17 Ecosystems and managing the dynamics of change

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A decade after Rachel Carson's *Silent Spring* was published, describing the toxic legacy of the twentieth century, Annie Dillard in her Pulitzer prize winning book *Pilgrim at Tinker Creek*, opened up a different way of looking at the world. It presaged a twenty first century in which the global economy would be based on a more thorough understanding of nature, its functioning and material wealth. Wholly descriptive, yet increasingly relevant, her book captured the very essence of what this chapter is about: that amongst the observations which routinely help to predict the evolution of the natural world are the seeds of surprise — surprise of the unusual and surprise as a portent of future change. Our systemic failure to anticipate such surprises forms the core of this chapter. A series of case studies from fisheries, forests, savannah and aquatic systems are used to underline how early warnings about changes in these natural systems emerged but were not used.

The chapter highlights how the division of knowledge into political, disciplinary and geographic silos has led to the 'recurring nightmares' of short-term interests outcompeting long-term vision; situations where competition replaces co-operation; fragmentation of values and interest; fragmentation of authority and responsibility; and fragmentation of information and knowledge leading to inadequate solutions or even additional problems. In addition, the lack of institutional fit has often confounded the effectiveness of the stewardship of ecosystem services, and led to unexpected surprises, excessive rent seeking and high transaction costs.

Using counterfactual thinking (i.e. the dependence of *whether*, *when* and *how* one event occurs on *whether, when* and *how* another event occurs and the possible alteration of events), built around the four interconnected concepts of *planetary boundaries, tipping points, panarchy* and *resilience*, the chapter provides an analytical lens through which to explore why many of the warning signals were not seen. The chapter concludes by suggesting why ecosystems are likely to be even more at risk in the future and why we will need to observe and interpret the dynamics of both nature and institutions ever more closely if we are to avoid sudden irreversible ecological changes.

17.1 Introduction

> 'The road we have been traveling is deceptively easy, a smooth superhighway on which we progress with great speed, but at its end lies disaster. The other fork of the road — the one 'less travelled by' — offers our last, our only chance to reach a destination that assures the preservation of our earth' (Carson, 1962).

A decade after Rachel Carson called the world's attention to the dangers of industrial chemicals in her book *Silent Spring* (Carson, 1962), another writer, Annie Dillard (1974) took her readers on a yearlong investigation into nature's beauty and complexity in her Pulitzer prize winning story *Pilgrim at Tinker Creek*. Quintessentially descriptive, the book shows how close observation of nature and its inherent surprises — both of the unusual and as a portent of things to come — is vital for achieving an understanding of the resilience of ecosystems and the resources within them. Charles Keeling, dubbed the father of climate change science, followed this same approach throughout his lifetime's work on measuring the levels of carbon dioxide in the atmosphere.

Detailed observation of past forms of nature is also vital for anticipating surprises. As R. G. Collingwood (1939) argued in his autobiography, history provides something 'altogether different from [scientific] rules, namely insight'. The historian is like a woodsman compared to an ignorant traveller who might say 'Nothing here but trees and grass' whereas the woodsman says 'Look, there is a tiger in that grass'.

Memory is also an important element in determining current ecosystem structure and function (Hendry and McGlade, 1995). For example, the history and age of an individual tree determine its susceptibility to physiological shock, native disease and parasites; this generally rises with age, leading to an increased probability of accelerated death in elderly stands. However, the history of each position within a forest also has an influences on the current stand, as the state of the soil, the height of the water table, the level of nutrients are affected by the species that have grown there over previous centuries.

By combining insights such as these with detailed observations from comparative analyses of ecosystems and heuristics from the natural and social sciences, scientists have begun to build a more general theory of the dynamics of socio-ecological change across a broad range of ecosystems (Walker et al., 2006); they include lakes and wetlands (Carpenter and Brock, 2004), rangelands (Janssen et al., 2004), forests (Bodin et al., 2006) and coral reefs (Hughes et al., 2003). These developments have also highlighted just how limited many more classical scientific approaches really are for dealing with real-world situations (i.e. developing hypotheses and testing them with simple causal models validated with controlled experiments or statistical sampling). As the case studies in this chapter show, the continued dependence of many resource managers on these more traditional approaches has contributed to the catastrophic decline of some resources.

The chapter looks at how scientific evidence and advice are generated and used in policies for managing natural resources and ecosystems. Through case studies of key events, resources, important actors and institutions and the lens of planetary dynamics and resilience of socio-ecological systems, the chapter explores the reasons why the evidence was sometimes flawed, how and why scientific advice influenced or was ignored during the process of decision-making, and looks at some prospects for the future.

17.2 Data, knowledge and counterfactual thinking

Field ecologists have traditionally adopted a diversity-oriented approach to gathering data and creating knowledge. Their assessments are often based on detailed case studies using measurements of many system-specific attributes with configurational complexity (McGlade, 2003). Conversely, resource managers, have historically adopted a variable-oriented approach based on the measurement of a small number of attributes relating to global patterns emerging from surveys of a large number of cases. The two approaches represent the ends of an inverse relationship between the number of cases and variables. They represent a fundamentally different way of developing counterfactual thinking (i.e. the dependence of whether, when and how one event occurs on whether, when and how another event occurs and the possible alteration of events) and their misapplication has contributed to the catastrophic demise of some the world's key ecosystems and resources.

This section contains two case studies (Box 17.1 and Panel 17.1): the first demonstrates how a well-structured diversity-oriented approach, using close observation at carefully selected sites and correct counterfactual thinking, produced a data series which influenced the global community's thinking about climate change. In contrast, the second shows how a variable-oriented approach based on flawed counterfactual thinking and a poorly described polythetic scheme, led to the catastrophic demise of an international fishery. This second case study shows how false inferences were used to suppress early warnings leading to an unanticipated, sudden collapse and irreversible demise and highlights how ill-suited the models and observations were in relation to the complexity of the socio-ecological system; and the consequences of separating knowledge about the resource into disciplinary, community and geographic silos.

17.2.1 *Complex causality and configurations — context matters*

The diversity-oriented approach uses information about cross-scale interconnections amongst many parts of the system to produce a detailed representation of a particular ecosystem. Causation is viewed as conjunctural, or combinatorial and heterogeneous and there is no assumption that the same causal factors operate in the same way in all contexts or in all instances. Diversity-oriented analyses tend not to provide insights into causal generalisations, but rather into the validity of specific processes. This approach builds links between the detail of specific ecosystem analyses and the broad view of ecology via an understanding of complex causality and the identification of specific necessary and sufficient conditions for a particular set of interactions to influence the overall system (Hogg et al., 1989). It works best when causation is complex, where no single condition is either necessary or sufficient or when causes are sufficient only in combination. Identification of the necessary conditions for change and their detection are extremely important steps in ecosystem assessment and can have very powerful policy implications.

Few variable-oriented studies are framed in such terms. Instead, the variable-oriented approach takes a small number of dependent variables across many instances in order to identify a parsimonious set of causal variables. Causation is dealt with through simplifying assumptions about chains of association between independent variables, reflecting the inferential framework of many resource managers. The theoretical basis is an additive linear model, which relies on the fact that it is possible to assess the independent effect of each causal variable, net of the effects of all others. The assumption is that for a particular outcome, the necessary conditions need only be presence or absence.

Typically, variable-oriented analyses focus on statistical similarities and differences and inductively derive a small number of groupings where within-group differences are minimised and between-group differences maximised. These schemes are polythetic, i.e. the cases that are grouped together can differ substantially from each other for one or more attribute as long as they are similar for the majority of attributes selected by the researcher. By contrast in diversity-oriented analyses, context matters and cases are examined as configurations in which as many as possible relevant aspects as possible are looked at in the form of combinations. Such analyses concentrate on the specific features of individual cases, identifying those that are most relevant, whilst considering how those features cohere with each other as distinct types.

Polythetic schemes, typical of the variable-oriented approach widely used in resource management, violate the core principles of the configurational or diversity-oriented approach used for studying resilience and the dynamics of socio-ecological systems. The question is whether the approach adopted can make a difference in terms of being able to better understand or anticipate surprises and change.

