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The Economy, The Biosphere and Planetary Boundaries: Towards Biosphere Economics

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ABSTRACT

Nine planetary boundaries have been proposed, capturing essential biophysical processes that sustain the Earth System and its biosphere in an accommodating state for humanity. Drawing on economics literature, we propose conditions under which remaining within these boundaries is in line with economic policy. We assert that pervasive uncertainties combined with impacts of trespassing planetary boundaries clearly legitimate using safe minimum standards or precautionary approaches. Moreover, information about the risk structure of these processes, including potential large-scale regime shifts, could help refine policies for how to relate to the zones of uncertainty of the boundaries. Planetary

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boundaries may be interpreted as "growth within limits" especially in relation to the biophysical expansion of the human dimension. Here, we picture them as warning signs creating incentives for shifting development into new directions, new pathways, where growth in human well-being is the focus rather than growth in GDP. In this sense, we reiterate the framework of ecological economics of sustainable scale (i.e., developing within planetary boundaries), efficient allocation, and fair distribution, and emphasize the need for "biosphere economics" to help navigate globalization within the capacity of the biosphere as the complex adaptive system it truly is.

1 Introduction

The rapid expansion of human activities into globalized societies implies that human beings now have expanded from local and regional environmental impacts into imprints at the planetary scale, shaping the dynamics and functioning of the entire biosphere and the Earth System as a whole (Steffen *et al.*, 2011). This major achievement, and at the same time major challenge for the future wellbeing of humanity, now leaves marks at geological time scales, defining a new geological era, the Anthropocene — Earth shaped by human actions (Turner, 1990; Crutzen, 2002; Steffen *et al.*, 2007).

The view and analysis of the environment in relation to economic development as presented here differs from approaches that address the environment as a sector, as a subpart of the development agenda, or as an amenity only. Here, we adhere to the view that the biosphere provides the biophysical preconditions for social and economic development, preconditions that need to be accounted for to secure human wellbeing and prosperous social and economic development. In line with the ecological economics approach, we see society and the economy as part of the biosphere, as subsystems of the living planet (Costanza, 1991; Jansson *et al.*, 1994; Folke *et al.*, 2011). The biosphere is the thin layer on planet

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Earth where life exists — the global ecological system integrating all living beings, including humans, and their relationships and how they interact with the elements of the Earth's crust, the water cycle, atmosphere, and the poles and permafrost regions. Concepts like natural capital, ecosystem services, and life-supporting ecosystems have been developing to reflect essential features of the biosphere for human wellbeing and development (e.g. Odum, 1989; Costanza and Daly, 1992; Jansson *et al.*, 1994; Arrow *et al.*, 1995; Daily, 1997; Dasgupta *et al.*, 2000).

The size, connectivity and speed of the human enterprise combined with the necessity to sustain life-support services from the biosphere's ecosystems call for clarifying safe zones of human operations for prosperous development. Approaches like planetary boundaries (Rockström *et al.*, 2009a; Rockström *et al.*, 2009b; Steffen *et al.*, 2015), the precautionary principle (Costanza and Perrings, 1990; Cameron, 1991; Timothy and Jordan, 1995), safe minimum standards (Ciriacy-Wantrup, 1952; Bishop, 1978; Bishop, 1979) and others have been suggested. The task is not trivial since the global Earth system and its subsystems, human societies and economies included, operate as complex adaptive social-ecological systems,[1] where periods of gradual change interact with periods of rapid, abrupt change and where there may be regime shifts[2] between alternate basins of attractions or pathways of development (Levin *et al.*, 2012) with substantial impacts on human well-being.

In this article, we discuss to what extent economic analysis and tools can help bring more light on how to address the role of the biosphere for human well-being. We present current knowledge on biosphere dynamics, the significance of a functioning biosphere and the planetary boundaries framework and relate it to the economics literature on safe minimum standards, precautionary approaches, economic growth, regime shifts and thresholds. We discuss whether or not the planetary boundaries concept motivates setting safe standard or being precautionary. Further, we address the challenges of managing a global social-ecological system in relation to economic growth and increase in the human population and discuss to what extent growth is possible given current biosphere conditions. We also discuss to what extent current economic knowledge

[1]Social-ecological systems are linked systems of people and nature (Berkes and Folke, 1998).

