Ecological Economics 84 (2012) 15–22

Contents lists available at SciVerse ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Survey

Regime shifts and management

Anne-Sophie Crépin [a,b,*], Reinette Biggs [b], Stephen Polasky [a,c], Max Troell [a,b], Aart de Zeeuw [a,d]

[a] The Beijer Institute of Ecological Economics, Sweden
[b] Stockholm Resilience Centre, Sweden
[c] Departments of Applied Economics and Ecology, Evolution and Behavior, University of Minnesota, USA
[d] Tilburg Sustainability Center, Tilburg University, The Netherlands

ARTICLE INFO

Article history:
Received 8 August 2011
Received in revised form 31 August 2012
Accepted 1 September 2012
Available online 13 October 2012

Keywords:
Regime shift
Management
Valuation
Social–ecological systems

ABSTRACT

Regime shifts are substantial reorganizations in system structure, functions and feedbacks, which can lead to changes in the provision of ecosystem services with significant impacts on human well-being. Recent research has documented cases of regime shifts in local and regional systems and there is mounting concern about regime shifts of global significance. In this paper we discuss management of social–ecological systems in light of the potential for regime shift. Management that increases system resilience and lowers the probability of regime shifts is beneficial when regime shifts are likely to reduce human well-being. It may not always be possible to avoid harmful regime shifts, so building capacity to adapt should a regime shift occur is beneficial too. Adaptive management can help reduce uncertainty about the likelihood of regime shifts, how this likelihood can be affected by management action, and the impact of regime shifts on well-being. Linking scientific understanding with decision-making is important but distributional consequences can impede decision making and action.

1. Introduction

The dynamics of human activities and ecosystems have become tightly interlinked at local to global scales (Levin, 2003; Lutz et al., 2008; Steffen et al., 2004). Evidence suggests increased occurrence of regime shifts—substantial reorganizations in system structure, functions and feedbacks—in social–ecological systems (Carpenter, 2003; Walker et al., 2004). Regime shifts can occur in social systems (e.g., the so-called Arab Spring, see http://en.wikipedia.org/wiki/Arab_Spring.), in ecological systems (e.g. algae invasion in coral reefs in Jamaica 1998), and in interlinked social–ecological systems (Berkes and Folke, 1998). In this paper, we focus on regime shifts that take place in ecological systems. However, the likelihood of regime shifts occurring and the resulting impacts on human well-being if they do occur are affected by management and other aspects of the social system.

Regime shifts pose several difficult challenges for management. Regime shifts in ecosystems can result in large, abrupt, and persistent changes in the provision of ecosystem services, and can therefore have significant impacts on human well-being (Millennium Ecosystem Assessment, MA, 2005; Stern, 2006). Regime shifts at the global level could have profound impacts on future well-being (Rockström et al., 2009). Regime shifts can also impact the distribution of well-being between people within and between generations and may give rise to new conflicts over resource use. Regime shifts are often hard to predict, especially if they have not been previously observed. (Carpenter, 2003; deYoung et al., 2008; Scheffer, 2009). Once thresholds are crossed it can be difficult to go back to the original regime because new system dynamics and feedback effects keep the system locked into the new regime (Nyström et al., 2012; Scheffer et al., 2001). Close to a threshold, large dramatic changes can be triggered by small changes in variables. Scheffer et al. (2001); Muradian (2001) and Folke et al. (2004) contain useful reviews of regime shifts in ecological systems.

In this paper we discuss consequences of regime shifts for human well-being and the implications of regime shifts for management. We focus specifically on regime shifts that lead to large and persistent changes in ecosystem services. Our goal is to link understanding of the mechanisms underlying regime shifts to insights on how to manage systems subject to regime shifts in order to enhance human well-being. Section 2 explains the concepts and mechanisms underlying regime shifts in ecosystems, while Section 3 describes the social and economic consequences of regime shifts based on review of a few empirical examples. Section 4 discusses management approaches to cope with the challenges of managing potential regime shifts in an uncertain world. Section 5 identifies key research gaps.

2. Understanding Regime Shifts

We define a regime shift as a substantial reorganization in system structure, functions and feedbacks that often occurs abruptly and persists over time (Biggs et al., 2009; Biggs et al., 2012; Scheffer et al., 2009). Such change typically affects several of the ecosystem's state

* Corresponding author at: The Beijer Institute of Ecological Economics, The Royal Swedish Academy of Sciences, Box 50005, 10405, Stockholm Sweden. Tel.: +46 8 673 95 40; fax: +46 8 15 24 64.
E-mail address: asc@beijer.kva.se (A.-S. Crépin).

0921-8009/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ecolecon.2012.09.003

variables. Regime shifts have been documented in a variety of terrestrial and aquatic ecosystems and studied in mathematical models. Well-known empirical examples of regime shifts are listed in Table 1 and include the shift from clear to eutrophic conditions in lakes, from diverse coral ecosystems to algae-dominated reefs, and from open to closed wooded savannas (Folke et al., 2004; Gordon et al., 2008; Scheffer et al., 2001). Importantly, a particular regime (e.g. open savanna) is not a stable, unchanging condition; rather it encompasses a range of different conditions (savanna to grass ratios) in which the system maintains essentially the same basic structure and function, and produces the same suite of ecosystem services (Beisner et al., 2003; Biggs et al., 2012).

Dynamical systems theory provides insight into the mechanisms underlying regime shifts. All complex systems contain both damping (also known as negative or balancing) and amplifying (also known as positive or reinforcing) feedback loops. Over time, the many feedbacks within a system can evolve and combine in only a limited number of ways, leading the system to self-organize around one of several possible equilibrium points, attractors or stable states. A particular combination of dominant feedbacks that structure the system and lead it to evolve towards a specific attractor corresponds to a particular domain of attraction or regime (Beisner et al., 2003; Biggs et al., 2012). For example, in clear water lakes, rooted plants provide a strong damping feedback by absorbing and trapping excess phosphorous in the water column, and thereby limiting the possibility for algal blooms. However, when phosphorous levels exceed the absorptive capacity of the rooted aquatic plants, the excess nutrients in the water lead to dense growth of planktonic algae. The algae reduce light penetration, leading to the rooted vegetation's death. This in turn destabilizes the phosphorous that has been trapped in the sediments, creating an amplifying feedback that further fuels algal growth (Carpenter, 2003).

As this example illustrates, a regime shift is associated with a change in the dominant system feedbacks and entails the shift of the system from one domain of attraction to another. A regime shift typically results from a combination of an external shock, such as a hurricane or an earthquake, and gradual changes in inputs to the system (Fig. 1). Gradual changes in inputs (e. g. level of phosphorous runoff) may slowly weaken the dominant damping feedbacks that keep the system within a particular domain of attraction. Changes in the strength of the dominant feedbacks typically result in little or no obvious system changes (e. g. the types and magnitudes of ecosystem services provided) until a critical threshold is reached where a different set of feedbacks become dominant, and drive the system into a different domain of attraction. Changes in system resilience associated with a weakening of dominant system feedbacks therefore usually goes unnoticed until an actual regime shift occurs. Once the system is close to a critical threshold, a shift in dominant feedbacks can be precipitated by even a small shock to the system. These dynamics explain why regime shifts are often experienced as large and abrupt shifts in the system structure and function, and come as a surprise to the people living in or managing the ecosystem (Biggs et al., 2012; Scheffer et al., 2001).

