common-pool resource problems are well established within neoclassical economic theory. Aside from the direct regulatory Leviathan option (Hobbes, 1962 [1651]), are the indirect options of environmental taxes and subsidies (Pigou, 1920), and that of assigning to a resource property rights in a tradable form[10] that allows for economically efficient market resolution (Coase, 1960). More recently, direct institutional solutions to common-pool resource dilemmas have been advocated, in a manner that recognises their inherent complexity (Ostrom, 2010).

There has been a heightened awareness over recent decades of issues of environmental and ecological sustainability, as exemplified by a range of multilateral initiatives from the Stockholm Declaration (UNEP, 1972) to the Rio+20 Earth Conference (UNCSD, 2012). This awareness has contributed to recognition that the exploitation of renewable natural resources cannot be managed in isolation, but that the effects of both the resource upon the ecosystem, and the ecosystem upon the resource, must also be accounted for (Mahon et al., 2008). Many resources requiring management within an ecosystem context, are common-pool resources, including examples from: fisheries (O'Boyle and Jamieson, 2006, Olsson et al., 2008), rangelands (Dong et al., 2009, Homewood, 2004), catchments (Likens et al., 2009, Prato, 2003), groundwater (Madani and Dinar, 2012), forests (Chhatre and Agrawal, 2008), and, with respect to climate change, the atmosphere (IPCC, 2007b). The management complexity of common-pool resource problems is amplified through the international shift in management focus from resource to ecosystem, for example through payment for ecological services schemes (Farley and Costanza, 2010), emissions reduction through forestry initiatives such as REDD+ (Corbera and Schroeder, 2011), and ecosystem-based fisheries policies (Garcia et al., 2003). This provides a compelling argument for a complementary shift in the basis of policy analysis/development from reductionist-determinist science to evolutionary-contingent science. Since it is not immediately clear how this is to be achieved, it is informative to consider the manner in which policy now practically evolves, and how it might alternatively develop within a dialectical form.

10 Property rights may be used to describe a wide range of institutional forms ranging from private rights held by an individual person or company, or a form of communal right for example as traditional rights a group hold to a commons (Milonakis and Meramveliotakis, 2012). Unless otherwise specified, in the context of this dissertation property right refers to an individually held property right which is tradable in a manner consistent with neoliberal market ideals.

A diagrammatic framework for discussing a process of policy evolution that describes both arithmomorphic and dialectical phenomena, and their development in the direction of unresolved contradiction or consilience, is presented in Figure 2.1. The horizontal axis shows reductionist and evolutionary methodological approaches, with the reductionist approach represented as simple[11], and the evolutionary approach represented as complex. The vertical axis shows resource and ecosystem policy foci, with resource focussed policy represented as simple and an ecosystem policy focus as complex. When considered over policy and methodological axes this gives rise to a framework of four quadrants.

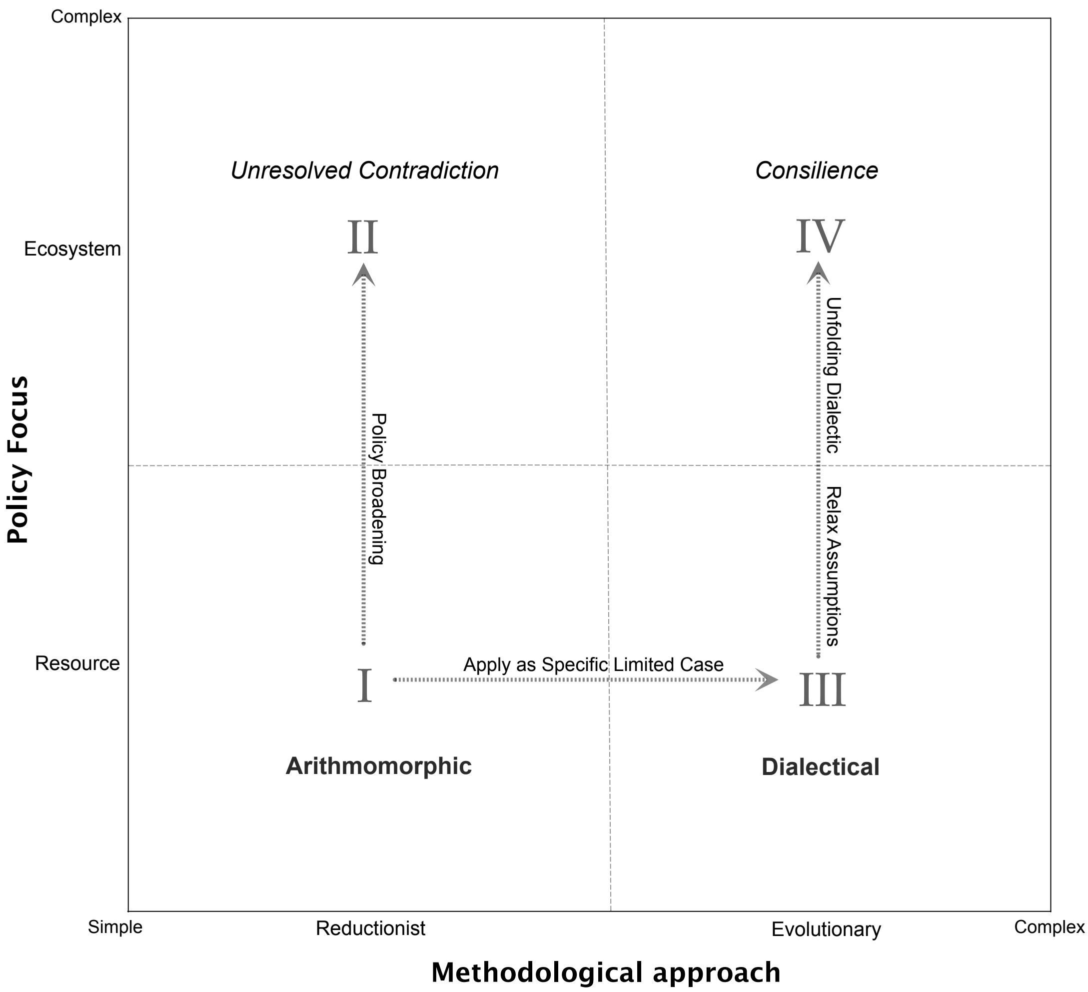

Figure 2.1. Four quadrant framework for discussing the process of policy evolution.

11 The denotation of 'simple' is chosen purely as an antonym to 'complex', without suggesting that the issues raised, and models by which they are analysed, are either trivial, or necessarily easy to understand.

The horizontal bifurcation line in the diagram represents a somewhat fuzzy distinction between resource and ecosystem foci, which may simply be a definitional matter. In the case of a fishery, the fishery may represent single or multiple target species and may be spatially constrained, for example a reef or lake, or effectively unconstrained, for example the open ocean. This choice, one in the process of abstraction, reflects the establishing of boundaries that are necessary to allow for the application of a reductionist method. These boundaries may shift as contradiction is encountered as a result of the underlying assumptions contained within the abstraction.

The interpretation of the diagram's vertical bifurcation line depends on which of three ontological perspectives is adopted. The first perspective is that implicit to neoclassical reductionism, which rejects all dialectical concepts. Since reductionism lies only within quadrants I and II, from this perspective the vertical bifurcation line forms a distinct boundary and the quadrants to its right hand side, which represent the evolutionary perspective, are not considered at all. The second perspective is the Hegelian view that all phenomena are dialectical, so that from this wholly dialectical perspective only quadrants III and IV are considered and again the vertical bifurcation line forms a distinct ontological boundary. The third perspective recognises as real both arithmomorphic and dialectic phenomena, so that the vertical bifurcation line then represents the penumbra in which they overlap. This third ontological perspective then encompasses all four quadrants. This perspective is a representation of the sublation that is the basis for fresh insight into the process of policy development, and for the consilience of reductionist and evolutionary perspectives that is required to effectively understand and to manage ecological systems. It provides a pragmatic means, within an interdisciplinary context, by which the quasi-dialectic provides an ontological bridge between reductionist and wholly dialectic ontological perspectives, so moving reductionist thinking toward dialectical thinking and raising the prospect of consilience.

The manner of consilience proposed by Wilson (1998), and the basis for much policy development that seeks to meet ecosystem objectives, considers only the first two quadrants. As such, this consilence cannot succeed. The mere broadening of resource-focused management policies to account for ecosystem objectives, represented as a move from quadrant I to quadrant II, applies a restricted scientific paradigm to a complex adaptive problem. As a consequence, the science upon which the policy is based does not provide a view of part-whole relations that is sufficient to address the system's complexity, and the resultant contradiction remains unresolved, its fundamental cause being neither revealed nor addressed. Policy objectives of relevance to the whole, including its ontologically emergent properties, cannot be consistent with the part, where such properties do not exist. Similarly, the objectives relevant to the whole may not be dependably addressed by policy instruments designed for objectives that are relevant only to the part. By moving from quadrant I to quadrant II in this manner, policy development effectively stalls in the face of deepening contradiction that remains unresolved, and may be misconstrued as paradox[12].

The solution to this problem is a shift to an evolutionary paradigm, that is a shift to the consilience offered in quadrant IV. The consideration of a direct route from quadrant I to quadrant IV cannot be entertained since each point within quadrant IV represents a moment in an unfolding dialectical process, and the contingent nature of the dialectic leading there means that a precise destination cannot be presupposed.

In a practical sense, the relevance of the policy instruments typical of quadrant I lies in their being applied to particular abstractions within the whole. Policy instruments consistent with an objective of relevance to the part will be relevant to the whole only where that specific part of the whole is considered, that is within the context of an abstraction representing a specific limited case. Such

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12 The misperception of paradox is further considered in Chapters 4 and 5 of this dissertation.

abstractions are contained by quadrant III. The move from quadrant I to quadrant III represents a shift from a neoclassical economic perspective to an evolutionary economic perspective.

One mechanism by which the move from quadrant I to III and thence to IV can be achieved is described in the commons work of Ostrom (1990), which represents a shift by which economic approaches to resource management adopt an evolutionary understanding. For instance, with respect to the approach of establishing property rights, Ostrom asserts that the economic efficiency of such rights fails to address how they should in fact be established and managed over time. These are institutional and political questions that are often ignored by reductionist models of resource management.

Ostrom (2005: 255) argues that with respect to common-pool resources:

> I am willing to predict given the large number of components that combine in a nonadditive fashion, that our knowledge of these systems will continue to grow but will never be complete. As soon as one design has proved itself in one environment, innovations in strategies adopted by participants or changes in the environment in which a humanly designed system is in operation will produce unexpected results.

This prediction is consistent with our claim that the 'destination' in quadrant IV is not a point but rather an unfolding process that is uniquely determined by the circumstances in which it emerges. Which is to say, dialectically, it is determined by the abstraction by which it is analysed.

Ostrom stresses that the complexity of phenomena across both temporal and spatial scales means that system parts are not uniformly applicable at different levels, which is again consistent with the dialectic. The argument does not, however, render redundant policy instruments promoted through reductionist analysis, rather it appropriately positions them as specific cases limited by the context, rules and assumptions relevant to their particular analytical scale. It is then possible to consider how changes to the analytical scale, in order to encompass a more complex system, may lead to different instruments being considered. Such instruments will need to respond to the emergent phenomena in a manner that can be anticipated by the unfolding dialectic, which may also lead to the development of new institutional forms.

4. An application to fisheries management

We examine the applicability of the quasi-dialectical process that we have described, to the management of a marine resource, the fishery. Since the late nineteenth century, fisheries policy has largely been underpinned by a series of reductionist mathematical models, an approach which continues to form the basis of modern fisheries policy. The relatively recent international endorsement of a shift to an ecosystem-based fisheries management (EBFM)[13] (FAO, 2003), has resulted in this approach being adopted within the policy positions of national jurisdictions (Curtin and Prellezo, 2010, Hilborn, 2011, O'Boyle and Jamieson, 2006, Pikitch et al., 2004). However the operationalisation of EBFM — that lacks both clear objectives (Cury et al., 2005) and appropriate tools (Smith et al., 2007) — continues to be problematic (Dickey-Collas, 2014), and raises contradictions, an examination of which illustrates the usefulness of adopting a dialectical approach to policy development.

4.1. A brief review of fisheries management

A range of formative biological fishery models were developed following the Second World War, including the fundamental work of Schaefer (1991 [1954]), Ricker (1954), and Beverton and Holt (1957). The typical economic model of a fishery, a single-species bioeconomic model, is built upon these, or similar, biological models (Prellezo et al., 2009). The bioeconomic models describe the sustainable yield relationship linking fishing effort and fish stock, which is the primary functional relationship of fishery management. The unconstrained maximisation of either this function, or of

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13 The shift to an ecosystems focus in fisheries management is variously referred to as 'ecosystems based fisheries management', as 'integrated management' and as an 'ecosystems approach to fisheries' ((Garcia et al., 2003)) These concepts are broadly similar and for the purposes of this dissertation the term ecosystem based fisheries management is used. We refer to the complement of EBFM as standard fisheries management.

the biological function on which it is based, determines maximum sustainable yield (MSY), which represents the maximum long run output from a fishery and commonly underpins fisheries management (Hilborn, 2007c). The economic counterpart to MSY is maximum economic yield (MEY), the point on the sustainable yield function at which fisheries resource rents are maximised[14].

Bioeconomic fishery models, then, utilise a sustainable yield relationship within an economic framework, with the purpose of optimising economic exploitation (Hilborn and Walters, 1992). For example, the original bioeconomic model, published by Gordon (1954), is based on the description of a fish stock using a logistic growth function, in a similar manner to Schaefer's biological model. The principal result of the Gordon-Schaefer model, as it is commonly known, demonstrates that the economic equilibrium for an open access fishery is achieved at the point of bionomic equilibrium, where economic rents are fully dissipated. The static model produces the convenient result that the economically efficient point of MEY occurs at a higher level of fish stock than MSY, which in turn is higher than the fish stock at the bionomic equilibrium.

The relevance of such economic modelling to the management of fisheries is questioned, bypassing as it does the dynamic aspects of fish stock conservation and of natural capital (Clark, 2010). However, the alternative use of a dynamic capital-theoretic fisheries model is not itself unproblematic. This model produces a result where, for high value, slow growing fishery resources that provide a lower rate of return than is attainable from alternative economic investments, the theoretical economic rationality of fishing a resource to extinction, or near extinction, is demonstrated (Clark, 2010). While the empirical reasonableness of this position continues to be

14 Management of fisheries requires the setting of stock levels which are both sustainable and profitable for all target fish species, followed by the implementation of the policy instruments appropriate to their realisation. The target stock levels of MSY and MEY are most commonly used.

debated (Clark et al., 2010b, Grafton et al., 2010, Grafton et al., 2007), the potential for policy conflict, between the biological and economic objectives of a fishery, is nonetheless clear[15].

In a similar manner to these models, on which decisions regarding target stock levels are sometimes based, the policy instruments available to fisheries managers encompass both the biological and the economic aspects of the fisheries-yield relationship (Sissenwine and Kirkley, 1982), and reflect a tradeoff between them. Arnason (2000) categorises fisheries policy instruments as those with a direct biological or economic effect on the fishery, and those where the effects are indirect. Instruments with a direct effect include the implementation of catch quotas, the spatial and temporal regulation of fishing activity, and gear restrictions. Those with indirect effects are based on Pigouvian taxes or property rights. Clark (2010) demonstrates, in neoliberal terms, the economic efficiency of the indirect instruments, resulting in optimal MEY outcomes, and the economic inefficiency of the direct instruments, which produce economically sub-optimal outcomes at constrained bionomic equilibria.

The focus of EBFM is the ecosystem within which target fish stocks are contained. Specific objectives then focus on habitat integrity, ecological diversity, improved resource resilience and ecosystem health, as well as broad social and economic considerations (Curtin and Prellezo, 2010). The consideration by EBFM of the ecosystem, its components, and the interdependencies between them, contrasts with standard fisheries management, where, if these components are considered at all, they are considered separately (Levin et al., 2009). While the advancement by EBFM of these very different objectives, and its targeting of a different spatial construct, has resulted in some development of models with a broader multispecies focus (Plagányi, 2007a) and the reconsideration of management frameworks (Garcia et al., 2003), EBFM remains essentially an extension of standard fisheries management practice (Garcia and Cochrane, 2005, Skern−Mauritzen et al., 2015).

15 The contradiction in the neoclassical capital theoretic model is examined in detail dialectically in Chapter 3 of this dissertation

This inevitably gives rise to contradiction since it ignores the tendency for system stability at a lower level of organisation, that of the fish stock, to be at a cost to higher levels of organisation, those of the community or ecosystem — for example in the loss of biodiversity (Rice and Garcia, 2011). In a similar manner, the theoretical economic efficiency of property-right based management instruments, such as transferable quotas (Arnason, 2007), in practice is often compromised in the face of EBFM objectives (Gibbs, 2010).

The reliance by EBFM on the same set of policy instruments as standard fisheries management reinforces existing policy inconsistencies and results in deepening contradictions, unless a shift to an evolutionary-based paradigm occurs. This is illustrated below through the application of the process of policy evolution described earlier (Figure 2.1).

4.2. Applied policy evolution

Consider a fishery in which the policy objective is to pursue the sustainable and economically efficient exploitation of the target fish stock, alongside a broader objective of ecosystem sustainability. Although the use of property rights is held to deliver stock sustainability and economic efficiency (Arnason, 2012), their use may have adverse consequences both for by-catch species and for ecological diversity (McKay, 1995), while their contribution to improved resource stewardship is at best unclear (van Putten et al., 2014) and at worst may perversely act as a disincentive to stewardship (Gilmour et al., 2012), and so fail to deliver against policy objectives with respect to ecological sustainability (Essington et al., 2012). To address this failure it may be necessary to subsequently employ supplementary policy instruments, for example marine protected areas (Brady and Waldo, 2009). The failure of property rights to provide the theoretically promised economically efficient panacea to the issues of overexploitation of fisheries ecosystems, and the subsequent supplementary use of economically inefficient instruments, is contradictory and exemplifies a form of double policy movement. First described by Polanyi (2001 [1944]), this double movement is associated with neoliberal free market policy in which the effects of the implementation of an initial policy requires secondary policy formulation to offset the unanticipated consequences brought about by the first. This illustrates both the contradiction facing fisheries managers and policy makers, and the limitations of the neoclassical economic method as a basis for policy.

To better understand this contradiction it is helpful to consider an archetypal process describing the development of standard fisheries policy, and the manner in which the requirements of EBFM are subsequently met. The tracing of pathways of policy evolution in Figure 2.1, and their consideration from a dialectical perspective, identifies various constraints and suggests a process that will improve the prospect of achieving a successful implementation of ecosystems objectives.

Branch (2006) describes a typical process of policy development within a fishery. In the absence of controls designed to specify a particular level of harvest, and thereby to maintain a particular level of fish stock, the uncontrolled exploitation of a common-pool fishery resource under conditions of open access leads to the tragedy of the commons (Hardin, 1968). The result of a harvest restriction, a policy setting described as Total Available Catch (TAC), is often reflected in an attempt by fishers to increase their catch share through a race to fish. To address this dilemma, a fishery manager must consider the use of other regulatory combinations including vessel and gear restrictions, season-length restrictions, and area-based controls. The effect of such regulatory activity has been one of economic inefficiency due to overcapitalisation (Hilborn et al., 2005). The contention that methods that fail to directly address the open access nature of the resource operate at the expense of economic efficiency (Clark, 2006) points to the consideration of property rights as a solution (Grafton et al., 2006). In many ways this is unsurprising — an issue that is cast in terms of neoclassical economic theory might be expected to have a theoretically consistent economic solution.

In terms of policy evolution, this entire process is within the standard economic framework, and represents a management process of continuous adaption that is played out in quadrant I. The ongoing formation of fisheries policy through a cycle of issue-policy-consequence-policy — Polanyi's double movement — is visible in many actual fisheries (Arland and Bjorndal, 2002, Hentrich and Salomon, 2006, Olsson et al., 2008), and may result in economic optimality if the policy objective is one that is framed only in terms of a defined target resource. However, where the policy evolves to incorporate ecosystem-level objectives, both economic and ecological outcomes may be compromised.

The adoption of EBFM, broadens the policy objective to one where ecosystem complexity must be considered, represented by a move from quadrant I to quadrant II in Figure 2.1. Here the promise of tradable property rights holding the key to the resolution of the issues (Arnason, 1991, Gibbs, 2009) becomes uncertain. The relationships between the target species, that are the subject of these rights, and other ecosystems components are often unclear, which then casts doubt on the efficacy of the property right (Gibbs, 2010). For example, the issues of by-catch discard and high grading represent negative ecosystem outcomes associated with property rights (McGarvey, 2003). A further example is the previously noted existence of theoretical circumstances in which the holder of a property right, acting rationally, will exploit a fish stock to extinction (Clark, 2010). This second example is clearly a poor outcome under any circumstance and, while it may be an extreme case that is rarely, if ever, realised, it nonetheless underlines the requirement for supplementary policy instruments beyond property rights in order to achieve EBFM objectives, again a double movement.

In a case study illustrative of Polanyi's double movement, Brewer (2011) describes a circularity in policy development, together with its negative ecological consequences, in an analysis of the Maine ground-fishery over a forty year period. He explains how fleet and trip quotas, gear restrictions, and temporal and spatial restrictions failed to conserve fish populations. Introduced property rights were observed to result in a cynical short-term approach by fishers, who maximised the TAC though catch-limit negotiations in the face of their own clear understanding of consequential ecosystems decline.

The route out from this dilemma provided by the dialectic, a move from quadrant I to quadrant III, is the shift to an evolutionary perspective consistent with a biological metaphor, which then leads to quadrant IV through an unfolding dialectical process. The implication of this shift is not the rejection of the policy instruments associated with stock-focused fisheries policies, but rather the careful definition of their boundary conditions in a manner that provides for their use within different levels of abstractions, and the validation of dialectically determined policy. The shift does not offer a simplification of policy, but rather promises increased policy complexity in concert with increased understanding of system complexity (Ostrom, 2010, Walters, 1986).

5. Discussion - the operationalisation of resource policy

The policy task of maintaining the viability of environmental resources while meeting society's needs for material consumption, is complicated by the understanding that this must be achieved while maintaining the integrity of the complex adaptive systems that encompass both of these social and environmental aspects. History is replete with examples of the high cost paid by societies that fail in this task, including ultimately ceasing to be viable themselves (Diamond, 2004). The recognition that effective resource policy must be realised within such a complex ecosystems context, has implications both for operational management, and for the policy and management instruments that it utilises.

The management processes and tolerances associated with the use of poorly known systems need to be different from those that are associated with the use of systems for which the parameters have been established. While there will be some uncertainty associated with the use of a well known system, it will be largely stochastic, and negative outcomes will be unwelcome, even regarded as negligence on the part of management. By contrast, when dealing with a poorly known system, uncertainty is endemic and the precautionary principle indicates that caution should be exercised proportionate to the consequence of any potentially negative outcome (Garcia, 1994). It can be argued, however, that, in terms of their usefulness in improving knowledge and informing future action, negative outcomes should be embraced equally to positive ones. A management approach that embraces both positive and negative policy outcomes is needed, a well established example of which is adaptive management (Walters, 1986).

5.1. Adaptive management and dialectic abstraction

Adaptive management recognises that problems arise when we attempt to apply the management and organisational methods suited to mechanical determinist activities, to the management of complex biological resources, and has been widely utilised in the management of renewable resource systems, including marine systems (Fulton et al., 2011). While adaptive management was developed directly in response to the uncertainty of policy impacts on resources under management within inadequately understood ecosystems, and demonstrated early theoretical promise of improved performance (Smith and Walters, 1981), its success has been mixed (McLain and Lee, 1996). Problems in its operational implementation have arisen from a failure of stakeholders to appreciate the inability of resource management to offer certainty in the face of variability (Walters, 2007). The use of dialectical abstraction to examine systems anticipates and contextualises such uncertainty, provides a mechanism for confronting stakeholder difficulties, and so supports the successful use of adaptive management. The quasi-dialectical form is particularly valuable in this respect because the explicit duality it describes between arithmomorphic problems, where traditional scientific methods apply, and contingent problems, where these methods are insufficient so that a dialectic understanding is needed, does not require any change of ontological position on the part of particular stakeholder groups/disciplines. Natural systems may require different management approaches, depending upon the perspectives required for particular problems and the associated abstraction.

For example, an aquaculture farm may be seen as an effectively closed system where the key parameters and relationships are well established and understood. An abstraction describing this enterprise may be presented arithmomorphically and in terms of a mechanical metaphor, so that a high degree of positivity of outcome may be expected from its management. In this case, limited flexibility and tolerance for failure is required from the management system.

On the other hand, a managed single-species fish stock is more difficult to perceive of as a closed system and there will be an incomplete knowledge of key parameters and relationships, both within the stock itself and in terms of its relationship with the broader ecosystem. While this enterprise may still be described arithmomorphically and in terms of a mechanical metaphor, in this case complementary qualitative modelling methods may be required to address data deficiencies, and the degree of management tolerance for negativity will need to be higher, meaning that management must be more flexible and more tolerant of failure.

However, where there are abstractions that are wholly consistent with the evolutionary paradigm and biological metaphor, that is where non linearity and emergence make the system unknowable, for example the biotic and abiotic interrelationships of a reef system, or socio-ecological systems. Such abstractions can only be understood dialectically, and a high degree of uncertainty and potential for failure must be tolerated in the management of outcomes. For this kind of abstraction, seeking to solve the problem in terms of a mechanical metaphor only delivers the deepening of mathematical sophistication, in what Georgescu Roegen (1971: 52) has termed ‘arithmomania'.

In managing complex ecological systems it is probable that abstractions of all of these types will be encountered, and for these dialectical constructs to be useful we need to consider how they unfold in the process of dialectical abstraction shown in quadrant IV of Figure 2.1. The modelling method of loop analysis (Puccia and Levins, 1985) is sympathetic to and coherent with the dialectic, allowing us to better understand the process by which abstractions unfold, and furthermore is consistent with a biological metaphor and so provides a useful tool in the operationalisation of resource policy.

5.2. Loop analysis

Loop analysis provides an understanding of the dialectically anticipated interchange of cause and effect in complex adaptive systems, addressing a weakness of reductionist analysis where causality is viewed as running in one direction from the part to the whole, and is often considered only at one level (Levins and Lewontin, 1980). This means that reductionist analysis fails to consider the interaction and feedbacks that occur across all systems levels, where relationships can run in both directions from part to whole and from whole to part. These relationships depend on that which has preceded them - that is they are historically contingent in the manner contemplated by the dialectic. The strategy of dialectic abstraction combined with loop analysis permits the qualitative consideration of relationships between system components at all levels of spatial and temporal abstraction (Levins, 2007) and can be used to penetrate the structure of a system, in particular system feedback, so that its behaviour in the face of change or perturbation can be better predicted.

The qualitative algebra of loop analysis allows for the specification and graphical representation of a system and its interaction in purely qualitative terms, namely positive, negative and neutral, and provides for expression of a biological metaphor in a manner that is familiar to community ecology, and useful in developing a contingent view of economics (Hodgson, 1993). Considered qualitatively the interactions of communities may be described to be beneficial (+), or detrimental (-) or as non-existent (0). This gives rise to six pairwise relationships: neutral (0,0), commensalism (0,+), amensalism (0,-), predator-prey (+,-), mutualism (+,+) and competition (-,-), and self-effects on communities which may be either positive, negative or null. These relationships may be represented both as community matrices and as sign directed graphs, or signed digraphs, in which qualitative interaction links (the signed digraph edges) between variables (the signed digraph nodes) are symbolised → for positive links, ⊸ for negative links or with no symbol where there is no interaction.

The community matrices and signed digraphs for the possible interaction types between two population variables X and Y are presented together in Figure 2.2, where for simplicity all two way relationships are shown by means the appropriate positive or negative symbol place at either or both ends of a single link[16]. Self-effects are the effects of a variable upon itself and are shown by an appropriately signed link that starts and ends in the same node. An interaction link from variable Y to X is designated a_{XY}, and if X and Y are set to the relevant row subscript on the community matrix for which the effects upon each of the populations is contained, then this notation extends to standard matrix element row, column notation.