A good example of a configurational, diversity-oriented approach with strong counterfactual thinking is the work of the climate scientist, Charles Keeling (Box 17.1). Whilst there are some sceptics who maintain that the cause of global warming is evidenced in measurements of solar radiative output, the vast majority of policymakers and scientists now agree that the root cause, i.e. human activity, can be seen in the measurements of carbon dioxide. To a large extent, this view is the result of the Keeling's work. Having built up a picture of the causal linkages between greenhouse gas emissions and human activities, he carefully chose sites where he then took precise measurements of carbon dioxide at rapid intervals over more than four decades. What he was able to show was the inexorable increase in CO_2 over that time. The Keeling Curve (see Figure 14.1) is now one of least disputed pieces of evidence of climate change. Keeling adhered to the idea that close observation of a natural phenomenon — the 'breathing of the planet' — was an essential part of understanding the dynamics of global changing.

Box 17.1 The Keeling Curve — how close observation revealed the secret of climate change

Fifty-five years ago, the young American scientist Charles Keeling began one of the most important projects in the study of climate change, recording in immense detail the changing levels of carbon dioxide in the atmosphere. Starting out in January 1958, Keeling set up his equipment on the northern slope of world's largest volcano, Mauna Loa and started a lifelong experiment that would change our view of humans on the planet.

The real story had begun much earlier, when Keeling was only 27, and had told colleagues that all the existing measurements of carbon dioxide were wrong or misleading. Recognising that no one else was really interested in taking consistent, continuous measurements of the levels of carbon dioxide in the atmosphere, he decided to take on the task himself. He had studied chemistry, but his great love was being close to nature. So he jumped at the chance to combine these two passions in a post at the California Institute of Technology.

Keeling had by then developed his own protocols and started taking measurements of CO_2 every three hours in different areas, including the roof of Caltech. He did not mind that it was not the most exciting science; collecting samples gave him the chance to do what he loved — packing up his car and family and heading off into the wilderness, camping in forests and national parks, far away from any urban areas.

He kept meticulous records of all his measurements in a series of notebooks, and it was from these that he got his first clue as to how carbon dioxide in the atmosphere was changing — work that would later see him dubbed 'the father of climate change science'.

Scientists already knew that CO_2 levels fluctuated according to the seasons and location, but they did not know why or whether there was a global base level. Keeling wanted to use his new measuring techniques to find out if there was. He and colleagues began getting measurements from carefully selected sites all around the world, including Antarctica, with the intention of making comparisons between them.

What Keeling understood from his own counterfactual thinking was that the measurement of CO_2 in the atmosphere was vital to the development of an understanding of humanity's effects on the planet. He also realised that persistence and attention to detail were essential to the success of the experiment, so whilst other scientists might have moved on to discover new phenomena, Keeling decided that he could not give up — he had to stay with it. In this sense, the science itself forced him to behave unusually as a scientist.

By 1956 he had accepted a post at the Scripps Institute of Oceanography; realising that he needed to measure CO_2 over the course of years not months he knew he had to find the ideal spot to run the experiment. The site he chose was a former US military site on the slopes of the world's largest volcano Mauna Loa in Hawaii. In the middle of a huge ocean, it was away from contamination and any sources of CO_2 which would have interfered with the measurements. Given that Keeling had to pick an initial site to represent the whole of the world, Mauna Loa observatory was probably the best choice he could have made.

In this ideal environment Keeling started his project, taking samples of air and making CO_2 measurements for the next 40 years. Each day he would venture outside and, after holding his breath, fill a specially designed flask with the incoming ocean breeze. The air would be taken back to the lab to measure its carbon dioxide content.

The result was one of the most famous graphs in science, and would become known as the Keeling Curve. It showed a jagged edge with an amazing regularity and a steep relentless rise of carbon dioxide in the Earth's atmosphere, showing the world's inability to absorb the excess carbon dioxide that human activities were producing.

Placing a temperature curve on top of this curve gave Keeling the foreboding in the 1970s of what was to come. The clean curve of the increase in carbon dioxide spoke to the magnitude of the forces at work, and a picture of all of humanity's exhausts superimposed on the 'breathing' of the planet.

What Keeling discovered is one of the few undisputed pieces of evidence in climate science. Several times he faced cuts to his funding, but always found ways to carry on. His analyser, which was installed in March 1958, collected carbon dioxide data in its original configuration until it was decommissioned in January 2006; even the original strip chart recorder operated from 1958 until 2006. Charles Keeling died in 2004 and today his son Ralph continues the work.

17.2.2 A tale of two cods

The widespread use of variable-oriented approaches in resource management has thrown up a number of problems, especially a general lack of anticipation about sudden collapses. In fisheries, a simple equilibrium model became paradigmatic during the 1960s; it was based on determining the Maximum Sustainable Yield (MSY) under different extraction rates and constant rates of birth, growth and death. The model was related to the larger literature of optimal control techniques and the calculus of variations, which had been successfully applied in theoretical physics, aeronautics, chemistry and management (Hotelling, 1931; Pontryagin et al., 1962), and then spread to economics and resource policy (Dasgupta, 1982; Clark and Kirkwood, 1986). Concerns were raised by some about the utility of MSY models (Larkin, 1977), but these early warning signals were ignored.

It was only when the northern cod (*Gadus morhua*) off Newfoundland collapsed in 1986 (Panel 17.1) that questions began to be raised about its effectiveness. The story of what happened in Newfoundland exposed fundamental flaws in the inferences being made about why the cod population was decreasing, about the roles of the scientists and fishermen in the collection of data, the development of advice and the delays in actions taken by the government. However, the comparison with what happened in Norway is just as interesting. The immediate reaction by the Norwegian government to the collapse of the Barents Sea cod was to impose a moratorium and to invest in more research. The outcomes of the two government actions could not have been made clearer when three years later the Barents Sea cod spawning biomass was bigger than it had been in twenty-five years, whilst the potential collapse of Canadian fish stock was still being covered up.

What is also interesting from the perspective of *Late lessons from early warnings* was the reaction by Norway's Fisheries Minister, Oddrum Pettersen, who said that although the warning signs were there, the knowledge to understand them was missing. As a consequence the government took precautionary actions through the moratorium and invested in research to increase knowledge about the linkages between species of fish, especially cod and capelin, and mammals in the Barents Sea. This led Norwegian scientists to develop new counterfactual thinking about the collapse of the cod stock. They believed that the large year-classes of two and three-year old cod had eaten over a million tonnes of capelin at the same time as there was overfishing of the same capelin stock. The result was a sudden collapse of the capelin, which led to the cod eating each other; the seal population, which fed on capelin, also turned to feeding on cod. At the same time a change in ocean temperatures triggered collapses in stocks in the coastal waters of Russia, Iceland, Sweden, Finland and the Faeroes and Lofoten islands.

Meanwhile in Canada, the government scientists insisted that there was no proven connection between fishing on spawning stocks and the survival of the 0-year class. Senior officials maintained that there was no evidence that fishing on spawning grounds in any way harmed the stock. In Norway such fishing was banned on the basis that although it was difficult to find the relation between recruitment and spawning stock, the scientists were convinced that there was such a relation. The Norwegians had understood that no evidence of harm is not the same as evidence of no harm.

17.2.3 Post moratorium

What lessons can be learnt from the demise of the northern cod, especially as the majority of the world's commercial fisheries are over-exploited and many resources are managed using similar models and approaches?

Fisheries management is like a black-box; it is very difficult to see how things are calculated or how things work. In the case of the Canadian moratorium, the Minister of Fisheries, John Crosbie, blamed the collapse on three main factors:

- overestimation of the stock leading to the setting of total allowable catches that were too high;
- foreign overfishing;
- devastating ecological factors.

The effects of ecological factors became myth-like, but in fact as Finlayson and McCay (1998) point out, there were some very obvious problems with these assertions which showed that the counterfactual thinking behind the assessment was deeply flawed.

First of all the stock was treated as one unit whereas it was known to be comprised of distinct populations with different migratory behaviour and patterns; not including this variability may have contributed to the overestimation of biomass (deYoung and Rose, 1993; Finlayson, 1994).

Panel 17.1 The last hunters

Jacqueline McGlade

A view from inside

In 1980, as a newly recruited scientist in the Department of Fisheries and Oceans (DFO), in the Canadian federal government, I was given the responsibility for assessing the size of the stocks of pollock (*Pollachius virens*) off the eastern coast of Canada and determining the size of the quotas. Pollock was one of the less valuable stocks, but nevertheless thousands of tonnes were landed each year. At the time, DFO was the largest employer of biologists in the public service and the second largest of research scientists and technicians; it was heavily decentralised with more than 2 200 personnel and nearly one third of the departmental budget. When the 200 nautical mile limit was declared, the offshore area accounted for one third of Canada's territory.