The presence of internal system feedbacks also explains why regime shifts are hysteretic ("sticky"): once the system is in a particular regime, it tends to remain there even if the change in inputs that caused the shift is reduced or removed. Because different sets of dominant feedbacks are associated with different regimes, the critical threshold for a shift from Regime 1 to 2 often differs from the critical threshold for a return shift from Regime 2 to 1 (Fig. 2). As a consequence, regime shifts may be very difficult or even impossible to reverse. Rehabilitation work aimed at restoring a system after a regime shift may involve breaking unwanted feedbacks that become dominant and/or rebuilding or strengthening other feedbacks that promote organization around a certain attractor (Suding and Hobbs, 2009; Norström, 2010; Horan et al., 2011; Nyström et al., 2012.) The degree of reversibility in a system depends on the strength of the dominant system feedbacks, which is usually a function of multiple factors (e. g. plant types, sediment type). The degree of irreversibility of, for instance, lake eutrophication will therefore vary between different lakes, and maybe even

Table 1
Well-known examples of regime shifts and the supporting sources of evidence (based on Scheffer et al., 2001; Gordon et al., 2008; Biggs et al., 2012). Other examples of regime shifts and their impacts on ecosystems and human well-being can be found at www.regimeshifts.org.

Regime shift	Regime A	Regime B	Ecosystem services impacted	Sources of evidence for RS
Freshwater eutrophication	Non-eutrophic	Eutrophic	Freshwater, fisheries, water purification, pest and disease regulation, recreation, aesthetic values, biodiversity	Observations, experiments, models
Coastal hypoxia	Non-hypoxic	Hypoxic	Fisheries, wild animal and food plants, water purification, recreation, aesthetic values	Observations, models
Coral reef degradation	Diverse coral reef	Reef dominated by macro-algae	Fisheries, water purification, regulation of soil erosion, natural hazard regulation, recreation, aesthetic values, knowledge and educational values, spiritual and religious values, biodiversity	Observations, experiments, models
Fishery collapse	High abundance of a commercial fish species	Low abundance of a commercial fish species	Fisheries, pest and disease regulation, recreation, knowledge and educational values, spiritual and religious values	Models, observations, experiments
Bivalve mollusc abundance	High bivalve abundance	Low bivalve abundance	Freshwater, fisheries, water purification, biodiversity	Models, observations, experiments
Bush encroachment	Open grassland	Closed woodland	Livestock production, wild animal and food plants, woodfuel, timber, climate regulation, biodiversity	Observations, experiments, models
Vegetation patchiness	Spatial pattern	No spatial pattern	Livestock production, regulation of soil erosion, water regulation	Observations, experiments, models
Forest-Savanna ecosystems	Forest	Savanna	Crop production, livestock production, wild animal and food plants, timber, woodfuel, climate regulation, water regulation, natural hazard regulation, regulation of soil erosion, aesthetic values, knowledge and educational values, spiritual and religious values, biodiversity	Observations, models
Soil salinization	High productivity	Low productivity	Freshwater, crop production, livestock production, water regulation, regulation of soil erosion, recreation, aesthetic values, biodiversity	Observations, experiments, models
River channel position	Old channel	New channel	Regulation of soil erosion, water regulation, damage to trade and infrastructure	Observations, models
Arctic sea ice	Summer sea ice	No summer sea ice	Wild animal and food plants, climate regulation, water regulation, aesthetic values, spiritual and religious values, knowledge and educational values	Observations, experiments, models

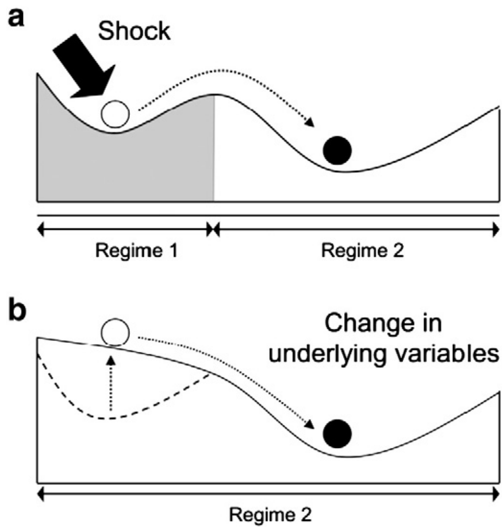

Fig. 1. Different regimes can be mathematically represented by a stability landscape with different domains of attraction (valleys). A regime shift entails a shift in the current system state (represented as a ball) from one domain of attraction to another. Regime shifts are usually due to a combination of a) a shock (e.g. drought or flood), and b) slow changes in external drivers and/or internal feedbacks that change the domains of attraction (or resilience) of the different regimes (from Biggs et al., 2012).

change over time within a particular lake (Carpenter, 2003). The same system may show linear or hysteretic input responses depending on local conditions (Fig. 3) (Collie et al., 2004).

The threshold at which a switch in dominant feedbacks and hence a regime shift occurs is similarly determined by multiple factors. For instance, the safe level of a toxic chemical may change with the concentration of other chemicals, and the safe atmospheric CO_2 level for avoiding a threshold in the climate system may change with solar activity (Lenton et al., 2008). Shifting or uncertain thresholds has important consequences for management, as discussed in Section 4.

In practice, determining whether an observed ecosystem change indeed represents a regime shift is often difficult. Knowing whether a given change is a regime shift is important for determining whether an active intervention may be needed. Sophisticated statistical techniques are required to identify significant changes in time series data because they do not always appear as visible large and persistent jumps in the data, especially in highly variable systems like the Arctic Ocean (Carstensen and Weydmann, 2012). Once the occurrence of a significant change has been recognized, the cause of this change and the feedback mechanisms underlying the shift must be established. Identifying regime shifts requires a clear definition of the system being investigated, the focal system variables of interest, and the characteristic temporal and spatial scales of the key processes underlying the dynamics of the focal variables (Biggs et al., 2012; Brock and Carpenter, 2006). For example, bush encroachment arises from changes in feedbacks related to fire and herbivory. These occur at smaller spatial scales (e.g., field or farm) over periods of a few years. The focal variable is the amount of tree cover, and the system of interest is typically an individual field or farm. When such small-scale shifts occur over extensive areas, they can trigger changes in regional atmospheric moisture recycling, which can lead to regime shifts between savanna and forest biomes at regional to subcontinental scales. While the focal variable is the same (amount of tree cover), the system of interest in this case is the regional or biome-level vegetation type and dynamics.