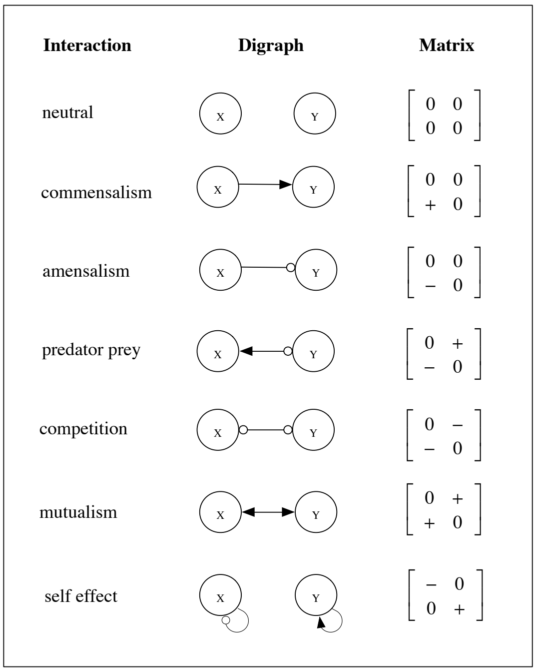

Figure 2.2. Community ecology interaction type.

16 In this dissertation signed digraph links are shown using one way links, in which two links may be shown between any pair of variables, or as single two way links variables where this aids with the clarity of the diagram.

Loop analysis, through examination of interactions and feedbacks, allows a system's stability and response to perturbations to be analysed, permitting the examination of the dynamic impact of both parameter and structural changes to the system. The analytical methods of loop analysis allow for i) the examination of feedback cycles and stability of the system in the face of transient shocks; and ii) the exploration of the non-transient effect on a system's variables arising from a substantial change in a system parameter. The first of these is addressed by examination of Lyapunov stability using reformulated Hurwitz criteria (Dambacher et al., 2003), and the second through a method that allows examination of shifts in the equilibrium level of system variables — that is analysis of the adjoint matrix (Dambacher et al., 2002).

The application of qualitative modelling, jointly and individually, to both ecosystems and economic systems (Dambacher et al., 2007) provides for the examination of linkages and feedbacks at differing levels of spatial and temporal abstraction. This approach allows for the complexity encountered by policy to be better understood and the potential for failure anticipated in a manner consistent with the requirements of adaptive management in the context of complex adaptive systems.

6. Conclusion.

The management of natural resources using policy that is solely informed by reductionist and determinist views of part-whole relations fails because it cannot encompass the emergent aspects of complex ecological systems and the contingent manner in which these systems develop. This failure has become increasingly apparent as holistic interdisciplinary ecosystem management approaches are mandated over management of individual resources, or groups of resources, that are part of a larger system. In this new context the effective development of policy requires an evolutionary perspective that in turn requires a dialectical approach.

In moving from a reductionist to a dialectical analytical approach, the quasi-dialectic context established by Georgescu-Roegen is useful because it provides a bridge between reductionism and the dialectic that allows for the problems associated with complex ecological systems to be perceived by stakeholders without requiring an ontological acceptance of the dialectical nature of phenomena. The use of abstraction provides continued support for reductionist 'arithmomorphic' forms and the wealth of management and policy models to which they have given rise. This joint use of reductionism and the dialectic, of mechanical and evolutionary forms, is a step towards consilience that is both pragmatic and necessary. This approach provides a clear and structured dialectical foundation and avoids both the potentially insurmountable difficulties associated with pursuing a unified ontological position, and the danger of methodological pluralism becoming an unstructured eclecticism (Spash, 2012).

To contain an arithmomorphic construct within a dialectic abstraction relies on constraining assumptions, and in this way the potential for contradiction in the abstraction is moved to the boundaries. The dialectic expectation is that as the assumptions of such an abstraction become compromised — for example by the passage of time, or by the necessity to incorporate wider spatial considerations — then the contradiction deepens and eventually reasserts itself. From the perspective of a dialectical ontology, this is the limit of the reductionist and quasi-dialectical ontological perspectives which do not consider this possibility. The hope of the dialectician is that when such contradictions become visible they will not be regarded as paradox and addressed through an widening of the boundaries of analysis (in the manner of the move from resource based fisheries management to EBFM), but rather that they will be perceived as contradiction which is dialectical.

Chapter 3

Species commodification - a dialectical perspective on fisheries policy.

1. Introduction

Hardin's seminal essay on the commons (Hardin, 1968) suggests that the abandonment of the natural commons through enclosures is a process necessitated by increased population pressure. While Hardin advocates, in the manner of Malthus, the blunt instrument of population control, radical theorists, starting with Marx (1990 [1867]), instead concern themselves with the implications of commons enclosures for social, and increasingly ecological (Foster, 2000), relations. These theorists recognise that such relations cannot be understood apart from their particular historical, social and economic context: this currently being that of neoliberal capitalism, within which context the environment becomes indistinguishable from capital circulation and accumulation (Harvey, 1996).

The term 'commons' is not used consistently across the literature and this conceptual confusion has both theoretical and policy implications for resource management (Johnson, 2004). Common property refers to an ownership arrangement that can apply to any good, so that a common property resource is simply a resource owned in common by a defined group of people. The term common pool resource, however, refers to specific characteristics of the resource itself — it is both non-excludable, or the transaction cost associated with exclusion makes it effectively so (Libecap, 2005), and rivalrous, so that use by one person affects use by another. Inexorable resource degradation though overexploitation, the so called 'tragedy of the commons', is not as Hardin (1968) describes a problem of the property type and unchecked human population growth, but a problem of the rules and institutions associated with the management of the commons, or rather the lack thereof under conditions of open-access (National Research Council, 2002). This problem of open-access to a common pool resource is negated where suitable institutional arrangements exist to control exploitation of the resource (Ostrom, 1990), and so is not a problem inherent in the nature of the resource itself.

Four classes of property regime are widely described: state property, private property, common property and *res nullis* (Bromley, 2005: 219). It is only the last of these regimes, *res nullis*, that is associated with the open-access problem, and even then this is only a problem under the specific social relations assumed by neoclassical economics and the rational, egotistical logic of *homo economicus* (Milonakis and Meramveliotakis, 2012). This is the limiting case, the 'thin model' described by Ostrom (1998) in her consideration of a wide range of institutional alternatives that move beyond the strictly rational actor and by which commons problems have been observed to be solved directly by the participants in particular commons without the exogenous imposition of alternative property regimes or other solutions. While fisheries have the characteristics of common pool resources (Ostrom et al., 1992), enclosures through the creation of exclusive economic zones extending 200 miles offshore in the early 1980's significantly reduced the *res nullis* open-access nature of the oceans, particularly for non-migratory species and when accompanied by well developed institutions for governance. Despite this, the manifestation of the problem described by Hardin continues to afflict fisheries (Mullon et al., 2005).

From a radical perspective it is suggested that the tragedy of the commons with respect to fisheries is not solely a tragedy of open-access but that it increasingly represents a tragedy of commodification (Longo and Clausen, 2011) which presages an observed loss of bio diversity and species extirpation (Worm et al., 2006). The commodity is the starting point of Marx's examination of capital (Marx, 1990 [1867]), with the process of commodification describing the conversion of classes of goods and services into commodities (Leys, 2003: 87), including environmental goods and services (Harvey, 2014). A prerequisite for the application of the market paradigm to management of the fishery is the commodification of both the fish catch and the stock that produces it. Thus, a biological organism, the fish, is alienated into a tradable market commodity, while its progenitor, the fish stock, is also ultimately alienated as an homogenous capital machine whose continued survival depends solely upon its comparative financial return considered against a whole of economy benchmark representing the opportunity cost of capital, the discount rate. This application of the neoclassical capital theoretic model gives rise to contradictions whereby both social and ecological relations are appropriated in the services of capital accumulation.

A putative solution to the observed problem of fisheries overexploitation has been the further effective enclosure of the fishing commons (Mansfield, 2004) through the issue of marketable fishing rights in the form of an individually transferable quota (ITQ) (Arnason, 2008). This fundamentally alters the social relations of both fishing communities and the broader society (McKay, 1995). In this process the connection to the socio-ecological relations of the fish is weakened as the survival of the resource becomes increasingly dependent upon economic and financial considerations unrelated to the ecological needs of the resource and the ecosystem that contains it.

The capital fungibility implicit in the application of the neoclassical capital theoretic model to a biological stock (Gowdy and O'Hara, 1997) gives rise to a policy contradiction that is expressed as a choice between weak and strong sustainability (Dietz and Neumayer, 2007) and to a potential optimality of resource extinction as identified for a number of fisheries (Clark et al., 2010a). The theoretical validity and empirical likelihood of this particular outcome forms the basis of a lively debate between leading fisheries economists (Clark et al., 2010c, Grafton et al., 2010) that remains unresolved nearly 40 years after it was first raised (Clark, 1973).

We maintain in this paper that the debate must necessarily remain unresolved within a neoclassical framework as the contradiction is inherent in the manner in which it conceives the fishery. More particularly we argue that commodification is the underlying cause of contradictions that persist within fisheries management based on the neoclassical economic paradigm and which make observation of continued resource overuse unsurprising. The market process of commodification, and consequent social-ecological alienation, disguises the true fisheries problem because its views of the part and the whole are circumscribed by the reductionism that informs neoclassical economics. A more promising approach is dialectical, providing a reconsideration of part-whole relations, an understanding and embracing of contradiction, and an appreciation that outcomes are contingent (Ollman, 2003). The materialist dialectic (Engels, 1935), together with attendant strategies of abstraction (Lewontin and Levins, 2007b) and sympathetic qualitative modelling methods (Puccia and Levins, 1985), provide an alternative analytical framework for the support of fisheries policy. When applied to the capital theoretic model of a fishery system this dialectical framework uncovers the subsystems and feedbacks that give rise to the contradictory policy outcomes described.

In this paper we offer a critique of the development of the standard capital theoretic model of a fishery from a radical perspective and describe its inherent contradictions. We next reconsider the model as a dialectical abstraction, using the method of qualitative modelling, or loop analysis, (Puccia and Levins, 1985) to both demonstrate the mechanism and to expose the source of contradictions within the model. This process is followed not in the expectation of providing resolution but in endorsement of David Harvey's (2014: 265) conviction that "an understanding of capital's contradictions is more than a little helpful, for as the German Bertolt Brecht once put it, 'hope is latent in contradictions.' "

2. A radical critique of neoclassical analysis.

A fundamental consideration of the dialectic, that contradiction arises with motion (Engels, 1935: 121), implies that any contradictions that appear to arise in a static context may be simply addressed in terms of methodology, for example in the given assumptions of a particular model. However the moment that movement occurs, as with the introduction of considerations of space, or time, or both, in a dynamic model, then any contradiction must be addressed ontologically. This association of dynamics with contradiction is quite apparent in the management of fisheries.

Within fisheries the issue of establishing a level of harvest and fishing effort associated with sustainable biological and economic outcomes arises. Fisheries policy entails the pursuit of a fish biomass level sufficient to withstand environmental shocks and to allow for any miscalculation due to incomplete knowledge (Schrank, 2007), while providing the maximum return in terms of net revenues, employment and other social benefits (Hilborn, 2007a). The pursuit of such a multiplicity of objectives compels a process of policy tradeoff, the consistency of which is seen to disappear and become contradictory when dynamic considerations are introduced.

Mathematical modelling methods appropriate to the bioeconomic examination of fisheries and the formulation of fisheries policy are described in the three influential papers of Schaefer (1991 [1954]), Gordon (1954) and Scott (1955). The conceptual evolution of these three papers reflects three distinct natures of fish within modern fisheries management - respectively: biological species, market commodity and capital machine. Schaefer examines the biological relationship between fishers, as apex predators, and the biomass of fish stock, their prey. In viewing the fish as a market commodity and addressing the economics associated with the common property nature of a fishery, Gordon considers the use of de-facto property rights to control the cost increases that arise as externalities to catch limiting policies when fishers compete for the available catch by investing in capacity. Scott describes the capital nature of the biological fish stock and the implications that this holds for long run economic optimality.

The static model of the fishery based on the work of Gordon and Schaefer is commonly known as the Gordon-Schaefer model and is often used for the exposition and determination of management targets within fisheries. This model takes the biological fish and establishes the same fish as a commodity, in the process producing the convenient result that the biological and economic objectives of a fishery are equally well served by addressing the open access nature of its resource through policy settings that target the marginalist economic optimum, known as maximum economic yield. No contradiction is revealed here, which is precisely the dialectically anticipated characteristic of static analysis.

Scott (1955) describes the problem of managing the fishery as one of maximising the present value of the sum of its discounted net returns and observes that this model, which assumes de-facto sole ownership and enclosure of the oceanic commons, will result in different harvest decisions to those obtained in the static model. The mathematical formulation of Scott's dynamic model (Crutchfield and Zellner, 2003) considers the fisheries problem in the context of a neoclassical macroeconomic growth model in which the biomass of fish is explicitly treated as capital, and a tradeoff is made between consumption and investment in productive capacity today, and the prospect of increased consumption in the future. The result of the optimisation problem embedded in this capital theoretic model is a modified version the golden rule of capital accumulation (Phelps, 1961), which holds that the stock of a capital asset will be increased or decreased until its marginal return is equal to a more general rate of return to capital arising from all other economic activities available for the employment of capital, that is the discount rate. In this fishery specific formulation of the golden rule the return on the stock in situ, its biological growth rate, is additionally adjusted to reflect the responsiveness of the cost of harvesting in the fishery to the size of the fish stock. This so-called marginal stock effect has important implications for the potential sustainability of the fishery in terms of the model and the policy settings that stem from it.

The relationship between economic and biological maxima in the dynamic capital theoretic formulation of the fisheries problem is no longer unambiguous, as was the case with the static

Gordon Schaefer model. For a particular stock the optimum economic outcome depends on the relative strengths of the discount rate on the one hand and the described marginal stock effect on the other. In effect the fully commodified fish biomass becomes analogous to a 'fish bank' where the relative strength of the discount rate pressures the bank's clients to make withdrawals, through the capture and sale of fish, and to hold less fish in the water; whereas the strength of the marginal stock effect in any particular fishery pressures these clients to make a deposit, through allowing biological growth, in order to keep fish stocks high and so to keep capture costs down.

Where a high discount rate combines with a low biological growth rate, or where the marginal stock effect is otherwise weak, the optimality of choosing to exploit a stock to the point of extinction exists[17] (Clark et al., 2010a). Even if the cost of catching the last fish were infinite this may not suffice in preventing this outcome since, where some minimum viable population level exists, a fishery may potentially collapse before the biomass reaches zero, which increases the risk of extinction through such a threshold being inadvertently crossed.

The argument of some neoclassical fisheries economists that the risk of extinction is a purely theoretical result (Grafton et al., 2007) is refuted by others (Clark et al., 2010c) with evidence given of the Tasman orange roughy fishery between 1997 and 2007, whose discovery, managed exploitation and rapid collapse negates any assertion that the economic optima are fully consistent with goals of biological conservation and sustainability in all cases. More generally, these authors hold that although the strength of marginal stock effect would prevent stock collapse, weakness is more common, and that when considered together with a high likelihood of there being a minimum viable population the possibility of optimal extinction exists even at low discount rates, or where

17 It is unclear that actual biological extinctions of marine species have occurred as a result of fishing activity. For the purposes of this paper a localised extirpation of a species is an effective 'economic' extinction and so the term extinction is used without further qualification.

the net return from capturing the last fish is substantially negative. The result is an expression of the dialectically predicted contradiction associated with dynamic phenomena.

That this contradiction remains unresolvable within the neoclassical paradigm is further evidenced by theoretical attempts to resolve it. Particularly instructional is the incorporation of an existence value for the fish species into the cost function associated with its exploitation. This will fail to resolve the issue of extinction since existence value has the characteristic of a public good, meaning that while in the case of a publicly owned resource a policy setting of a sufficiently high existence value for the resource will prevent the possibility of extinction, in the case of the rational private fisher focused only on net returns, *homo economicus* in the fishery, existence value will be zero and resource extinction may still result (Clark et al., 2010a).

Where conditions are such that a private owner is expected to view extinction as optimal, its prevention through the application of additional direct policy restrictions is prescribed, for example in the use of marine reserves to protect these biological stocks (Brady and Waldo, 2009) or in vessel and gear restrictions to limit fishing effort (Mace et al., 2014). Since they seek to introduce inefficiencies into a policy environment where privatisation has been advocated as 'sufficient' (Arnason, 2012: 212), such policy restrictions are further expressions of contradiction within the model. The restrictions represent an ecological form of Polanyi's 'double movement' (Polanyi, 2001 [1944]: 138) with a counter step of environmental protection required for every step towards the neoliberal market (e.g. van Putten et al., 2012).

While the issues of extinction and existence value would seem to be resolvable by the designation of fish resources as either common or state owned assets, there are inherent features in the nature of the fishery that make these solutions less likely within a strongly market oriented economic regime. The fisheries problem differs from a general macroeconomic problem in the nature of the consumption good and the capital good that produces it, which, as we have seen, are both fish. They are not different kinds, or species of fish, they are the same fish, differing only in their location — one living in the ocean and the other lying on the dock. The commodification of an individual fish occurs directly, upon its capture and the subsequent delivery of the fish to market. However, since the fish stock cannot be physically separated from the ecosystem, its context, which is a prerequisite for commodification (Castree, 2003), it remains incompletely commodified. The enclosure of the fishery by means of a privately held marketable fishing right, such as an ITQ, overcomes this problem by enabling its representation as a financial instrument which is fully separable as a qualitatively specific entity. In this manner the process of commodification of the fishery is only completed when it becomes private property, even where this relies upon the proxy of an ITQ in the context of a state owned resource, and not when the fishery is simply common or state property. Thus we see the issuing of private property rights is increasingly advocated as a solution to the common pool problem within global fisheries (Arnason, 2012, Grafton et al., 2000, Wilen, 2006).

The three distinct natures of the fish represented in the capital theoretic model, then, are reflected in an inescapable tension between fisheries objectives that span ecosystem health, short-term economic gains based on catch and the act of catching (in particular consumption and employment), and the long term sustainability of yield. The true nature of this tradeoff is not readily apparent within a reductionist model, which is too narrow to demonstrate the source of the contradiction described. The dialectic provides a method that anticipates contradiction in a dynamic system and in particular provides a process of abstraction that appropriately broadens the field of enquiry to reveal the source of contradiction.

3. A dialectical analysis

3.1. Dialectic abstraction

Cartesian reductionism, which is associated with classical mechanics, treats parts as given ingredients for the construction of wholes, moving freely from whole to part and then back to whole. Reductionism negates the whole, however in turn it is negated by the contingent and emergent properties of the wider system. Dialectically this represents a negation of the negation (Ollman, 2003). The dialectic concept of abstraction reflects an understanding of part-whole relations, where parts and wholes are not independent concepts but are contingent upon one another. In describing the dialectic, Hegel (2010 [1812-1816]) argues that separated from the whole, parts are not parts but are themselves totalities, and that the parts taken together are not parts but are precisely the whole.

In this manner we find that particular arguments may be valid only when viewed from a particular position, or from within a particular context. That is, any distinct abstraction may be understood only by considering how it relates to its own particular concept of the whole, which is in itself a further distinct abstraction. This process has been described as one of continuously asking where the rest of the world lies with respect to a particular abstraction (Lewontin and Levins, 2007b).

To be effective, the whole considered by the set of abstractions must be sufficient to accommodate solutions to the problem under consideration. The exposure of contradiction, and the metamorphosis which results from it, requires a level of abstraction that is sufficiently broad to encompass all of those objects within a system in which the elements giving rise to the contradiction are contained (Ollman, 2003). While the contingent nature of the materialist dialectic recognises that sufficiency can never be fully realisable, the consideration of multiple abstractions safeguards the continued consideration of the whole, and hence the relevance of all abstractions. Indeed, in his description of method, Marx (1973 [1939]) argues that the process of abstraction must start by breaking down reality into ever thinner abstractions, which once established can be used to reconstruct a conceptual reality in which the totality of functions and relationships are revealed. It is not the act of breaking down but the act of reconstruction that provides ‘the scientifically correct method‘ (Marx, 1973 [1939]: 121) for understanding, so that it is within such a reconstruction that the metabolism of a system can be understood.

The dialectical analysis of a problem and the consideration of alternative normative viewpoints demands that a modelling technique sympathetic to dialectal analysis is used. The analytical method of loop analysis provides such a technique. The unitary nature of quality and quantity within the dialectic means that abstractions based upon a qualitative consideration of the whole must be held of equal importance to quantitative abstractions.

In order to uncover the source of the contradictions described - that conditions may arise in the capital theoretic model where species extinction is optimal and a countering ‘double movement’ in policy required - we apply this method to a qualitatively specified capital theoretic model. This requires the specification of an abstraction for the model that is sufficient to encompass and demonstrate the concept of strong sustainability and the relationship of this concept to the relative strengths of the cycles that both comprise the model and determine its stability.

3.2. A qualitative model

The process that follows in this paper, through the use of the calculus of loop analysis, is to establish an equivalent qualitative abstraction to the neoclassical capital theoretic model described earlier, a mathematical formulation of which is provided in Clark (2010: 23-25)[18]. Continuing to employ this calculus, the model is consolidated and simplified to core elements relevant to the analysis of a particular abstraction (Puccia and Levins, 1985) in a process that reveals the dialectically anticipated metamorphosis of system components, while still retaining the mathematical equivalence of the systems. This qualitative representation of the capital theoretic model describes the interactions, transformations, and feedback cycles within a fishery. The cycles

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18 The capital theoretic formulation of the fisheries problem can be described in terms of the following model:

$$\max_{\{h(t)\}} PV = \int_0^\infty e^{-\delta t}[p - c(x(t))]h(t)dt$$

$$\text{subject to } \frac{dx}{dt} = F(x) - h(t) = 0,\ x(0) = x_0$$

$$h(t) = qE(t)x(t)$$

$$c(x) = \frac{c}{qx}$$

$$x(t) \geq 0,\ E(t) \geq 0$$

The objective of the model focuses on the present value PV of a stream of future returns which are subject to an instantaneous rate of discount δ. The returns from the fishery in terms of resource rent, are the difference between the unit price of fish p and the cost of its capture c(x), multiplied by the harvest h(t), where prices are assumed constant and capture costs, which depend on the cost of effort c, are a linear function of the biomass level x. The harvest h(t) in any time period t depends upon the fishing effort E(t) applied to the biomass x(t), and a measure of catchability q. The biomass is in equilibrium when the harvest level is the same as the growth of the biomass as determined by the biological growth function F(x).

Solving this yields a modified golden rule equation:

$$F'(x^*) - \frac{c'(x^*)F(x^*)}{p - c(x^*)} = \delta$$

where F'(x*) is the intrinsic growth rate of the resource, c'(x*) is the marginal cost of capture, and x* is the optimal biomass which is a dynamic MEY and equal to the xMEY obtained from the static Gordon-Schaefer model only as a special case when δ = 0.

The well known economic result of the golden rule of capital accumulation, which holds that the stock of a capital asset will be increased or decreased until its marginal product is equal to the rate of return for the asset class, that is F'(x*) = δ, is modified through the second term on the left hand side, the marginal stock effect. The marginal stock effect reflects the responsiveness of the cost of harvesting in the fishery to the size of the biomass, and has significant implications for the sustainability of the fishery. The left hand side of is the internal rate of return to the fish stock and the right hand side its opportunity cost, that is the rate of return available from all other economic activities.

at different levels within the qualitative system and their effects on the overall dynamic stability, or otherwise, of the system are then examined in terms of the criteria laid down by Dambacher et al. (2003).

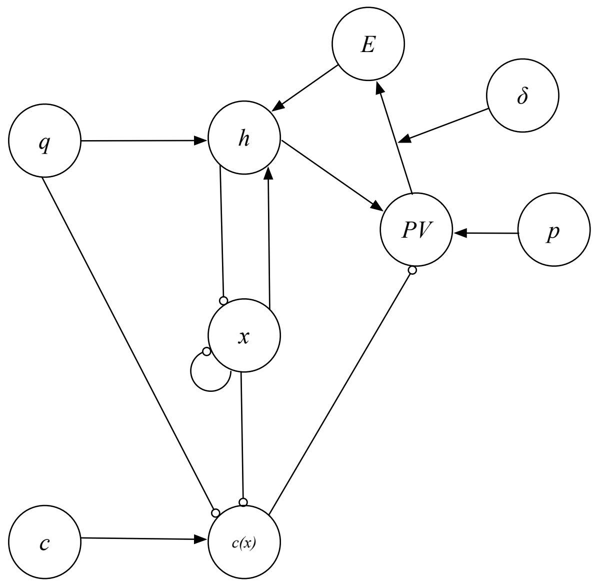

Figure 3.1. Signed digraph representing the capital theoretic fisheries model.

The objective of the model is present value *PV* of a stream of future returns that are subject to an instantaneous rate of discount δ. The returns from the fishery are the difference between the unit price of fish *p* and the cost of its capture *c(x)*, multiplied by the harvest *h*, where prices are assumed constant and capture costs, which depend on the cost of effort c, are a linear function of the biomass level *x*. The harvest *h* depends upon the fishing effort *E* applied to the biomass *x*, and a measure of catchability *q*.

Our consolidated model is represented as the signed digraph model shown in Figure 3.1. Representing a particular qualitative abstraction of a system, and the starting point of loop analysis, a signed digraph model comprises nodes shown as circles, positive effects (depicted as a link ending in an arrow), and negative effects (depicted as a link ending in a ring). The information in the signed digraph mirrors that contained in a Jacobean matrix of a system, comprising the sign value of the partial derivatives of the model's equations, when the mathematical operator $sgn(.) \in \{-1, 0, 1\}$, $sgn(x) = x \div |x|$ is applied. This supports a highly intuitive modelling process.

The signed digraph in Figure 3.1 is reduced to an interaction of the three core components of the fishery, that is: the biomass of fish (*x*), the effort of fishers (*E*) and a management function (*M*). The process by which this is achieved is shown in Figure 3.2. Because of its importance to the decision making of the golden rule, the discount rate node δ is retained as a modified interaction (Dambacher and Ramos-Jiliberto, 2007) in the reduced form signed digraph.

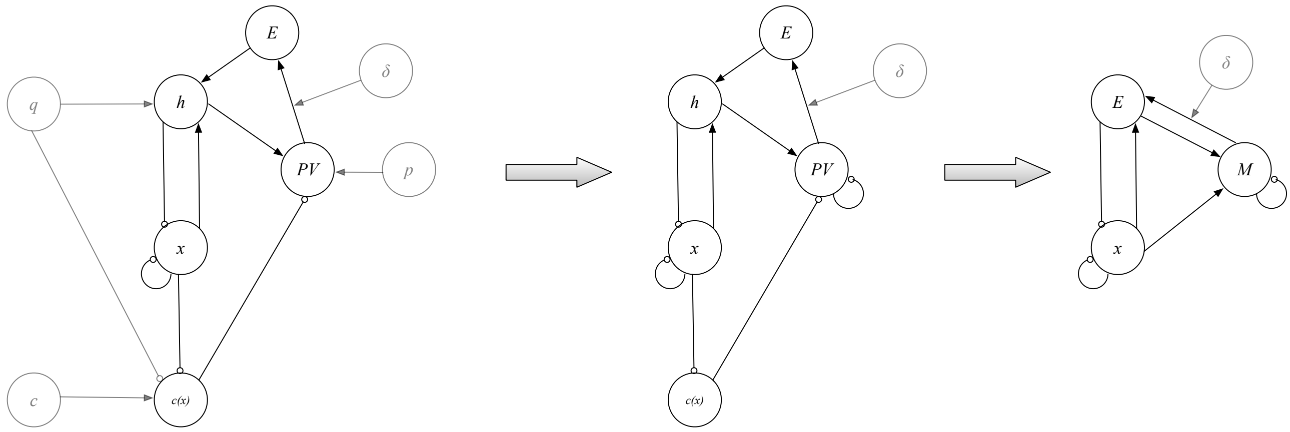

Figure 3.2. Simplification of a signed digraph representing the capital theoretic fisheries model.