My task involved estimating the size of the spawning biomass, determining the distribution of potential yield in terms of catch per unit of effort by all the fleets across all age-classes. I was given a small team, a computer, historical data sets and a model, derived from the equilibrium model of Beverton and Holt, known as a Virtual Population Model, plus a few weeks of ship-time on a research vessel in the middle of the winter to complete the annual recruitment survey, an inshore programme for tagging juveniles and a genetics laboratory to determine stock structures. Estimates of catches and effort from the dockside and fleets would arrive at the Bedford Institute of Oceanography in Nova Scotia and we would quality check the data, enter the various numbers, and eventually age-biomass tables would be calculated and graphs produced for different levels of fishing mortality: the target of choice was $F_{0.1}$. — the level of fishing mortality at which the increase in yield to be obtained by adding one unit of fishing effort is 10 % of the increase in yield to be obtained by adding one unit to a lightly exploited stock.

When we went out tagging, we would talk to the fishermen about what they were observing but this was not a common practice, nor was it a regular part of the assessment for most of the stocks. Once a year, the scientists from the department responsible for groundfish would meet under the auspices of CAFSAC (Canadian Atlantic Fisheries Scientific Advisory Committee) and go over the analyses for each stock to set annual predictions of stock abundance on which to establish the total annual allowable catches and harvesting rules. I used to say that you had to leave your ego at the door, because you would often be sent out again and again to redo the analysis using new combinations of recruitment, fishing effort and mortality rates: this was the reason why it was called 'tuning'.

My colleagues had similar experiences to me, but there was always the worry especially with some of the more valuable stocks that the models were too simple to capture the complexity of the real-life situation and the mechanics of running them on the available computers were not straightforward. There was also the issue of the quality of the data: they were often out of date and even though we had an observer programme to check what was going on at sea, there was no guarantee that the fishermen were accurately recording the locations or the size of their catches. Successive ministers would say that science was the foundation of everything, and that fisheries management required a sound knowledge of the fish stocks.

Canada's northern cod

Many official reports, articles and books have been written about the collapse of the northern cod (*Gadus morhua*) in the 1980s (see especially Finlayson, 1994; Harris, 1998, Steele et al., 1992). The question is: why, with such open support and well funded research, did DFO scientists not anticipate the problem?

From the fisherman's perspective, there were signs in the 1980s that the condition of the inshore cod was deteriorating. The industry asked Memorial University biologists to review the1986 cod assessment for Newfoundland waters. Their conclusion was that the DFO assessment had seriously overestimated the size of the stock. The authors also postulated a connection between the large offshore landings and the poor inshore catches. The surprise was that they had used the same data and come out with startlingly different conclusions.

In the 1986 CAFSAC Advisory Document there were inconsistencies between the projected increases in biomass and the fact that the total allowable catches had been at least twice as high as they should have been over the previous eight years. The document suggested that something was very wrong. When the research survey results came in, pointing to an enormous abundance of cod, scientists should have realised that there was no biological means for the stock to have increased as much when there were still

Panel 17.1 The last hunters (cont.)

so few fish inshore. There was, however, one potential explanation for the increase: in the 1960s, another biologist Wilfrid Templeman had warned that if the dense schools of cod which gathered to spawn in the deep warmer waters were overfished, they would continue to concentrate but in a smaller areas. Thus catch rates might continue to increase even as the stock was collapsing. Unfortunately, DFO accepted the data as they stood.

The next year, in 1987, another external panel of experts was commissioned to write a report on the cod; this time they were given access to the DFO data and also looked at the anecdotal evidence of fishermen. The report concluded that DFO had got its figures tragically wrong (Alverson, 1987). The Chairman, Lee Alverson said that the problem had been caused by errors in interpretation of some of the survey information, compounded by a reliance on a faulty mathematical model. He said that the error had been magnified because it had taken several years to find and admit to the problem and by then the stock was already on a downturn. When asked who was to blame he pointed to the government who owned and managed the resource on behalf of all Canadians and were reticent in making effective and timely decisions. He also pointed out how little the DFO scientists knew about the biology of the species and the ecosystem in which it lived.

It was at this point that the DFO scientists came up with the idea that the absent cod inshore were trapped in warmer water, avoiding the cold intermediate layer, rather than being fished out.

Alverson's report was the first time that the government's concerns about the health of the stock were made public, yet the politicians and senior staff in Ottawa remained convinced that the ocean would continue to provide fish and raised the allowable catch level for 1988. This was a clear indication that any concerns about the health of the stock were put far behind socio-economic considerations.

In December 1988, DFO scientists in a dramatic reversal of advice proposed a fifty per cent cut in the quota for 1989.The Federal and Newfoundland Ministers knew that this would lead to thousands being out of work and bankruptcies everywhere. They decided that the consequences would be too devastating, supporting their decision by saying that the scientists had been wrong before. Moreover, there was resistance amongst some senior DFO scientists to admit that any mistakes had been made. The assistant deputy minister later published the official line: 'It appeared that the sudden, unexpected decline in northern cod during 1991 was the result not of high fishing mortality, but rather abnormal environmental conditions … which, through mechanisms not yet understood, may have led to an abrupt increase in natural mortality in the early 1980s' (Parsons, 1993).

Despite the increasing evidence that the unthinkable was happening to the cod stock, the politicians asked for more evidence. In 1989 the Northern Cod Review Panel, led by Leslie Harris, began its work. Meanwhile the inshore fishermen took the federal government to court to stop destructive fishing practices on the spawning grounds. They lost and DFO officials maintained the line that there was no evidence that fishing on spawning grounds in any way harmed the stock. By now Ottawa was already subsidising Newfoundland to the level of 2.56 billion Canadian dollars (CAD). The release of the Harris report in 1990 showed how dire the situation had become: it concluded that the reduction in quotas in 1990 would not be enough to reverse the trend of a declining spawning stock but would rather contribute to a further decline (Harris, 1990).

On the point of how had the collapse come about, Harris pointed to the disastrous advice given to managers and politicians by the DFO scientific branch. He stated that the scientists 'lulled by false data signals and, to some extent, overconfident of the validity of their predictions, failed to recognise the statistical inadequacies in their bulk biomass model and failed to properly acknowledge and recognise the high risk involved with state-of-stock advice based on relatively short and unreliable data series … it is possible that if there had not been such a strong emotional and intellectual commitment to the notion that the $F_{0.1}$ strategy was working, the open and increasing scepticism of inshore fishermen might have been recognised as a warning flag demanding more careful attention to areas of recognised weakness in the assessment process' (Harris, 1990).

Harris recommended that the assessments be peer reviewed by those not involved in DFO. He warned that the models had become more important than the study of the species themselves; he said that what was needed was nothing short of a massive research effort to understand the life in the oceans. Ottawa

Panel 17.1 Case study: The last hunters (cont.)

accepted nearly all the recommendations made by Harris, but reducing the total allowable catch on cod was not approved. In 1992 the minister closed the northern cod fishery, saying it had collapsed due to unusual ecological and environmental conditions.

The collapse of the northern cod stock was one of the most catastrophic failures in fisheries and an ecological disaster. The social and economic consequences have been enormous and many communities remain devastated. DFO now admits that it had evidence as early as 1986 and that 'the model used to determine the status of most of the key groundfish stocks has consistently overstated their abundance and understated the level of mortality' (Auditor General of Canada, 1997).

Barents Sea cod

Meanwhile on the other side of the Atlantic Ocean, in Norway, the 1989 autumn survey results showed that cod stocks in the Barents Sea were at their lowest for over a hundred years. Scientists and fishermen had already been worried that the fish were too small and earlier estimates of abundance too high. Cod quotas were slashed and the capelin fishery also closed. Fishermen warned that the fish they were catching appeared to be starving. 'When scientists told the Norwegian politicians that there had to be severe quota cuts, the politicians acted immediately and backed the cuts despite a firestorm of criticism from their constituents. Oslo also immediately implemented policies to reduce the number of cod fishermen and vessels' (Harris, 1998).

In January 1990 the government imposed a moratorium. Fishermen's incomes dropped by up to 40 per cent and in the end the Norwegian government spent more than EUR 50 million to remove capacity from the fleet. However, the prompt action by the government meant that by 1991 signs of a recovery were seen and in 1992 the spawning biomass of the stock was larger than it had been for 25 years.