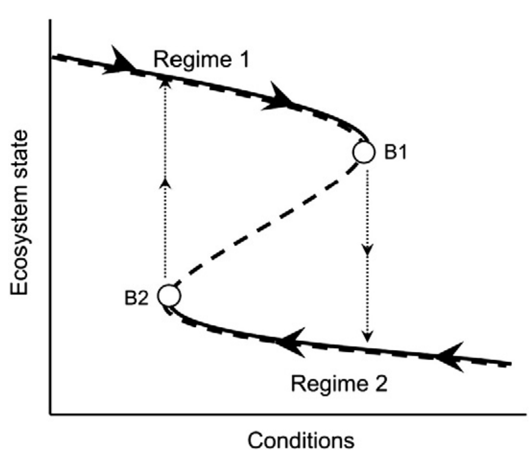

Fig. 2. Systems that undergo regime shifts often show hysteresis. If the system is in regime 1 close to bifurcation point B_1, an incremental change in conditions may induce an abrupt shift to the alternate regime 2. If one then tries to restore regime 1 by reversing the conditions, the system shows hysteresis. A return shift to regime 1 only occurs if conditions are reversed far enough to reach the other bifurcation point, B_2 (based on Scheffer et al., 2001).

3. Consequences of Regime Shifts on the Provision of Ecosystem Services

Ecosystems provide both basic life-support as well as benefits that enrich human well-being. Ecosystem services include provisioning services (e.g. crops, fish, and timber), regulating services (e.g. pollination, erosion and climate regulation) and cultural services (e.g. aesthetics, recreation and spiritual fulfillment). The state of the ecosystem (structure and function) determines the supply of ecosystem services. The supply of services combined with access and demand conditions determine the benefits humans derive from ecosystem services. Even within a specific ecosystem regime, environmental variability generates fluctuations in the supply of services (see also Section 2). Linear deterioration of ecosystems can have large potential impacts on well-being, but the changes come gradually and are thus easier for people to anticipate. In response to gradual deterioration people can either change practices to prevent further deterioration or gradually adapt to lower levels of service provision. In contrast, regime shifts can cause sudden and potentially large changes that may be difficult to anticipate. These features of regime shifts make it difficult to prevent deterioration or adapt. Here we present two examples illustrating how a regime shift can cause substantial changes in the provision of ecosystem services with significant impacts on human well-being.

3.1. Regime Shifts in Coral Reefs

Coral reefs are important ecosystems rich in marine life (Goreau et al., 2005) that produce up to 10% of all fish consumed by humans (Moberg & Folke, 1999). The most commonly identified regime shifts in coral reefs consist of shifts from coral dominated reefs to algae dominated reefs and permanent coral bleaching (Norström et al., 2009). Regime shifts in coral reefs are often associated with effects on tourism and fisheries, leading to decreased food security and unemployment. These direct impacts can also have further impacts on local economies and potentially detrimental effects on other local resource systems. The potential annual value of losses in recreational values have been estimated up to AUS$ 682 million in the Great Barrier Reef (Driml, 1994) and in 1990 the Caribbean tourism earned US$ 8.9 billion, and supported 350,000 related jobs (Moberg & Folke, 1999). The latter not exclusively related to coral reefs but to overall healthy marine environment. In the long run (decades to centuries), coral mortality will also have implication for e.g. shoreline protection (Goreau et al., 2005), which can lead to costly impacts on coastal infrastructure and the transformation of sand beaches. Increased erosion can also lead to the degradation or loss of other coastal ecosystems like mangroves and sea-grass areas, which provide valuable ecosystem services such as fish nurseries.

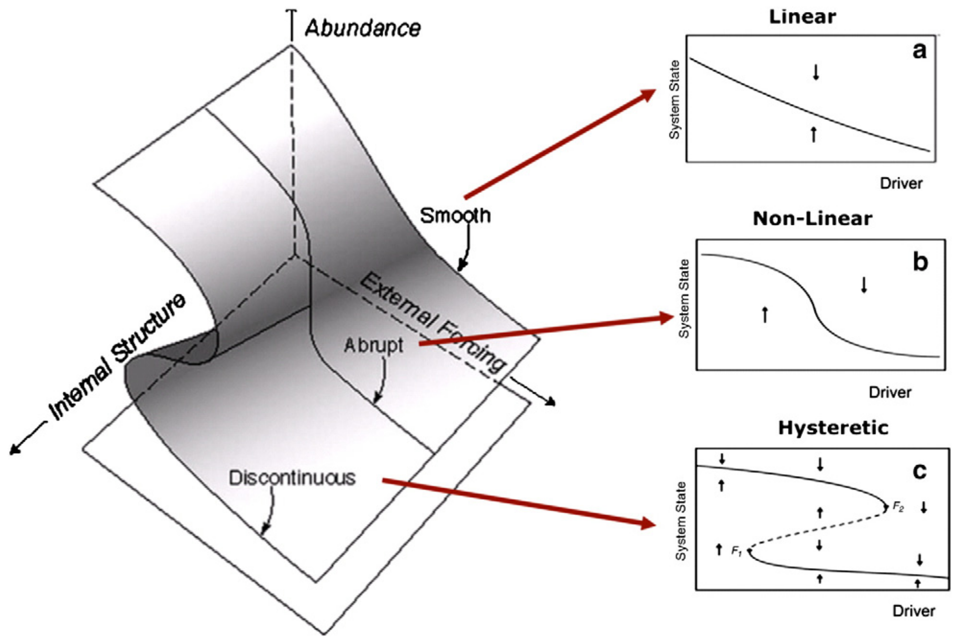

Fig. 3. Variations in the strength of the internal system feedbacks determine whether a system will respond in a linear, nonlinear or hysteretic way to changes in external drivers. Multiple factors determine the strength of the internal system feedbacks, so that a regime shift such as the collapse of a fishery may be readily reversible in one situation but irreversible in another. Figure modified from Collie et al. (2004).

3.2. The Collapse of the North West Atlantic Cod

The North-West Atlantic cod (*Gadus morhua*) was once the largest cod stock in the world, estimated at millions of tons in the late 1960s and generating annual catches of up to 800,000 tons (Fudge and Rose, 2008). In 1992 the stock collapsed to 1% of earlier levels. Overfishing was the main cause but climatic factors may also have played a role (Myers et al., 1997; Rose, 2004). Despite a long period with a general fishing moratorium, today's catches of the North-West Atlantic cod still only reach a few thousand tons (Schrank, 2005). In Newfoundland, the collapse directly affected the livelihoods of some 40,000 fishermen, fish–plant workers and associated jobs, and caused a fall in revenue from cod landings of over $200 million per year (Brubaker, 2000; Gien, 2000; Hamilton and Butler, 2001; Steele et al., 1992). This loss had significant indirect impacts on the local economy and society as well (Finlayson and McCay, 1998; Hamilton and Butler, 2001). Adaptation strategies to the ecosystem change included new investments in invertebrate fisheries and other high value species. In Newfoundland, the Northern shrimp (*Pandalus borealis*) fishery combined with snow crabs (*Chionocetes opilio*) and American lobster (*Homarus americanus*) is now much more valuable than the cod ever was (Worm and Myers, 2003).