The simplification of the model is achieved by focusing on the feedback and cyclical dynamics that it contains. Nodes without incoming links do not affect these dynamics and therefore *p*, *c* and *q* can simply be removed[19]. This is the equivalent of assuming the unit price of fish, the cost of effort and the catchability, that is fishing technology, are constant. Harvest activity with constant technology is simply a function of effort and so the *h* and *E* nodes can be lumped together. Although lumped nodes take on broader system characteristics we will continue to designate them *E*. Dynamically the two negative links from *x* through *c(x)* to *PV* are equivalent to their sign product, and can therefore be replaced with a single positive link from *x* to *PV*. The outcome of the maximised present value in the objective function, that is the golden rule equation, is a management decision-making rule. This use of the value of PV in policy, a behavioural intervention in the system, is explicitly recognised in the re-designation of the node *PV* as *M* .

19 While prices p are assumed constant, that is they are externally constrained, there is nevertheless an exogenous subsystem by which they are determined and that must be accounted for by a negative self effect upon M.

The simplified signed digraph for the capital theoretic model contains three feedback cycles, two of which are negative and one of which is positive, and two self-dampening cycles. Negative feedback provides regulation to a system and assists in its returning to an equilibrium state following a perturbation in a system variable or parameter. On the other hand, positive feedback is self-reinforcing and supports syndromes that push a system away from equilibrium following such a perturbation. Self-dampening cycles reflect constraints on a variable's growth that are exogenous to the model (Puccia and Levins, 1985).

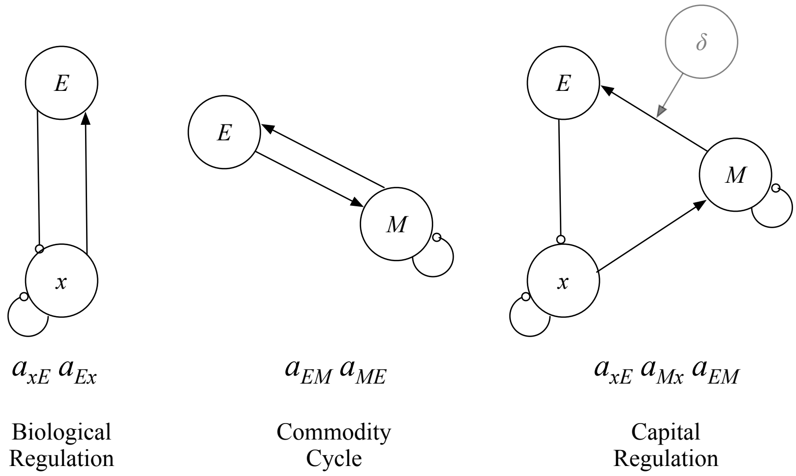

Figure 3.3. Principle signed digraph feedback cycles from Figure 3.2 and their symbolic representation.

The biological regulatory cycle is a predator-prey relationship, a commonly used form of which is described by the Lotka-Volterra equations (Odum, 1953). The fish exists here in its biological nature.

The commodity cycle is a short-term cycle of seasonal effort decisions in which the fish appears only implicitly, its nature being that of a commodity.

The capital regulatory cycle is an inter-temporal cycle considering the future value of the fish stock. The fish exists here in the nature of a machine that produces a fish commodity.

The feedback cycles, illustrated in Figure 3.3, reveal the three natures of fish that are obscured in the process of commodification described earlier - namely biological species, market commodity and capital machine. The cycles are:

Biological regulation cycle, which reflects the predator-prey relationship between person and fish, whereby the capture of fish in one turn of the cycle reduces fish availability in the next turn of the cycle, thereby increasing the difficulty of catching fish and allowing the fish stock to recover.

Commodity cycle which, reflects the relationship between the sale of the fish commodity and reinvestment in further productive capacity. Described as a treadmill of production (Schnaiberg et al., 2002), this process is one of continuous accumulation unless controlled by some other factor.

Capital regulation cycle which, reflects the inter-temporal view of the fish stock as the source of future fish production, with the presence of the discount rate establishing the fungibility of capital and the weak sustainability implicit within the model.

The self-effect on the stock variable a_{xx} reflects the productivity of the stock in terms of the birth rate, the death rate, and the carrying capacity of its containing ecosystem. The self-effect on the management variable a_{MM} originates in the exogenous price effect shown in the disaggregated model of Figure 3.1. In the simplified model M represents a general measure of the economic attractiveness of the fishery as an investment, which will be influenced by exogenous factors including both the price of fish and the availability of alternative investment opportunities.

The simplified three-node signed digraph of the capital theoretic model resulting from the process shown in Figure 3.2 is expressed in eq. (3.1) as a qualitatively specified Jacobean matrix **A**. Each of the matrix elements a_{ij} represents the effect of component j upon component i [20].

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20 So that for the matrix A in 3.1 the first row elements read from left to right provides the effect upon x of changes in x, E and M respectively. Similarly, the second row shows these change effects upon E and the third row upon M.

$$\mathbf{A} = \begin{bmatrix} -a_{xx} & -a_{xE} & 0 \\ a_{Ex} & 0 & a_{EM} \\ a_{Mx} & a_{ME} & -a_{MM} \end{bmatrix} \tag{3.1}$$

$$\left|\mathbf{A} - \lambda\mathbf{I}\right| = 0,\ \alpha_0\lambda^3 + \alpha_1\lambda^2 + \alpha_2\lambda + \alpha_3 = 0$$

3.3. Results

The viability of a biological stock depends on the stability of the system within which it is contained. In the case of an unexploited fish stock, which is contained within an ecosystem, this viability depends only on biological features and relationships. An exploited stock, however, is contained also within a particular economic context and its viability therefore has both biological and economic components.

The stability of a system is the tendency of the system to return to equilibrium following a perturbation, as opposed to its either moving away from equilibrium or entering an oscillatory state around the equilibrium (Levins, 1975a). Dambacher et al. (2003) describe two criteria, based on the well known results of Lyapunov and Hurwitz, that establish the overall effects and relative feedbacks of a system's dynamics, while providing necessary and sufficient conditions for its stability. These criteria disentangle the two ways in which a system can be unstable: the first arises through the existence of positive feedback, such that no correction occurs following a perturbation; the second arises through an insufficiency of low level feedback when compared against high level feedback, such that overcorrection and oscillation occurs post perturbation. Mathematically, the first criterion requires that all of the coefficients of the characteristic polynomial of the system, established in matrix form, be negative, and the second criterion that the second to penultimate

Hurwitz determinants all be positive. Individually these criteria are necessary for system stability, while taken together they are sufficient for system stability.

In order to examine the stability of the simplified capital theoretic system in eq. (3.1) the characteristic equation of matrix **A** is solved for λ based on the values of the polynomial coefficients. Then to examine conditions for the stability of the system we must determine the conditions under which a polynomial coefficient will be unambiguously negative. This requires examination of the symbolic structure of the polynomial coefficients in terms of the elements of the Jacobean matrix, as shown in eq. (3.2) (α_0 = -1 by convention and so may be ignored).

$$\begin{aligned}\alpha_1 &= -a_{MM} - a_{xx} \\ \alpha_2 &= a_{EM}a_{ME} - a_{xx}a_{MM} - a_{xE}a_{Ex} \\ \alpha_3 &= a_{xx}a_{EM}a_{ME} - a_{MM}a_{xE}a_{Ex} - a_{xE}a_{EM}a_{Mx}\end{aligned} \tag{3.2}$$

Only α_1 is unambiguously negative, while the negativity of α_2 and α_3 depends on the relative sizes of their symbolic components, that is upon the feedback loops of the system.

Positivity of Hurwitz determinants Δ_i for i = 1...n, excluding the first and the nth determinants, provides the second indicator of system's stability. In this case n = 3 and only the second Hurwitz determinant Δ_2 is required. The symbolic examination of Δ_2 in eq. (3.3) shows its sign to be ambiguous.

$$\Delta_2 = -a_{MM}a_{EM}a_{ME} + a_{xx}a_{MM}^2 + a_{xx}^2a_{MM} + a_{xx}a_{xE}a_{Ex} - a_{xE}a_{EM}a_{Mx} \tag{3.3}$$

These results demonstrate that this system may be stable both in the sense that there is no preponderance of positive feedback destabilising the system, and in the sense, that there is insufficient low level against high level feedback, such that overcorrection and oscillation post perturbation is prevented. However, as a more detailed examination of the three conditions arising from eqs. (3.2) and (3.3) demonstrates, stability is not certain. These conditions are described in eqs. (3.4), (3.5) and (3.6) below.

$$\alpha_3 < 0 \ \textit{if} \ a_{xE}(a_{Ex}a_{MM} + a_{Mx}a_{EM}) > a_{xx}a_{EM}a_{ME} \quad (3.4)$$

$$\alpha_2 < 0 \ \textit{if} \ a_{xx}a_{MM} + a_{xE}a_{Ex} > a_{EM}a_{ME} \quad (3.5)$$

$$\Delta_2 > 0 \ \textit{if} \ a_{xx}(a_{MM}^2 + a_{xx}a_{MM} + a_{xE}\ a_{Ex}) > a_{EM}(a_{xE}a_{Mx} + a_{ME}a_{MM}) \quad (3.6)$$

The condition in eq. (3.4) examines the overall feedback of the system, that is cycles involving all three nodes. Stability at this level requires that the biological regulation cycle ($a_{xE}\ a_{Ex}$) and the capital regulation cycle ($a_{xE}\ a_{Mx}\ a_{EM}$) taken together, must outweigh the commodity cycle ($a_{EM}\ a_{ME}$). This condition indicates that the system is particularly sensitive to the parameter a_{xE}, which measures the effectiveness of fishing in depleting the stock. The parameter appears twice on the left hand side of the condition in eq. (3.4), representing both the biological and the capital regulatory cycles described for the system, and dampens the potentially destabilising effect of the positive commodity cycle on the system.

The condition in eq. (3.5) examines feedback at the second level of the system and indicates that stability requires the self-effects on biomass a_{xx} and management a_{MM}, respectively the productivity of the biological system and economic attractiveness of the fishery investment, taken together with the biological regulation cycle must outweigh the commodity cycle.

The condition in eq. (3.6) is based on the Hurwitz determinant and indicates that stability requires that the biological productivity a_{xx} and economic attractiveness a_{MM}, taken together with the feedback of the biological regulation cycle must outweigh both the capital regulation cycle and the commodity cycle. Furthermore, the condition suggests that stability by the second Hurwitz criterion will fail, and that system oscillation will result, where there is a combination of a strong a_{EM}, the tendency to reinvest in fishing capacity as a result of high short-term returns, in the face of a weak a_{xx}, a stock with low natural productivity.

4. Discussion

Since the cycles in the model relate to the three natures of fish in the modern fishery, it follows that the stability conditions, which are based upon the relative strengths of these cycles, reflect an implicit tradeoff between these cycles. The tradeoffs between the biological cycle and two economic cycles, commodity and capital, within fisheries are not immediately apparent within quantitative bioeconomic models — although their impacts on systems sustainability are widely observed in fisheries' crises around the globe. Once the tradeoffs are revealed, however, it is possible to make a number of informed observations with respect to the stability of a resource managed in the neoclassical tradition of capital theory.

The commodity cycle describes the tendency for the fishery to expand in terms of catch or, where catch is constrained by policy, through investment in technology, equipment or other capacity enhancement. As the only positive, and hence destabilising, cycle in the system this view of fish as a commodity is particularly important. If the commodity cycle is too strong, it may overwhelm both the biological and the capital regulatory cycles in the system and lead to the economic or biological collapse of a particular fish stock. This is demonstrated in each of the stability conditions in eqs. (3.4), (3.5), and (3.6) where the position of the commodity cycle in the inequality is such that its strength will tend to cause each condition to fail.

Cycles of accumulation, such as this commodity cycle, are at the core of both radical and mainstream socio-economic studies of fisheries, however, there is an important difference in the way that they are perceived. While in mainstream fisheries economics, an observed over-investment in capacity has been argued to be a one way accumulative process, an upward ratchet effect

(Ludwig et al., 1993) resulting in resource overexploitation, this is understood as a difficulty of policy setting (Alverson, 2002) and not as a systemic problem. The result of this understanding is that subsequent attempts to address the difficulty through policy initiatives are similarly doomed to failure, as exemplified in the rent seeking behaviours that confound attempts to conserve fishery resources through capacity buyback schemes (Clark et al., 2005). In contrast radical treadmill theories of accumulation (Schnaiberg et al., 2002) link the syndrome of continuous growth, that drives market capitalism, to ecological degradation in explaining the biomass depletion affecting most major fisheries in the world (Clausen and Clark, 2005). This reflects an understanding of the problem as systemic, which is illustrated in our model by the commodity cycle and its contribution to the dynamics of the system.

The model suggests that all policy formulation requires the consideration of the entire dynamics of the system and that policies that address only one part of the system dynamic risk the emergence of unanticipated feedbacks and policy failure. The regulatory role of countervailing cycles, that is the biological and the capital regulatory cycles, must be considered for successful policy formulation.

Conditions in eqs. (3.4), (3.5), and (3.6) unambiguously indicate that the biological regulatory cycle needs to outweigh both of the economic cycles for stability to be realised. In particular the feedback associated with the biological regulatory cycle needs to be strong enough to prevent the unlimited expansion of the fishery through the commodity cycle, as anticipated by treadmill theory. Biological regulation delivers a short-term impact on catch as stocks are reduced through fishing, that is as fish are being caught they become more costly for fishers to catch because of the contemporaneous fall in stock levels, as described by the marginal stock effect in the golden rule. Any disruption of biological regulation such that the fisher, as predator, is prevented from feeling the effects of their predation on the stock, will have detrimental effect on the stability of the overall system. For example a replacement of small-scale fishing by factory fishing, which allows for fish to be viably captured even at very low stock levels, may weaken the feedback to fishers from stock reductions through the link described by a_{Ex} in the model. This is demonstrated in the case of bluefin tuna where an effect of the adoption of globalised ranching methods has been to interrupt stock level feedback mechanisms resulting in resource overexploitation, environmental degradation and social dislocation in artisanal fishing communities (Longo, 2011).

The capital regulatory cycle, that is the view of fish as machine, plays an important role in determining overall system stability, including determining whether cyclical behaviour will result from a perturbation of the system. However the appearance of this cycle on either side of the inequalities expressed in the set of stability conditions makes its effect ambiguous, and reveals it as a mechanism for contradiction. On the one hand, capital regulation works together with biological regulation within the overall feedback of the system in eq. (3.4) to counteract the destabilising effects of the commodity cycle. Capital regulation recognises that any fall in stock levels will reduce future recruitment to the biological stock and thereby reduce the potential for the production of fish as a commodity over the longer term. In this way capital regulation provides a focus on the strategic value of the stock as a source of future value, as opposed to the short-term operational view of stock that is driven by the commodity cycle. On the other hand, the Hurwitz condition in eq. (3.6) indicates that the capital regulatory cycle may also work together with the commodity cycle to overwhelm the biological cycle and, as the regulatory cycles move out of sequence, cause the system to oscillate such that a cycle of boom and bust to develops.

An inspection of the relevant stability conditions shows that the ambiguous effect of the capital cycle arises because of the common link a_{EM} it shares with the commodity cycle. This link expresses the operational re-investment of profits in increased fishing capacity, while simultaneously providing the mechanism for changing the investment holdings in the 'fish bank' as a source of future of returns. In terms of the overall feedback stability in eq. (3.4) the effect of a_{EM}

is balanced out by its appearing on both sides of the inequality, however in eq. (3.6) this link appears only on the right hand side of the inequality meaning that its strength will contribute to cyclical instability. Since the amplifying effect of the discount rate on the capital regulation cycle works through the modified interaction on a_{EM}, the discount rate is an important stability consideration.

The problem with the capital cycle arises not because it provides for a long term view on the value of the fish stock, but rather in the opportunity cost role that the discount rate plays in the capital theoretic model, in essence determining whether continued investment in a particular fish stock is attractive in comparison to some other economic opportunity. The implied substitutability of different capital stocks supports weakly sustainable approaches as opposed to strong sustainability where the viability of all stocks must be maintained. While in practice it seems unlikely that any decision maker would consider that a widget factory is a suitable substitute for a wild stock of fish in the sea, or indeed that policy makers would support any such a substitution, the choices facing decision makers in practice are more nuanced than this. A tendency to homogenise and simplify productive processes has been part of the capitalist system of production since the beginnings of industrialisation and is equally applicable to renewable resource management which prefers mono, or limited, species and ease of harvest (Foster et al., 2010).

The drive to homogenisation improves returns and economic outcomes, but reduces ecological diversity and consequently the robustness of ecosystems, for example in their ability to absorb exogenous perturbations such as climate change. This leads to a further expression of contradiction, that is decisions made on the basis of the opportunity cost of capital improve economic outcomes when measured in terms of profitability and accumulation, yet the same decisions may worsen ecological outcomes through homogenisation. This in turn points to another mechanism by which this contradiction arises when the capital theoretic model is used as a basis for fisheries policy, that of the discount rate. Discount rates are normally set in consideration of macroeconomic factors that are non-ecological in nature, for example a government bond rate (Sumaila, 2004), so that they are entirely exogenous to the fishery. This means that the role of the discount rate in providing the benchmark for the performance of the fish stock, through the golden rule, obscures the biological nature of the fish resource and ultimately of its species, which becomes simply another commodity. It is this commodification of the species in fisheries in terms of the capital theoretic model, and the weakly sustainable approach it engenders, that is the ultimate source of the contradictions we observe.

5. Conclusion

The use of models based on neoclassical economics in fisheries management carries an assumption that the market provides a silver bullet for ecological problems. Once all is internalised to the market system then sub optimal outcomes are to be understood as market distortions that result from incomplete specification of a system such that effects external to the market mechanism remain. It is believed that any inconsistency in policy outcomes will disappear if only theoretical relationships between variables can be correctly specified and the required data gathered. Policy failure then is seen as an epistemological issue. Even if we were to accept this position, the complex adaptive nature of ecosystems and the opaque and fugitive nature of fish resources, make the application of standard economic epistemology at best problematic, and at worst damaging for the resource, for the ecosystem within which it is contained and ultimately for social outcomes.

The issue with the neoliberal economics of all-embracing markets, with its imperative to reduce components of any system such that they can be described in terms of standard economic metrics, is that this process of alienation hides the fundamental social and ecological relationships of the system. In addressing the problem of open access through oceanic commons enclosure and the institution of property rights, the fish that both individually and in collective provide ecosystem services, including as a source of protein for its human predator, becomes simply a marketable commodity which, in turn, becomes a productive capital that produces more of the same commodity. As capital the fish is no longer valued for its biological and ecosystem roles or for protein provision, but is valued only insofar that as capital it produces a comparable return when benchmarked against all other capital employed in the economy. Hence if the return of the particular stock of capital is lacking it becomes rational to liquidate the resource that the capital represents, that is to take the resource out of the ecological system by catching and selling it, even to the point of extinction.

The exploitation of the stock of biological capital is accelerated by the commodity nature of the fish itself, as returns from fishing drive more fishing effort. It is here that the crisis of the commodity occurs, which deepens the tension and contradiction within neoclassical fisheries models and suggests that any notion of a convenient congruence between the application of market economics and optimal ecological outcomes in fisheries is fanciful. The traditional mathematical formulation of the capital theoretic model does not in fact provide a policy choice between weak and strong sustainability, rather it requires capital fungibility and weak sustainability making resource extinction a real possibility. The alternative qualitative formulation of the model and the framing of analysis in dialectical terms allows us to demonstrate the tradeoff between the biological, ecological and socio-economic natures of the fishery and in so doing provides the possibility of choice between weak and strong sustainability in policy. Without this possibility the achievement of the improved ecological outcomes currently sought through policy will be problematic.

Since its inception modern fisheries economics has seen the problem of resource overexploitation and degradation in the fishery as primarily a problem of the commons. In a number of instances this recognition has conflated the typological issue of a common pool resource with the institutional issue of common property. Then, in seeking to address a perceived institutional issue, a market solution has been brought to bear, including the abstract capital theoretic treatment of the fish stock and ongoing commons enclosures. This, however, has had the effect of commodifying a fish resource - as catch, as capital stock and as species - and in so doing laid the seeds for a greater ecological tragedy than the one it originally hoped to solve. This tension between commodification and ecological function is then the essential contradiction within fisheries and is one that is fully revealed dialectically.

Applying a process of dialectic abstraction to the neoclassical capital theoretic model, supported by loop analysis, allows for the examination of tradeoff between its variables in their actual underlying form, both revealing the source of contradiction within the system and demonstrating its effects. This advances our understanding of tensions that arise within the management of fisheries based on the model. While we do not necessarily expect to reach resolution of these tensions, in describing a dialectical perspective and sympathetic modelling method we hope to provide open conclusions as an engine of an alternative discourse within fisheries' management and that of ecological resources more generally.

Chapter 4

The unanticipated consequences of environmental management in a full world.

1. Introduction

Since the Industrial Revolution, the growth in human populations, their productive activities and concurrent consumption of resources, has had significant deleterious effects on both ecosystems and the services they deliver. Humans have transformed over 50% of the global land mass to their use (Hooke et al., 2012) and it is estimated that our species directly consume over 20% of the net primary production of all terrestrial ecosystems (Haberl et al., 2007). All marine ecosystems are now affected in some part by human activity with over 40% being significantly adversely impacted (Halpern et al., 2008), and comparable impacts are evident in freshwater ecosystems (Carpenter et al., 2011). The collective effect of human impacts is to have impaired the provision of ecosystems services to an extent that full restoration is not possible (Hobbs et al., 2011). There is, however, evidence that environmental management, through either a reduction of these impacts or restorative activities, may deliver a partial recovery (Bullock et al., 2011, Lotze et al., 2011) and thereby contribute to both ecological and socio-economic welfare improvements (Aronson et al., 2006).

While many of the negative environmental effects of human activity went unnoticed when the scale of production was small relative to the overall size of the biosphere, they have become more evident as the limits of various biotic subsystems to provide services are reached and abiotic resource availability is reduced. The shift from an empty world, where man-made capital is free to accumulate, to a full world, where this process is necessarily constrained by the limits of natural capital (Daly, 2005), holds implications that must now be accounted for both in economic theory and in policy formulation.

As the dominant paradigm underpinning natural resource management, neoclassically-based environmental economics, with its focus on economic production in isolation from the system within which it is contained, seeks resolution of the issue of resource limits and environmental damage through a process of commodification of ecosystem services (Castree, 2003). Such commodification, it is argued, ensures the efficient allocation of environmental resources and promises to efficiently address the external effects the production system imposes upon them through the market. It also allows environmental limits to be addressed through substitutability between natural and manmade capital. The extension of the neoclassical metaphor to the environment in this manner is supported by a measure of human welfare based on an abstract concept of utility and where the equivalence of manufactured widgets to ecological services becomes one of a rate of exchange, or price, so that any value which is intrinsic to nature is removed and instrumental market value is instituted across the biosphere (Foster, 2002). The ability of technological improvement to overcome the environmental limits first raised by Malthus, is seemingly without end (Persson, 2008).

The implication is that, if only we continue to grow, the negative ecological consequences of such growth will be ameliorated (Grossman and Krueger, 1995). This will be achieved as a result of some form of environmental health-income relationship, such as that suggested by the Environmental Kuznets Curve, whereby a material living standard threshold level must be reached before ecosystems are valued (Kijima et al., 2010). However, in considering the three aspects by which living things should be understood — their individuality and self interest, the group within which they reproduce and the biocoenosis within which they exist (Faber and Manstetten, 2010) — the rational egoist of neoclassical economics describes only the first and in doing so fails to recognise the need for the three aspects to be addressed as a whole.

It is apparent that environmental policy developed using the approaches and methods of mainstream economics fails to resolve the tension that exists between the economics of growth and the ecology of a finite planet (Levallois, 2010) and the question remains as to whether this tension is a resolvable contradiction or an apparent paradox. The complex adaptive nature of the whole system (Levin, 1998) is characterised by the prospect of irreversible ecological damage (Prieur, 2009) and the potential for transitions over critical thresholds at the scale of the global biosphere (Barnosky et al., 2012), both of which increase the importance of understanding the feedback dynamics of human and ecological subsystems. The immediacy of the interrelationships between system parts, and the contradictions to which they must give rise, requires their examination within a framework that is sufficient to observe the whole of the system in which they are contained.

The anticipation of the effect of environmental management policies in complex adaptive systems, in which change is intrinsic, is best undertaken dialectically. While it is not possible to fully describe the totality of a complex system, it is nevertheless important that its broad processes and parameters be considered. Dialectically, our understanding of a complex system can be developed through abstraction, which is both a construct and a process (Hegel, 2010 [1812-1816]). As a construct an abstraction establishes a particular spatial and temporal extent, a level of generality or system detail and the perspective of the observer. The specific detail of any particular abstraction should be that which is sufficient for a particular problem, while always considering where the remainder of the system whole lies with respect to it. As a process, abstraction involves the consideration of multiple abstractions of the whole, each of which increases our understanding of the reality of whole, although this real whole cannot be fully defined or known (Ollman, 2003).

Schumpeter describes an ideologically conditioned pre-analytic cognitive act or vision (Schumpeter, 1986[1954]: 39) that establishes the boundaries for analysis, with the implication that omissions cannot be incorporated into later analysis without a process of re-envisioning. Thus, the pre-analytic vision of neoclassically rooted environmental economics is an abstraction in which analysis starting from independent, although interacting, parts — economy, society and environment — cannot later be successfully reformulated into an integral whole. In contrast, the pre-analytic vision of the discipline of ecological economics was established as that of a socio-economic subsystem contained within a closed biosphere (Costanza, 1991), that is, a whole ecology. The inseparable nature of the constituent social, economic and natural elements of this ecology make their consideration through the application of the neoclassical metaphor and reductionism problematic. The alternative of non-reductionist system models, however, where everything leads to everything, does not imply that everything must be viewed or known at one time (Whitehead, 1948 [1925]), a necessity which is avoided by a dialectical process of abstraction.

A risk to the efficacy of environmental management policies in complex systems is that we confuse a particular abstraction, which may itself be a large complex system, with the real whole with which it is associated. This is described as misplaced concreteness (Whitehead, 1948 [1925]), and may result in feedbacks from those parts of the real whole that are not considered in the abstraction, creating unexpected outcomes that are then seen by the observer as paradoxical simply because they are unaware of the feedbacks elsewhere in the whole. What is needed to address system feedback dynamics is an evolutionary[21] science of the whole, in which the examination of subsystems considers how these relate to the whole in terms of what they reveal and also what they obscure (Levins, 2007) .

Advances in natural resource management also demand a whole-of-system's perspective. For instance, adaptive management (Holling, 1978), the origins of which lie in the scientific management of an ecosystem, provides a whole-of-system evolutionary approach to management that accounts for the relationships and feedbacks within resource systems. It also accounts for uncertainty and moves away from a view of natural resource management in which the focus is on optimisation of yield for discrete populations of resources, and instead focuses on management of the whole system. While the implementation in practice of adaptive management has been less

21 The use of the term evolution in an economic or sociological context implies the development of a system to an indeterminate end in a non-teleological fashion rather than having any biological meaning.

successful than the claims made for its use (Walters, 2007), its concepts are reflected in the whole-of-system's based management perspectives of ecosystem based fisheries management (Garcia et al., 2003) and in the broader conception of Interactive Governance (Bavinck et al., 2013) whereby the manner of governance is dynamically determined by the changing characteristics of the governed system, including its social aspects.

The implied need for a whole-of-system's view: ecological, economic and social introduces an imperative for a suitable interdisciplinary framework. Because these systems, which may be described as socio-ecological systems, are complex adaptive systems, the metaphor for such a framework needs to be biological, evolutionary and qualitative rather than mechanical, reductionist and quantitative. There is, in economics, a rich tradition of evolutionary thought outside of neoclassical economics (Radzicki, 2003) that is compatible with the analysis of such whole ecologies and offers the advantage of embracing the nature of economics as a social science, so that the social function required of the analysis does not require separate introduction.