Second, key variables, such as recruitment and natural mortality, were treated as constants in the models used. This in combination with problems in the periods used to derive averages used to generate the constants also resulted in overestimates (Finlayson, 1994).

Thirdly, data from the fishing industry used in stock assessments, in combination with research vessel survey data, were seriously distorted by the practice of discarding undersized fish. There was also a bias towards the use of offshore versus inshore landings as an index of abundance to 'tune' the stock assessment model. Inshore fisheries landings were not systematically used in the assessments because of difficulties obtaining consistent measures of 'catch per unit effort' and otherwise dealing with messy and often anecdotal data. Therefore evidence of decline in the abundance and size of inshore migrating fish was apparently missed (Steele et al., 1992; Neis, 1992), contributing to DFO's inclination to dismiss the concerns of inshore fishers.

Why was the research on basic cod biology not being carried out? One obvious reason was the career structure of fisheries scientists who were assessed on their publications in peer reviewed journals. The number of papers published on northern cod, one of the most important resources in eastern Canada fell from more than 10 per year to 2 annually over a twenty year period, in contrast to the increase in papers seen in the Norwegian setting, where research was being actively encouraged.

Another problem however was the hubris amongst senior government officials in denying that there was anything wrong. This was a projection of the government's own crisis around its institutional authority and epistemological legitimacy. For example, in the February 1988 issues of *Fo'c'sle*, aimed at fishermen and the general public, the DFO Newfoundland office published an article entitled '*The Science of Cod*'. In the introductory statement the Director General says:

> 'It is reassuring that the conclusions of the Task Group [the Alverson Report, 1987] and CAFSAC about northern cod are quite similar with respect to the present stock size and the causes for the decline in the inshore fishery since 1982. The credibility of DFO scientific advice was not questioned. The northern cod stock continues to increase, but perhaps not as fast as projected several years ago'.

Finlayson and McCay (1998) also asked why it was that scientists who knew or suspected that there were problems with the stock assessment did not speak up. It is clear from the inside that some DFO scientists had misgivings about the quality of the scientific advice given about cod, but as in any civil service they were not allowed to speak publicly about the issues once it had become policy. It was also the case, however, that many assessment scientists had little contact with the fishing industry or actual fish, dealing rather with 'paper fish'. There was also a tendency when scientists were presenting their assessments to the relevant advisory body that they would minimise the problems associated with data reliability, uncertainty, the models and data-sets, issues of stock structures or even admitting to the possibility of unknown unknowns! ([1]).

17.2.4 Knowledge systems

The fisheries case studies serve to underline the fact that simple variable-oriented analyses are no match for the complexity of real socio-ecological systems. So why have these approaches not been replaced, especially given that it has long been recognised that the majority of the world's fisheries are over-exploited (Pauly et al., 2002; FAO, 2010)? One reason is perhaps the lack of consensus about which approaches could replace them in order to understand complex systems and manage resources more effectively. This partly stems from the low pedigree of knowledge about the causality linking many of the processes and elements in socio-ecological systems (Table 17.1).

The division of knowledge into political, disciplinary and geographic silos can lead to Yaffee's (1997) 'recurring nightmares' of short-term interests outcompeting long-term vision; situations where competition replaces co-operation because of conflicts in management; fragmentation of values and interest; fragmentation of authority and responsibility; and fragmentation of information and knowledge leading to inadequate solutions or even additional problems. In situations where strong counterfactual thinking is needed, for example in developing early warnings, the presence of silos of knowledge can become a real hindrance.

The fact that ecosystem and resource management is highly interdisciplinary, involving fields of varying states of maturity and with very different heuristic and social practices is also a challenge. Those involved in planning and policy development often find themselves having to use inputs from areas of expertise with which they are potentially unfamiliar, making it difficult to apply the same level of judgement as in their own core field. The result can be a dilution of quality control in the information gathering process and a weaker quality assurance of results. It is unsurprising that planning and management institutions have been unable to respond to crises or change, as in many instances, the organisations are suffering from a chaotic mixture of information, analysis and interpretation with no paradigmatic structure in which to incorporate all the various forms of scientific, interdisciplinary, and indigenous knowledge (McGlade, 2001).

In the pre-modern environment, knowledge was rich and adapted to the requirements of living locally. Individuals today are just as knowledgeable but they receive information from an enormous number of sources, some technical, some cultural. In this way we can see a form of second-order science emerging in which individuals must rely on other peer groups and experts to be able to evaluate the information within their own domains of expertise.

Table 17.1 Pedigree of knowledge

Pedigree	Theoretical paradigm	Data	Peer acceptance	Colleague consensus
4	Established	Experimental	Total	All but cranks
3	Theoretical model	Historical/field	High	All but rebels
2	Computer model	Calculated	Low	Competing schools
1	Statistical procedures	Educated guess	Low	Embryonic field
0	Definitions	Random guess	None	No opinion
∞	Unknown unknowns	Unknown	Unknown	Unknown

Source: McGlade, 2002.

([1]) This phrase, cited by many military experts, was made infamous by Donald Rumsfeld (2002) in his press briefing on weapons of mass destruction in Iraq, where he said '[T]here are known knowns; there are things we know that we know. There are known unknowns; that is to say there are things that, we now know we don't know. But there are also unknown unknowns — there are things we do not know we don't know.' 12 February 2002.

This type of interaction is especially important in ecosystem and resource management, because direct scientific evidence is likely to be missing but there is often a wealth of local and lay knowledge to be gained through the close observation of and proximity to nature, as Annie Dillard experienced during her year spent next to Tinker Creek. In this sense the concept of an expert as part of the system of governance has to be broadened to include those who have particular knowledge about a system but who do not necessarily walk the corridors of power and/or of science. It is interesting in this regard to note that the newly established Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) explicitly recognises the contribution of indigenous and local knowledge to the conservation and sustainable use of biodiversity and ecosystems, yet it is still struggling to find operational ways to include such knowledge into its work.

17.3 Planetary dynamics and ecosystem change

This section looks at ecosystem change through the lens of four interconnected concepts arising from the scientific field of non-linear dynamical systems behaviour: **planetary boundaries** (Rockström et al., 2009); **tipping points** (Lenton et al., 2008; Schellnhuber, 2009), **panarchy** (Gundersen and Holling, 2001) and **resilience** (Walker and Salt, 2006). Based on information drawn from socio-ecological systems around the world, we explore whether or not these concepts could help communities and managers anticipate sudden change or the collapse of a resource and provide a practical basis for sustainable management of our relationship to ecosystems.

17.3.1 Navigating the Anthropocene

The dynamical behaviour of the planet's natural systems is now changing more rapidly than at any time previously during the previous 10 000 years of the Holocene. Evidence of the scale, magnitude and significance of these changes has been sufficient for geologists to conclude that an epoch-scale boundary has been crossed and that we are now in a new epoch — the 'Anthropocene' (Steffen et al., 2011; Zalasiewicz et al., 2011). Living in the Anthropocene will require us to deal with ongoing and rapid or sudden onset threats such as oil spills, chemical and nuclear accidents, earthquakes, landslides, tsunamis, volcanic eruptions, severe weather, storms and cyclones, floods, wildfires and epidemics, and slow-onset threats such as air quality, droughts and desertification, food security and epidemics and climate variability (UNEP, 2012).

The 1980s and 1990s saw the emergence of the theories of chaos, non-linear dynamics and many other highly sophisticated mathematics as a source to explain the complexity of ecosystems (May 1982; McGlade 1999). At the same time, knowledge about the planet's own dynamics was growing: from debates about the impact of the Milankovitch cycles on climate to the idea that the 'flap of a butterfly's wing' could cause changes thousands of kilometres away.

The analytical basis of ecosystems science was also growing but the sophistication of the tools and computational methods meant that few field biologists could really make use of the ideas beyond concepts and definitions. Instead, the advances were largely taken forward by climate scientists, meteorologists, oceanographers and biogeochemists under the aegis of the Intergovernmental Panel on Climate Change. The models of global change which were developed, however, generated scenarios of the likely magnitude of global temperature increases, sea-level rise, melting of the ice caps, glaciers and sea ice, droughts and tropical storms which would have direct consequences for ecosystems.

It was with this information, that a network of theoreticians and mathematical ecologists began to expand their ideas on four major concepts: *planetary boundaries* (Rockström et al., 2009); *tipping points* or *elements*, (Lenton et al, 2008; Schellnhuber, 2009), *panarchy* and *resilience* (Holling, 1996; McGlade, 1999).