In West Greenland fishermen turned to shrimp (*P. borealis*) and Greenland halibut (*Reinhardtius hippoglossoides*) when the cod vanished (Hamilton et al., 2000; Hvingel, 1999). After the shift from cod to shrimp, two West Greenland municipalities (Paamiut and Sisimiut) followed completely different paths. Paamiut had specialized as a cod fishing center, and when it suddenly lost its main resource it lost its economic vitality and there was a subsequent decline in population due to out-migration. Sisimiut, 500 km farther north, was less specialized and the fishermen targeted multiple species, including shrimp. The cod declined and as shrimp became the dominant catch, Sisimiut grew rapidly (Hamilton et al., 2000; Rasmussen and Hamilton, 2001).

There are now some signs of cod stocks recovering but to what extent and how this will influence the existing fishery is too early to say. This example illustrates the difficulties of evaluating the socio-economic impacts of regime shifts.

4. Policies and Management with Regime Shifts

The potential of regime shifts raise a number of issues for management. One management objective should be to reduce the risk of regime shifts that have harmful impacts on well-being, or encourage shifts with beneficial impacts (Section 4.1). It may not always be possible to avoid harmful regime shifts, so a second management objective should be to build capacity to adapt should a regime shift occur (Section 4.2). In the context of climate change, the first objective corresponds to mitigation while the second objective corresponds to adaptation. Folke et al. (2010) use terms slightly differently and refer to adaptability as adjusting management to remain with a particular regime and transformability as changing management to better fit with conditions in a new regime. Another important element of regime shifts is uncertainty. There may be uncertainty about the likelihood of regime shifts, how this likelihood can be affected by management action, the structure and function of the new regime and the impact of regime shifts on well-being. Adaptive management strategies can be used to learn about system dynamics and reduce uncertainty (Section 4.3). Finally, uncertainty combined with the distribution of costs and benefits across different groups of people, both now and in the future, complicates the politics of managing systems with potential regime shifts (Section 4.4).

4.1. Reducing the Probability of Regime Shift

The likelihood of a regime shift is determined by how far the state of the system is from a critical threshold and the magnitude of potential shocks that alter the state of the system (Fig. 1 illustrates this in one dimension). To reduce the probability of a regime shift, management strategies can aim to: a) increase the average distance of the state of the system from a threshold (e.g. Fig. 2), b) diminish the magnitude of shocks, or c) gather information about the likely location of thresholds or the magnitude of shocks.

If the mechanisms underlying a particular regime shift are understood, it may be possible to monitor inputs into the system or internal system variables directly and provide warning when they approach levels at which a regime shift becomes likely. For example in Australia, clearing native vegetation has led to rising groundwater table levels. Groundwater has little or no impact on agricultural productivity until the water table reaches about two meters below the surface. At this point, capillary action draws water to the surface, leading to salinization of the topsoil and dramatically reducing crop growth. Management actions have been put in place to keep water tables from rising to the two meter level. Pumps have been installed and in some places native vegetation has been restored. The closer the water table is to the two meter level the more likely that a shock such as a large rain event will push the water table up past the critical level (Walker et al., 2010). Managing the system with an adequate margin of safety reduces the risk that the water table will rise to the critical level but tend to increase costs (e.g., additional pumping costs). Optimal management, in the sense of optimizing expected social welfare, requires balancing these costs with the reduced risks. Because providing a margin of safety is more costly, optimal management will reduce but not eliminate the probability of regime shift (Peterson et al., 2003).

Even with deterministic regime shifts, if mitigation costs are too high a manager may simply allow a regime shift to occur (Brock and Starrett, 2003). In an optimal control problem with two saddle-point-stable steady states, initial conditions may determine whether it is optimal to move to one or the other steady state. In such a problem there is a point where the policy maker is indifferent between moving toward one or the other steady state. Such a point is called an indifference threshold or a Skiba point in one dimension (Brock and Starrett, 2003; Mäler et al., 2003; Skiba, 1978; Wagener, 2003). In higher dimensions there can be a line or a manifold of indifference or Skiba points (Crépin, 2003; Crépin, 2007; Grass et al., 2008). Brock and Starrett (2003) demonstrated that whether it is optimal to manage a lake in a clear state or to allow it to become eutrophic depends on initial conditions in the lake. Similarly the initial condition of a specific boreal forest patch will determine whether it is optimal to manage it for timber production or for moose hunting (Crépin, 2003). The indifference threshold point at which optimal management switches from aiming at one regime to aiming at another one typically differs from the ecosystem thresholds because optimal management also factors in costs of actions and impacts on human well-being under alternative regimes.

Management strategies that bolster diversity and redundancy can help ensure that vital system functions are maintained even in the face of unexpected shocks to the system (Elmqvist et al., 2003). For example, reducing the number of species can make the system more vulnerable to shocks such as a virus that reduces the population of a key species essential for system function (Crépin et al., 2011; Norberg et al., 2001). High species diversity within the functional group of herbivores on coral reefs increases response diversity and thereby resilience because the different species of fish and sea urchins that graze on algae increase the probability that the grazing function stays intact during shocks such as a virus outbreak (Hughes et al., 2007; Nyström et al., 2000).

In many cases, several factors contribute to the likelihood of regime shift. For example, the risks of coral bleaching is thought to be affected by water temperature, ocean acidification, over-fishing, and terrestrial-based pollution (Hughes et al., 2003). Which factors managers should concentrate their efforts upon depends on the relative importance of the factor, where the manager can have the most influence as well as the relative costs of influencing particular factors. In protecting coral reefs, given the difficulty of addressing global climate change and ocean acidification, it may the best for local managers to focus on reducing nutrient and sediment loadings and fishing pressure.

4.2. Adapting to Regime Shifts

Beyond actions to reduce the probability of regime shift, foresighted managers also should be prepared to adapt should a regime shift occur. Adaptation can take the form of actively promoting regime shift back towards a more favorable regime, or adjusting to conditions under the new regime.

The ease with which a system may be returned to the original regime depends in part on when actions are undertaken and on an understanding of the nature of the feedbacks maintaining the system in an unwanted state. It may be possible to react quickly and return to the original regime before new system feedbacks become fully established that make a return difficult to accomplish (Nyström et al., 2012). For example, it may be possible to eradicate an invasive species before it becomes widely established, but virtually impossible once it is fully established. Successfully re-crossing a threshold often requires a capacity to react quickly and with enough strength to reverse the pull of the system in a harmful direction. The components of this type of management are similar to discussions of early warning and action to avoid a regime shift discussed in Section 4.1.

Being prepared to take action may also mean being aware of windows of opportunity in the policy realm (Olsson et al., 2004) as well as potential changes in the ecological realm. For example, in South Africa, the water law reform (National Water Act, Act number 36 of 1998) addressed sustainability and environmental integrity thanks to a long preparation phase by scientists and a window of opportunity due to democratization (Biggs et al., 2008).