[2]Regime shifts are abrupt and persistent changes in system structure and function. (Biggs *et al.*, 2012).

can help manage the biosphere with its inherent uncertainties, complex interactions across spatial and temporal scales and potential regime shifts. We present recent advances that shed light on the management strategies available. In particular, we touch on the concept of resilience as insurance in relation to growth within planetary boundaries. Finally, we identify new insights obtained from analysing jointly these different strands of literature and highlight potential directions for future research.

2 The Global Scene

2.1 The Anthropocene

The last 10,000 years of the Earth have been unusually stable and have provided favourable environmental conditions for humanity. In this era, called the Holocene, agriculture was born, villages and cities have developed, and human civilizations have flourished (Costanza *et al.*, 2007; Steffen *et al.*, 2007). Humanity has built its infrastructure, interactions, and collaborations under the unusually stable conditions of the Holocene. Environmental conditions on Earth before that period may have been too unpredictable for humans to settle down and develop in one place (Young and Steffen, 2009).

The Anthropocene is the result of what some refer to as the Great Acceleration of human actions reflected in rapid increases in, e.g., population numbers, economic activities, resource extraction, land use change, technical progress, health improvements, and so on, and in a fashion never experienced before (McNeill, 2000; Steffen *et al.*, 2004). The acceleration propelled after the Second World War, made possible through the development of the fossil fuel-based infrastructure, innovation, and novel institutional arrangements.

The amazing increase in size of the human enterprise has resulted in a world that is much more connected, with information travelling fast and where things can rapidly change and at large scales. Not only the political, economic, and technical systems but also the Earth's biophysical life support systems connect societies around the world creating complex new dynamics across sectors, areas, and societies in yet unknown ways (Young *et al.*, 2006; Walker *et al.*, 2009).

Over 50 percent of the world's population dwell in cities that ecosystems worldwide support with essential ecosystem services like food, water purification, fertile soils, storm protection, sinks for greenhouse gases, and other wastes (Folke *et al.*, 1997). Climate change is very likely to alter the variability of rainfall patterns that may affect the frequency, magnitude, and duration of droughts, fires, storms, floods, and other shocks and surprises. This may impact food production, trade, migration, and possibly socio-political stability. In addition new phenomena may accelerate the pace of these changes, like the increasing size of a prosperous middle class and its effects on consumption and diets. Information technology, nano-technology, and molecular science are accelerating with unknown potentials.

The favourable Holocene conditions and the capacity of the biosphere to sustain economic development are generally taken for granted in investment decisions, political actions, and international agreements. However, the success of all human activities rest on the capacity of the Earth's biosphere to sustain them with natural capital, ecosystem services, and a hospitable environment, even though people may not perceive this support or believe it valuable (Arrow *et al.*, 1995; Millennium Ecosystem Assessment (MA), 2005). The human expansion of the Anthropocene in particular was supported by escalating use of the natural capital and ecosystem services of the biosphere, and it has led to side effects in the form of global environmental challenges confronting the future well-being of the human population on Earth (Steffen *et al.*, 2011).

2.2 Natural Capital and Ecosystem Services

Natural capital is the stock of ecosystems and environmental assets and their dynamic capacity to provide a flow of goods or services of significance to people now and in the future (e.g. Costanza and Daly, 1992). In addition to non-renewable natural capital like ore, minerals, fossil fuels, living ecosystems provide a huge range of services like food production, climate amelioration, water recycling, and biodiversity (Daily, 1997; MA, 2005). Some services operate on large temporal and spatial scales and form critical support functions for human wellbeing. These include the provision of fertile soils, the upwelling of ocean circulation that brings nutrients from the deep ocean to support many of the marine ecosystems, and glaciers that act as giant water storage facilities. Earth System regulatory services also include storage of carbon into the ocean, the chemical reactions in the atmosphere that form ozone (essential for filtering out ultraviolet radiation from the sun) and regulation of Earth temperature thanks to large polar ice sheets (Steffen *et al.*, 2011).

Natural capital complements physical capital (factors of production such as machinery, buildings, or computers), human capital (stock of competencies, social and personality attributes, including creativity), and social capital (the expected collective or economic benefits derived from cooperation between individuals and groups) (Ostrom, 1994; Putnam, 1995; Partha and Serageldin, 1999). Human activities and well-being as well as the generation of physical, human and social capital all rest on the capacity of ecosystems from local levels to the biosphere as a whole, with its stock of natural capital and ecosystem services (Odum, 1989).