Balancing the goals of economic growth and sustaining ecosystem services presents a challenge for policymakers, particularly in the marine environment where ecosystem dynamics and human interactions are both complex and poorly understood. Implementing environmental management policies — for example habitat restoration (Bullock et al., 2011), improved fisheries management (Fulton et al., 2011), and programs such as eco-labelling designed to raise environmental awareness (Brécard et al., 2009) — is a common response where economic and environmental goals conflict. However, evaluation of such policies in complex socio-ecological systems is problematic, as interventions will have effects which are difficult to anticipate, and consequences beyond those intended. This particular problem is compounded because biologists and economists often consider different views of the same system, which may give the appearance of paradox to one, or other, or both, groups where these viewpoints are insufficient to capture all relevant feedback effects.

Here our aim is to examine the efficacy of policy that seeks ecological improvements within a socio-ecological system, and to consider how this efficacy is affected both by feedback across all subsystems, and by the manner in which these subsystems are understood. We address this aim by developing and analysing a qualitative model representing a dialectic abstraction of a stylised regional fishery-based socio-ecological system comprising linked ecological (habitat and biological resource) and human (economic and social) subsystems, in which economic production is inseparable from the broader ecological system. We develop a base model that is novel in that we derive the qualitative relationships of the market from the equations of a standard neoclassical model of market adjustment, thereby translating these components of the system from neoclassical economic to evolutionary biological metaphor and making them amenable to a process of dialectic abstraction. Our base model further reflects the fundamental contradiction of full-world economics (Daly, 2005), depicting a social demand for both instrumental and intrinsic values, which express people's following their need to consume, their materialism[22] (Sirgy et al., 2013), while perceiving the state of their world, their environmentalism (Spash, 2009).

We describe the feedback behaviour of our base model and use this model to examine the ecological outcomes, in terms of resource stock and habitat, of a number of alternative environmental management policies, which are modelled as perturbations to appropriate social, economic and ecological system variables. We then embed details of a complex ecological food web and additional economic production in our abstraction, which enables us to further explore the dynamic response to environmental management of key variables in a complex marine socio-ecological system.

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22 While our simplified model contains a single consumer good, fish, the fact of commodification, as demonstrated in Chapter 3 of this dissertation, means that the model's revealed contradictions may be applied beyond the simple utilitarian consideration of hunger, and made more generally applicable to considerations of material consumption within a neoliberal market context.

Our results reveal a number of contradictory outcomes that, when considered within a sufficiently wide pre-analytic vision, are not unanticipated, but which may be misconstrued as paradox within a more traditional resource management framework. We further highlight the potential for loop analysis (Puccia and Levins, 1985), and the associated method of dialectic abstraction, to improve our overall understanding of a complex socio-ecological system and to support interdisciplinarity in management and working practices within fisheries.

2. Modelling method

Loop analysis describes the relations and feedbacks between components of a system which determine the movement between states of equilibrium. Furthermore, since a qualitative model can be read both in terms of the economic concepts of stocks and flows and the biological concepts of communities and metabolisms, it provides a tool for achieving interdisciplinarity, with the practical advantages of being intuitive and requiring limited data.

Qualitative models are formed by considering a set of n variables of interest to a particular abstraction, such that the n variables define the scope of any subsequent analysis and are sufficient to inform the problem under consideration. The interactions between these variables are then described in one of three possible qualitative states: positive (with value +1), negative (with value -1), or null (with value 0). These can then be represented as an n x n matrix $\mathbf{A}[a_{ij}]$ where each column displays the relationships running from that variable to each of the other variables of the system, that is a_{ij} describes the relationship running from the jth to the ith variable.

The principle diagonal terms of the matrix, where $i=j$, describe the self-effects of the variable and will contain the system behaviours of the whole that are not reflected in the particular abstraction. For the purposes of this paper we assume that all self-effects are negative reflecting constraints on the growth of model variables.

The matrix **A**, which in economic terms is a non parametric Jacobian matrix (Hale et al., 1999b) and in ecological terms is a qualitatively specified community matrix, contains the complete qualitative information set describing the abstraction at a point of equilibrium. An analysis of the adjoint of the negative of matrix **A** (adj -**A**), indicates the dynamic behaviour of the system following a sustained change to the parameters of its variables, in ecological terms a press perturbation (Bender et al., 1984, Dambacher et al., 2002). The *j*th column of the adjoint matrix indicates the effect of a perturbation of the *j*th variable upon all of the variables of the system, including itself. Each element of the adjoint matrix is an expression in terms of the a_{ij} elements of the matrix **A** and presents the specific combinations of direct and indirect effects and complementary feedback cycles — that is feedback from subsystems of variables not included on the path from the input to the response variable — that describe the relationship between the particular row and column variables under consideration.

The post perturbation effect of a direct or indirect pathway of interaction will be inverted if there is positive complementary feedback, or removed altogether where such feedback is zero (Levins, 1974: 132). This may give rise to apparently paradoxical observations of a response opposite to the one logically expected, or even of no response, in a variable with strong connections to an input variable.

The effects of a positive perturbation of the variables in the models are read from the signs of the elements of the adjoint matrix in the manner described. These effects may be positive, negative or neutral, however, the results are sometimes ambiguous, and so we determine a degree of confidence that a particular result will hold based on a probabilistic analysis of the adjoint matrix (Dambacher et al., 2003, Hosack et al., 2008).

The examination of the symbolically specified output of the adjoint matrix can be an algebraically onerous process and meaningful simplification of results is often not possible. For this reason, in this paper, we apply a 90% confidence threshold for a particular response prediction. When the results fail to meet this confidence threshold, and then only where the model contains a small enough number of variables to make the algebra tractable[23], we examine the symbolic composition of the adjoint matrix elements in order to understand the relative values of various feedbacks and to specify conditions by which the overall sign of the effect will be unambiguously determined.

3. Models

3.1. Qualitative market adjustment model

We ground the loop analysis for the economic component of our base socio-ecological system model in the neoclassical competitive market adjustment model described by Beckmann and Ryder (1969) (referenced here as B&R). The manner in which loop analysis generally reflects underlying economic relationships could have the appearance of being ad hoc and lacking in a theoretical rigour equivalent to that applied to the modelled ecological relationships (see for example Dambacher et al., 2007, Ortiz and Levins, 2011), and also to that applied in neoclassical economic applications of a similar non parametric algebra (see for example Hale et al., 1999b, Lady, 2000). This paper is novel in its attention to this issue in that we derive from first principles a qualitative model of a competitive market adjustment that is consistent with established economic theory. We then expose the social and ecological relationships that are implicit within the market model by applying a biological metaphor. We apply the concepts of stocks and populations commonly used in community ecology, to the examination of market equilibria. The B&R specification provides a necessary dimension to the market model by considering the gaps between prices and quantity, and the resulting market adjustments rather than considering the demand and supply relationships themselves. Furthermore, because it considers small perturbations around equilibrium rather than

23 There is no hard and fast rule for tractability, which depends both on the number of variables and the complexity of the links between them, however in the case of this paper for the base system of 7 variables some limited symbolic analysis is undertaken, whereas in later examples containing 18 and 22 variables, it is not.

the equilibrium itself, it provides an approach that is consistent with that of the examination of perturbation within loop analysis.

The supply and demand functions are specified as:

$$Q_D = a_0 + aP \ , \ P_S = -\frac{b_0}{b} + \frac{1}{b}Q \qquad (4.1)$$
$$a < 0,\ b > 0,\ a_0 > b_0,\ a < b$$

where Q is quantity, P is the price, Q_D is the demand function and P_S is the inverse supply function. Restrictions on the parameters a and a_0, which are the coefficients of conventional demand functions, and on b and b_0, which are those of conventional supply functions, mean that convergence to a market equilibrium is assured.

Following B&R and defining $p = P - \overline{P}$ and $q = Q - \overline{Q}$, where $\overline{P}$ is equilibrium price and $\overline{Q}$ is equilibrium quantity, we specify a combined Marshallian-Walrasian competitive market adjustment mechanism for eq. (4.1) as:

$$\dot{p} = \lambda(ap - q)$$
$$\dot{q} = \mu(p - \frac{1}{b}q) \qquad (4.2)$$
$$a < 0,\ b > 0,\ a < b$$

where $\dot{p}$ and $\dot{q}$ are derivatives with respect to time of the price and quantity gaps and λ and μ denote speeds of adjustment. The Jacobian matrix **J** for this system is:

$$\mathbf{J} = \begin{bmatrix} \lambda a & -1 \\ \mu & -1/b \end{bmatrix} \qquad (4.3)$$

which can be expressed in a non parametric form, **A** in eq. (4.4), by applying the mathematical operator sgn(.) ∈ {-1, 0, 1}, sgn(x) = x ÷ |x| to each of the elements of **J** in turn.

$$\mathbf{A} = \begin{bmatrix} -1 & -1 \\ 1 & -1 \end{bmatrix} \tag{4.4}$$

This system may be represented as a sign directed graph, or signed digraph, in which the nodes are the variables of the system and the edges are the interactions between the variables with positive direct effects shown as an arrow (→), and negative direct effects shown as a line ending in a circle (⊸). The signed digraph in Figure 4.1 can then be used to represent the neoclassical competitive market adjustment qualitative model as a predator-prey relationship in terms of a biological metaphor.

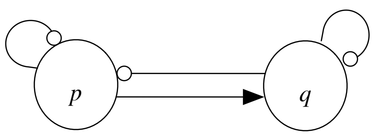

Figure 4.1. Competitive market adjustment mechanism signed digraph.

The variables *p* and *q* represent deviations from their equilibrium (or market clearing) values, and in the context of our qualitative model have equilibrium 'population' levels of zero. In effect then, any deviations from market equilibrium will be reflected in non-zero values of *p* and *q*, which then invigorate the system so that the market adjusts, otherwise their role is passive. The variables *p* and *q* behave in a manner that is consistent with the comparative statics of the competitive market model. This is shown in the signed digraph in Figure 4.2 which operates as a joint Marshallian-Walrasian model in which a perturbation through demand (*D*) affects the equilibrium through price, the Marshallian side, and the perturbation through supply (*S*) affects the equilibrium through quantity, the Walrasian side.

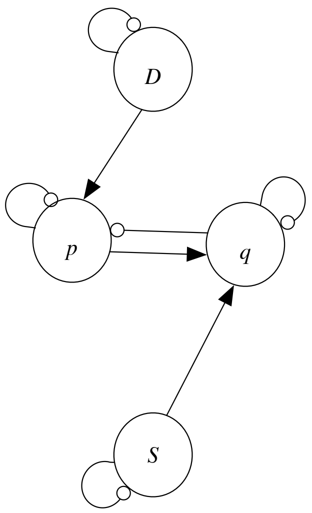

Figure 4.2. Becker and Ryder (1969) market signed digraph.

3.2. Qualitative socio ecological system model

In order to embed the B&R competitive market adjustment process within a regional fishery socio-ecological system, we apply a process of dialectic abstraction and consider where the rest of the world lies in relation to it (Levins, 2007). For simplicity we initially treat the demand for fish (*D*) as exogenous. However, we consider supply (*S*) from the perspective of the object from which it derives, linking the market adjustment process to fishing activity and thereby making it endogenous to the broader socio-ecological system. Adding a fishery to the model in this way links the price signal though a new variable *F*, fishing activity, while maintaining the positivity of the original relationship between *p* and *q* from Figure 4.2. For clarity we subscript all of the other variables with *F* to identify them as referring to the commodity fish. The system now becomes that depicted in Figure 4.3.

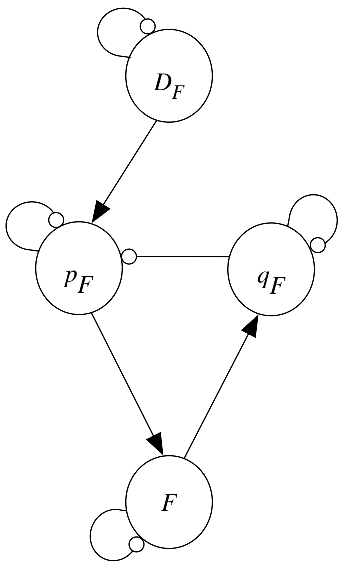

Figure 4.3. A fishery market signed digraph.

Asking further where the market lies in relation to the ecological part of the whole, the relationship of fishing activity (F) to the fish stock (X) is the familiar predator-prey specification (Schaefer, 1991 [1954]). This depiction is then extended to consider the habitat (Y) within which the commercial fish stock (X) sits, and the relationship between them, which we specify as a positive commensal relationship, that is the fish stock benefits from its habitat without impacting upon it. We capture the assumed negative impact of production on the ecosystem with an negative amensal relationship between fishing activity (F) and the habitat (Y) (Martinet and Blanchard, 2009, Wilcox and Donlan, 2007).

We describe a direct relationship between a social demand for habitat health, D_Y, and people's observation of the existence of the habitat[24] (Y) that mirrors the relationship between the demand for fish (D_F) and its supply (F) but without a market adjustment mechanism. Biologically both are predator-prey type relationships.

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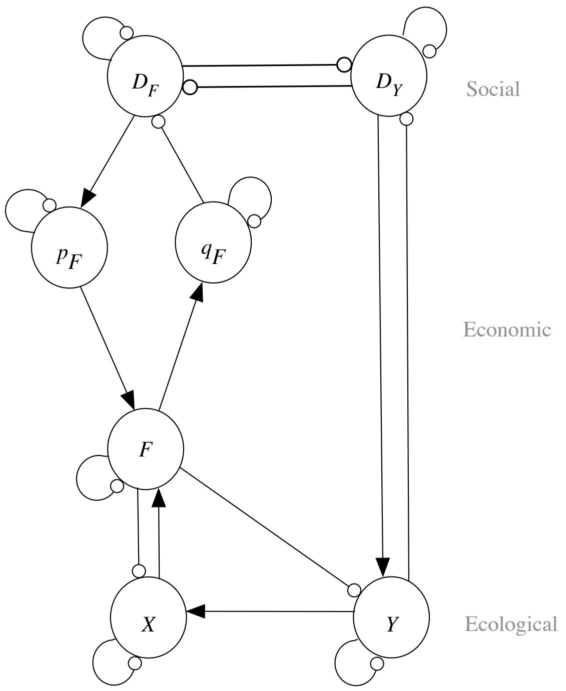
24 While formal measures of ecosystem health are described in the literature, for example (Costanza and Mageau, 1999) (Tett et al., 2013), in this paper we are simply interested in the perception of ecosystem health that people may have, for example through observing the appearance of a environment and the apparent abundance of iconic species within it.

Our abstraction is then completed by considering the relationship between societies preference for consumption, in this case the demand for fish (D_F), and its demand for ecosystem health (D_Y). Since these preferences are contradictory in terms of the economics of a full world, we depict the relationships as competitive in terms of the biological metaphor employed by the model.

The complete abstraction of the regional fishery system is shown as a signed digraph, together with its associated qualitative community matrix, in Figure 4.4. The perspective afforded by the abstraction represented by this base model is sufficient to reveal the distinct ecological, economic and social components of the socio-ecological system and the feedback relationships between them.



Key

D_F ... demand for fish

p_F ... price gap for fish, zero at equilibrium

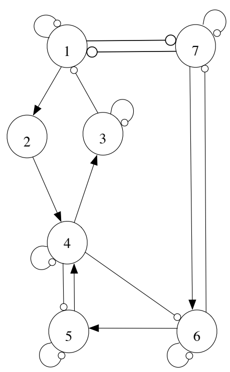
q_F ... quantity gap for fish, zero at equilibrium

F … fishery catch and supply of fish

X ... fish stock

Y ... habitat

D_Y ... demand for habitat health



$$A = \begin{bmatrix} -1 & 0 & 0 & 0 & 0 & 0 & -1 \\ 1 & -1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & -1 & -1 & 1 & 0 \\ 0 & 0 & 0 & -1 & 0 & -1 & 1 \\ -1 & 0 & 0 & 0 & 0 & -1 & -1 \end{bmatrix}$$

Figure 4.4. Base socio-ecological system signed digraph shown with qualitative community matrix **A** and index of signed digraph variable location in the matrix.

Following an exploration of the feedback behaviour of the base model, we consider an alternative ecological scenario representing the marine ecology of Chesapeake Bay (Carey et al., 2013) and, finally, an alternative economic scenario, based on the same ecology, in which we introduce aquaculture as a substitute source of marine food production. For each scenario considered, we describe the predicted response of the exploited fish stock (X) and the health of its habitat (Y) due to changes in system parameters. Such parameter changes, which are exogenous to the model, may result from the implementation of environmental policy or other management action. The conditionality of the responses is then examined, and their importance to policy considered.

4. Results

4.1. Feedback behaviour of the base socio-ecological system model

Positive shifts in demand for both the consumer good fish (D_F) or for habitat health (D_Y) shown in Figures 4.5a and 4.5b respectively, are unambiguous in their effects upon the fish stock (X) and the habitat (Y). Increased demand for fish has a negative effect on both of the environmental variables while an increase in demand for habitat health has a positive effect on both. This reflects the fundamental contradiction described earlier, that is people following their materialist desire to consume, the act of which damages the environment, while valuing environmental health, that is materialism versus environmentalism.

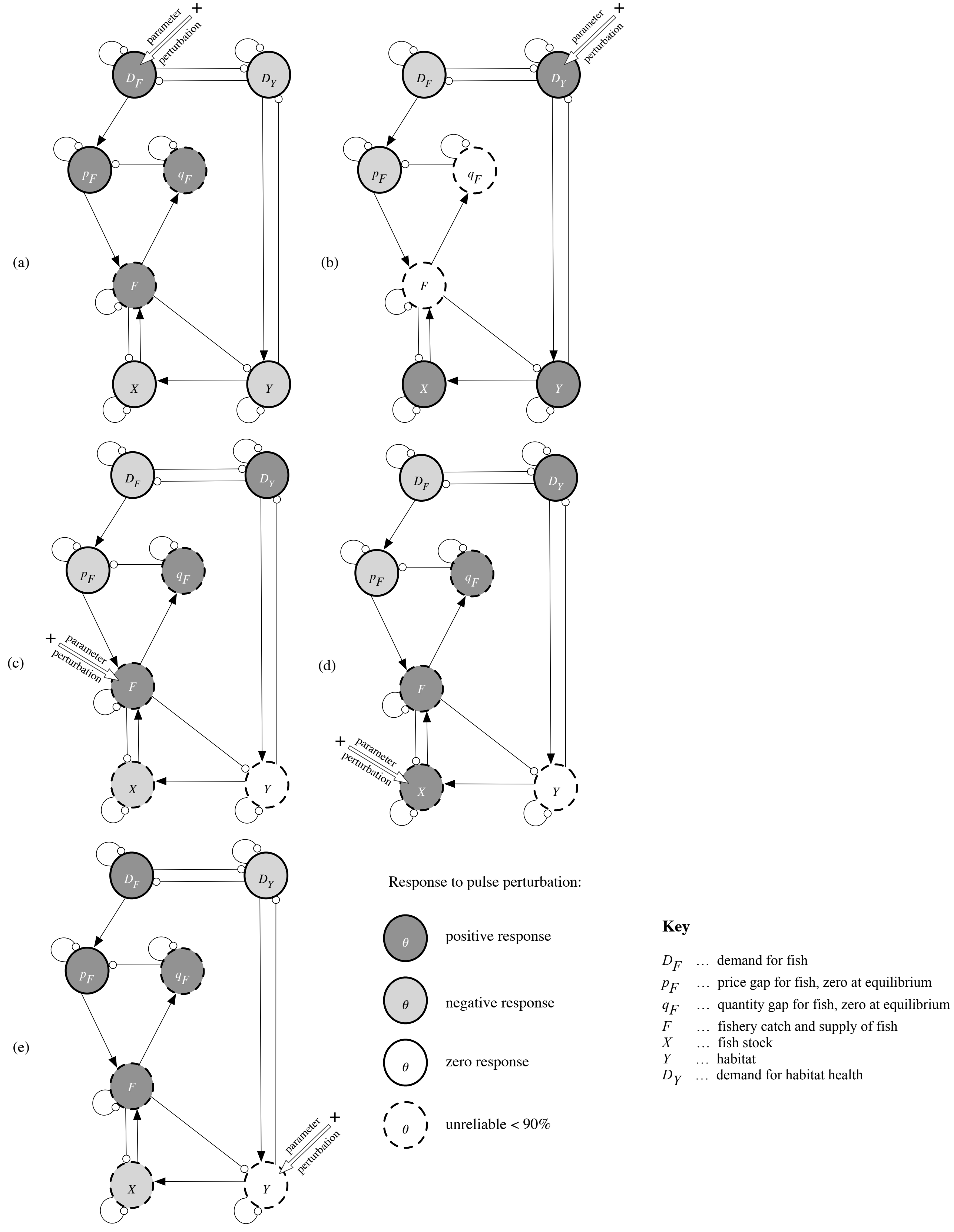


Figure 4.5. Base socio-ecological system signed digraphs showing response of system variables to perturbations to (a) D_F, (b) D_Y, (c) F, (d) X, (e) Y.

A positive perturbation of either fishing activity (*F*), the target fish stock (*X*), or the habitat (*Y*) will, however, all have ambiguous impacts on both environmental variables *X* and *Y* (Figures 4.5c, 4.5d and 4.5e). An examination of the symbolic output of the adjoint matrix for this system reveals that the feedback cycles associated with the two demand variables D_F and D_Y are central to determining the direction of these outcomes. The importance of these feedback effects in achieving positive environmental outcomes is shown in Table 4.1 which describes the conditions under which there will be positive responses in *X* and *Y* to separate perturbations of *F*, *X* and *Y*, and indicates whether a particular condition described is sufficient or not. For results where the strong feedbacks are strictly greater than the weak feedbacks, it is possible to state sufficient conditions for the indicated outcome. However, in cases where it is not possible to state sufficient conditions, the most that can be provided is an indication that the strength of some feedbacks and the weakness of others will assist in achieving the indicated result[25].

A positive perturbation to	results in positive outcome for	if $a_{71}\,a_{17}$	and/(,) $a_{77}\,a_{11}$	(and) $a_{..}\,a_{..}$	Sufficient conditions
F	*Y*	strong	weak	-	yes
F	*X*	strong	weak	weak ($a_{76}\,a_{67}$)	yes
Y	*Y*	weak	strong	-	yes
Y	*X*	weak	strong	weak ($a_{76}\,a_{17}$)	no
X	*Y*	strong	weak	-	yes
X	*X*	weak	strong	strong ($a_{76}\,a_{67}$)	no

Table 4.1. Conditions for positive press perturbations to fishing activity (F), fish stock (X), or habitat (Y) to result in positive outcomes for habitat (Y) and fish stock (X) in the base socio-ecological system model.

25 For the purposes of this paper our focus will be on those results for which sufficient conditions can be established.

With reference to the subscript index in Figure 4.4, the feedback effects described in Table 4.1 are interpreted as follows: a_{71} describes the negative effect from D_F to D_Y, that is a preference for consumption of fish (materialism) at the expense of valuing habitat health (environmentalism), and a_{17}, the effect from Y to X, is the reverse of this, so that the cross effect $a_{17}\,a_{71}$ represents the important social tradeoff between environmentalism and materialism. Similarly a_{11} is the self limiting effect of D_F and a_{77} is the self limiting effect of D_Y, representing the strength of social response to marginal changes in fish availability and habitat health respectively. With respect to the fish stock (X), these outcomes are further assisted by the effects a_{76}, that is the effect from Y to D_Y, or the responsiveness of demand for habitat health to changed habitat, and a_{67}, that is the effect from D_Y to Y, or the realisation of demand for habitat health.

The base model describes a commensal relationship between the commercially exploited fish stock (X) and the habitat (Y). It is possible, however, that an exploited resource may provide feedback to the habitat in either a predator-prey or a mutualist relationship, for example reef fish are seen to both enhance coral growth (Thompson, 2004) and to feed upon coral (Bruckner et al., 2000). Describing these alternative relationships and conducting the same analysis as for the base model, the results revealed that additional ecological complexity increases the ambiguity of responses, and will potentially present managers with unexpected policy outcomes in both the socio-economic and ecological subsystems that may then be construed as paradoxical.

4.2. Socio-ecological system models with Chesapeake Bay foodweb ecology

Carey et al (2013) describe an abstraction of the ecosystem of Chesapeake Bay reflecting its key trophic relationships, however, they subsume the socio-economic aspects of the system into a single management node. They use this model to consider the performance of policy settings that increase the abundance of the target commercial marine species and improve ecosystem health. In this paper we take this abstraction of the Chesapeake Bay system[26] and integrate it with the economic and social components of the base socio-ecological system (Figure 4.6).

We assume that a significant existence value for iconic species of piscivorous birds (*PB*), for example pelicans and ospreys, is held by society and that their observable abundance is taken as an indicator of habitat health by society. In our modified abstraction, we further assume an economic sector comprising a blue-crab (*BC*) fishery that has a detrimental impact on the piscivorous bird populations as a result of derelict fishing gear in the form of crab pots (Bilkovic et al., 2014). This detrimental effect could be mitigated directly by changing fishing technology, which would have the effect of weakening the link from fishing activity (*F*) to blue crab stock (*BC*). Alternatively increased social pressure, or environmentalism, which is reflected in the form of the positive link from the demand for habitat (D_Y) to the iconic species, *PB*, might lead to restorative programs. The signed digraph (Figure 4.6) shows the impact of a restorative policy to increase the population of blue crab, for example a stock enhancement program (Zmora et al., 2005), which is a positive perturbation of the blue crab stock (*BC*) producing a positive outcome for the resource itself and a conditionally neutral outcome for the iconic species (*PB*) that is taken as the indicator of habitat health in our model.