Rockström and colleagues have proposed nine hard global biophysical limits, or planetary boundaries, for human development — land-use change, biodiversity loss, nitrogen and phosphorous levels, freshwater use, ocean acidification, climate change, ozone depletion, aerosol loading, and chemical pollution. Each has its own metric, for example greenhouse gas emissions, concentrations of various pollutants in air and water, and aragonite concentrations in the ocean. At present, none of these limits can be entirely dismissed either by firmly ruling out a possible anthropogenic triggering of irregular dynamics or confirmed by providing relevant estimates for activation or reaction times. Nor can the response times of the various sub-elements be estimated beyond a certain resolution e.g. yearly in the case of aerosol loading and loss of summer sea ice or millennia in the case of ocean acidification. However, the widespread lack of in situ observations to validate the models underpinning these limits and the inbuilt latency of the planetary system itself, mean that there will be many decades of tantalising ignorance about whether or not any of these boundaries *per se* have been crossed.

Instead it is more likely that the effects of the tipping elements described by Schellnhuber, Lenton and co-workers, will come to define future surprises. We are experiencing some of them already — Arctic sea-ice loss; boreal forest dieback; melting of Greenland ice sheet; instability of the west Antarctic ice sheet; Atlantic deep water formation and permafrost and tundra loss. Others are potentially yet to come — climatic change-induced ozone hole; greening of the Sahara; chaotic multi-stability of the Indian monsoon; changes in the amplitude or frequency of the El Niño Southern Oscillation (ENSO); dieback of the Amazon rain forest; west African monsoon shift; and changes in Antarctic bottom water formation. The causality and inter-linkages between these potential tipping elements raises both long- and short-term questions. For example, will increasing levels of greenhouse gases lead to a permanent change in the ocean current system including the north Atlantic Gulf Stream and the El Niño regime that could ultimately suppress the Quaternary glacial 'cycles', while drastically altering the number of extreme weather events such as droughts, storms, cyclones and tornadoes?

Tipping elements pose one of the toughest challenges for contemporary science, because key emergent properties (and consequently early warning signals) are likely to arise on a range of spatial and temporal scales and be observed by scientists across many disciplinary silos, which are themselves populated by elites and people with their own paradigms and language. Global changes in climate, ocean acidification and even possibly ozone depletion may cause thresholds on a planetary scale to be crossed that alter or reconfigure the functioning of some ecosystems, leading to abrupt transitions and potential irreversible changes on a local scale. Identifying thresholds based on a generic model of tipping points is an exercise in futility; instead we will need to adopt an approach based on cascading thresholds, where early warnings and signals of change are linked to observations of key processes on a local and regional scale.

17.3.2 *Anticipating surprises — adaptive cycles and panarchy*

Over the past fifteen years, Buzz Holling, Brian Walker, Carl Folke, Terry Hughes, Steve Carpenter and colleagues have been exploring socio-ecological systems around the world (www.resalliance.org). The idea has been to create an empirical and theoretical base on which to understand abrupt change in managed resources and to develop a general theory with heuristics and principles to better understand resilience (Holling, 1973; Gunderson and Holling, 2002; Walker et al., 2006).

The concept of resilience in ecosystems was introduced by Holling in his classic paper on non-linear dynamic models that captured the relationship between stability and resilience in ecosystems (Holling, 1973). Whilst some ecologists considered resilience to be a measure of how quickly a system returns to an equilibrium state after a disturbance (what is now known as engineering resilience), Holling kept to the notion that ecological resilience was the measure of how far an ecosystem could be perturbed without experiencing a regime shift (Hogg et al., 1989; Holling, 1996; McGlade, 1999).

There are many examples where ecological resilience has been described and its loss recorded (Table 17.2). In most instances, the dynamics of the adaptive cycles are the product of the interlinkages between the ecosystem and people, and it is generally these, sometimes hidden, cycles that managers are actually coping with. As the diversity of the case studies shows, the scale of the management challenge is enormous. However, one aspect that is of particular importance is the anticipation of surprise or abrupt changes, and the rapid shift to a new regime. In some literature, the term 'alternative state' is used: this is a misnomer. Complex ecological and socio-ecological systems are better expressed as configurations of states with the same controls at work, i.e. the same feedbacks, but where the configuration describes the kinds and strengths of feedbacks and where the different internal controls on functions represent alternate regimes with thresholds between them. Striking examples of this are the desertified regions of the Sahel and the emergence of permanent summer algal blooms in the Baltic Sea.

As part of the development of a more general theoretical basis for managing socio-ecological systems, Walker and colleagues (Walker at al., 2006) proposed five heuristics: two describing the dynamics across scales — adaptive cycles and panarchy, and three describing the properties of the system — resilience, adaptability and transformability. Adaptive cycles in ecosystems generally follow a path known as 'ecological succession', involving growth (r) where resources are plentiful, and conservation (k). Most socio-ecological structures are not scale invariant but are built on combinations of slow and fast

Table 17.2 Case studies of socio-ecological systems

Location of case study (researcher; cited in Walker et al., 2006)	Socio-ecological characteristic	System change	Vulnerabilities	Resilience
Causse Méjan, France (Etienne & Bousquet)	Ecosystem diversity is totally dependent on grazing.	Pine trees from neighbouring forest stands are invading the steppic grasslands. Agriculture has destroyed many flatlands.	New social groups, including forest owners, secondary residents.	Keeping alive the Causse culture and traditions of environmentally friendly farming through sharing labour and knowledge and the co-evolution of habitat and farming.
Caribbean coral reefs (Hughes, 2003)	Coral reefs have been on a trajectory of serious decline. In the 1950s a single species of sea-urchin was keeping macro-algal blooms in check. In the 9170s a disease outbreak led to the catastrophic loss of urchins, precipitating blooms that persist today.	Collapse of many reefs due to overharvesting, pollution, disease and climate change. Loss of key habitat forming *Acropora* species.	Long-term trajectory of a shift from fish- to echinoid-dominated destructive herbivory.	Reefs exhibit numerous alternate states, but the resilience of these is unknown. Experiments with No Take Areas and protection of hotspots may help locally, but are unlikely to stem region-wide loss of resilience.
Dry spiny forests, southern Madagasar (Elmqvist)	High degree of endemism; inhabited by the People of the Thorn Bush who protect dense forest patches through strong informal institutions.	Fragmentation and loss of forest due to insecure land rights.	Tensions between Christianity ad customary institutions, government policies and local informal arrangements.	Strong social capital and the large capacity of spiny forests to regenerate.
Everglades, Florida (Gunderson, 2001)	Internationally recognised wetland, which was historically partitioned into agricultural, recreational and conservation areas. Area is now maintained through canals, pumps and levees.	Ecological crises brought on by changes in water quality and quantity caused by the volume and timing of flooding.	Institutional reformation and realignment, plus the need for large-scale, expensive, technologically based solutions. Conflicts over water use amongst institutions and actors.	Example of a perversely resilient social system based on conflict and a formal closed network of government agencies and policies.
Gorongosa National Park, Mozambique (Lynan)	Park was home to large herbivore and carnivore populations but these were decimated in the war of Independence in the 1980s. Now home to some 500 bird species and 10 000 people.	The loss of major species.	There are no schools, clinics or facilities for the people living in the park who provide local protection to the ecosystem. No local enforcement of existing conservation policies in the buffer zone.	Remains one of the prime protected areas in southern Africa.
Goulburn-Broken Catchment, Australia (Ryan)	Sub-catchment of the Murray River. Climate temperate with sparse vegetated plains. Originally occupied by Aboriginal people but subsequently populated by Europeans after the discovery of gold. Today heavily agricultural.	Irrigation infrastructure and clearing of more than 70 % of the native vegetation cover have substantially altered the hydrological balance.	Climatic variation causing changes in vegetation and groundwater recharge. Substantial land-use change, with dry-land areas delivering significant salt and nutrient loads to the waterways. Increasing demand for non-consumptive water and conflicts amongst property rights.	Property rights and downstream accountability in place. Costs of maintaining the regime mounting, resource base degrading, regional economy more brittle. System more vulnerable to shocks and disturbance (Anderies et al. 2006).
Northern Highland Lakes District, Wisconsin (Petersen & Carpenter)	Pristine wilderness with management focused on protection and promotion as a wilderness tourist destination.	Lakeshore development for tourism and second homes. Invasive species including rainbow smelt, rusty crayfish and Eurasian milfoil have reduced the quality of fishing and boating. Proliferation of suburban life.	Stakeholders with many divergent views. Natural resource management has been slow to adjust to ecological and social change. Invasive species and eutrophication.	Multiple states and thresholds are known relating to eutrophication, collapse of fisheries, trophic cascades, woody habitat and inertia of long-lived predator and tree populations. Non-reversible threshold may be caused by species invasions and a shift from old-growth timber harvesting to pulpwood rotation.