Some regime shifts are irreversible, or are reversible at prohibitive cost or over a long period of time. For example, if climate warms sufficiently to melt Arctic Sea ice, leading to changes in surface albedo and self-reinforcing heat absorption, it may not be possible to return to conditions with an Arctic polar ice cap in the near future (Notz, 2009). In such cases, the only strategy available is to adapt as best as possible to the new conditions.

In some situations it can be fruitful to invest in both adaptation and restoration strategies. After the collapse of the Newfoundland cod stocks, fishermen adapted to the new regime by fishing new species. At the same time, investments have been made to try to rebuild the cod stock (Schrank, 2005; Worm and Myers, 2003). After the collapse of cod stocks in the Baltic Sea fisherman adapted by increasing harvest of herring. Fishing herring may have helped to recover the cod because herring feed on juvenile cod, though efforts to reduce nutrients were probably more important in the restoration process (Österblom et al., 2007).

Similarly, even before a potential regime shifts occurs, it may be optimal to invest in strategies to reduce the likelihood of regime shift as well as strategies to adapt should a regime shift occur. For example, the Intergovernmental Panel on Climate Change (IPCC, 2008) has called for climate change policy to include investing in greenhouse gases mitigation and adaption strategies. In principle, choosing optimal mitigation prior to potential regime shifts depends on the choice of optimal adaptation, and vice-versa. If mitigation makes it unlikely a regime shift will occur then it may not be essential to invest much in adaptation strategies. On the other hand, if investment in adaptation makes post-regime shift well-being similar to pre-regime shift well-being then it may not be essential to invest much in mitigation strategies. In general, however, both investments will be needed. The right mix and size of investment expenses in both strategies depends on the degree of reversibility of the shift, the probability of a shift, the extent to which well-being is affected by the shift, and the relative cost of mitigation and adaptation investments.

4.3. Uncertainty, Learning and Adaptive Management

A significant problem facing managers is that knowledge of the location of thresholds and ability to predict regime shifts is often quite limited. For example, there is major uncertainty about the level of climate change necessary for dramatic changes in the extent of arctic summer ice, changes in the volume of permafrost, or amplitude of the El-Nino Southern Oscillation to occur (Lenton et al., 2008). In some cases, there is uncertainty even about whether a threshold exists. When the processes leading to regime shifts are only partially understood, or key data are missing, it becomes more difficult to plan as well as to provide early warning of an impending regime shift in time to take action to reduce the risk. In these cases, it may nevertheless be possible to detect changes in the statistical behavior of the system (e.g., variance or autocorrelation) as dominant damping feedbacks in a system weaken when a critical threshold is approached (Scheffer et al., 2009). While research is evolving rapidly (Carpenter et al., 2011), the current set of early warning indicators will often not provide sufficient warning to take action in time to avoid a regime shift, given lags and inertia in the ecological system (Biggs et al., 2009). There may also be lags and inertia in the social system that mean it may take a long time before appropriate measures are implemented (Contamin and Ellison, 2009).

A second important knowledge gap facing managers is the lack of information about the likely impacts of regime shifts on human well-being. Some studies have provided detailed qualitative descriptions of how regime shifts impact the generation of ecosystem services (e.g., Folke et al., 2004; Scheffer et al., 2001; Troell et al., 2005), which provide a basis for comparing pre- and post-regime shift well-being. But quantitative assessments of the change in the value of ecosystem services with potential regime shift are generally lacking (Gómez-Baggethun et al., 2011).

Empirical estimates of market and non-market values generated under current conditions may be of limited use for estimating post-regime shift values (the out-of-sample prediction problem). The impact of a regime shift on well-being also depends on how people will adapt to new conditions (Section 4.2), which may also be difficult to predict ahead of time. Empirical analysis of impacts is complicated by the fact that regime shifts can cause large changes in conditions (Limburg et al., 2002). The difficulty of predicting impacts of future potential changes on human well-being are aptly illustrated by analyses of climate change and the wide range in estimates of the reduction in future well-being from climate change. For example, Nordhaus (2010) estimates a 2.8% reduction in global GDP for a 3.4 °C warming while Stern (2006) predicts reductions of up to 20% for similar warming. In principle, economic valuation methods (e.g. discrete choice models) can be applied to evaluate the impact of a regime change on well-being in a manner similar to application of valuation methods in other contexts but the results, of course, depend on how the changes are described. Given the large uncertainty about these changes, the valuation can strongly vary. In some cases it may be possible to do comparative analyses of similar systems which have already undergone regime shifts (e.g., lakes within a specific region). In general, however, predictions for what the impact of potential future regime shifts might be will need to be pieced together from different sources. Evidence of prior regime shifts in other systems is important but also predictions of future conditions by using simulation models that take into account our best understanding of the system dynamics and the behavioral reactions to these dynamics. These insights can be used to apply standard valuation methods in order to get post-regime shifts economic values that are based on our best understanding.

Reducing uncertainty about location of thresholds or the likely magnitude of future shocks can be of great value to managers in their efforts to reduce the probability of crossing a threshold. Adaptive management uses active experimentation to learn about system dynamics and could be useful in gaining information about the location of thresholds (Carpenter, 2003). For example, deliberately increasing phosphorus input into a small subset of lakes can generate information about how much phosphorus input is needed to flip a lake into a eutrophic state. This information can then be used to improve management of other lakes to reduce the risk of eutrophication. However, it is not always possible or advisable to undertake experimentation. Experimentation could be useful for systems that have substitutes but dangerous when the system is unique and of substantial value. With climate change or other global phenomenon, experimentation may risk triggering large-scale harmful regime shifts, the very outcome that experimentation is designed to learn about and avoid.

Even where experimentation is unadvisable, some knowledge of likely system dynamics can be used to inform management. For example, if increasing intensity of human actions, such as increasing harvest intensity in marine systems or greenhouse gas emissions into the atmosphere, will likely increase the probability of detrimental regime shifts, then the potential for regime shift can lead optimal management to be more precautionary (Keller et al., 2004; Polasky et al., 2011). The increased potential of a harmful regime shift with increasing activity is like an additional cost so less of the activity should be undertaken. In a similar vein, if more information about post-regime shift conditions are expected in the future and regime shifts are irreversible or costly to reverse, there is value to preserving flexibility by avoiding the regime shift, referred to as (quasi) option value (Arrow and Fisher, 1974).

However, the potential for a regime shift does not always cause managers to become more precautionary. The manner in which regime shifts affects the ecological system matters. If a regime shift causes a sudden loss of natural capital (e.g., a forest fire), the risk of regime shift can cause management to use resources more aggressively (Reed 1984, 1987). The potential for regime shift to reduce natural capital stocks reduces the incentive to maintain stocks ("use it or lose it") and works in a similar fashion to an increase in the discount rate. Combining the increasing probability of regime shift with increasing intensity of use with a catastrophic loss in stock with regime shift yields an ambiguous effect on management (e.g. Reed and Echavarria Heras, 1992; Tsur and Zemel, 1998).