26 The variables for the ecosystem are described in Figure 4.6 and remain the same for Figure 4.7.

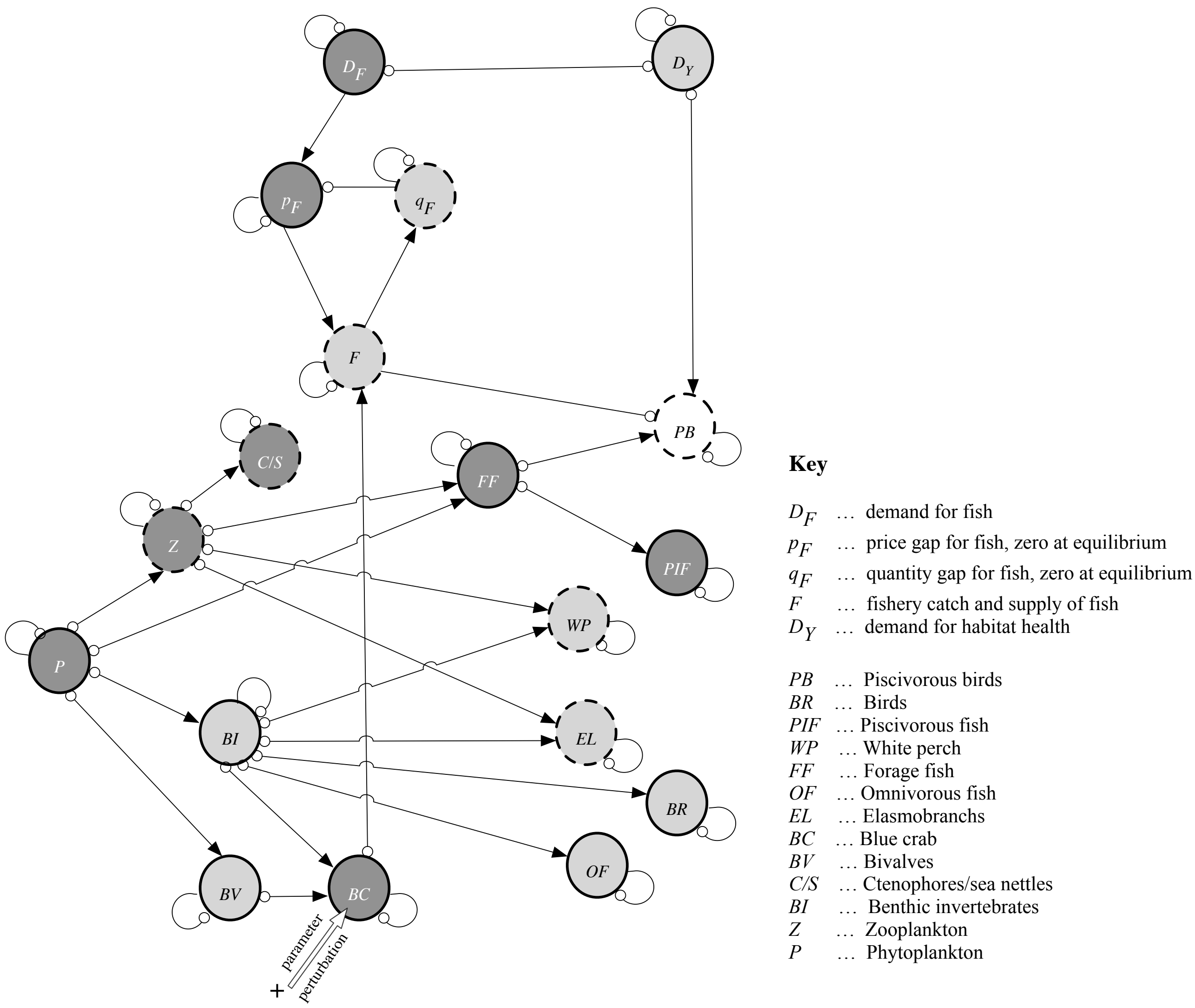
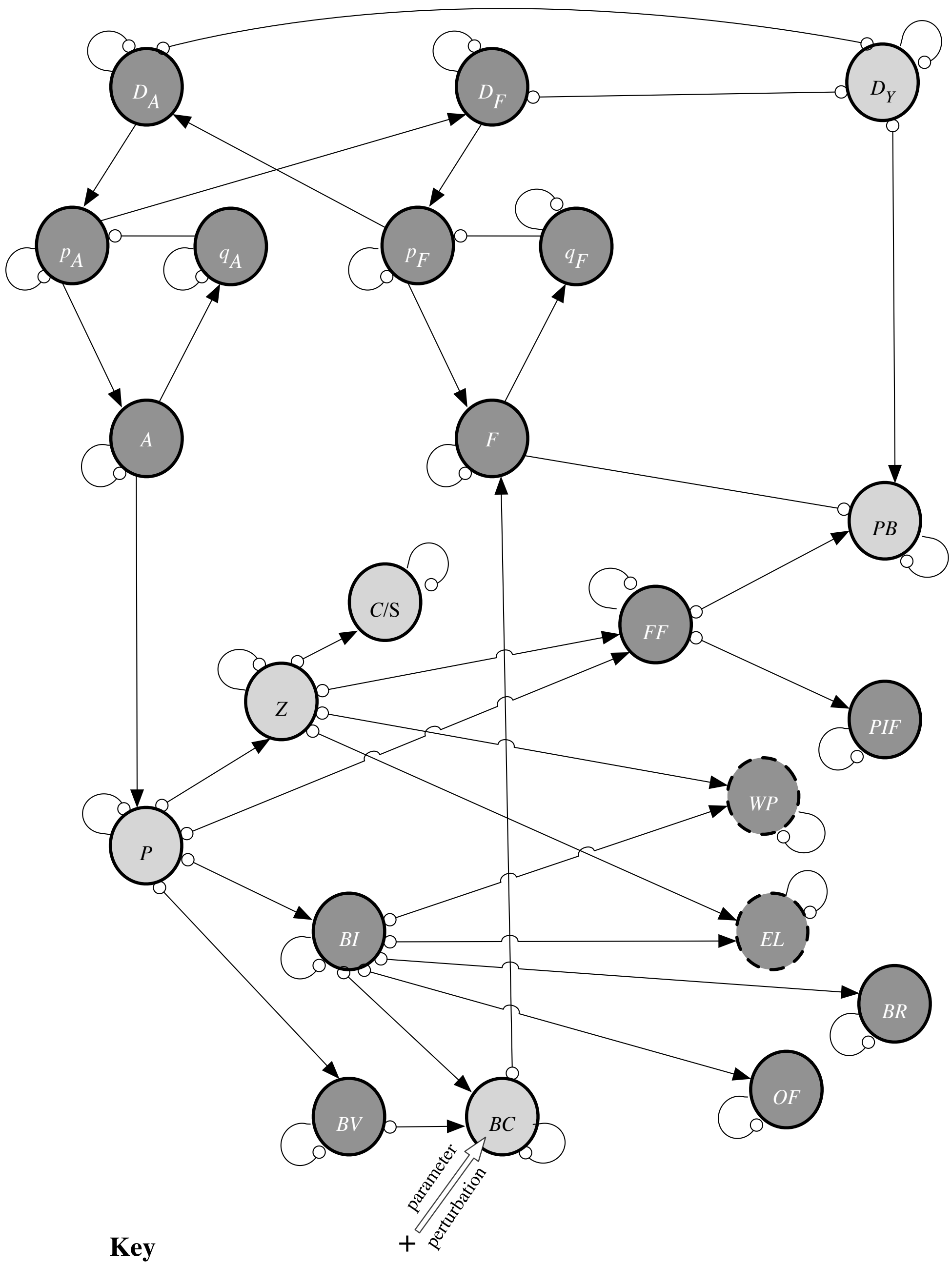


Figure 4.6. Socio-ecological system with Chesapeake Bay ecology showing the response of system variables to a restorative policy to increase the population of blue crab.

Our modified Chesapeake model in Figure 4.6 focuses one economic activity, namely the production of commercially wild-caught blue crab. We then extend the abstraction in Figure 4.7 by introducing a second economic activity, aquaculture (*A*), which we assume extends the negative environmental impacts of production by introducing nutrients into the ecological system and so stimulating the production of phytoplankton (*P*). This is reflected in the signed digraph (Figure 4.7) by the commensal relationship between them *A* and *P*. Aquaculture produces a substitute good for wild-caught crab and we introduce the market dynamics to reflect this, so that an increase in the price of either good invigorates the system and triggers the market adjustment mechanism in the other. The constraints imposed by full-world economics mean that we also extend the competitive relationship between the demand for habitat health (D_Y) and fish (D_F) to include demand for the aquacultural good (D_A). The signed digraph again shows the impact of a positive perturbation of the blue crab stock (*BC*), however, the result in this case is counterintuitively negative, for the stock itself as well as for the habitat health indicator, the iconic species.



Key

D_F … demand for fish
p_F … price gap for fish, zero at equilibrium
q_F … quantity gap for fish, zero at equilibrium
F … fishery catch and supply of fish
D_Y … demand for habitat health

D_A … demand for aquacultural good
p_A … price gap for aquacultural good, zero at equilibrium
q_A … quantity gap for aquacultural good, zero at equilibrium
A … Aquaculture and supply of aquacultural good

PB … Piscivorous birds
BR … Birds
PIF … Piscivorous fish
WP … White perch
FF … Forage fish
OF … Omnivorous fish
EL … Elasmobranchs
BC … Blue crab
BV … Bivalves
C/S … Ctenophores/sea nettles
BI … Benthic invertebrates
Z … Zooplankton
P … Phytoplankton

Figure 4.7. Socio-ecological system with aquaculture and Chesapeake Bay ecology showing the response of system variables to a restorative policy to increase the population of blue crab.

5. Discussion

Our results have useful implications for environmental management practices in the marine context, notably in understanding the impacts and efficacy of environmental policies aimed at environmental restoration or impact reduction. Policy addressing the human social and economic systems may target reduced impacts on environmental and habitat health through, for example, a reduction of fishing pressure (Collie et al., 2013), the cleanup of derelict fishing gear (Cho, 2011), influencing demand for particular species or fishing practices through eco-labelling (Tlusty, 2012), and social programs to raise environmental awareness and environmentalism (Sharpless and Evans, 2013). An increasingly important form of policy intervention in fisheries, however, is that of stock and habitat restoration (Moore and Moore, 2013), which may be achieved through direct biological intervention including the restocking of target species (Greenl et al., 2013, Ortiz and Levins, 2011), the restoration of habitats (Cunha et al., 2012, Skov et al., 2012), and through indirect biological interventions, such as the efforts to reduce the impact on sea birds by elimination of non native predator populations from breeding sites (Donlan and Wilcox, 2008).

The perturbations analysed in this paper introduce sustained changes to the parameters of one or more of the variables within any particular abstraction. The effects of policy driven perturbations in alternatively specified abstractions of natural and human subsystems have highlighted the potential for a systemic ambiguity that reflects the impact on policy outcomes of contradictory social pressures of environmentalism and materialism. Our results further demonstrate the importance of both the relationship between an exploited resource and its supporting habitat, and between human and natural subsystems. The feedbacks and effects in the models explored run between the biological, economic and social subsystems and highlight the need for a broad analytical vision that allows for interdisciplinary consilience within a single structured framework and method.

5.1. Ambiguity and tradeoff

The models described in this paper show the demand for fish with environmental loss as an unanticipated consequence (Merton, 1936). In general terms this forces a tradeoff between the demand for fish, a commodity, and the demand for environmental health, as captured through the existence value of habitat in situ. This tradeoff reflects the contradictory social pressures of environmentalism and materialism, by which people follow their desire to consume while simultaneously recognising that their consumption damages the health of the ecosystem they value. This fundamental tension between materialism and environmentalism, that becomes of increasing consequence in the context of a natural-capital constrained full world, introduces ambiguity in determining the efficacy of policy aimed at improving environmental outcomes.

The tradeoff between materialism and environmentalism is reflected in our base model in the competitive relationship between the demand for the consumer good, fish, and the demand for the environmental good, habitat health. Of particular importance to this tradeoff is the size of the cross-effect between these two variables — which determines the strength or the weakness of a particular response — and their respective self-effects — which determine the persistence of the response — such that the weaker the self-effect the greater the persistence of the cross-effect. In other words the persistence of the effect of any particular policy on the social tradeoff between environmentalism and materialism will be determined by the strength of the social response to marginal changes in the availability of consumptive and non-consumptive goods. Specifically, we find that the likelihood of achieving positive environmental outcomes is greater in systems where the effect of strong environmental values is reinforced through the active suppression of consumption. This suppression will be at its strongest when combined with a weak social response to marginal improvements in habitat health and suggests that the demand for environmental improvement will not be easily reduced by the observation of actual environmental improvements. Similarly, in a system characterised by weak materialism, the active suppression of environmentally-motivated demand in service of a desire to consume will be low and, when combined with a weak social response to marginal reductions in the availability of consumption goods, will ensure that the weak suppression of environmental demand is not countered as consumption falls. Importantly, however, the role of the self-effects in our model is a two edged sword. For example, in the face of declining environmental health in the system, a weakness in the social response to marginal improvements in environmental health will ensure that demand for environmental management is slow to respond in correction.

This means, for example, that a positive outcome for both fish stock and habitat in the face of increased fishing pressure requires a strong cross-effect/tradeoff between consumption and environmental preferences and weakness in their associated self-effects. In other words, the negative impact of increased fishing pressure on habitat will cause a strong reaction in terms of suppressing consumption preferences and increasing demand for the environmental good, a reaction that will persist through a weak self-reinforcing effect, preventing society's appetite for environmental improvement being satisfied by small gains.

Since a policy involving direct rebuilding of the stock will initially increase fishing activity through a reduction in costs, a strong cross-effect/tradeoff and weak self-effect will behave in the same manner with respect to habitat health as described for the case of increased fishing pressure. This suggests that the overall effect of resource exploitation upon habitat will necessarily remain negative, even where the resource is rebuilt, unless response to the consumer demand for the resource is offset through strong and persistent environmentalist values.

In contrast, we find the opposite effect for environmental restoration through direct habitat repair or remediation. Positive outcomes for habitat and stock will only be achieved, after all feedback effects are accounted for, if the cross-effect/tradeoff between the demand for fish and the demand for habitat health is weak, and where the self-effect for one or both is strong, thus ensuring that that any cross-effect does not persist. This is consistent with the view that an improvement in habitat has the potential to stimulate consumption and fishing at the ultimate expense of the improved habitat. While the effect of a stock improvement upon itself may be positive under similar conditions to these, in this case feedback complexity means that we cannot be definitive in this assertion.

Our analysis also highlighted a clear difference between policies aimed at increasing environmentalism and those which act to directly remediate habitat. Our results showed that a direct positive perturbation of the demand for habitat health leads to improvements in both components of the ecosystem, that is the stock and the habitat. On the other hand, a positive perturbation of the habitat potentially leads to a neutral impact on habitat itself and a negative impact on the resource. The reason for this is that increased environmentalism, has the effect of directly dampening the demand for fish, that is materialism. While this effect may also be dampened when habitat is remediated directly, the precise result has been shown to be conditional on the relative strengths of the social tradeoff between environmentalism and materialism and the social response to marginal changes in fish availability and habitat health. In this way feedbacks from the social system affect ecological outcomes and the importance of the social tradeoffs is made clear.

5.2. Alternative specification of subsystem relationships

The relationship between the exploited resource and its supporting habitat is another important consideration in determining the effect that a policy of resource or habitat restoration will have on all the subsystems. For example, the effect of introducing the additional ecological detail in the Chesapeake Bay scenario is to make the improvement of the resource, following restoration, unconditional, so that the demand for consumption increases and the demand for ecological restoration falls. The effect upon the iconic species however cannot be determined from the model because the impact of restoration on fishing is unclear. These ecological results are the same as those seen by Carey et al.(2013), with the single exception that the basal resource is expected to increase so increasing the risk of eutrophication.

From this it is clear that feedback cycles arising from alternative understandings/abstractions of ecological relationships have an important influence on the predicted outcome of restorative policy. Similarly, alternative relationships between the human and natural subsystems present alternative feedback effects. The effect of introducing the additional economic detail of aquaculture to the Chesapeake Bay model is to change the predicted ecological outcomes from those observed in the base model, such that the effect of habitat restoration on the fish stock is ultimately negative because it unambiguously stimulates fishing activity which has a further effect of reducing the iconic sea bird populations through the negative derelict gear externality. Furthermore, social environmental values are unambiguously overwhelmed by consumer values so that the demand for fish increases while the demand for habitat health falls.

5.3. Interdisciplinary consilience

Our results indicate that the introduction of additional economic detail to the system may affect the way in which environmental management impacts the foodweb such that its results are sometimes reversed, perhaps becoming paradoxical to a biologist who has treated the socio-economic components as beyond the boundaries of the system. This suggests that the understanding of policy outcomes depends on the ability of policy makers to observe feedback cycles across all relevant subsystems, with the implication of a requirement for both a broad vision and interdisciplinarity.

The areas that we model from a specific disciplinary perspective, even when they include subsystems relating to other disciplines at a low level of detail, may provide predicted outcomes such that actual outcomes appear paradoxical. However, when the larger system is examined at a greater level of detail it may be more correctly understood that these results are not paradoxical but in fact the result of feedback cycles that had not previously been considered. To avoid encountering such apparent paradox, and in order to fully understand the contradiction within the system, the management of the whole, or any subsystem part, of an socio-ecological systems must consider integrated responses. This means that a range of models must be considered in a process of dialectic abstraction through which we understand that we are only considering those aspects of the whole relevant to a particular problem under consideration. Loop analysis works together with dialectic abstraction in delivering an interdisciplinary framework to management practice and avoiding the paradoxical outcomes that may appear when those parts of the system emphasised by separate disciplines are treated as black boxes.

5.4. Methodological limitations

The simplicity of using qualitative models within a process of dialectic abstraction makes it suitable for interdisciplinary work and for building models where data is scarce. However there are some methodological limitations. For example, for the purpose of this paper we assumed that all variables have negative self-effects, which has the advantage of aiding the stability of the model so making it amenable to analysis. However, this assumption must be considered carefully during model design. While self-effects will more often be negative, denoting a limit on the ability of a variable to grow, due for example to some resource constraint on a population, or an income constraint on demand, they may also be neutral or positive. A neutral self-effect indicates that all of the processes affecting a particular variable are present as relationships with other model variables, that is the system is fully specified with respect to that variable. Positive self-effects arise where there are reinforcing syndromes in a system. These tend to arise with certain economic relationships (Ortiz and Levins, 2011), for example with the tendency for production to enter a treadmill of accumulation (Gould et al., 2008), or the ratchet effect which reflects the ease with which a fishery may increase capital investment compared to the difficulty it faces in reducing it (Caddy and Seijo, 2005). These neutral and positive self-effects make it less likely that a system will in fact be stable which is a precondition for the analysis of press perturbation response.

6. Conclusion

When considered from an orthodox reductionist viewpoint, be it biological or economic, loop analysis and dialectic abstraction may appear to lack rigour. In the approach adopted in this paper, we have anticipated such criticism and, in the application of a process of dialectic abstraction to an orthodox economic market relationship, have applied mathematical rigour in developing a qualitative model and demonstrating that it displays equivalent behaviours to the original. In order to then understand the feedback system within a wider social and ecological context we have applied commensurate rigour, albeit dialectical, and remained true to the instantaneous direct effects of the system. The qualitative model has been demonstrated to capture the indirect effects of the feedback loops that are the source of perceived paradox. This is not to diminish the value of the wealth of models described in the reductionist manner, both economic and biological, that are available to resource managers. It merely positions such models as particular constructed abstractions, which a process of abstraction shows as belonging to a set of abstractions that together improve our understanding of the complex adaptive systems we are called upon to manage.

Chapter 5

Revealing paradox as resolvable contradiction in a socio-ecological system.

1. Introduction

The prevalent policy basis for examining the human-environmental nexus expresses the worth of an ecosystem in terms of the value of the services it can sustainably deliver to the social and economic systems (Millennium Ecosystem Assessment, 2005). Thus the lines between ecology, economics and sociology have become blurred around a conceptualisation of sustainability, which sets aside the outright rejection of anthropocentric approaches to the environment associated with deep ecology (Naess, 1973), to associate value of ecosystems with human well-being, expressed in terms of neoclassical welfare economics. Furthermore, the application of neoliberal economic values to ecological policy carries the implicit assumption that economic growth is positively linked to both ecological and human well-being, or at least that ecological well-being is subordinate to economic growth (Schneider et al., 2010).

The possibility that there are limits to the growth, of both the social and economic components of the human system, imposed by the productive capacity of nature has been debated since Malthus (1998 [1798]) first warned of impending calamity. Particular interest in the issue of limits was reignited following the publication of The Silent Spring (Carson, 1962) and the emergence of environmentalism as a social force in opposing neoliberal market outcomes. There followed a range of different perspectives on these limits, including social limits (Hirsch, 1977), human population limits (Ehrlich, 1968), physical resource and economic limits (Meadows, 1972), and the systemic limits imposed by entropy (Georgescu-Roegen, 1975). Responses to what is essentially a trinity of social, economic and environmental limits have included attempts to shift economic thought to a sustainable paradigm as system boundaries are encountered (Daly, 2005); warnings that the deepening rift between economic, social and natural relations threatens a crisis for the whole system

(Foster et al., 2010); and calls for the active pursuit of degrowth (Georgescu-Roegen, 2010 [1989], Martínez-Alier et al., 2010).

Nevertheless, the neoclassical device of contriving ongoing economic growth in non-material terms — for example, by commodifying environmental existence as monetary value — as opposed to directly in material terms — for example, in the production of physical commodities — perpetuates the belief that growth can be maintained within a finite resource base. Indeed, in a convenient ecological construct analogous to the trickle-down economics that have failed to resolve poverty (Giddings et al., 2002), the Environmental Kuznets Curve goes so far as to suggest that growth will in fact lead to improved ecological outcomes once a some threshold in per capita income is attained (Kijima et al., 2010). The explanation is proffered that social and economic preferences will shift from material consumption to environmental considerations with income growth (Roca, 2003).

Some writers have anticipated that any degradation of ecosystems, and consequential loss of ecosystem services, would in turn be associated with reduced social well-being (Daily, 1997, Gallopin et al., 1989). Evidence indicates, however, that improved levels of social well-being and increased per capita incomes are not necessarily associated with environmental improvements (Grafton and Knowles, 2004), and that improvements in human well-being can occur alongside declines in ecosystem services (Millennium Ecosystem Assessment, 2005). One reason proposed for this so called environmentalist's paradox, is the nuanced argument that human well-being is impacted by those ecosystem services that directly affect economic production, or provisioning services, rather than by non-consumptive regulating and cultural services (Raudsepp-Hearne et al., 2010).

In general terms, a perception of paradox may arise when, for any particular problem, too narrow a perspective is taken of its containing system, such that the perspective prevents us from seeing all of the relevant processes and feedbacks within the system. Such a perspective may lead us to misunderstand, or to be unaware of, the contradictions and tradeoffs within the system that arise when it is perturbed by either unanticipated shock or deliberate policy.

In this paper, we seek the reason for such paradox in the neoclassical macroeconomic pre-analytic vision, in which the relationship between the economic, the social and the ecological occurs within a closed economic system, thereby committing any conflicts between them to resolution through the market. This is a case of misplaced concreteness, that is one in which an abstraction is confused with the whole from which it is drawn (Whitehead, 1948 [1925]), where the economic system is perceived as the entire system. This narrow perspective prevents us from observing all of the feedbacks and interactions within the system so that any counterintuitive results then appear to be paradoxical. We seek to redress this by considering the trinity of limits to growth within the context of a socio-ecological system, which is a broad complex adaptive system whole comprising coupled economic and social subsystems constrained within the biosphere.

We explore the potential for contradiction within a socio-ecological system using the method of dialectical abstraction supported by qualitative loop analysis. We first describe a socio-ecological system, comprising intersecting social, economic and ecological subsystems, their capital stocks and the flows of services between them. Next, we present this abstraction as a simple qualitative model in which all subsystem capital stocks are depicted as variables and the key economic and ecological flows as linking processes between these variables. Accounting for its evolutionary or adaptive nature we describe the system in terms of a biological metaphor, rather than the mechanical metaphor associated with neoclassical economics.

The nature of system feedbacks and interactions in our socio-ecological system is thoroughly explored using the standard algebra of loop analysis. We then develop a parameterised version of the socio-ecological system qualitative model with known stability properties and use simulation to examine the dynamic response of subsystem capitals to shock, or pulse, perturbations to the various subsystems of the socio-ecological system. Our parameterised base model is then used to demonstrate how counterintuitive outcomes to parameter change, or press perturbation, may be experienced as paradox.We show how policies for improving the health of natural resources may instead lead to their decline, and how human population growth manifests as pressure on the system differently in alternate abstractions. Finally, we extend the model to consider the effects of the direct social pressure from environmentalism expressed as a dampening of the predator-prey relationship between the economic and ecological subsystems. The potential for ambiguity in the behaviour of this extended system is tested in alternatively specified socio-ecological systems.

Our approach allows for consideration of the biophysical and the human dimensions of such systems in a way that the full scope of effects, feedback and system dynamics are revealed, so that what was apparently paradoxical is revealed as contradiction. This avoids an overemphasis on any individual system parts in a manner that obscures the reasons for contradiction, with the result that contradiction becomes penetrable. The question of paradox is shown to arise from the tradeoff dynamics between social considerations of a material-commodity nature and social considerations of an aesthetic-environmental nature — that is between materialism (Sirgy et al., 2013) and environmentalism (Spash, 2009) — which is understood as contradiction within a whole-of-system's context. We further demonstrate how environmental policy aimed at mitigating against the heavy footprint of the human subsystems upon the ecological can lead to similarly contradictory outcomes. We suggest that the contradiction resolves in a manner that is consistent with the idea of economic degrowth. The method of dialectic abstraction working in concert with loop analysis, and with the lens of a biological metaphor, is shown to enhance our understanding of the behaviour of socio-ecological systems and hence our ability to understand the outcomes for economic, social and ecological subsystems, in response to perturbations of both system structure and function.

2. An abstraction

2.1. The preanalytic vision of economic orthodoxy

The pre-analytic vision (Schumpeter, 1986 [1954]), of economic orthodoxy does not explicitly identify separate ecological or social subsystems. Rather, in describing the economic system, the neoclassical approach employs a mechanical metaphor and treats the economic system as a self-contained circular flow of production and consumption. The social system, effectively subsumed within the economic system, is represented by households and government who, between them, provide the financial capital and labour resources for the productive processes. These entities also provide the natural resources that are used in production, which are often represented within the economic system simply as land, or are missing from the neo classical production function entirely, the assumption having been made, in a pre-analytic vision, that natural resources can be fully substituted by other factors (Daly, 1997), and where limits imposed by mass balance have not yet been reached (Solow, 1997). The neoclassical approach employs the institution of the market, the processes of which ideally require that all productive inputs are explicitly owned, either privately or publicly, including natural resources, so that everything is priced and traded in a process that has been described as commodity fetishism (Georgescu-Roegen, 1971, Marx, 1990 [1867]). This commodification of resources simplifies nature as an object of consumer utility and in so doing removes the merit that is intrinsic to nature itself, instituting market value across the biosphere (Foster, 2002). The effect is to mask the true relationships that underlie the market and its commodities, giving rise to a contradiction that is potentially destabilising for all of the interrelated systems: social, economic and ecological.

In pre-industrial or early industrial times, when ecological resources appeared to be the effectively limitless bounty of nature, it was possible to either ignore or misperceive the actuality of the whole of the system. However, with accelerating industrial growth and market globalisation, the limits of the system are increasingly being reached, so that it has now become clear that the economic system is both contained within, and constrained by, a finite ecological system (Costanza, 2000, Daly, 2005). The conception of the economy simply as a circular flow of exchange is inadequate (Daly, 1985), not least because it takes no account of the throughput of resources and energy in an economic system and the inescapable physical constraints that this imposes (Georgescu-Roegen, 1975).

The strictly closed nature of this orthodox view of the economic system is compromised by the reality that impacts of production, which affect the social and ecological systems, occur outside of the economic system in a manner that the market does not account for. Feedbacks between systems, however, mean that ultimately the effects from these externalities will be felt within the economic system itself. For example, the impact on the social, environmental and economic systems arising from anthropogenic carbon emissions (IPCC, 2007b), or the loss of biodiversity in the oceans and its detrimental consequences on essential ecosystem services (Worm et al., 2006). The orthodox economic solution to the problems raised by externalities is to internalise them to the economic system (Coase, 1960), for example the advocacy for emission trading as a mean of addressing climate change (Sandor et al., 2002, Stern, 2007), or the creation of property rights over marine resources (Arnason, 2012, Grafton et al., 2000). The neoclassical market model has become pervasive in environmental and natural resource policy, and whether we consider project prioritisation by means of cost benefit analysis (Pearce et al., 2006), the redressing of anthropogenic ecological damage (Nordhaus, 2008), or the active management of renewable natural resources (Arnason, 2000), as examples, the framing of ecological problems is informed by the economics of the market. However, internalising the economic-environmental interface to the economic system in this manner reasserts the closed nature of the envisaged economic system and maintains the circularity of its processes (Raymond et al., 2013).

In contrast to orthodox neoclassical economics, the heterodoxy of ecological economics explicitly recognises the interconnectedness of the economic, social and environmental systems (Costanza, 2000). Each of these systems is characterised by specific elements and processes that define its own structure and function and the manner in which it interrelates to the other systems across multiple spatial and time dimensions. If problems that cross the boundaries of all of these systems are to be addressed effectively, they cannot be considered separately but must be considered together as a single system. This is not to imply that the resulting subsystems cannot then be independently analysed, however it means that any such analysis must be understood as clearly defined abstractions of the actual whole system.

Abstractions are considered within boundaries defined by space and time and a particular perspective or aspect of a system (Ollman, 2003). The process of abstraction involves starting from a real concrete whole, slicing it into ever thinner abstractions to reveal its relations and then reforming the whole in which a system's relations lie revealed (Marx, 1973 [1939]). Here the whole is both the start and the end point, although the end whole is itself an abstraction, whereas in the reductionist thinking that informs economic orthodoxy, the whole is simply the result. The relationship between part and whole informing such thinking is dialectical and, by reference to the systemic whole, explains as contradiction the apparent paradoxes that arise within neoclassical economics, when the ecological and social systems are both subsumed within the economic system be means of property and market institutions.

2.2. A socio-ecological meta system

We propose a meta system comprising intersecting social, economic and ecological subsystems, as shown in Figure 5.1, in which key elements and processes of both the economic and social subsystems have been expressly specified. The resulting abstraction of the complex socio-ecological system comprises stocks and flows. The stocks are described in terms of capitals, and in our analysis households play the role of a biological proxy for the stock of human population and appear both in their neoclassical guise as agents within the economic subsystem, and also as an analytical unit within the social subsystem.