Source: Adapted from Walker et al., 2006. Detailed descriptions of each case study can be found at www.resalliance.org.

processes; panarchy is the term that describes how these different types of processes operate across time and space scales. Disturbances can lead to another connected regime in which resources that have been historically bound-up are released (Ω) and the fundamental structure collapses; this is followed by a phase of re-organisation (α) in which novel structures can take hold leading to another growth phase in a new cycle. There are many examples of disturbances causing shifts in this way, including forest fires (Dublin et al., 1990), forest pest outbreaks (Ludwig et al., 1978), algal blooms in eutrophied aquatic systems (Carpenter and Brock, 2004) and droughts.

17.4 Socio-ecological systems — institutional fit and resilience

In this section we look at socio-ecological systems from the perspective of institutional fit and resilience as sources of anticipation and adaptive capacity. As Elinor Ostrom (2005), Carl Folke and colleagues (Folke et al., 2007) have pointed out, the lack of institutional fit can confound the effectiveness of stewardship of ecosystem services and resource management, and can lead to unexpected surprises, excessive rent seeking and high transaction costs (Kofinas, 2009).

Despite innovations in institutional arrangements and a greater awareness of the importance of the need for more effective forms of governance, the loss of trust in bureaucracies has been growing. Deeply embedded differences in attitude towards conserving ecosystems versus exploiting resources have led to highly politicised public debates around false dichotomies, such as choosing between protecting the environment and employment or energy, or diversionary arguments such as the tragedy of the commons. In the case of the collapse of the northern cod, the commons were neither open-access or unregulated, but the use of this discourse meant that the only solution sought was downsizing of the fleets, rather than a closer examination of the complexity of the causes of the problem, such as flawed scientific advice, vested interests and government priorities.

The key question is what happens when there is a real crisis, brought about by sudden change in a resource or ecosystem? Do those institutions with most to lose become destabilised or do they attempt to renegotiate their power relations? Do those with most to gain seize the opportunity for restructuring?

In Newfoundland it has been the social structure of the fishery that has collapsed even though the inshore fishermen potentially had the most to gain in the aftermath. The resource scientists and managers on the other hand have only made modest changes despite being at the core of the problem. This might suggest that modern science is much stronger and more deeply embedded as a social and political authority than generally assumed. It means that it will take more than the collapse of a resource or a shift in an ecosystem to displace the existing form of authority that has been built on a certain control of science. It also raises questions about how to build up institutional fit and resilience and develop effective science-policy interfaces.

17.4.1 Institutional fit and governance

Institutional infrastructure, along with governance and leadership, heavily influence our capacity to manage complex systems and cope with abrupt change. It has been the lack of institutional fit that has often confounded the effectiveness of the stewardship of ecosystems and the systems they provide, and led to unexpected surprises, excessive rent seeking and high transaction costs. The causes of a lack of institutional fit are many and can stem from mere folly (Tuchman, 1984), complexity, uncertainty about roles, a lack of ownership and property rights, institutional frailty and vested interests.

An example of the consequences of the confounding effects of a poor institutional fit can be seen in the 1997 legal case of Nunavut Inuit concerning the Canadian Fisheries Minister's decision to increase the turbot quota against the advice of the NAFO scientific council and then to assign the additional tonnage to his own constituents rather than to the Inuit of the Nunavut region or Denmark ([2]). It was said in an internal memo to the Fisheries Minister that the Canadian government could be seen as hypocritical by the international community because it exhorts others to share the burden of conservation but was unwilling to do likewise.

Judge Douglas Campbell set aside the Minister's decision and referred the matter back for

([2]) Nunavut Tunngavik Inc. v. Canada (Minister of Fisheries and Oceans) (C.A.), [1998] 4 F.C. 405. 13 July 1998 (http://reports.fja.gc.ca/eng/1998/1998fc22910.html).

reconsideration of the quota. The Minister appealed, stating that he possessed:

> 'absolute discretion… to issue leases and licenses for fisheries or fishing. The rationale for such discretion is that Canada's fisheries are a common property resource belonging to all the people of Canada and licensing is a tool to manage fisheries which is given to the Minister whose duty it is to manage, conserve and develop that resource in the public interest. … The actual exercise of such discretionary power is influenced by numerous fluctuating policy concerns which go beyond the necessary issue of conservation and protection of fish to include cultural, political, scientific, technical and socio-economic considerations or policies.'

The Court of Judicial Review rejected the appeal for reasons that the Minister had not acted lawfully, but it made clear that the Court was 'not to become an academy of science to arbitrate conflicting scientific predictions, or to act as a kind of legislative upper chamber to weigh expressions of public concern and determine which ones should be respected… [it] is concerned with the legality of the ministerial decision resulting from an exercise of discretion, not its opportunity, wisdom or soundness'. There was clearly a lack of institutional fit between the legality of the defined role of the Minister and a legal framework in which the Minister's actions could be judged on the basis of evidence of fairness and long-term sustainability of the resource.

Over the past two decades, a number of important institutions and initiatives have been created to bridge the science-political divide and support international agreements on managing and protecting our global resources. These range from the UN Convention on Biological Diversity and the UN Conference on Straddling Fish Stocks and Highly Migratory Species to initiatives such as the Millennium Ecosystem Assessment, IPBES (International Platform on Biodiversity and Ecosystem), TEEB (The Economics of Ecosystems and Biodiversity) and ABS (Access and Benefit Sharing). These are primarily aimed at reducing the likely impacts of a growing human population and climate change on ecosystems and ensuring the sustainable use and equitable distribution of natural resources. However, as we show in the case study on European Union fisheries, even with highly cohesive, well-resourced institutions the consequences of a poor institutional fit remain one of the largest obstacle to the resilience of our fisheries (Panel 17.2).

There are a number of structures of governance; including the minimal state, corporate governance; new public management; good governance; sociocybernetic systems and self-organising networks (McGlade, 2001). This last type involves complex sets of organisations drawn from the public and private sector and is particularly interesting in relation to the governance of resources. The key to understanding their importance comes from the observation that integrated networks can resist government steering; they develop their own policies and mould their environment. This leads to interdependencies between organisations in order to exchange information and negotiate shared resources and a significant degree of autonomy. In the end, this form of governance can hollow out the state through privatisation and by limiting the scope of public intervention. A manifestation of this type of governance is swarms of amorphous groups that link together to tackle single issues such as dolphin-friendly tuna fishing and anti-sealing and whaling. In managing resources it is necessary to understand that governance is becoming increasingly operative, where lines of authority are less formal, legitimacy is more ambiguous and where people are choosing when and where they want to engage in collective action.

The majority of fisheries are operated through instrumental actions, i.e. where technical rules are developed and implemented. However, in many of the case studies listed in Table 17.2, the communities manage the resources through consensual actions and norms, such as religion, deity or faith, rather than legal ones. The effectiveness of this type of action and user participation is that in times of crisis, participants learn more quickly and show a greater capacity to adapt and even transform. For example, after the initial water-table crisis in the Goulburn Broken Catchment in the 1970s, conflicts gave way to networks that connected people and interests to deal with issues of flooding, waterlogging and drainage (Anderies et al., 2006). Leaders emerged to form committees to represent the concerns of the various networks throughout the catchment. They pooled existing knowledge, identified gaps and invested in research and effectively lobbied government agencies for support. Despite all this, government leaders opted for adaptation rather than transformation.