Even in cases where regime shift does not result in sudden loss of natural capital, the impact of uncertainty on management can be ambiguous. Brozovic and Schlenker (2011) show that increases in uncertainty do not necessarily lead to more precaution. The potential for learning about parameter values that control system dynamics also can have ambiguous effects on management depending on the form of learning (Keller et al., 2004; Kelly and Kolstad, 1999). Overall, however, Keller et al. (2004) found that the potential for regime shifts in the case of climate change should lead to much higher levels of mitigation.

4.4. The Politics of Regime Shifts

All policy and management options have costs and benefits with different net benefits accruing to different groups. For example, climate change may mean that growing crops around the Mediterranean will become more challenging due to drought, whereas high latitude Nordic countries may benefit from a longer growing season. Some countries like Bangladesh and the Netherlands will be much more vulnerable to flooding. Oil rich states such as Saudi Arabia would lose if there is a major shift away from petroleum towards renewable energy. In addition, different groups have different options for adapting in the face of regime shifts. When fish disappear from fishing grounds on Africa's coasts, international companies simply move on to fish elsewhere but local people often have few alternatives.

Distributional politics combined with uncertainty about potential regime shifts greatly complicates getting effective management that takes account of the factors described in Sections 4.1 and 4.2. Like many environmental problems, dealing with regime shift may require an up-front cost in exchange for future benefits. With regime shifts, however, the problem is amplified because the costs of actions are tangible whereas the benefits may not be. Devoting resources to avoid future potential problems can be hard to justify. If a regime shift does not occur is it because of the investment to avoid it was successful or because it was unlikely anyway? Further, groups that benefit from activities that may increase the risk of a regime shift have an incentive to raise doubts about whether regime shift is likely, whether it is even possible, or worth worrying about (Oreskes and Conway, 2010). In the U.S., fossil-fuel and anti-regulatory interests have been quite successful at increasing doubts about climate change science and the wisdom of taking action to reduce emissions of greenhouse gases. Implementing good management when there are different interests in play means there is a premium on reducing uncertainties and clearly articulating the risks of regime shift with its consequent impacts on future well-being.

5. Future Directions

Research over the past decade has documented a number of cases of regime shift in local and regional systems (Biggs et al., 2012; Scheffer et al., 2009) and there are mounting concerns about potential regime shifts at the global level (Lenton et al., 2008, Rockström et al., 2009). Regime shifts can result in large, abrupt, and persistent changes in the provision of ecosystem services, and can therefore have significant impacts on human well-being. With this potential in mind, there are benefits to increasing system resilience to reduce the risk of regime shifts as well as plan for how to adapt should a regime shift occur. Managers can do a better job reducing risks and planning for adaptation if they can reduce uncertainty about location of potential thresholds and gain better understanding of likely post-regime conditions. Improved understanding of system dynamics can be gained through a combination of monitoring programs, data analysis, modelling and testing by scientists with a wide range of scientific backgrounds. Improved understanding of how regime shifts impact on human well-being can be gained through integration of natural and social science that builds from understanding of likely changes in ecosystems linked to the changes in provision of ecosystem services, as well as linking to adaptation strategies that allow people to better cope with new circumstances.

To date, much of the work on regime shifts has been more concentrated in the natural science and somewhat removed from actual management and policy decision-making. There is a pressing need to link science and practice and to begin to evaluate what works and what does not. What are the practical steps that can be taken to increase system resilience? How can society better prepare for potential future changes? And how can we better link scientific information about risks and consequences of potential regime shifts with managers and political leaders to take action to build resilience? In reality, implementing good management in the face of regime shifts is complicated by the combination of uncertainty and vested political interests. It may take courage for managers or political leaders to recommend action that has immediate costs in return for uncertain but potentially large future benefits.

In this paper we considered regime shifts that originated in the ecological system. A rich area for further work is to consider the potential for regime shifts that originate in social systems, or are caused by the interaction of social and ecological dynamics. For example, regime shifts can occur in economic and social systems where individuals care about what others are doing such as with fashion fads and financial markets (e.g., Azariadis, 1981; Bikhchandani et al., 1992; Scharfstein and Stein 1990). Regime shifts in common property resources can emerge as a result of harvesting behavior combined with resource growth dynamics (Crépin and Lindahl, 2009). Reducing risks of harmful regime shift and building adaptive capacity in social-ecological systems in such situations requires integration of natural and social sciences to better understand linked system dynamics. More work in this area is needed.

Acknowledgment

We thank two anonymous reviewers for their valuable suggestions. We acknowledge funding from the Ebba and Sven Schwartz foundation and the European Union 7th framework project on climate change impacts and thresholds on Arctic Ocean systems: Arctic Tipping Points, 226248.