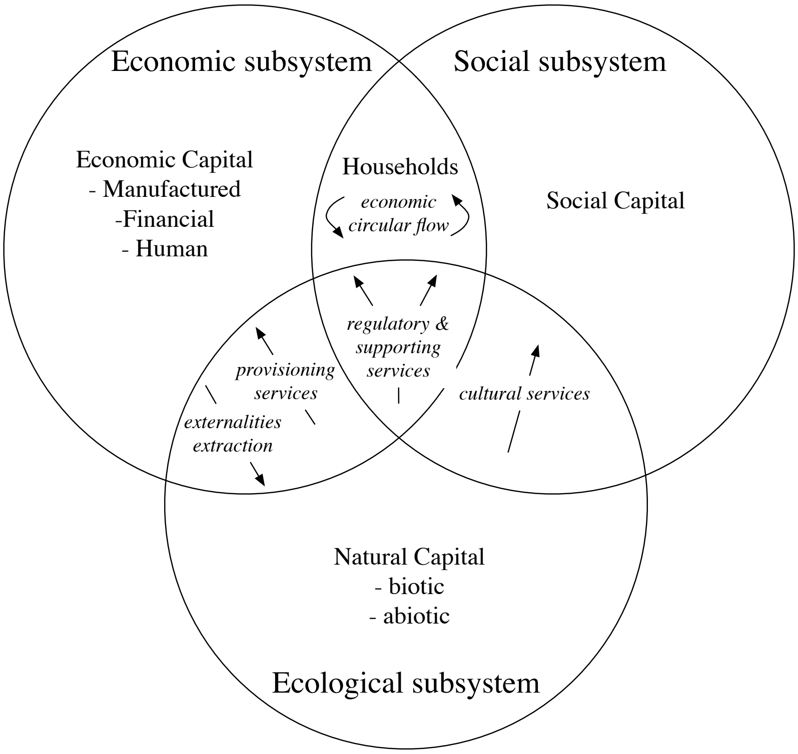


Figure 5.1. A socio-ecological meta system.

The stock concepts used in the formulation of coupled human and ecological systems are often expressed in terms of capital assets specified to include ecological or natural capital, social capital, human capital, and manufactured or built capital (Costanza et al., 2013, Ekins, 2002) to which may be added financial capital (Chesson, 2013). While human capital has been variously considered as a function of social capital (Sequeira and Ferreira-Lopes, 2011), as a source of economic growth (Whiteley, 2000) and an integral part of labour provision by households to the productive processes, we include it here in the economic sub system. For simplicity we aggregate manufactured, financial and human capital as economic capital.

The flows or process interactions between the subsystems comprise ecosystem services, economic externalities and economic flows between households and economic enterprises. The benefits that humans obtain, both directly and indirectly, from the environment are simply described as ecosystems services (Costanza et al., 1998). Four categories of ecosystem services are defined by the Millennium Ecosystem Assessment (2005), namely provisioning services, regulating services, supporting services and cultural services. The provisioning services involve extraction of resources from the ecosystem for purposes of production and consumption, and are regarded here as servicing the economic subsystem, whether the extraction is directly undertaken by households (for example recreational or artisenal fishing) or through the economic enterprises (for example, commercial fishing). The remaining categories of ecosystem services are non-extractive. Cultural services are non-material environmental benefits, for example the existence value placed by humans on iconic or culturally significant species. Regulating services benefit both the social and economic subsystems, for example the provision of carbon sinks for climate control. Supporting services are those ecosystem services that enable the ecological subsystem to produce the other services, for example nutrient recycling.

Externalities are the unintended, although perhaps anticipated, consequences of economic activity that impact the other subsystems either positively or negatively, and that are not accounted for or priced by the market system. In the analysis here, we are concerned with externalities that negatively impact on the ecological subsystem, for example pollution and habitat destruction, and for simplicity only these are shown in Figure 5.1[27]. Similarly, while there are processes within the individual subsystems, for example productive and market processes within the economic subsystem, these are not highlighted in our abstraction.

27 Positive externalities may mitigate the overall negative effect of economic production on the environment, however we assume that on balance the net effect is negative.

The socio-ecological system in Figure 5.1 represents a sufficiently broad abstraction to allow contradictory feedback to emerge endogenously and allows for the explanation of various occurrences of paradox. The appearance of paradox may arise within the abstraction if it is insufficiently broad to demonstrate particular feedbacks of relevance to the issue being considered, which is why it is always necessary to consider where the whole lies with respect to any particular abstraction, that is its perspective. The whole to which the system relates depends upon the spatial scale within which it is considered. For example, an abstraction considered at the level of a particular nation will relate to the economic and social systems of other nations as well as to the biosphere, however, an abstraction considered from the vantage point of global economic production, human society and the biosphere will itself represent the whole, although an abstraction of it. The socio-ecological system presented in Figure 5.1 is a highly aggregated model with many simplifications that represent limitations but that also make it tractable. Recognising what these simplifications remove is to consider where our abstraction lies with respect the rest of the world.

3. Method

3.1. A biological metaphor

The consideration of material production and consumption in the context of a broad socio-ecological system, such as that described in Figure 5.1, becomes essential as contemporary society increasingly confronts hard limits in the ability of natural capital to absorb the impacts of economic activity. However, the complexity and non-linearity associated with socio-ecological systems (Young et al., 2006) is such that they can neither be fully specified nor measured so that they are less amenable to reductionist and quantitative analysis. This provides an imperative to our consideration of alternative whole systems methods, including qualitative methods, that will assist in the understanding of these systems. Levins (1975a) describes a method of qualitative abstraction in community ecology, loop analysis, that is consistent with dialectical abstraction (Levins, 2008) and furthermore supports the alternative use of a biological metaphor. This is described in section 3.2 of this paper.

Models containing both economic and biological or ecological systems have typically been approached using the language and concepts of economics, that is, using a metaphor based on the mechanical view of systems favoured by neoclassical economics.The mathematical bioeconomic literature contains many examples of such models (Bjorndal and Munro, 1999, Clark, 2010, Foley et al., 2012, Knowler, 2002, White, 2000). However, the use of this metaphor and its associated reductionism fails to encompass the complex and indeterminate character of ecological systems, and is ill suited for a world where human systems are pressing the boundaries of the containing ecological system (Costanza et al., 2013). Thus, an alternative metaphor is required.

There are good reasons for preferring a biological to an economic metaphor for certain purposes. For example, in using an economic metaphor to consider a loss of ecological services resulting from externalities to economic production, both the Environmental Kuznets Curve (Stern, 2004) and full-world economics (Daly, 1992), where the size of the economic system hits hard ecosystem limits, leads to the proposition that a threshold in material living standard must be crossed by a society before ecosystems are valued, other than for their provisioning role. This suggests that the need for remediation may be realised only once ecological damage has been done, by which time it may be irreversible (Prieur, 2009). It is, therefore, prudent in considering problems of this type, where the focus is on populations and ecological services, to apply a biological metaphor. In this paper we employ the language and modelling approaches of community ecology.

Ecosystems can be considered in terms of function or community structure, or both (O'Neill et al., 1986), where community ecology presents ecosystems as hierarchies of species and describes the interactions between them (Odum, 1953). One such interaction, the predator-prey relationship, is familiar ground in the economic examination of renewable resources. For instance bioeconomic fisheries models consider fishing activity as a predator in relation to the biomass of fish, its prey. This relationship is often presented in terms of Lotka-Volterra equations (Schaefer, 1991 [1954]). In a similar manner, other relationships described by community ecology may be extended to support the specification of broader socio-ecological system relationships. The application of ecological relationships as metaphors for a range of subsystem interactions provides a useful lens through which to consider the social, economic and ecological subsystems of a socio-ecological system and is the basis of their expression as qualitative models (Levins, 1974).

3.2. Loop analysis

The strategy of dialectic abstraction combined with loop analysis (Puccia and Levins, 1985) permits the qualitative consideration of relationships between system components at all levels of spatial and temporal abstraction (Dambacher et al., 2007), and can be used to penetrate the structure of a system, in particular system feedback, so that its behaviour in the face of change can be better predicted. A system may experience change in a number of ways, three of which we consider here. Change may be in the form of a temporary shock, or pulse perturbation, that does not alter the parameters of the system, although the transitory impacts of such a perturbation may nevertheless be long lasting. Secondly, a sustained input or change to a system, or press perturbation, has an ongoing affect on a system's parameters and may result from changing conditions, for example climate change, or from deliberate policy intervention, for example ecological restoration (Bull et al., 2012). A third type of change that a system may experience comes about through a structural change to the system itself in the form of the addition or subtraction of variables or relationships between variables.

The qualitative algebra of loop analysis allows for the specification and graphical representation of a system and its interactions in purely qualitative terms, namely positive, negative and neutral. Through examination of interactions and feedbacks, loop analysis allows a system's stability and response to pulse perturbation to be analysed, and permits the examination of the dynamic impact of both parameter and structural changes to the system. The analytical methods of loop analysis are applied in this paper to a qualitative abstraction of the socio-ecological system in Figure 5.1 to i) examine the feedback cycles and stability of the system in response to a pulse-type perturbation and ii) to explore the response to a press-type perturbation on a system's variables. The first of these is addressed through examination of the Lyapunov stability of the system using reformulated Hurwitz criteria (Dambacher et al., 2003) The second exercise is addressed through analysis of the adjoint matrix as described by Dambacher et al. (2002). Structural changes to the model are examined using modified interactions (Dambacher and Ramos-Jiliberto, 2007).

Within the context of the analysis of perturbation, numerical simulations of qualitative models are used to examine the time dependant trajectories of the system using a two step process. We first establish a known stable equilibrium for the system that uses arbitrary starting values for the variables and choose values for the interactions of the community matrix to reflect compliance or otherwise with the stability conditions. We then perturb the equilibrium value of a system variable and examine the dynamic behaviour of economic, social and ecological capital stocks.

More specifically, in the manner described for population biology (Levins, 1968: 53), the interactions between the variables of the system are described as a matrix equation

$\mathbf{Ax}^{*}=\mathbf{k}$ where: (5.1)

> **A** is the square matrix of n interaction coefficients a_{ij}, or the community matrix;
>
> $\mathbf{x}^{*}$ is a vector of equilibrium population or stock values x_i; and
>
> **k** is a vector of growth rates k_i.

Reverse engineering the equation system from a point of forced equilibrium, we assume values for $\mathbf{x}^{*}$ and their interaction levels, following which we calculate the overall flow affecting each variable, before ensuring that the net flow for each variable is constrained at zero and that the system is consequently at equilibrium. The model is expressed in per capita terms to determine the community matrix, from which the system of ordinary differential equations:

$$dx_i \Big/ dt = x_i(\sum_{j=1}^{n} a_{ij}x_i - k_i)\forall i = 1...n \tag{5.2}$$

are determined and normalised to an equilibrium value of 1 for all x_i.

The system is then perturbed and the dynamics of system recovery observed. This is done in two ways. Firstly the system is perturbed by moving one or more of the x_i from equilibrium, that is a pulse perturbation, such as would arise from an exogenous shock, and its equilibrium response is observed. Secondly the system is perturbed by changing the parameter k_i at a point in time, that is a press perturbation such as would arise from policy change, and its equilibrium response is again observed. In this second approach we use a known stable system (the base parameterisation of the socio-ecological system used in the previous case) and perturb it in a manner that it moves to a new equilibrium. In both cases, making changes to the values of the a_{ij} interaction coefficients allows for a number of alternative regions of stability in the parameter space of the model to be explored.

4. Model

We present the socio-ecological system described in Figure 5.1 as a sign directed graph, or signed digraph, taking the capital types within each subsystem as its variables (*E*, *N* and *S*) and the described processes as its graph edges, or links , with terms of the biological metaphor described in section 3.1 described in parentheses (Figure 5.2). The links may be positive, shown as an arrow (→), or negative, shown as a line ending with a circle (⊸). This abstraction of the socio-ecological system provides the qualitative model for the analysis that follows, and is also shown in the form of the ecological community matrix in eq. (5.3).

$$\mathbf{A} = \begin{bmatrix} -a_{EE} & a_{EN} & a_{ES} \\ -a_{NE} & -a_{NN} & 0 \\ a_{SE} & a_{SN} & -a_{SS} \end{bmatrix} \quad (5.3)$$

In applying the biological metaphor the relationship between the economic and the social subsystems is considered as mutually beneficial, or mutualism in ecological terms. The relationship of the economy to the natural environment is considered as a predator-prey relationship, in the manner of a number of bioeconomic models (Clark, 2010). A beneficial relationship, or commensalism in ecological terms, is presented between the natural environment and the social system to indicate the non-consumptive use of the environment by humans (Fisher et al., 2009, Pearce et al., 2006), for example in its cultural and regulatory services.

Our model has negative self-effects for all three subsystems indicating that resource constraints make them self-limiting systems. For example the density limits to the size of species populations constrain natural capital, the availability of economic capital constrains economic systems, and social systems may be similarly constrained by limits to social capital (Putnam, 1995). While conditions exist that produce self-effects that are positive — for example heavily over exploited biological populations (Ortiz and Levins, 2011), economic systems driven by unbridled growth (Levallois, 2010) and capital accumulation (Foster, 2002) leading to a social and ecological rift (Foster et al., 2010), and instances where social capital is not subject to diminishing returns (Thomas, 1996) — these will not be considered here.

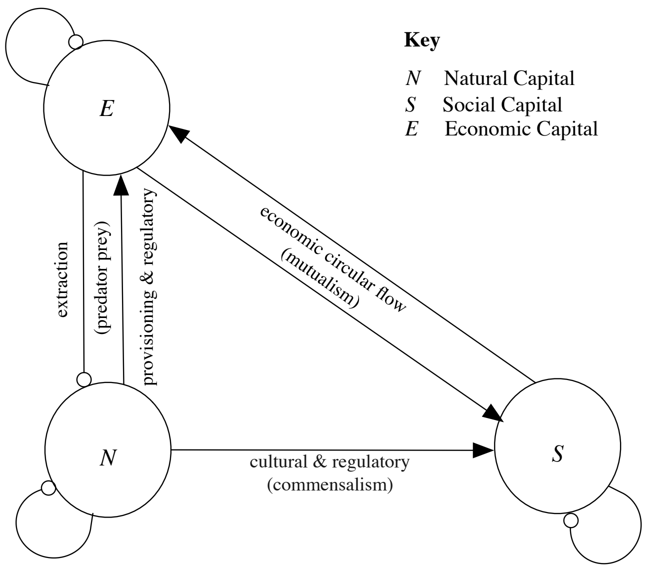


Figure 5.2. Socio-ecological system signed digraphs with equivalent ecological processes shown in parentheses.

5. Results

5.1. Feedback cycles and stability

The signed digraph in Figure 5.2 comprises three stock variables (*E*, *N*, and *S*), and six feedback cycles describing the relationship between the variables, and of variables with themselves. Feedback cycles, or loops, consist of one or more individual links each of which may be positive (→), or negative (⊸), and may appear in more than one feedback cycle. The sign of a feedback cycle is determined by the product of the signs of the links of which it comprises. The signed digraph in Figure 5.2 has five negative feedback cycles — one with three variables (*E*⊸*N*→*S*→*E*), one with two variables (*E*⊸*N*→*E*), and three comprising a single variable (*E*⊸*E* , *N*⊸*N*, *S*⊸*S*) — and one positive feedback cycle with two variables (*E*→*S*→*E*). Positive feedback cycles tend to destabilise a system and negative feedback cycles to stabilise a system, although the relative strengths of negative feedback cycles at different levels of a system may destabilise the system in an oscillatory manner if there is insufficient low level stabilising feedback. Stability is assured if, firstly, feedback is negative at every level of the system and, secondly, the value of each Hurwitz determinant is positive. These two conditions are described by Dambacher et al. (2003) as Hurwitz criteria i and ii.

The first Hurwitz criterion for the system shown in Figure 5.2 can be determined by inspection of the signed digraph. While an analysis of the determinant and minors of the community matrix generates the same result, the simplicity of the model presented here allows for an heuristic analysis that provides a strong intuitive appreciation of the system dynamics. However, the second Hurwitz criterion is not amenable to similar intuitive analysis and must be examined algebraically. Taken together these results provide the basis for understanding the behaviour of the system in the face of a pulse perturbation, and provide symbolic conditions for thresholds, at which system stability behaviour changes.

5.1.1. Hurwitz criterion i

Feedback cycles are considered at every level of the system. Feedback at the system or three variable level (F_3) is a sum of four components each of which is either a product of links comprising all feedback cycles containing three variables, or combinations of shorter feedback cycles and their complementary feedback cycles such that a three variable product is formed. Level three feedback comprises:

- One feedback component reflecting the only path between all three variables $-a_{NE}a_{SN}a_{ES}$ (read as the effect from *E* to *N*, followed by the effect from *N* to *S*, followed by the effect from *S* to *E*) and demonstrates the negative impact of economic capital on natural capital transmitted to social capital. This in turn leads to downward pressure on economic capital, for example through weakening of the circular flow driven by increased social pressure for environmental regulation, in an expression of the effects of environmentalism on the social value of the environment (or a_{SN} in terms of the model).

- Two feedback components reflecting the paths between variable pairs together with their respective complementary feedbacks, that is $-a_{NE}a_{EN}a_{SS}$, which describes the predator-prey relationship from *E* to *N* to *E*, and its complement, the self-effect of S; and $+a_{SE}a_{ES}a_{NN}$, which describes the mutualist relationship between *E* and *S* and its complement, the self-effect of *N*. The presence of the complement changes the sign of the loop with which it is associated when it is positive, and retains the same sign when it is negative. Intuitively, the negative complement dampens the effect of that system such that the subsystem for which it provides the complementary feedback is unaffected by it, whereas the opposite is true when the complementary feedback is positive.
- Finally, there is a component comprising the self-effects of each variable $-a_{EE}a_{NN}a_{SS}$.

Feedback at the second level of the system (F_2) comprises all feedback cycles containing two variables and those with single variables together with their complements, that is the combinations of the self-effects taken two at a time. There are four negative feedback cycles and one positive feedback cycle at the second level. Specifically:

- The predator-prey feedback cycle $-a_{NE}a_{EN}$, which reflects the relationship between the economic and ecological subsystems as it is commonly depicted in orthodox bioeconomic models.
- The mutualist feedback cycle $+a_{SE}a_{ES}$, which reflects the relationship between the economic and the social subsystems, that is the circular flow maintained in orthodox economic depictions of the relationship between household and productive processes, and that is essentially one of materialism. In our model the effect a_{SE} expresses materialism, however a_{ES} is a shared transmission mechanism providing feedback to the economy from the social subsystem of both materialism and environmentalism.

Finally, there are the pairwise combinations of capital self-effects $-a_{EE}a_{NN}$, $-a_{EE}a_{SS}$ and $-a_{NN}a_{SS}$.

The feedback at the first level of the system (F_1) is simply the product of self-effects of the variables reflecting the productivity of the subsystems [28], that is $-a_{EE}$, $-a_{NN}$ and $-a_{SS}$. The feedback at level zero (F_0) is by convention set at -1.

In summary, the feedback results for the system in Figure 5.2 are shown in eq. (5.4) and must all be negative for stability in terms of Hurwitz criterion i.

$$\begin{aligned}
F_3 &= -a_{NE}a_{ES}a_{SN} + a_{SE}a_{ES}a_{NN} - a_{NE}a_{EN}a_{SS} - a_{EE}a_{NN}a_{SS} \\
F_2 &= -a_{NE}a_{EN} + a_{SE}a_{ES} - a_{NN}a_{SS} - a_{EE}a_{SS} - a_{NN}a_{EE} \\
F_1 &= -a_{EE} - a_{NN} - a_{SS} \\
F_0 &= -1
\end{aligned} \tag{5.4}$$

The stability of our system is found to be ambiguous since there are the two positive feedback terms — one at the system level (F_3) and one at the second level of feedback (F_2) — each of which hold the potential to destabilise the system. These terms, which both contain the mutualist relationship between the economic subsystem and the social subsystem ($a_{SE}a_{ES}$), need to be weak relative to the negative terms for stability to be assured. The negative terms of the system are the regulatory feedback cycle across the three subsystems ($a_{NE}a_{ES}a_{SN}$), the feedback from the ecological subsystem to the economic subsystem ($a_{NE}\,a_{EN}$) and the self-effects of each subsystem ($a_{EE},\, a_{NN},\, a_{SS}$).

---

28 If we have $\frac{dx_1}{dt} = -\alpha_{11}x_1^2 - \alpha_{12}x_1x_2 + \beta_1 x_1 - \delta_1 x_1$ the self-effect is found by $a_{11} = \partial\left(\frac{1}{x_1}.\frac{dx_1}{dt}\right)\Big/\partial x_1 = -\alpha_{11}$. Assuming a logistic growth function for a fishery stock S and effort E then $\frac{1}{S}\frac{dS}{dt} = r\left(1-\frac{S}{K}\right) - qE$ and $\partial\left(\frac{1}{S}\frac{dS}{dt}\right)\Big/\partial S = -\frac{r}{K}$, where r is the intrinsic rate of growth of the stock and K is the carrying capacity of the environment.

5.1.2. Hurwitz criterion ii

Hurwitz stability criterion ii requires the calculation of Hurwitz determinants, although in the case of the three variable socio-ecological system system analysed here it is sufficient to examine only the second Hurwitz determinant (Δ_2) for positivity. This result is shown in eq. (5.5).

$$\begin{aligned}\Delta_2 = {} & a_{SS}(a_{NN}a_{SS} + a_{EE}a_{SS} + a_{EE}a_{NN} - a_{SE}a_{ES}) + a_{EE}(a_{EE}a_{SS} + a_{EE}a_{NN} + a_{NE}a_{EN} - a_{SE}a_{ES}) \\ & + a_{NN}(a_{NN}a_{SS} + a_{NN}a_{EE} + a_{EE}a_{SS} + a_{NE}a_{EN}) - a_{NE}a_{ES}a_{SN}\end{aligned} \tag{5.5}$$

It can be seen that Δ_2 contains two potentially destabilising negative terms:

- The mutualist relationship between the economic and the social subsystems ($a_{ES}a_{SE}$) reinforces the earlier result obtained from analysis of Hurwitz criterion i, that is strongly materialist behaviour will be destabilising.

- The regulatory feedback cycle ($a_{NE}a_{SN}a_{ES}$), which acts as a stabiliser in the first criterion, now has a destabilising effect. This arises because if the higher level feedback cycle is too strong compared to the lower level feedback then there is a danger that the system may experience an oscillatory instability.

5.2. Two paradoxes of natural capital

Improvements to the natural capital of our socio-ecological system, either through increasing its productivity (a_{NN}) (Tilman et al., 2012), or increasing its abundance (N) (Heide-Jørgensen et al., 2007), can both be shown to lead to negative ecological outcomes under certain conditions. These outcomes may appear paradoxical if encountered without the nature of feedback within the system being understood. We examine the effects of these two types of improvements by means of numerical simulation.

We choose a set of parameter values for the community matrix **A** that are consistent with the requirements of Hurwitz criteria i and ii for a stable equilibrium, together with an chosen vector of equilibrium stock levels **x*** [29]. This provides the base parameterisation for our analysis. Next we apply the numerical simulation method described in section 3.2 to our model.

The effect of increasing the economic capital stock (E) for the base parameterised model is shown in Figure 5.3. The system experiences a period of oscillation following which it returns monotonically to equilibrium. The system stability in terms of the Hurwitz criteria is independent of which variable is perturbed and similar behaviours are observed with respect to the other capital stocks (N and S).

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29 The stability results in eqs. (5.4) and (5.5) can be expressed as the following set of inequalities that if met are both necessary and sufficient for socio-ecological system system stability in terms of the Hurwitz criteria.

$$\mathrm{F}_3\text{:}\quad a_{SE}a_{ES}a_{NN} < a_{NE}a_{ES}a_{SN} + a_{NE}a_{EN}a_{SS} + a_{EE}a_{NN}a_{SS}$$

$$\mathrm{F}_2\text{:}\quad a_{SE}a_{ES} < a_{NE}a_{EN} + a_{NN}a_{SS} + a_{EE}a_{SS} + a_{NN}a_{EE}$$

$$\begin{aligned}\mathrm{H}_2\text{:}\quad & (a_{SS}+a_{EE})a_{SE}a_{ES} + a_{NE}a_{ES}a_{SN} < a_{SS}(a_{NN}a_{SS} + a_{EE}a_{SS} + a_{EE}a_{NN}) + a_{EE}(a_{EE}a_{SS} + a_{EE}a_{NN} + a_{NE}a_{EN}) \\ & + a_{NN}(a_{NN}a_{SS} + a_{NN}a_{EE} + a_{EE}a_{SS} + a_{NE}a_{EN})\end{aligned}$$

The equilibrium is established using data values that are essentially arbitrary apart from their meeting these inequalities. The base parameter values for the population vector X* and the community matrix A1, which are not intended to represent any particular socio-ecological system, are:

$$\mathbf{X}^* = \begin{bmatrix} 10 \\ 30 \\ 60 \end{bmatrix}, \mathbf{A}_1 = \begin{bmatrix} -1 & 4 & 2 \\ -3 & -2 & 0 \\ 4 & 3 & -1 \end{bmatrix}$$

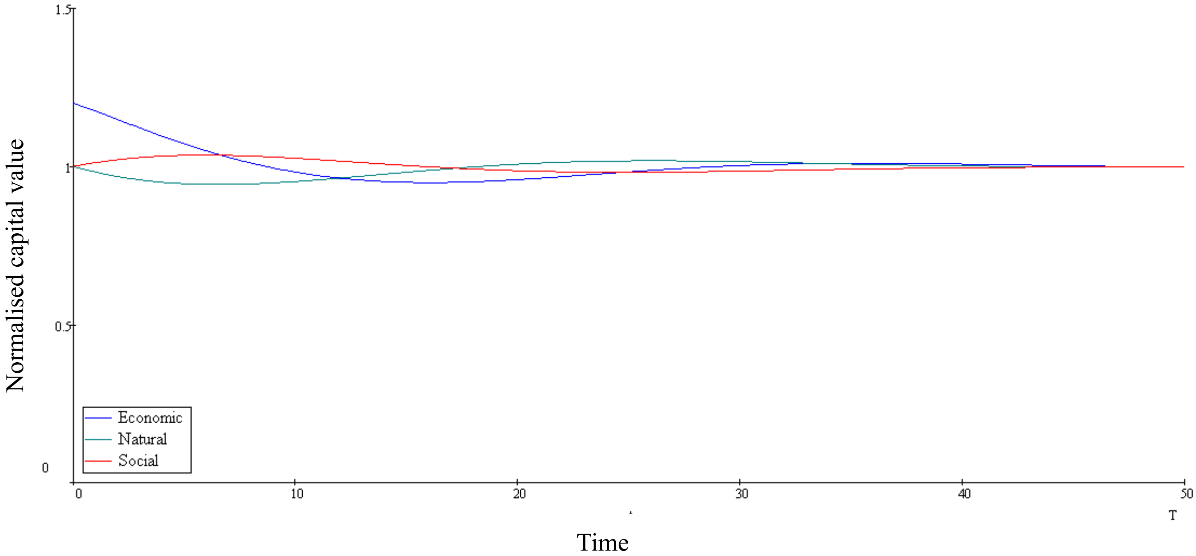


Figure 5.3 - Pulse perturbation of economic capital for stable socio-ecological system.

5.2.1. The effect of improved natural capital productivity

We model an increase in the productivity of natural capital in the socio-ecological system, for example though climate change (Doney et al., 2012), by strenghening the absolute value of the self-effect on natural capital a_{NN} from the base parameterisation by a factor of 2.5, leaving all other parameters unchanged[30]. The system now fails to meet Hurwitz criterion i, that is system feedback F_3 is positive, indicating that the strengthening of natural capital has placed the system at an unstable equilibrium, that may appear paradoxical if encountered as a policy outcome. Considered in terms of loop analysis, this result arises because the self-limiting effect on the natural resource (a_{NN}) is the complement of the positive feedback cycle between economic and social capital ($a_{ES}a_{SE}$), so that their joint effect is to counter the stabilising effect of a negative system level feedback cycle F_3.