The recent large scale degradation of natural capital may not be a crucial problem if human-made capital can replace natural capital (weak sustainability, Solow, 1974a, 1974b, 1986, 1993; Hartwick, 1977, 1978a, 1978b). Natural resources may then decline as long as human-made capital increases to offset the decline (Solow, 1974a; 1974b; Hartwick's rule, 1977). For example, extracting oil to produce plastic products replaces the natural resource oil with the manufactured plastic product useful for people.

However, supporters of weak sustainability focus on non-renewable resources, and do not account for the life-support and ecosystem services provided by the biosphere. In particular, production of essential life-support services like food and air is a prerequisite for humans to exist on the planet. Hence, many ecosystem services cannot be replaced by human-made capital (Turner *et al.*, 1997). The concepts of critical natural capital and strong sustainability clarify that perfect substitutability is more of an exception than a rule in relation to natural capital (Pearce *et al.*, 1996; Ekins *et al.*, 2003; Ayres, 2007). Furthermore, substitution between natural and human-made capital could trigger disturbances and alter the resilience of the system (van den Bergh, 2007) and substitutability of ecosystem goods and services becomes tricky when they perform multiple functions. For example, trees not only provide wood but also contribute to climate regulation, erosion control, shading, etc.[3] (Foley *et al.*, 2005; Raudsepp-Hearne *et al.*, 2010a).

It is clear that we live in a human-dominated world where many ecosystem functions and services are difficult to replace given current technology, and where such replacement may cause greater problems which are difficult to solve at larger scales (Holling and Meffe, 1996; Sterner *et al.*, 2006; Westley *et al.*, 2011). The real challenge is to align economic development with the capacity of the biosphere to sustain it, or even enhance this capacity instead of degrading it (Folke *et al.*, 2011).

2.3 Regime Shifts and Uncertainty

Ecosystems are complex adaptive systems (Levin, 1999b; Levin, 1999a). They consist of individual species and physical variables that interact and evolve over time and human actions increasingly influence this dynamics (Folke *et al.*, 2004) and should even be analysed as part of their dynamics and essential for the production of ecosystem services (Reyers *et al.*, 2013). The possibility of non-marginal changes, unobserved slow structural changes, spatial variation, and selection are all features of complex adaptive systems (Levin *et al.*, 2012). In particular, regime shifts are an essential aspect of ecosystem dynamics (Scheffer *et al.*, 2001; Biggs *et al.*, 2012) with potential major impacts on well-being (Crépin *et al.*, 2012).

While most of the earlier economic and ecological literature focused on incremental change, recent developments provide substantial evidence that abrupt change occurs and may sometimes be irreversible (Holling, 1973; MA, 2005, Regime shift database,[4] Dasgupta and Mäler, 2003; Crépin *et al.*, 2012).

Resilience is the capacity of a system to absorb disturbance and reorganize while undergoing change so as to retain essentially the same function, structure, and feedbacks (Folke *et al.*, 2010). Most economic policy and the results it generates assume incremental change. In contrast, regime shifts are more difficult to deal with and many decision problems involving the economic exploitation of systems with regime

[3]For further discussion on substitutability and other references see Ang and van Passel (2012).

[4]www.regimeshifts.org.

shifts have proved to be non-trivial (Carpenter *et al.*, 1999; Mäler *et al.*, 2003; Crépin, 2003; Crépin, 2007). In particular, multiple regimes can sometimes be optimal depending on what has happened in the past (Mäler *et al.*, 2003; Brock and Starrett, 2003; Crépin, 2003; Crépin, 2007), and it is unlikely that conventional policy tools can be used in the same way as for situations with no regime shifts (Mäler *et al.*, 2003; Crépin *et al.*, 2011) and precaution may be an optimal policy (Margolis and Nævdal, 2008; Polasky *et al.*, 2011b). Further, the reversibility or irreversibility of such regime shifts has implications for the level of uncertainty in the system, the degree of its predictability, and the time over which predictability extends (Polasky *et al.*, 2011a).