References

Arrow, K.J., Fisher, A.C., 1974. Environmental Preservation, Uncertainty, and Irreversibility. The Quarterly Journal of Economics 88 (2), 312–319.
Azariadis, C., 1981. Self-fulfilling prophesies. Journal of Economic Theory 25, 380–396.
Beisner, B.E., Haydon, D.T., Cuddington, K., 2003. Alternative stable states in ecology. Frontiers in Ecology and the Environment 1, 376–382.
Berkes, F., Folke, C., 1998. Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience. Cambridge University Press.
Biggs, H.C., Breen, C.M., Palmer, C.G., 2008. Engaging a window of opportunity: synchronicity between a regional river conservation initiative and broader water law reform in South Africa. International Journal of Water Resources Development 24 (3), 329–343.
Biggs, R., Carpenter, S.R., Brock, W.A., 2009. Turning back from the brink: detecting an impending regime shift in time to avert it. Proceedings of the National Academy of Sciences 106 (3), 826–831.
Biggs, R., Blenckner, T., Folke, C., Gordon, L.J., Norström, A., Nyström, M., Peterson, G.D., 2012. Regime shifts. In: Hastings, A., Gross, L. (Eds.), Encyclopedia of Theoretical Ecology. University of California Press.
Bikhchandani, S., Hirschleifer, D., Welch, I., 1992. A theory of fads, fashion, custom and cultural change as information cascades. Journal of Political Economy 100 (5), 992–1026.
Brock, W.A., Carpenter, S.R., 2006. Variance as a leading indicator of regime shift in ecosystem services. Ecology and Society 11 (2), 9 Online URL: http://wwwecologyandsocietr.org/vol11/iss2/art9/.
Brock, W.A., Starrett, D., 2003. Managing systems with non-convex positive feedback. Environmental and Resource Economics 26, 575–602.
Brozovic, N., Schlenker, W., 2011. Optimal management of an ecosystem with an unknown threshold. Ecological Economics 70 (4), 627–640.
Brubaker, E., 2000. Unnatural disaster: How politics destroyed Canada´s Atlantic ground fisheries. In: Andersson, T.I. (Ed.), Political Environmentalism: Going Behind the Green Curtain. Hoover Institution Press.
Carpenter, S.R., 2003. Regime Shifts in Lake Ecosystems: Patterns and Variation. International Ecology Institute, Oldendorf/Luhe Germany.
Carpenter, S.R., Cole, J.J., Pace, M.L., Batt, R., Brock, W.A., Cline, T., Coloso, J., Hodgson, J.R., Kitchell, J.F., Seekell, D.A., Smith, L., Weidel, B., 2011. Early warnings of regime shifts: a whole-ecosystem experiment. Science 332, 1079–1082.
Carstensen, J., Weydmann, A., 2012. Tipping points in the Arctic: eyeballing or statistical significance? Ambio 41 (1), 34–43 (February).
Collie, J., Richardson, K., Steele, J.H., 2004. Regime shifts: can ecological theory illuminate the mechanisms? Progress in Oceanography 60, 281–302.
Contamin, R., Ellison, A.M., 2009. Indicators of regime shifts in ecological systems: what do we need to know and when do we need to know it? Ecological Applications 19, 799–816.
Crépin, A.-S., 2003. Multiple species boreal forests—what Faustmann missed. Environmental and Resource Economics 26 (4), 624–646.
Crépin, A.-S., 2007. Using fast and slow processes to manage resources with thresholds. Environmental and Resource Economics 36, 191–213.
Crépin, A.-S., Lindahl, T., 2009. Grazing games: sharing common property resources with complex dynamics. Environmental and Resource Economics 44, 29–46.
Crépin, A.-S., Norberg, J., Mäler, K.-G., 2011. Coupled economic–ecological systems with slow and fast dynamics—modelling and analysis method. Ecological Economics 70 (8), 1448–1458.
deYoung, B.M., Barange, G., Beaugrand, R., Harris, R.I., Perry, M. Scheffer, Werner, F., 2008. Regime shifts in marine ecosystems: detection, prediction and management. Trends in Ecology & Evolution 23, 402–409.
Driml, S., 1994. Protection for Profit-Economic and Financial Values of the Great Barrier Reef World Heritage Area and Other Protected Areas. Great Barrier Reef Marine Park Authority. Research Publication No. 35. Townsville, Australia, pp. 83.
Elmqvist, T., Folke, C., Nyström, M., Peterson, G., Norberg, J., Bengtsson, J., Walker, B., 2003. Response diversity and ecosystem resilience. Frontiers in Ecology and the Environment 1, 488–494.
Finlayson, A.C., McCay, B.J., 1998. Crossing the threshold of ecosystem resilience: the commercial extinction of northern cod. In: Berkes, F., Folke, C. (Eds.), Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience. Cambridge Univ Press.
Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L., Holling, C.S., 2004. Regime shifts, resilience and biodiversity in ecosystem management. Annual Review of Ecology, Evolution, and Systematics 35, 557–581.
Folke, C., Carpenter, S.R., Walker, B., Scheffer, M., Chapin, T., Rockström, J., 2010. Resilience thinking: integrating resilience, adaptability and transformability. Ecology and Society 15 (4), 20 Online URL: http://www.ecologyandsociety.org/vol15/iss4/art20/.
Fudge, S.B., Rose, G.A., 2008. Life history co-variation in a fishery depleted Atlantic cod stock. Fisheries Research 92, 107–113.
Gien, L., 2000. Land and sea connection: the East Coast fishery closure, unemployment and health. Canadian Journal of Public Health 91 (2), 121–124.
Gómez-Baggethun, E., Alcorlo, P., Montes, C., 2011. Ecosystem services associated with a mosaic of alternative states in a Mediterranean wetland: case study of the Doñana Marsh (southwest Spain). Hydrological Sciences Journal 56 (8), 1374–1387.
Gordon, L.J., Peterson, G.D., Bennett, E.M., 2008. Agricultural modifications of hydrological flows create ecological surprises. Trends in Ecology & Evolution 23, 211–219.
Goreau, T.J., Hayes, R.L., MacAllister, D., 2005. Regional patterns of sea surface temperature rise: implications for global ocean circulation change and the future of coral reefs and fisheries. World Resource Review 17 (3), 350–374.
Grass, D., Caulkins, J.P., Feichtinger, G., Tragler, G., Behrens, D.A., 2008. Optimal Control of Nonlinear Processes With Applications in Drugs, Corruption, and Terror. Springer.
Hamilton, L.C., Butler, M.J., 2001. Outport adaptations: social indicators through Newfoundland's cod crisis. Human Ecology Review 8 (2), 1–11.
Hamilton, L.C., Lyster, P., Otterstad, O., 2000. Social change, ecology and climate in 20th century Greenland. Climatic Change 47 (1/2), 193–211.
Horan, R.D., Fenichel, E.P., Drury, K.L.S., Lodge, D.M., 2011. Managing ecological thresholds in coupled environmental–human systems. Proceedings of the National Academy of Sciences 108 (18), 7333–7338.