30 The revised community matrix A2 is:

$$\mathbf{A}_2 = \begin{bmatrix} -1 & 4 & 2 \\ -3 & -5 & 0 \\ 4 & 3 & -1 \end{bmatrix}$$

The effect of perturbing economic capital on system dynamics for this new system is shown in Figure 5.4a, and demonstrates the collapse over time of the biological resource. This collapse introduces a singularity to the system such that further prediction of behaviour of the represented real world system beyond this point is not possible. However, historical experience of human societies suggest that the absolute collapse of an ecological system will be followed by a similar collapse of any associated social and economic systems (Diamond, 2004), and we expect our system to behave in a similar manner.

Examination of the model suggests several ways in which system stability may be restored. Firstly, the positive feedback cycle that characterises the human subsystem may be weakened. This weakening can be achieved by either reducing the transmission mechanism from social capital to economic capital (a_{ES}), or weakening the effect running from economic capital to social capital (a_{SE}). Another way to restore system stability is through a strengthening of the social value of the environment (a_{SN}), that is the commensalism between the ecological and the social subsystems, which represents the non-consumptive use of the environment.

In all three of these cases, the variables may be seen to exhibit a smooth return to equilibrium following the perturbation of the economic system, as exemplified by the first case above, shown in Figure 5.4b, where a_{ES} is reduced by a factor of 0.5 [31]. However, in the last case, there is a limit to the degree to which such a shift in social values can effectively counter the destabilising effect of enhanced natural capital productivity, before it too gives rise to oscillatory instability. This arises where negative feedback at the higher levels of the system overwhelms negative feedback at lower levels so that a perturbation to economic capital results in the collapse of the system. This case is

31 The revised community matrix A3 is:

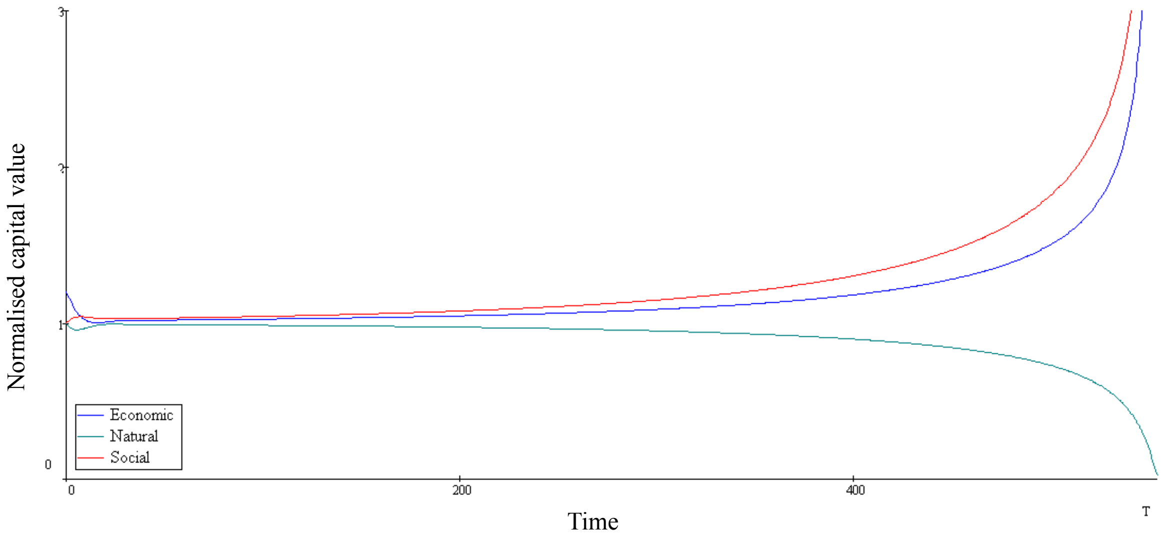
$$\mathbf{A}_3 = \begin{bmatrix} -1 & 4 & 1 \\ -3 & -5 & 0 \\ 4 & 3 & -1 \end{bmatrix}$$

shown in Figure 5.4c where a_{SN} is strengthened by a factor of 33.3[32], with the effect that the system no longer complies with the Hurwitz criterion ii and a perturbation of economic capital results in the increasing oscillation of all variables such that a collapse of the ecological subsystem occurs, with economic and social collapse following the loss of the natural resource base as before.

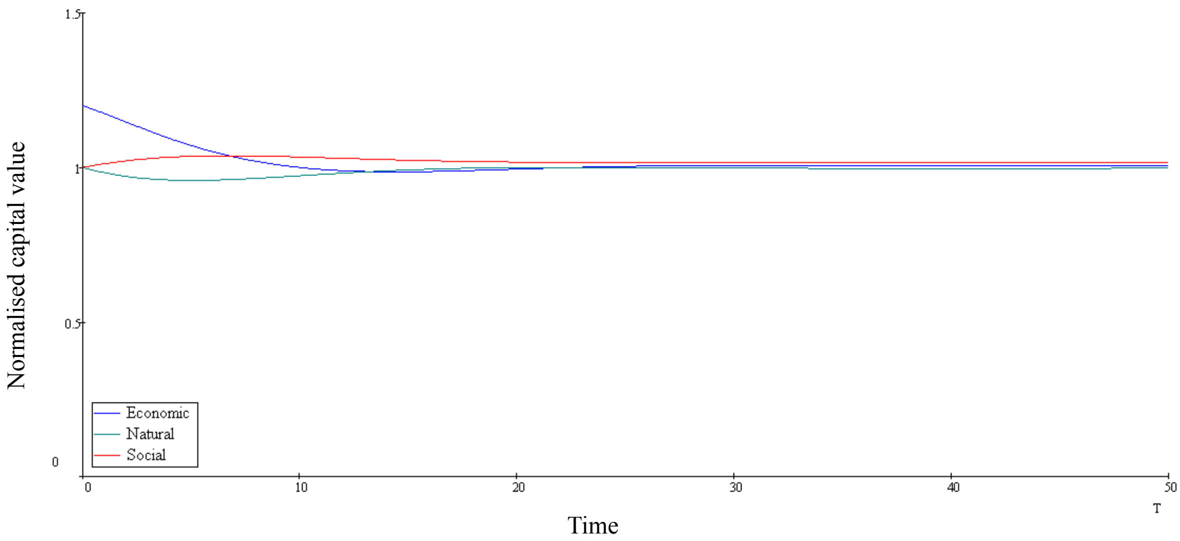
32 The revised community matrix A4 is:

$$\mathbf{A}_4 = \begin{bmatrix} -1 & 4 & 2 \\ -3 & -5 & 0 \\ 4 & 100 & -1 \end{bmatrix}$$

(a) Strong resource productivity a_{NN}



(b) Weakened transmission a_{ES}



(c) Strengthened environmentalism a_{SN}

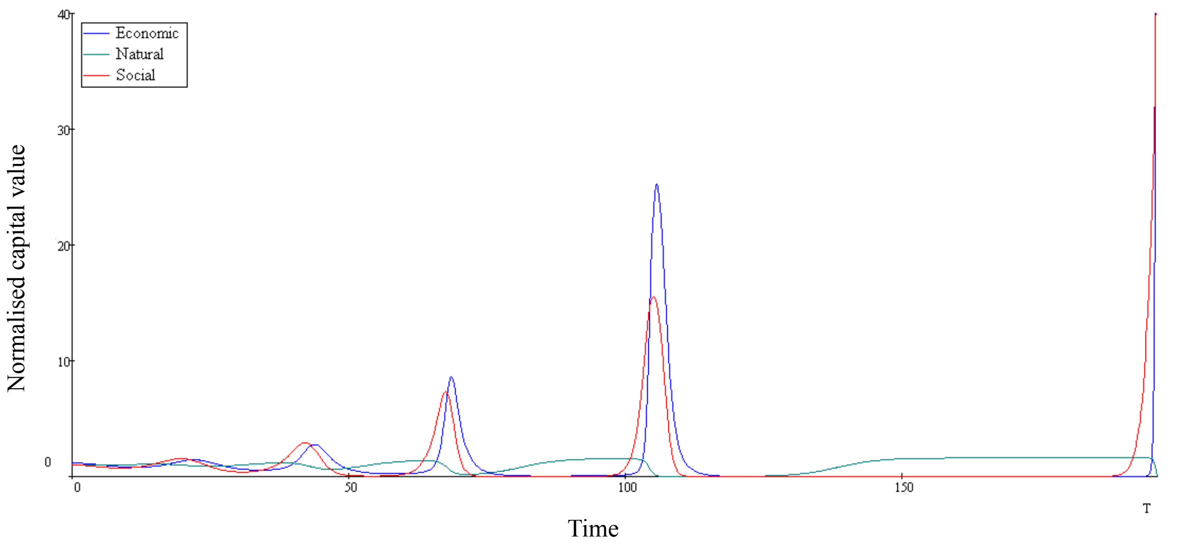


Figure 5.4 - Pulse perturbation of economic capital E with alternative parameterisations.

5.2.2. The effect of increased stock abundance of natural capital.

An improvement in the stock of natural capital, for example through environmental restoration (Aronson et al., 2006), might be expected to be of ecological benefit. We find, however, that this is not certain and that the effects of system feedbacks following such an increase may in fact result in a reduction of natural capital. This again appears paradoxical when the feedback effects are not understood.

Further insight into the behaviour of our system can be gleaned by analysis of the system's adjoint matrix. The symbolically specified adjoint of the negative of the community matrix of our model is:

$$\operatorname{adj}[-\mathbf{A}] = \begin{bmatrix} +a_{NN}a_{SS} & +a_{EN}a_{SS} + a_{ES}a_{SN} & +a_{ES}a_{NN} \\ -a_{NE}a_{SS} & +a_{EE}a_{SS} - a_{SE}a_{ES} & -a_{ES}a_{NE} \\ +a_{NN}a_{SE} - a_{NE}a_{SN} & +a_{EE}a_{SN} + a_{EN}a_{SE} & +a_{EE}a_{NN} + a_{NE}a_{EN} \end{bmatrix} \qquad (5.6)$$

The order of the variables in the system is *E*, *N*, *S* so that the effects of a press perturbation on *E* on *E*, *N* and *S* is found by reading down the first column of the adjoint matrix and similarly the effects of perturbations of *N* and *S* on *E*, *N* and *S* are found by reading down the second column and third columns, respectively.

Inspection of the second-column, second-row element in eq. (5.6), that is the predicted responses of *N* due to a press perturbation on *N*, shows that the ability of policies aimed at increasing natural capital to improve ecological outcomes is in fact ambiguous. This is illustrated for the two alternative parameterisations of the socio-ecological system shown in Figures 5.5a and 5.5b.

Figure 5.5a uses our base parameterisation, which we have shown to be a stable equilibrium position. A sustained policy of improvement to some part of natural capital at period $t = 20$ results in a new equilibrium position for natural capital that is lower than the previous one. This is a counterintuitive result and may appear paradoxical if observed in a context separated from the ability to understand the nature of system feedbacks —‚m we repair or enhance the environment but end up hurting it. When observed though the lens of the loop analysis it can be seen that the effect of the initial increase in natural capital is to excite the social and economic subsystems to the extent that they increase the amount they draw from natural capital, with the net effect that natural capital actually falls.

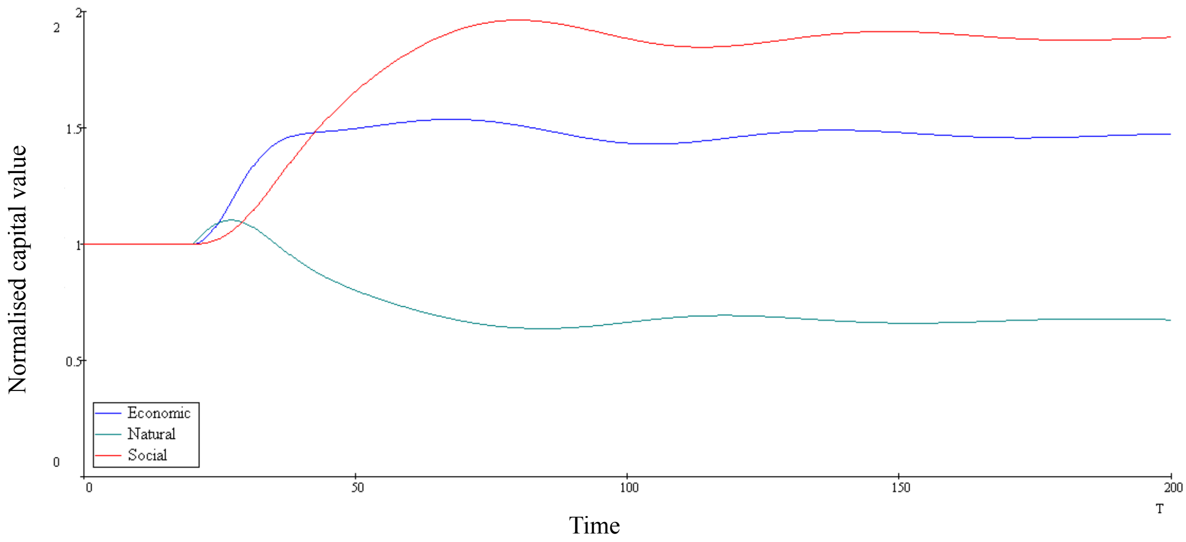
More specifically, referring to the adjoint result in eq. (5.6) we find that apparent paradox results from the relative strengths of the self-effects of the human system $a_{EE}a_{SS}$ and the circular flow between its economic and social components $a_{ES}a_{SE}$, which together describe the complementary subsystem to *N*. The solution, a complementary policy, is to either increase the self dampening effects on the social and economic subsystems or to reduce the strength of their mutually reinforcing relationship, either of which could be achieved through a policy that dampens economic growth.

Figure 5.5b shows the effect of re-parameterising the system[33] by introducing strong negative self-effects that dampen the potential for the mutualist positive social feedback cycle from becoming overstimulated in the face of increased resource availability. The effect of the increase in natural capital in this case still serves to stimulate the economic and social subsystems, with the result that again natural capital falls following its initial increase, however, in this case it falls to an equilibrium level that is above its original equilibrium level.

33 The revised community matrix A5 is:

$$\mathbf{A}_5 = \begin{bmatrix} -10 & 4 & 2 \\ -3 & -2 & 0 \\ 4 & 3 & -3 \end{bmatrix}$$

(a) Decreased natural capital result



(b) Increased natural capital result

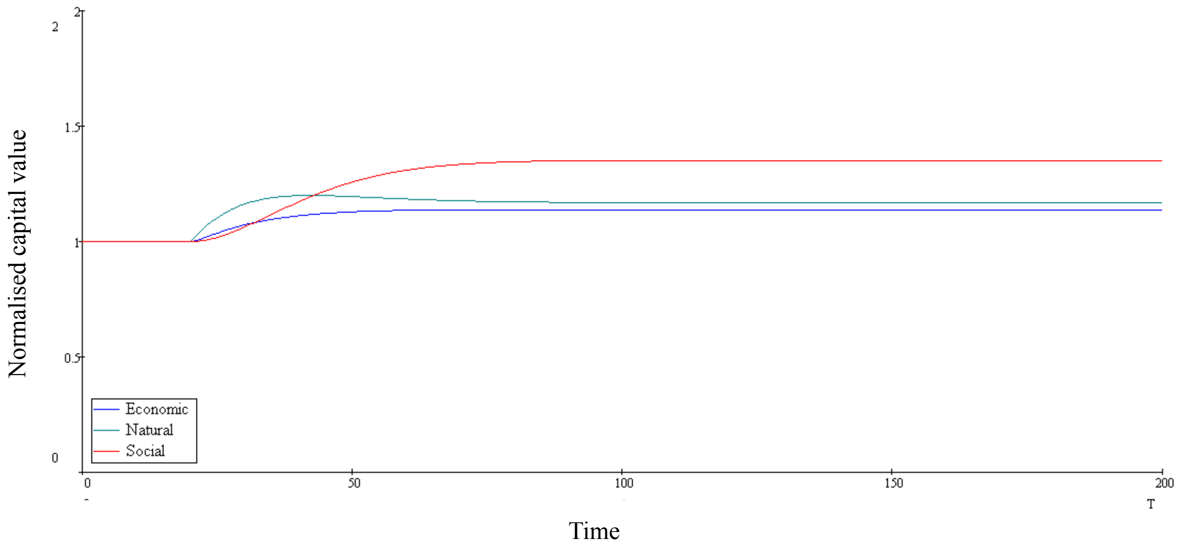


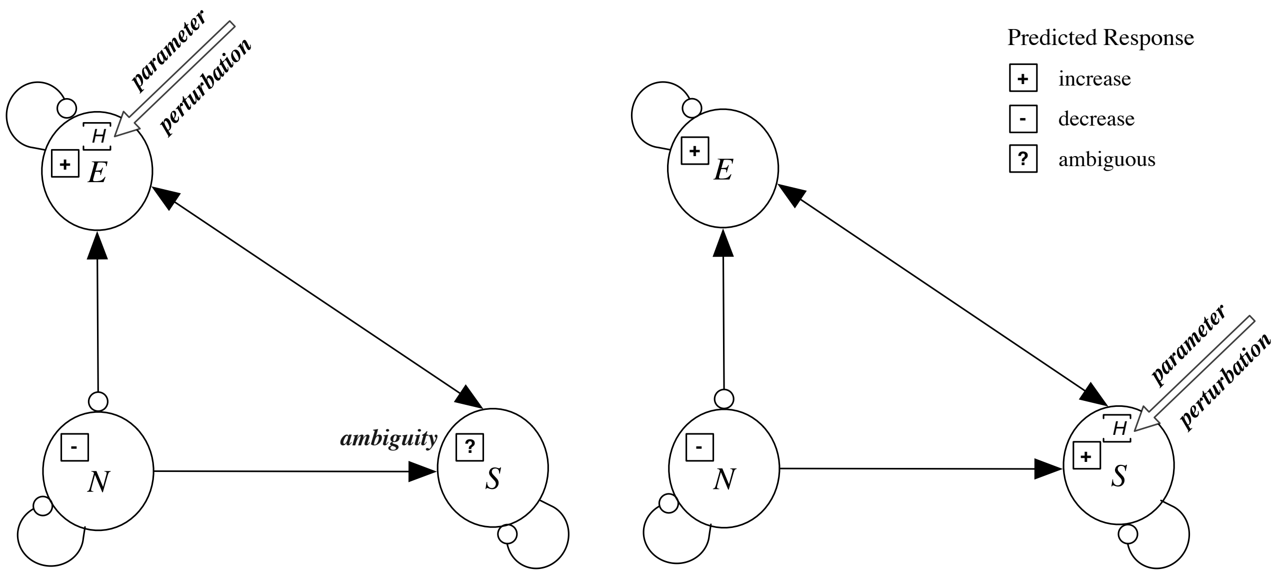
Figure 5.5 - Press perturbation of natural capital N with alternative parameterisations.

5.3. A paradox of social and economic capital

Where specific parameters are considered to lie within variables in our model of the socio-ecological system is the result of choices made in the process of dialectical abstraction. These choices are important to system dynamics. For example, whether households, which proxy here for human population, are treated as social or economic parameters, or both, leads to very different relations in the system that may give the appearance of paradox when not understood.

We explore two abstractions, representing the theoretical positions of neoclassical and heterodox economics respectively, by subsuming a parameter *H* representing households within either the economic subsystem (*E*) (Figure 5.6a) or the social subsystem (*S*) (Figure 5.6b). We then use this parameter to perturb the system and examine changes in equilibria through an analysis of the adjoint matrix in eq. (5.6).

The results of the adjoint matrix analysis for a perturbation of the parameter *H* in both abstractions are shown in Figures 5.6a and 5.6b respectively[34]. Although the models appear to be identical, the manner in which a sustained perturbation of population affects the system is quite different.



(a) Households *H* a parameter within the economic subsystem.

(b) Households *H* a parameter within the social subsystem.

Figure 5.6. The ambiguity arising from alternate parameterisation of population in a socio-ecological system.

Inspection of Figure 5.6a reveals that ambiguity arises from human population growth when modelled as a perturbation to the economic subsystem. An increase in human population degrades the natural environment, however its effect on the social subsystem is ambiguous. The relative

34 To aid diagrammatic clarity two way relationships between variables are shown single stemmed digraph links in Figures 5.6 and 5.8.

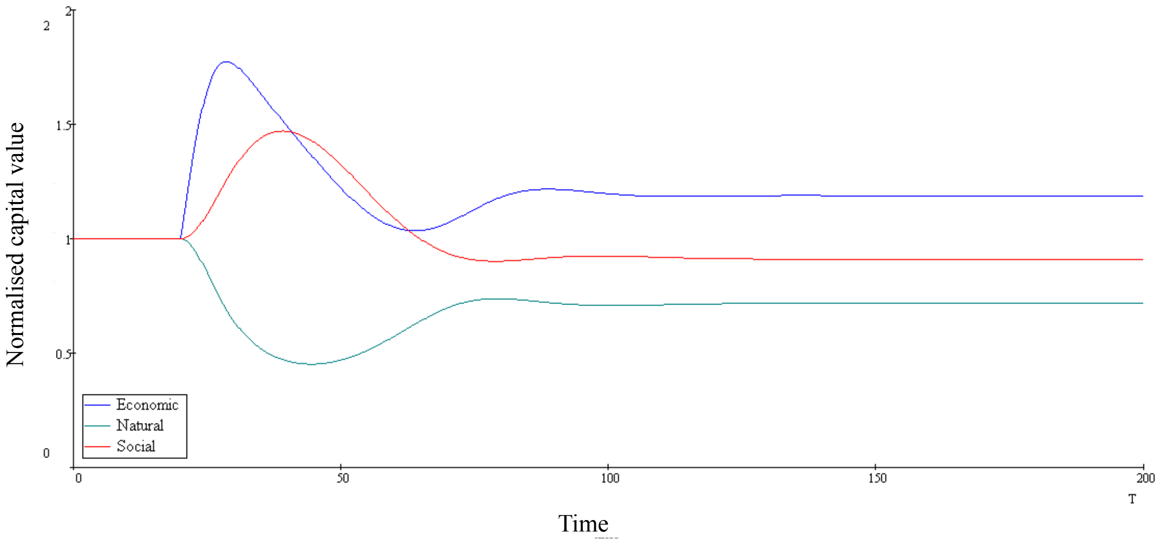
strengths of the links from N to S (a_{SN}) and from E to S (a_{SE}) in the model, which we have considered to be measures of environmentalism and materialism respectively, determine how the ambiguity will resolve. This is demonstrated in the numerical simulations shown in Figures 5.7a and 5.7b. Figure 5.7a uses our base parameterisation and shows a negative response in social capital to a positive press perturbation of economic capital. The system in Figure 5.5b is re-parameterised[35] by weakening the link a_{SN} so that a positive press perturbation of E now produces a positive response in S.

The contradiction is removed when we model human population growth as a perturbation to the social subsystem, as indicated in Figure 5.6b. In this case, population growth unambiguously improves the economy and degrades the environment (Figure 5.7c). However, if we further assume that population growth manifests in the socio-ecological system as perturbations to both economic and social subsystems simultaneously, then its impact will be the sum of these two effects (Dambacher et al., 2002, Puccia and Levins, 1985), that is the sum of columns 1 and 3 of the adjoint matrix, and the ambiguity of response remains as depicted in Figure 5.6a.

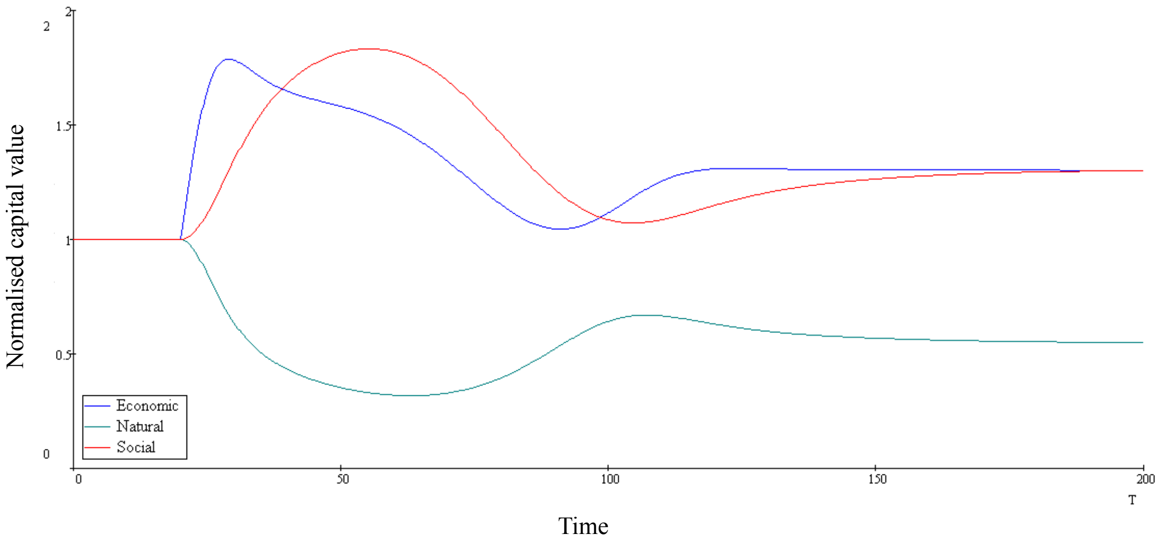
35 The revised community matrix A6 is:

$$\mathbf{A}_6 = \begin{bmatrix} -1 & 4 & 2 \\ -3 & -2 & 0 \\ 4 & 2 & -1 \end{bmatrix}$$

(a) Households as an economic parameter showing decreased social capital.



(b) Households as an economic parameter showing increased social capital.



(c) Households as a social parameter showing increased social capital.

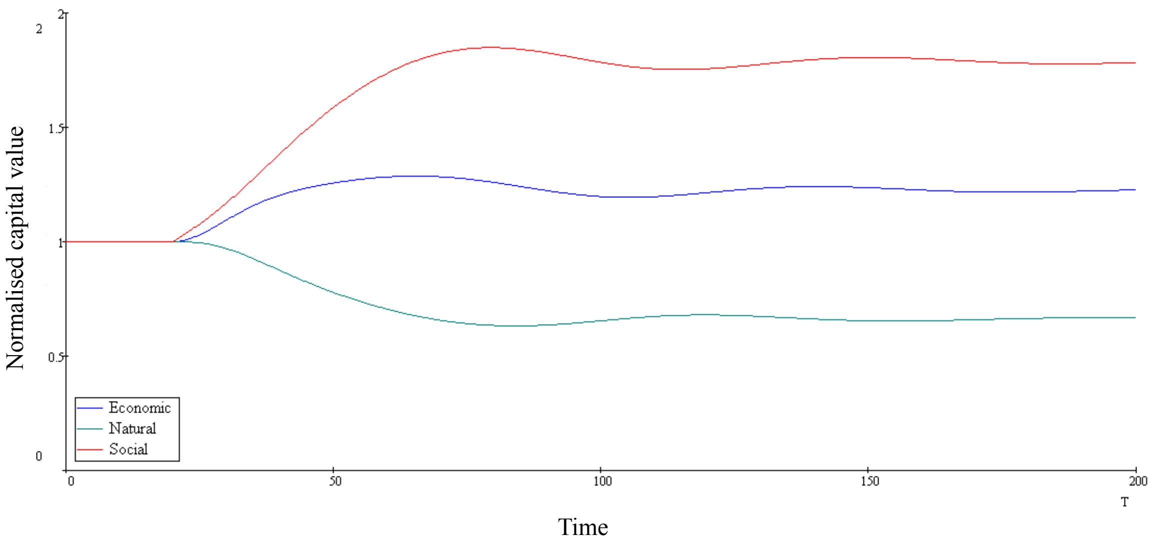


Figure 5.7 - Press perturbations to households considered as economic and social parameters.

5.4. Structural change through direct environmentalism

The analysis of the previous section has demonstrated the unambiguously negative effect, on natural capital, of sustained perturbations to either the social or economic capital stocks. This reflects the predicted results for press perturbations of *E* and *S* on *N*, respectively, that are shown in the first-column and third-column, second-row elements of the adjoint matrix in eq. (5.6). The result cannot be changed by a re-parameterisation of the system, but requires a response of structural change to the system. In this section we consider the structural change effect of a form of social environmentalist activism that acts directly on the interface of productive activity and its natural resource base, which we refer to as direct environmentalism[36]. We model this by introducing a dampening effect upon the predator-prey relationship between the economic and natural subsystems (*E* and *N*) by means of a modified interaction, in the manner shown in Figure 5.8.