Irreversibility is highly relevant since decisions leading to irreversible outcomes imply foregone opportunities (Arrow and Fisher, 1974; Henry, 1974) and require different policy tools. Pizer (2003) discusses regulation policies in the context of catastrophic climate change. In such extreme conditions, a comparison of price and quantity mechanisms shows that even if quantity control is to recommend, price incentives do not perform much worse compared to no policy at all. In case of catastrophic climate change, putting in place some kind of regulation to limit climate change is much more important and a better policy than delaying action to find the perfect regulation. Pizer (2003) argues in favour of price regulation that performs better for less catastrophic climate change.

The complex adaptive system nature of the global social-ecological system is difficult and even impossible to predict. Situations of radical uncertainty occur in complex adaptive systems, such that the probability of all the possible states may not be known and sometimes there are even totally unknown states. Some of this uncertainty may be resolved in the future, for example, through scientific discoveries. However, uncertainty about the global social-ecological system stems from a combination of imperfect understanding, the inherent variability of complex systems, and the coevolving nature of people and the biosphere. Research can improve our understanding, but we will never be able to fully predict the future evolution of the global social-ecological system because of its complex and potentially chaotic dynamics. (Polasky *et al.*, 2011a; Carpenter *et al.*, 2012). Positive feedbacks, occurring for example in the climate system, are likely to magnify uncertainties.

Experts can still use available knowledge to establish subjective probabilities of future conditions (IPCC, 2013), meanwhile science also tends to focus on manageable uncertainties and may fail to consider all potential outcomes, or to give adequate weight to "unlikely" outcomes (Polasky *et al.*, 2011a; Carpenter *et al.*, 2012). Risk and uncertainty can also be perceived in a biased way (Biggs *et al.*, 2009), particularly so when there is a non-negligible risk of catastrophic change and "fat tail" events may occur (Weitzman, 2009b; Weitzman, 2009a).

Uncertainties also imply that coming close to thresholds is more dangerous because irreversible thresholds may be trespassed by mistake. In the Anthropocene, this motivates the need to relate economic development to the proposed safe operating space at the planetary level. Indeed, the economy is embedded in all kinds of social interaction which in turn depend on ecosystem services provided by the biosphere. Such interdependence means that any sustainability-related issue must be considered holistically.

3 Defining Safe Zones of Operation

Facing a world of pervasive uncertainty and non-negligible risks of large-scale regime shifts and global welfare impacts, motivates defining and combining a global safe operating space for humanity with challenges of decision making in a world where risk, uncertainty, and potential catastrophic change is part of the picture.

3.1 Planetary Boundaries: A Safe Operating Space

While the Anthropocene unfolds, prosperous economic development would benefit from a planet that remains in a Holocene-like regime (Rockström *et al.*, 2009a; Steffen *et al.*, 2011). It becomes important to appreciate the range of variability that characterizes the Holocene as a baseline to interpret the global changes that are now developing.

Planetary boundaries attempt to visualize the biophysical preconditions of a Holocene-like regime, the only regime that we can be sure provides a favourable environment for the further development of human societies (Rockström *et al.*, 2009a; Rockström *et al.*, 2009b). Based on a major effort to synthesize current scientific understanding, nine planetary boundaries for critical biophysical processes in the Earth's system were identified. Together, they describe what Rockström *et al.*

(2009a) call an envelope for a safe operating space for humanity within which the biosphere is likely to remain in a Holocene-like regime.

Staying within the safe operating space means avoiding zones of uncertainty where there may be critical thresholds of large scale Earth System processes. The boundaries are set at a "safe distance" from a dangerous level or a global threshold, i.e., at the lower end of these zones of uncertainty. The proposed boundaries, recently updated based on the latest scientific developments, are coarse first estimates only, characterized by large uncertainties and knowledge gaps and so far their interactions have not been fully clarified. The updated boundaries include two core boundaries climate change and biodiversity integrity due to their critical role in the Earth system and its biosphere and with interactions to the other proposed boundaries stratospheric ozone, ocean acidification, the nitrogen and phosphorus cycles, land use change, freshwater use, aerosol loading, and novel entities (Steffen *et al.*, 2015). The boundaries for climate change, changes of the global nitrogen cycle, and the rate of biodiversity loss may already have been transgressed. The boundaries and the scientific analyses behind them are presented in detail and discussed in Rockström *et al.* (2009b) and Steffen *et al.* (2015). A significant message of the planetary boundaries work is that the global environmental and sustainability challenge is much more than climate change. Transgressing one or more planetary boundaries may have serious consequences for human well-being due to the risk of crossing thresholds that can trigger non-linear, abrupt environmental change within continental- to planetary-scale systems. Planetary boundaries are interdependent, because crossing one of them may shift the position of other boundaries or cause them to be transgressed. How far we are willing to move into the uncertainty zones and risk crossing critical thresholds with possible major impact on human wellbeing is a reflection of worldviews, choices, and actions — hence the urgent need to reconnect human actions and economic development, and economics as a subject area to the biosphere.