Hughes, T.P., Baird, A.H., Bellwood, D.R., Card, M., Connolly, S.R., Folke, C., Grosberg, R., Hoegh-Guldberg, O., Jackson, J.B.C., Kleypas, J., Lough, J.M., Marshall, P., Nyström, M., Palumbi, S.R., Pandolfi, J.M., Rosen, B., 2003. Climate change, human impacts, and the resilience of coral reefs. Science 301, 929–933.
Hughes, T.P., Rodrigues, M.J., Bellwood, D.R., Ceccarelli, D., Hoegh-Guldberg, O., McCook, L., Moltschaniwskyj, N., Pratchett, M.S., Steneck, R.S., Willis, B., 2007. Phase shifts, herbivory, and the resilience of coral reefs to climate change. Current Biology 17 (4), 360–365.
Hvingel, C., 1999. The fishery for northern shrimp (*Pandalus borealis*) off West Greenland, 1970–1999. NAFO SCR Doc. 99/107.
Intergovernmental Panel on Climate Change (IPCC), 2008. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland.
Keller, K., Bolker, B.M., Bradford, D.F., 2004. Uncertain climate thresholds and optimal economic growth. Journal of Environmental Economics and Management 48 (1), 723–741.
Kelly, D.L., Kolstad, C.D., 1999. Bayesian learning, growth, and pollution. Journal of Economic Dynamics and Control 23 (4), 491–518.
Lenton, T.M., Held, H., Kriegler, E., Hall, J.W., Lucht, W., Rahmstorf, S., Schellnhuber, H.J., 2008. Tipping elements in the Earth's climate system. Proceedings of the National Academy of Sciences 105 (6), 1786–1793.
Levin, S.A., 2003. Complex adaptive systems: exploring the known, the unknown and the unknowable. Bulletin of the American Mathematical Society 40, 3–19.
Limburg, K.E., O'Neill, R.V., Costanza, R., Farber, S., 2002. Complex systems and valuation. Ecological Economics 41, 409–420.
Lutz, W., Sanderson, W.C., Scherbov, S., 2008. The coming acceleration of global population ageing. Nature 451, 716–719.
Mäler, K.-G., Xepapadeas, A., de Zeeuw, A., 2003. The economics of shallow lakes. Environmental and Resource Economics 26 (4), 603–624.
Millennium Ecosystem Assessment (MA), 2005. Ecosystems and Human Well-being: Current State and Trends Assessment. Island Press.
Moberg, F., Folke, C., 1999. Ecological goods and services of coral reef ecosystems. Ecological Economics 29 (2), 215–233.
Muradian, R., 2001. Ecological thresholds: a survey. Ecological Economics 38 (1), 7–24.
Myers, R.A., Hutchings, J.A., Barrowman, N.J., 1997. Why do fish stocks collapse? The example of cod in Atlantic Canada. Ecological Applications 7, 91–106.
Norberg, J., Swanweey, D.P., Dushoff, J., Lin, J., Casagrandi, R., Levin, S., 2001. Phenotypic diversity and ecosystem functioning in changing environments: a theoretical framework. Proceedings of the National Academy of Sciences 98 (20), 11376–11381.
Nordhaus, W.D., 2010. Economic aspects of global warming in a post Copenhagen environment. Proceedings of the National Academy of Sciences 107 (26), 11721–11726.
Norström, A. 2010. Upholding the coral loop: resilience, alternative stable states and critical feedbacks in coral reefs. Ph.D. thesis, Stockholm University, Sweden.
Norström, A., Nyström, M., Lokrantz, J., Folke, C., 2009. Alternative states of coral reefs: beyond coral–macroalgal phase shifts. Marine Ecology Progress Series 376, 295–306.
Notz, D., 2009. The future of ice sheets and sea ice: between reversible retreat and unstoppable loss. Proceedings of the National Academy of Sciences 106 (49), 20590–20595.
Nyström, M., Folke, C., Moberg, F., 2000. Coral reef disturbance and resilience in a human-dominated environment. Trends in Ecology & Evolution 15, 413–417.
Nyström, M., Norström, A.V., Blenckner, T., de la Torre Castro, M., Eklöf, J.S., Folke, C., Österblom, H., Steneck, R.S., Thyresson, M., Troell, M., 2012. Confronting feedbacks of degraded marine ecosystems. Ecology (Published online).
Olsson, P., Folke, C., Hahn, T., 2004. Social–ecological transformation for ecosystem management: the development of adaptive co-management of a wetland landscape in southern Sweden. Ecology and Society 9 (4), 2 [online] URL: http://www.ecologyandsociety.org/vol9/iss4/art2.
Oreskes, N., Conway, E.M., 2010. Merchants of Doubt: How a Handful of Scientists Obscured the Truth on Issues from Tobacco Smoke to Global Warming. Bloomsbury Press.
Österblom, H., Hansson, S., Larsson, U., Hjerne, O., Wulff, F., Elmgren, R., Folke, C., 2007. Human-induced trophic cascades and ecological regime shifts in the Baltic Sea. Ecosystems 10 (6), 877–889.
Peterson, G.D., Carpenter, S.R., Brock, W.A., 2003. Uncertainty and the management of multistate ecosystems: an apparently rational route to collapse. Ecology 84 (6), 1403–1411.
Polasky, S., de Zeeuw, A., Wagener, F., 2011. Optimal management with potential regime shifts. Journal of Environmental Economics and Management 62, 229–240.
Rasmussen, R.O., Hamilton, L.C., 2001. The development of fisheries in Greenland, with focus on Paamiut/Frederikshåb and Sisimiut/Holsteinsborg. North Atlantic Regional Studies, Roskilde, Denmark.
Reed, W.J., 1984. The effects of the risk of fire on the optimal rotation of a forest. Journal of Environmental Economics and Management 11 (2), 180–190.
Reed, W.J., 1987. Protecting a forest against fire: optimal protection patterns and harvest policies. Natural Resource Modeling 2, 23–54.
Reed, W.J., Echavarria Heras, H., 1992. The conservation and exploitation of vulnerable resources. Bulletin of Mathematical Biology 54 (2–3), 185–207.
Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F.S., Lambin, E., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H., Nykvist, B., De Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B.H., Liverman, D., Richardson, K., Crutzen, C., Foley, J., 2009. A safe operating space for humanity. Nature 461, 472–475.
Rose, G.A., 2004. Reconciling overfishing and climate change with stock dynamics of Atlantic cod (*Gadus morhua*) over 500 years. Canadian Journal of Fisheries and Aquatic Sciences 61, 1553–1557.
Scharfstein, D.S., Stein, J.C., 1990. Herd behavior and investment. American Economic Review 80 (3), 465–479.
Scheffer, M., 2009. Critical Transitions in Nature and Society. Princeton University Press.
Scheffer, M., Carpenter, S.R., Foley, J.A., Folke, C., Walker, B.H., 2001. Catastrophic shifts in ecosystems. Nature 413, 591–596.
Scheffer, M., Bascompte, J., Brock, W.A., Brovkin, V., Carpenter, S.R., Dakos, V., Held, H., van Nes, E.H., Rietkerk, M., Sugihara, G., 2009. Early warning signals for critical transitions. Nature 461, 53–59.
Schrank, W.E., 2005. The Newfoundland fishery: ten years after the moratorium. Marine Policy 29 (5), 407–420.
Skiba, A.K., 1978. Optimal growth with a convex–concave production function. Econometrica 46.
Steele, D.H., Andersen, R., Green, J.M., 1992. The managed commercial annihilation of Northern cod. Newfoundland Studies 8 (1), 34–68.
Steffen, W., Sanderson, A., Jäger, J., Tyson, P.D., Moore III, B., Matson, P.A., Richardson, K., Oldfield, F., Schellnhuber, H.-J., Turner II, B.L., Wasson, R.J., 2004. Global Change and the Earth System: A Planet under Pressure. Springer-Verlag.
Stern, N., 2006. *Review on the Economics of Climate Change*. H.M. Treasury, UK. http://www.sternreview.org.uk.
Suding, K.N., Hobbs, R.J., 2009. Threshold models in restoration and conservation: a developing framework. Trends in Ecology & Evolution 24, 271–279.
Troell, M., Pihl, L., Rönnbäck, P., Wennhage, H., Söderqvist, T., Kautsky, N., 2005. Regime shifts and ecosystem service generation in Swedish coastal soft bottom habitats: when resilience is undesirable. Ecology and Society 10 (1), 30.
Tsur, Y., Zemel, A., 1998. Pollution control in an uncertain environment. Journal of Economic Dynamics and Control 22 (6), 967–975.
Wagener, F.O.O., 2003. Skiba points and heteroclinic bifurcations, with applications to the shallow lake system. Journal of Economic Dynamics and Control 27, 1533–1561.
Walker, B., Holling, C.S., Carpenter, S.R., Kinzig, A., 2004. Resilience, adaptability and transformability in social–ecological systems. Ecology and Society 9 (2), 5 [online] URL: http://www.ecologyandsociety.org/vol9/iss2/art5.
Walker, B., Pearson, L., Harris, M., Maler, K.-G., Li, C.-Z., Biggs, R., Baynes, T., 2010. Incorporating resilience in the assessment of inclusive wealth: an example from South East Australia. Environmental and Resource Economics 45 (2), 183–202.
Worm, B., Myers, R.A., 2003. Meta-analysis of cod–shrimp interactions reveals top-down control in oceanic food webs. Ecology 84, 162–173.