By contrast, the ecological crises in the Florida Everglades (Gunderson, 2001) which had originally given rise to a network dominated by government agencies and formal policies, gradually led to a network of government and non-governmental

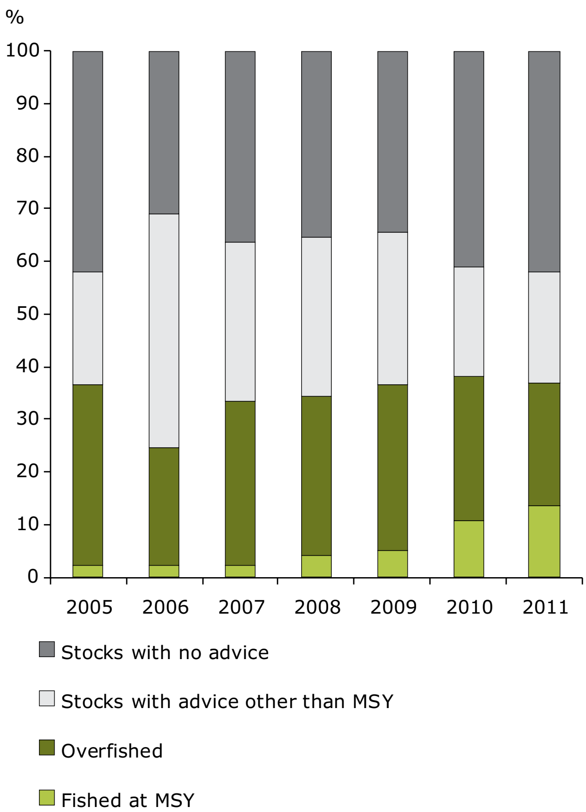
Panel 17.2 Knowledge-based management of EU fisheries — how much is scientific evidence being used?

Constança Belchior and Johnny Reker

Despite being managed under one of the most complex and expensive science-based management systems in the world, since 1983, the condition of Europe's fish stocks has continued to worsen (O'Leary et al., 2011; EU, 2011). The 2002 and 2012 reforms of the EU Common Fisheries Policy (CFP) aimed to deal with the failure to achieve the core objective of ecological, economic and social sustainability, where 72 % of all assessed EU fish stocks were estimated to be overexploited, and over 20% fished beyond safe biological limits, i.e. with a greater risk of collapse. (In the north-east Atlantic the number of stocks known to be overfished fell from 94 % to 63 % from 2004 to 2010, compared to 82% in the Mediterranean) (EC, 2010, 2011a).

One problem is that data of sufficient quality to support scientific advice on MSY and overfishing is missing for approximately two-thirds of the stocks for which quotas (Total Allowable Catches) are set in the north-east Atlantic (EC, 2011a) (Figure 17.1). This figure was intended to show fishing opportunities, but inconsistencies in the data on different stock parameters (e.g. number of stocks with no or insufficient data, or for which an excess TAC was set) point to the underlying difficulty of producing coherent assessments. For example, data quality and availability is so poor in the Mediterranean, that in 2010, only 16 out of 102 candidate species could be assessed (EC, 2010). Part of the problem is that Member States have not provided the relevant scientific data despite there being a legal responsibility to do so (EC, 2011a), introducing greater uncertainty into the scientific advice, and thus further undermining its credibility (Piet et al., 2010).

Figure 17.1 Trends in status and advice setting for north-east Atlantic fish stocks between 2005 and 2011



Source: EEA, based on EC, 2011a.

There have been many analyses of why EU fisheries management has not been successful (e.g. Sissenwine and Symes, 2007; Khalilian et al., 2010; EC, 2009; EU, 2011). The main conclusion, alongside the lack of scientific knowledge and ineffective management options to restore fish stocks and fisheries to profitable and equitable conditions, is the very nature of the decision-making process (Villasante et al., 2010; Piet et al., 2010; O'Leary et al., 2011). Overall, scientific advice has been largely overruled when setting fishing opportunities for EU fish stocks; between 1987 and 2006, the TACs only matched scientific advice in 8 % of the assessed stocks (Piet et al. 2010), and were consistently set well above the scientifically advised level by an average of 47 % since 2003 (EC, 2011a).

The actual impacts of such mismatches remains uncertain (O'Leary et al., 2011), but it is likely to be significant given the cumulative impacts of overfishing and increased capacity on the integrity of the wider marine ecosystem (Anticamara et al., 2011). For example, it has been estimated that the recovery time for benthic habitats in areas in the Greater North Sea where there was low natural disturbance, was between 7.5–15 years following only one pass of a beam trawl (OSPAR, 2010). In German waters some areas have experienced up to 4 000 hours of beam trawling (Pedersen, 2009). Fisheries are thus a significant contributor to pressures on European marine biodiversity where only 2 % of the species and 10 % of the habitats reported under the Habitats Directive are considered to be in favourable conservation status (HELCOM, 2010; EEA, 2010).

Panel 17.2 Knowledge-based management of EU fisheries — how much is scientific evidence being used? (cont.)

As a response to the current situation, an ecosystem-based approach to management has become one of the CFP's objectives under the EU Marine Strategy Framework Directive. The intention is to implement more holistic, integrated management strategies to achieve EU ambitions on securing healthy and productive marine ecosystems, including halting the loss of biodiversity, ensuring sustainable economic growth and improving resource efficiency.

The ecosystem approach sets out a framework for understanding the socio-ecological system, where the hidden long-term costs or externalities and subsidies are accounted for, in order that options that generate more societal value can be prioritised (e.g. ISU, 2012; Crilly and Esteban, 2011). In a recent study on the potential benefits of restoring 43 European fish stocks to their maximum sustainable yield from current levels (Crilly, 2012), the authors found that it could generate 3.53 million tonnes of additional landings, and an additional value of EUR 3 188 billion annually. This is more than five times the annual fisheries subsidies paid to EU Member States), and could in turn support the creation of more than 80 000 jobs in the sector in the EU.

Thus it seems that there is sufficient available knowledge to underpin informed decision-making to support an ecosystem approach to fisheries, but also one that prioritises solutions that will benefit society the most. At a time where the EU already depends on substantial imports to meet more than 65 % of total EU consumption of seafood (EC, 2011a) and where food security is becoming a global growing concern, managing fish stocks sustainably provides a competitive advantage to the EU which should not be overlooked by individual or national interests. However, as previously discussed, this is unlikely to happen as long as decision-making in the CFP allows for short-term economic interests to compete with and outcompete long-term sustainable and precautionary scientific advice at the very beginning.

The question remains: has Europe learned from past experiences? The short answer is yes, but we are still not reacting to our knowledge fast enough. Fisheries are still not being managed sustainably and the majority of European fish stocks are still overfished. Furthermore, there are considerable gaps in our knowledge regarding the status of fish stocks, yet on average TACs are still set well above scientific recommendations showing a disregard for scientific advice and also for the precautionary approach. From a societal perspective, further evidence also shows that overfishing also means the EU is getting much less out of its fish stocks than if they were restored and sustainably managed. This situation is mirrored at a global level, where the 'sunken billions' in world fisheries due to excess fishing capacity have been estimated at 50 billion US dollars annually (World Bank, 2009).

The new CFP proposal (EC, 2011b) features ambitious measures from the European Commission, namely the commitment to establish management measures 'in accordance with the best available scientific advice' and no longer just 'based on scientific advice'. Also, it proposes to give more power and responsibilities to the actual stakeholders, making them more accountable for the resource they are being allowed to exploit, alongside other measures which aim to better integrate the precautionary and ecosystem approaches into the CFP. Overall, it sets out a more flexible mechanism that should allow it to cope better with the inherent diversity in both EU fisheries and the changing marine environment.

It is questionable, however, whether a management system in which scientific evidence is consistently being undermined, either by lack of compliance by Member States in delivering sound fisheries data, or by disregarding it due to narrow political interests and negotiations, will ever be able to deliver its objective of long-term sustainability. This is a point recognised by the European Parliament in its review of the proposal for the new CFP regulation (EP, 2012). Therefore one of the greatest challenges in managing EU fisheries and specifically the EU 2012 CFP reform remains the level of respect for scientific advice as a fixed boundary condition for natural capital when negotiating political agreements.

A socio-ecological management system solidly grounded in science is undoubtedly a more objective way to manage natural resources following established criteria, whilst also coping and adjusting to uncertainties. Together with the precautionary approach, it could help to set out a long-term transparent management system for fisheries, unlike the vested political decision-making system that prevails in the CFP today. Governance arrangements in and around EU fisheries will need to respect scientific advice and ensure the compliance of national data obligations to support it, as well as allowing for more transparent and inclusive decision-making that favours a wider sectorial and public engagement. This could be through broader representative constituencies and greater societal benefits as opposed to the current practice that favours the exhaustion of natural capital whilst leading the fisheries sector towards a deteriorating future.

groups which opted for transformation. New institutions, technological solutions were created on the back of significant levels of investment. As many of the cases indicate, two of the most critical factors for adapting to change and transformation are institutional fit and leadership.