The modified relationship between the economic and ecological variables, resulting from the pressure of direct environmentalism, is found by taking the product of the signs of the modifying interaction and the affected links, and then creating new links between the source of the modified interaction and the destination of each affected link. In this case (Figure 5.8a), the modified interaction results in two new links: one from the social variable *S* to the ecological variable *N*, that may be thought of as direct social support for the ecological subsystem, and a second link from the social variable *S* to the economic variable *E*, that may thought of as economic dampening. This second link results in an ambiguity that gives rise to two possible cases: in the first case, the economic dampening that results from direct environmentalism is outweighed by the transmission mechanism for materialism and indirect environmentalism (a_{ES}), with the result shown in Figure 5.8b; and in the second case, the effect of materialism and indirect environmentalism is outweighed by the economic dampening, with the result shown in Figure 5.8c.

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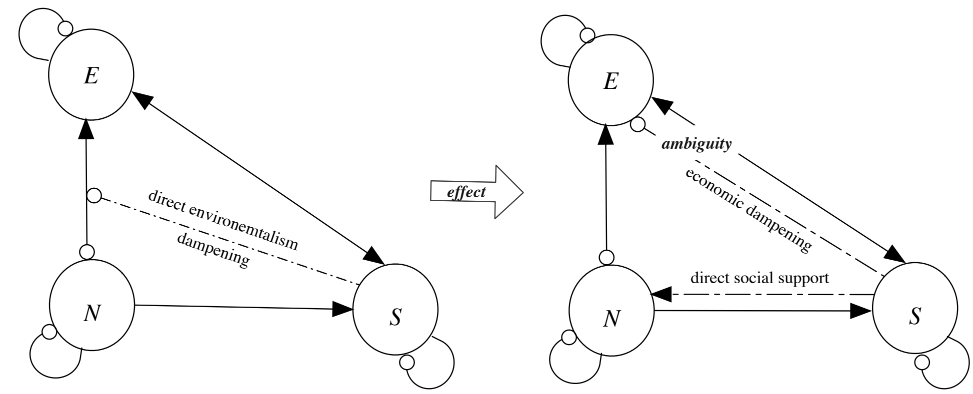
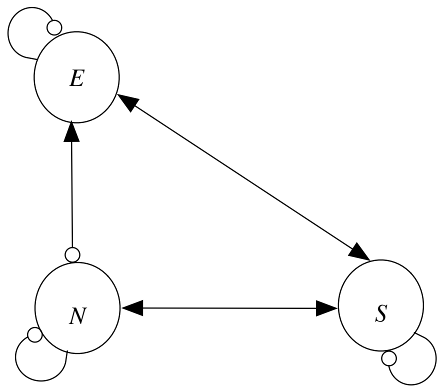
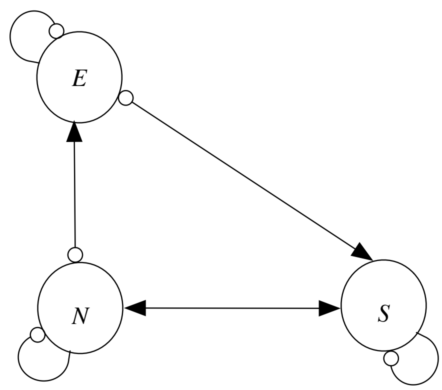
36 This is in contrast to the environmentalism described in previous section of this paper that acts upon the environment by means of the economy (aSNaES), a neoliberal form which we may think of as indirect environmentalism.



(a) Social control of the economic ecological interface.



(b) Materialism dominates.



(c) Economic dampening from environmentalism dominates.

Figure 5.8 The ambiguous effect of environmentalism on socio-ecological system dynamics.

The effects of parameter perturbations for the variables under the two scenarios depicted in Figures 5.8b and 5.8c are shown in their respective adjoint matrices shown in eqs. (5.7) and (5.8), where the order of the variables in the system remains as before in eq. (5.6), that is *E*, *N*, *S*.

$$\text{adj}[\text{-}\mathbf{A}_{5.8b}] = \begin{bmatrix} +a_{NN}a_{SS} - a_{NS}a_{SN} & +a_{EN}a_{SS} + a_{ES}a_{SN} & +a_{EN}a_{NS} + a_{ES}a_{NN} \\ -a_{NE}a_{SS} + a_{NS}a_{SE} & +a_{EE}a_{SS} - a_{SE}a_{ES} & +a_{EE}a_{NS} - a_{ES}a_{NE} \\ +a_{NE}a_{SN} + a_{NN}a_{SE} & +a_{EE}a_{SN} + a_{EN}a_{SE} & +a_{EE}a_{NN} + a_{NE}a_{EN} \end{bmatrix} \qquad (5.7)$$

$$\text{adj}[-\mathbf{A}_{5.8c}] = \begin{bmatrix} +a_{NN}a_{SS} - a_{NS}a_{SN} & +a_{EN}a_{SS} - a_{ES}a_{SN} & +a_{EN}a_{NS} - a_{ES}a_{NN} \\ -a_{NE}a_{SS} + a_{NS}a_{SE} & +a_{EE}a_{SS} + a_{SE}a_{ES} & +a_{EE}a_{NS} + a_{ES}a_{NE} \\ -a_{NE}a_{SN} + a_{NN}a_{SE} & +a_{EE}a_{SN} + a_{EN}a_{SE} & +a_{EE}a_{NN} + a_{NE}a_{EN} \end{bmatrix} \quad (5.8)$$

The result of a press perturbation on social capital (S) — shown by the third-column, second-row elements of the adjoint matrices in eqs. (5.7) and (5.8) — now provides for the possibility of an increase in natural capital. In eq. (5.7), a positive result requires that the impact of material consumption ($a_{ES}a_{NE}$) is less than the product of the new effect of direct social support for the ecological subsystem (a_{NS}) and the self-dampening of economic capital (a_{EE}). By contrast, in eq. (5.8) the result is unambiguous because the transmission mechanism (a_{ES}), which is a positive stimulus to economic growth when dominated by materialism, has been replaced by a dampening that provides an unambiguously negative pressure on the economy.

Two additional important results arise from the direct social support for the ecological subsystem and the dominance of environmental consciousness in Figure 5.8c. Firstly the complementary feedback ($a_{ES}a_{SE}$) to the productivity of natural capital (a_{NN}) is negative. Secondly the effect of an increase in abundance of natural capital upon natural capital (N) — the second row and column in the adjoint matrix in eq. (5.8) — is unambiguously positive. These results address the paradoxical outcomes described in section 5.2, as discussed below.

6. Discussion

Overall these results demonstrate the manner in which a chosen analytical perspective, or pre-analytic vision, affects the interpretation of observed outcomes and how, when this perspective is too narrow, it may give rise to seemingly counterintuitive results that are perceived as paradoxical. Specifically, ambiguity within the system may be interpreted as a paradox when the perspective is a limited abstraction of the whole, such as a single subsystem, and we then fail to consider where this subsystem sits in relation to the whole system, or consider that the abstraction is the whole, a case of misplaced concreteness. In loop analytical terms, this commonly arises when the effects of complementary feedbacks are unaccounted for and therefore unanticipated.

Using a stable parameterisation of our socio-ecological system model, that is one that returns to an equilibrium level of economic, social and natural capitals following a pulse perturbation, we show that an improvement in resource productivity can actually be destabilising. While such an improvement, due for example to either a favourable change in environmental conditions or to active resource policy, might reasonably be anticipated to produce a beneficial outcome, we instead see a system-wide collapse over time if it is too strong. This result is a direct consequence of the manner in which the links between the economic and social subsystems provide a feedback cycle ($a_{SE}a_{ES}$) that is complementary to the productivity of the resource (a_{NN}) and whose momentum contains the potential to collapse the system. The circumstances in which this occurs are shown to be where materialist values in the system overwhelm environmentalist values.

Weakening the individual links of the economic-social feedback cycle, either by diminishing materialism (a_{SE}), by which the economic subsystem drives the social subsystem, or by weakening the transmission mechanism (a_{ES}) from the social system to the economic subsystem, will counter the destabilisation that results from increased resource productivity. Of these two possibilities the reduction in materialism is likely to be the more effective because of the dual role of the social-to-economic subsystem feedback, which appears as both a positive and a negative term in the overall feedback of the system F_3. Viewing sustainability from a perspective of social consumption rather than that of economic production (Fuchs and Lorek, 2013), this duality reflects the competing social pressures of materialism and environmentalism on the productive processes.

Our results again counterintuitively show that attempts to re-stabilise the system following an increase in resource productivity by strengthening environmentalism (a_{SN}), if the effect is too strong, can cause unstable oscillations. This is because the link from the ecological subsystem to the social subsystem affects only the highest level of system feedback and provides no role at lower feedback levels of the system to potentially offset oscillatory instability. This reflects the tendency in any system for overly strong negative feedback at higher system levels to overwhelm feedback at lower levels, thus causing the system to oscillate.

It is clear therefore that achieving system stability requires the careful balancing of a suite of alternate policies. Here we have considered policies individually in order to isolate various effects, and in particular to demonstrate the importance of the role of the social system and social values in determining system stability and policy outcomes.

The demonstrated importance of the social system leads us to question how we consider households, the basic social unit for many analytical purposes, within systems, and in particular how they are narrowly considered by neoclassical economics when compared to their broader social context favoured by heterodox thinking. Our analysis of system behaviour in response to a population increase when households are considered as an economic parameter indicates that this treatment gives rise to an ambiguity that is not present when households are considered as a strictly social parameter. This ambiguity is consistent with the environmentalist's paradox and suggests that if environmentalism is weak and materialism is strong then improvements in human well-being will occur regardless of ecological degradation. On the other hand, if environmentalism is strong and materialism is weak then human well-being will decline in the face of environmental degradation. This is a significant result because it further indicates that our understanding of the behaviour of human and ecological systems is dependant on an understanding of social relations, and in particular of the growing tension between environmentalism and materialism, which raises contradiction that will be ultimately resolvable only in degrowth.

Our results have also shown that when the feedback from environmentalism is indirect, that is when it occurs through the economic subsystem, policy led positive perturbations of either the social or the economic subsystems unambiguously result in negative outcomes for the ecological subsystem. This is consistent with the lack of evidence found, by researchers, for enhanced environmental stewardship to result from the institution of property rights (van Putten et al., 2014), and suggests that other market-oriented institutional forms, favoured by neoliberal environmental policy, may similarly fail to improve ecological outcomes. In contrast to such indirect environmentalism, a direct form of environmentalism — one that acts to dampen the relationship between the economy and the ecological subsystem — provides the possibility of improved ecological outcomes. In this direct case, while the outcomes are ambiguous where materialism remains the dominant social norm, positive ecological outcomes are nevertheless possible; moreover, the strengthening of direct environmentalism, so that it dominates materialism, leads to unambiguously improved ecological outcomes.

The twin imperatives of reduced material consumption by society and increased environmental stewardship in improving environmental outcomes have the appearance of being commonplace. Our analysis, however, suggests that policies with direct ecological benefit have the potential to instead lead to system collapse, even one as simple as that explored in this paper.

Overall our analysis indicates the importance of considering policy formulation both in terms of particular system abstractions and the systemic whole if the potential for paradox is to be anticipated as contradiction and embraced. The combination of the counterintuitive nature of feedback and misplaced concreteness, in both economic and ecological analysis, means that the observed phenomena may appear paradoxical and the outcomes of policy ambiguous. Attempts to resolve issues of environmental degradation may produce contrary outcomes as a result of feedbacks that are not considered because of their complementary nature, or because the temporal and spatial perspective is not sufficient for the problem under consideration. While an isolated subsystem may usefully be examined with some consideration given to its external effects, sight of the systemic whole from which it comes must not be be lost if the appearance of paradox is to be avoided.

7. Conclusion

Discourse around the human-environmental nexus presents a strong emphasis on the economic and ecological aspects of the system, while the social aspects are often neglected (Orenstein, 2013). The method and model described in this paper broadens the discourse beyond the ecological and the economic to incorporate social concerns. The qualitative model developed here represents ecosystem services and the impact of externalities while also accounting for the intrinsic values which are of social benefit, for instance existence and cultural values. This provides for a sufficiently broad perspective that contradiction can arise within the context of the model, which once seen provides pointers to its origins within policy and suggests how it may be addressed.

It is increasingly clear that the ecological issue we face is equally a social one that raises the importance of considering the human dimension of the problem (Castree et al., 2014, Fulton et al., 2011), especially its social relations, beyond the simplistic manner in which these have been treated by neoclassical economics. A fundamental contradiction encountered is that between the social forces of materialism and environmentalism, with its resolution lying in the idea of economic degrowth and a rejection of the neoliberal mantra that economic growth is inextricably linked with ecological and human well-being. While the resolution of this contradiction through economic degrowth can be deferred by continuing to hold it at the boundary of abstraction and enlarging that boundary as needed through policy, for example ecological modernisation (Jänicke, 2008), it is a contradiction that cannot ultimately be avoided. This holds important implications for future forms of social and economic organisation, in particular the distributional equity of global economic output when its supply is strictly limited, that will have to be confronted.

Chapter 6

General discussion and conclusion

1. Complexity and consilience

Complexity has been described as the "central intellectual problem of our time" (Lewontin and Levins, 2007b: 183) and the management of marine resource systems is a significant public policy challenge. Marine systems, for example, which are themselves complex biological systems (Karsenti et al., 2011) about which we know very little, reside within equally complex socio-ecological systems (Folke et al., 2010) that are increasingly the focus of policy (Garcia et al., 2003). Furthermore, the pre-analytic vision necessary to encompass all the relevant aspects of the problems being considered is often limited within particular disciplines (Costanza et al., 1999) and the disciplinary elements relevant for a comprehensive analysis of these systems — for example biological, ecological, economic or sociological — are often either missing or are not effectively integrated (Sievanen et al., 2012).

The need to manage complex marine systems has led to a number of responses by fisheries managers and analysts. There has, for example, been a widening of the scope of fisheries models and a deepening of their mathematical complexity (Plagányi, 2007b, Plagányi et al., 2014), a broadening of interdisciplinarity support (Haapasaari et al., 2012), and improvements to data collection methods (Eayrs et al., 2014). However, the characterisation of marine resource problems, in the context of socio-ecological systems, as 'wicked problems' (Jentoft and Chuenpagdee, 2009) anticipates that their resolution in policy will invariably lead to further complex problems (Althaus et al., 2013) and there are ongoing calls for active experimentation in management processes (Walters, 2007).

The breadth and diversity of these issues and of the responses to them risks a yielding to loose analytical eclecticism in which anything goes. This dissertation has argued the need for a structured interdisciplinary response that is able to work across all systems levels, that is for a consilience the form of which relies upon our ontological understanding of the nature of such systems as complex, contingent and unknowable.

2. Key contributions of the dissertation

In this dissertation our purpose has been to challenge the conventional neoclassical economic perspective of marine ecosystems, and more broadly of socio-ecological systems, and to cast a dialectical lens upon aspects of policy and management. In general terms the dialectic method we employ, a process based on abstraction, loop analysis and a biological metaphor, has been shown to support consilience between reductionist-determinist approaches and those that are evolutionary and contingent. The details of our main findings follow.

2.1. Epistemological pragmatism

The dissertation has confirmed the need for a workable pragmatic form of consilience in marine resource management and policy formulation by demonstrating how the application of dialectical forms to the analysis of complex ecological systems facilitates the pursuit of broad system-focussed policy objectives. To this end the pragmatic use of the quasi-dialectical approach described in chapter 2 has been shown to accommodate phenomena that can reasonably be modelled and managed using a reductionist-determinist approach, and has demonstrated how they can be placed alongside those phenomena that are both contingent and evolutionary in nature and so resist being treated in this way. In other words, we have provided for an epistemological pluralism that includes both arithmomorphic and dialectic phenomena.

Nevertheless, the limits of this pragmatism have been made clear in chapter 3, where, through examination of the economist's golden rule for optimal resource use, a dialectical understanding of the whole system has been shown to reveal inherent contradictions in the face of reductionism. The ontological position of the dissertation is dialectical and this has been further reflected in the operational use of our dialectical method, at both microeconomic and macroeconomic levels, in chapters 4 and 5 respectively.

2.2. Theoretical equivalence

The qualitative models that we have developed as part of our dialectical method have been formally grounded in established neoclassical economic models that are relevant to the current understanding of marine resource management. In this way the theoretical equivalence of the qualitative model to a reductionist mathematical form has been shown, thereby establishing a basis for interdisciplinary consilience. We have shown that it is then possible to reveal the underlying relationships between the objects of study through a dialectical method and thereby to explain phenomena that may have been observed as paradox or points of impasse from a reductionist perspective.

More specifically, in chapter 3 we have taken the fisheries specific implementation of the neoclassical growth model and the associated golden rule, which underpins much of contemporary fisheries management, and have reduced it to reveal its core underlying relationships and the inherent contradictions within them. Similarly, in chapter 4 we have taken a formulation of a joint Walrasian-Marshallian market equilibrium model, represented its core relationships in terms of a qualitative model, and then demonstrated how it is possible to expand these through loop analysis to encompass a variety of ecological scenarios, again revealing the potential for contradiction to arise. Finally, in chapter 5 we have started from the neoclassical macroeconomic conception of the circular flow and its relations in terms of ecological services and externalities and have then demonstrated how the dialectical method allows us to understand the manner in which the macro-level components of socio-ecological systems relate to one another and how this anticipates the potential for contradiction within policy. Our use of loop analysis in this manner is novel since previous extensions of loop analysis to economic relations (Dambacher et al., 2009, Ortiz and Levins, 2011) have typically lacked the theoretical rigour that they afford to ecological relations.

2.3. Theoretical limits of reductionism

This dissertation has exposed the limits of the neoclassical paradigm in resolving the inescapable tensions implicit in management of complex marine systems. From a theoretical perspective we have shown in chapter 3 that the reductionist analytical vision of this approach leads to outcomes in which the promised synchronicity of economic, social and ecological results is not achieved. Furthermore the qualitative models presented in chapters 4 and 5 have demonstrated that this limited vision hides the nature of complementary system feedbacks so that contradictions are impenetrable.

We have shown, in chapter 3, an important implication of this myopia for orthodox fisheries management to be that the ongoing debate as to the theoretical, or practical, optimality of extinction, will remain unresolved within a neoclassical economic understanding of a fishery system, and that contradiction is the inescapable result of any such conception. The dissertation has shown commodification as the underlying cause of these contradictions and supports the contention that the tragedy of the commons is not a tragedy of open-access but rather one of commodification (Longo et al., 2014). Commodification and the complete separation from the environment of a commercially exploited fish species, through its financialisation in forms exemplified by ITQs, has been shown to successfully extinguish existence value, a public good, from effective policy consideration, completing the process of privatisation and commons enclosure.

The tension between ecological existence and economic wellbeing has been shown to further manifest in the tradeoff between environmentalism and materialism that we demonstrated in chapters 4 and 5 as being central to understanding apparently paradoxical results. This has led to our conclusion in chapter 5 that environmental improvement can only be assured through direct forms of environmentalism that act to dampen the interaction between the economy and the environment. By contrast, indirect neoliberal forms of environmentalism that are expressed through the economy have been shown to be ineffective when used in isolation. This finding does not deny the importance of economic policy with respect to the environment, but rather supports the view that economic relations are social relations and that the latter need to be made more explicit in the process of formulating policy. However, we have noted that the persistence of fisheries management based on the neoclassical economic paradigm means that the discourse around the human-environmental relationship continues to emphasise the neoliberal market economic and ecological aspects of the system at the expense of the social aspects, and that this makes observation of continued resource overuse unsurprising.

2.4. A policy framework

In practical terms, using the structured policy framework described in chapter 2, we have shown how policies and associated analyses, that might have initially been effectively informed by reductionism, can be transitioned to a dialectical approach that allows for the incorporation of complexity and contingency with a broadening of the analytical focus, such as that mandated by ecosystem based fisheries management. We have shown that the understanding of reductionist-determinist positions as specific limited cases in terms of particular abstractions, allows them to subsequently be generalised dialectically rather than simply deepened mathematically, or offset with further policy in an environmental expression of Polanyi's double movement.

This generalised theoretical process of management policy evolution, which we have shown to describe current fisheries management and policy development, suggests that the practical operationalisation of ecological management objectives in these circumstances is realisable through a dialectical method. In chapters 3 and 4 we have demonstrated that a wholly reductionist analysis can only lead to a point of impasse or apparent paradox and that while this may be deferred by redefining the boundaries of the abstraction within which the analysis is contained, resolution can only be found in recognising the dialectical nature of the problem and then allowing a process of policy evolution to unfold dialectically, in the manner we have conceived in chapter 2.

2.5. Management limits of reductionism

The dissertation has argued that since complex adaptive systems do not behave in a deterministic manner but are contingent, a management process in which outcomes are evaluated in terms of a binary pass-fail criterion is misguided. Instead, we have argued that in order for outcomes to inform managers and policy makers of appropriate directions for policy adjustment, in the manner we have described in chapter 2, these outcomes should be understood as providing information about the manner in which a dialectic process is unfolding, and not as an end in themselves. In explaining paradox or anticipating contradiction in terms of feedbacks, we have described how the dialectical method sets expectations so that policy development and management become processes of improvement that offer direction, rather than some idealised optimal destination. While we have recognised that marine resource managers need be tolerant of failure, we have not advocated a poor quality of management process.

In chapter 4 we have described the importance of interdisciplinarity and consilience in the management and analysis of complex marine systems. We have shown how disciplines acting in isolation risk adopting limited disciplinary views which treat as black boxes subsystems relating to other disciplines and in doing so missing important complementary feedbacks. Furthermore, we have shown how this may confound the observed results and cause the outcomes to be misconstrued as paradox instead of being understood as contradiction.

3. Loop analysis within dialectic abstraction and interdisciplinary management

In a seminal paper on biological model building, Levins (1966) identifies a strategic tradeoff between attributes of generality, realism and precision, in which one attribute is sacrificed for the remaining two. In the case of quantitative bioeconomic models realism has been sacrificed for generality and precision. This is also more generally true of economic models in the neoclassical tradition, for example the capital theoretic model or the competitive market adjustment model described in Chapters 3 and 4 of this dissertation respectively. Applications of quantitative economic models with respect to a specific fishery, for example in the form of various econometric studies (for example Buckworth et al., 2014, Zhang and Smith, 2011), sacrifice generality for realism and precision. The sacrifice of precision, however, for realism and generality allows a perspective which is often lacking in economic studies and which qualitative models provide.

Within systems ecology the essential purpose of qualitative and quantitative models differs: the primary purpose of quantitive models is to predict the future state of a system, while qualitative models seek rather to understand a system and its behaviour (Levins, 1975b). The two modelling types should be afforded equal importance, which is consistent with the unitary nature of quality and quantity within the dialectic. Similarly with bioeconomic models, abstractions based upon a qualitative consideration of the whole are of equal importance to quantitative abstractions. In his dialectical consideration of biological and ecological systems, Levins (1974) introduces qualitative loop analysis which this dissertation has used to consider aspects of fisheries management and policy within abstractions of sufficient breadth to encompass specific issues and to allow for the full exploration of policy and in particular the potential for contradiction to arise.

The use of dialectical abstraction supported by loop analysis in the dissertation allows for the development and implementation of policy consistent with an evolutionary approach in which contradiction is resolved in the manner described in Figure 2.1. Furthermore the advocated consideration of multiple abstractions to better approximate reality provides a method of management support that is of particular utility in an interdisciplinary context. Within ecosystem management, the utility of loop analysis in examining alternative understanding of complex socio-ecological systems is established (Dambacher et al., 2007). A range of alternatively specified models that reflect alternate understanding of a system's structure and interactions allow examination of alternative hypotheses about observed system behaviour (Dambacher et al., 2015) and for the formal analysis of uncertainty about systems though Bayesian Belief Networks (Hosack et al., 2008) and simulation methods (Raymond et al., 2011).

However, while the manner in which it is coherent with and sympathetic to the dialectic is strongly advantageous, loop analysis it is not a panacea and should be used with some caution. In particular loop analysis is one of comparative statics and is therefore applicable only to stable systems. The regions within which analysed systems are stable may be very small and their stability tenuous. Stability of models is strongly affected by the sign of the lowest level of system feedback, that is the self effects of the variables, and the temptation of modellers is to assume that these are all negative as this ensures the stability of the model — indeed that has been the practice in this dissertation. The reality is that many self effects, particularly within the human components of the system may be positive, for example the economic drive for continuous growth and capital accumulation described here, and this tends to result in instability that makes the application of loop analysis unviable. A further problem with loop analysis is that the feedback signals in a system weaken at increasing levels of detail so that the outcomes of perturbations become increasingly ambiguous. Likewise the ability to analyse the causes of the ambiguity becomes impossible as the symbolic output rapidly gets too complex for meaningful analysis.

There are a range of qualitative modelling techniques that have the potential to offer additional tools in support of dialectical abstraction. These have been utilised in the consideration of natural resource problems in general and fisheries problems specifically. Qualitative differential equations (Kuipers, 1994) provide a promising method that looks not simply at the stability of a system and how it may react to perturbation, but identifies the actual range of future equilibrium states. Regrettably this method has been abandoned from a software support perspective and the complexity of the method makes its ongoing use problematic. System dynamics (Forrester, 2007) is a long established method of qualitative simulation in management that has fruitfully been applied in the context of fisheries problems (Moxnes, 2005). Neither of these modelling methods has been applied in a dialectical context and may provide fruitful areas for future research, particularly if they are able to supplement the weaknesses identified for loop analysis.

4. Concluding remarks

There is an increasing realisation that human productive activity is reaching limits of the ability of natural resources and the biosphere to support it (Daly, 1992, Lovelock, 2009). Whether as a species we are encountering hard limits is open to debate and has been since Malthus (1998 [1798]) first raised the spectre of an unsustainable human system. This is a debate that has been beyond the considerations of this dissertation, however, the question of whether conventional resource management and economics fail to recognise the tension that exists between the economics of growth and the ecology of a finite planet is central to the analysis we have presented. Indeed, the basis of the original bioeconomic idea raised by Georgescu-Roegen (1975) is one of the bio-physical limits imposed by increasing entropy in a closed system. It is important then to ask what system we are considering, and whether the distinctions drawn between human socio-economic and natural systems obfuscate the question of limits?

The dialectical realisation that a thing is defined only by its relationships to other things, leads us to an understanding that a whole ecological system comprises more than simply its ecological relations, and that our existence means it also includes human relations, both economic and social (Harvey, 1993). In light of this realisation, we see that the concept of a socio-ecological system, while of analytical utility as an abstraction, risks merely supporting a broadening of a reductionist understanding in which the human and natural systems are interfaced but separate. For us, there is only an ecosystem in which social and economic relations have formed a continuous, integral and evolutionary part for millennia, and from which they ultimately cannot be separated. Grasping and referencing this whole, even when abstracting away from it for analytical purposes, helps to preclude the errors in policy formulation that must arise whenever we lose sight of the world beyond our immediate problem.

Both the start and end point of dialectical analysis is the whole. We take the whole and dissect it ever more finely into parts, examine the relationships between and within the parts, following which we reform the whole with its relations revealed. If such analysis is to be of practical value in improving resource management, rather than simply an exercise in philosophy in which we consider the nature of things, it must translate into improved policy or actions. The intent of the research presented in this dissertation has not been to ask how people should decide what to believe but rather how they should decide what to do, that is, its intent has been pragmatic rather than idealistic. The dialectical analysis of the dissertation has described contradictions that are currently debated or considered as paradox. Identifying contradiction, however, is not the same as resolving it, particularly where it is theoretically and systemically inherent in policy. However, providing open conclusions and explaining paradox as resolvable contradictions, in the manner of this dissertation, provides the stimulus and understanding for an alternative discourse around the manner of their resolution, which may not be a simple matter of policy choice but rather be implicit in the social systems in which they arise. The implication of this, indeed the central result of this dissertation, is that since in the management of complex marine systems the end is unknowable, then process is all; understood in this way, all management responsibility and commitment takes on substance and duration.

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