17.5 Future prospects

This final section looks at some of the key lessons that emerge from the various case studies and reflects on how they might be used to improve resource management and ecosystem stewardship in the future. The six major lessons that resource managers and those living in a particular socio-ecological system need to consider to ensure that sudden, abrupt changes do not lead to catastrophic collapse are as follows:

- Close observation of ecosystems and natural phenomena.
- Development of a diversity-oriented approach to resource management that reflects the complex causality of the real-world context.
- Widening the sources of information and knowledge about the dynamics of socio-ecological systems.
- Reducing delays between early warnings and actions.
- Developing a deeper understanding of the full adaptive cycle of the ecosystem and resource base being managed.
- Building up the learning, leadership and innovative capacities in the institutional and societal context to enable transformation rather than only adaptation. As seen in so many of the case studies there is a need for greater participation and transparency regarding vested interests.

The evidence used to develop management advice will also need to be far more explicit about the dynamics of processes across different time and space scales and uncertainty. Resource managers and the community at large will need to develop the skills and capacities to create consensus — and where not possible compromises (van den Hove, 2006) — about how to handle uncertainty and which diagnostic criteria and metrics will be used to elicit action in the case of early warning signals (Table 17.3). For example, thresholds in water use, size of patches of forest clearance, wildfire management and the extent of agistement have all been shown to be critical activities in determining the resilience of the socio-ecological systems examined.

Table 17.3 Examples of early warning and possible outcomes and responses

Type of early warning	Possible outcome	Examples	Possible solutions
Spatial	Potential rapid spread via multiple unknown pathways	Bird flu; various fungal diseases, invasive species	Establish broad jurisdictional authority to monitor spread and develop potential policy actions; develop in situ monitoring, and multi-scale and multi-interaction models
Temporal	Potential spread of problem on different time scales linked to ecological and physiological processes leading to collapse and a different regime	Drought, over-exploitation of key resources over time, invasive species	Develop an understanding of the adaptive cycle, multiple pathway and time-dependent models and ensure appropriate in situ monitoring of human and ecological systems
Demographic	Potential long-term impacts on the health of the ecosystem and human population	Age-related diseases	Develop more intense monitoring of entire adaptive cycle and long-term monitoring of age-related processes
Threshold behaviour	Potential for issue/events to create socio-ecological regime shifts with significant long-term economic and/or ecological impacts including irreversibility	Sustained over-harvesting of fish stocks leading to collapse of keystone species; runoff from nitrogen fertilizer leading to eutrophication	Develop integrated assessments with scenario analyses that include the potential to identify long-term physiological and ecological shifts
Cascading effects	Potential that problem effects cannot be buffered or can be amplified between domains leading to significant socio-ecological impacts	Reduction in the polar ice cap opens up northern sea routes to shipping; creating new forms of land use change and local harvesting of resources	Develop multi-jurisdictional approach to manage changes; develop integrated assessments and scenario analyses to understand the multi-dimensional dynamics and resilience of the socio-ecological systems; establish new monitoring systems

The fundamental assumption that the existing institutional landscape is fit for purpose should also be examined carefully. As Hobbes (in *Leviathan*, 1651) and Machiavelli (in *The Prince* ca. 1514) well understood, user participation and the frameworks of power are the most important elements to understand when mapping out the rights of the community. In ecosystem and resource management there are a number of regimes including: laissez-faire; market regulation; communal governance; state governance and international governance (generalising from McCay, 1993). As shown in each case study, property rights and the authority to constrain exploitation are at the heart of the matter and inevitably come under intense pressure during a crisis. Ensuring the resilience of socio-ecological systems requires an explicit understanding of the rights and responsibilities during periods of transformation.

A final observation is that many interventions in resource management are made on the basis of a belief that these would have predictable outcomes. The assumption has been that all interactions can be adequately understood and that all future states are contained within the present structure of the socio-ecological system. The hubris of this type of thinking parallels that of the financial world in which a constrained set of tools and those using them (known as 'quants') created short-term indebtedness, mispricing of securities and a false protection against unknowable uncertainties. Ultimately, the two worlds of finance and resources became intertwined via market volatility and the mispricing of commodities, and led to the catastrophic consequences of the economic crisis all over the world (McGlade, 2009).

We must avoid repeating the mistakes of the past, as these will ultimately result in the collapse of ecosystems and social crisis. Instead, we should acknowledge that resilience in nature contains the seeds not only of surprise but also of transformation.

Box 17.2 Definitions

Adaptive management
Adaptive approaches to management are defined as those that recognise uncertainty and encourage innovation while fostering resilience (after Chapin et al., 2009). It is often considered as an approach based on learning by doing and implemented through careful and regular observation of socio-ecological conditions, drawing on these observations to improve the understanding of the system's behaviour, evaluation of the implications of emergent conditions and various options for intervention and action and responding in ways that support the resilience of the socio-ecological system.

Configurational complexity
Characteristic of diversity-oriented analyses, where context matters. Cases are examined as configurations in which all relevant aspects are looked at in the form of combinations. Such analyses concentrate on the specific features of individual cases, identifying those that are most relevant, whilst considering how those features cohere with each other as distinct types (McGlade, 2003)

Counterfactual thinking
The dependence of *whether*, *when* and *how* one event occurs on *whether*, *when* and *how* another event occurs and the possible *alteration* of events.

Diversity-oriented approach
Analyses of socio-ecological systems based on detailed case studies using measurements of many system-specific attributes with configurational complexity (McGlade, 2003).

Earth System
The Earth System is defined by Schellnhuber (1999) as the conglomerate formed by human civilization and its planetary matrix, i.e. all parts of the Earth that interact with the members and manifestations of our species.

Institutional fit
This refers to the linkages between ecosystems and socioeconomic and cultural systems in their local, regional, national, continental and global contexts. The use of the word 'fit' in English refers to a match of sizes, e.g. if the shoe fits, then it is a good match for the foot. Social and ecological systems and processes have sizes too: they have spatial and temporal dimensions which interact and depend on each other within a specific geographical space. The degree to which these match is meant by 'institutional fit.'

Box 17.2 Definitions (cont.)

Panarchy
Describes the way in which nested evolving hierarchical systems with multiple interrelated elements interact on different time and space scales (Gundersen and Holling, 2001). Panarchy is the structure where natural systems (e.g. fish stocks) and of humans (e.g. capitalism), as well as combined human-natural systems (e.g. institutions that govern fisheries resource use), are interlinked in continual adaptive cycles of growth, accumulation, restructuring, and renewal. These transformational cycles can occur on scales ranging from a drop of water to the biosphere, over periods from days to geologic periods. Understanding these cycles and their scales can help identify leverage points to foster resilience and sustainability within the overall system.

Polythetic scheme
Characteristic of a variable-oriented approach in which the cases that are grouped together can differ substantially from each other for one or more attribute as long as they are similar for the majority of attributes selected by the researcher (McGlade, 2003).

Regime shift
An abrupt large-scale transition to a new state or stability domain characterised by a very different structure and feedbacks (Chapin et al., 2009).

Resilience
The capacity of a social-ecological system to absorb a spectrum of shocks or perturbations and to sustain and develop its fundamental function, structure, identity, and feedbacks as a result of recovery or reorganisation (Walker and Salt, 2006; Chapin et al., 2009).

Tipping point and tipping elements
Tipping points are popularly understood as a situation where at a particular moment in time, a small change can have large, long-term consequences for a system, i.e. popularly understood as 'little things can make a big difference' (after Gladwell, 2000). Lenton et al. (2009) offer a more formal definition for the earth system, introducing the term 'tipping element' to describe subsystems of the Earth system that are at least sub-continental in scale and can be switched — under certain circumstances — into a qualitatively different state by small perturbations. The tipping point is the corresponding critical point — in forcing and a feature of the system — at which the future state of the system is qualitatively altered. The term tipping point has been used to describe a variety of phenomena, including the appearance of a positive feedback, reversible phase transitions, phase transitions with hysteresis effects, and bifurcations where the transition is smooth but the future path of the system depends on the noise at a critical point.

Variable-oriented approach
Analyses of systems based on the measurement of a small number of attributes relating to global patterns emerging from surveys of a large number of cases (McGlade, 2003).

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