Figure 1 illustrates the concept of planetary boundaries in relation to the Holocene and the Anthropocene. The horizontal axis represents some critical dimension of the Holocene like mean temperature (climate) or species loss (biodiversity), and the vertical axis the probability of a planetary regime shift. The Holocene represents a safe operating zone limited by the planetary boundary here represented by the dashed line

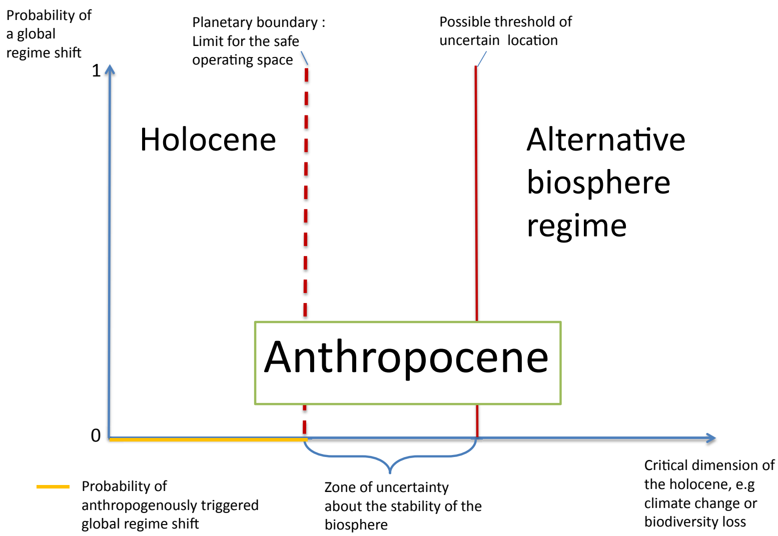

Figure 1: The Holocene, the Anthropocene, and planetary boundaries. There may be a threshold of uncertain location but a range of uncertainty can be defined with the Holocene zone as a range of a particular driver that for sure will not lead to crossing a threshold and an alternative biosphere regime as a range of the driver that we know will lead to radically different conditions for life. In between there is a zone of uncertainty. The Anthropocene spans over this zone. In the Anthropocene, we push drivers to limits never reached before and may have triggered a critical threshold already.

at the lower end of the uncertainty zone. The yellow line represents the probability of a regime shift, which is equal to zero left of the planetary boundary and strictly positive but unknown to the right of it. The full line represents the threshold to an alternative biosphere regime, a zone where humanity does not want to go because its capacity to support current global development of society and well-being is unknown. The Anthropocene is the current situation where humanity influences Earth system dynamics on a large scale, challenging the Holocene situation. Large parts of the Anthropocene span across a zone of uncertainty, in which there is risk that humanity may end up in an alternative biosphere. In this figure, we may still remain in the current biosphere configuration while living in the Anthropocene provided that human impacts on Earth dynamics are not substantial enough to trigger a shift into an alternative biosphere.

3.2 Precautionary Approaches to Uncertainty and Thresholds in Economics

The concept of planetary boundaries is emerging in the economics literature.[5] Planetary boundaries are tightly related to concepts of safe minimum standards and precautionary approaches. Here, we focus on the economics literature on problems of decision making with uncertain outcomes and possibly large impacts.

3.2.1 Decisions under large uncertainties and safe standards

Uncertainties surrounding global dynamics go beyond risk. We are unaware of the range of consequences associated with trespassing many of the critical thresholds and dangerous levels of particular variables described in Rockström *et al.* (2009b). We are even less likely to have information on the probability distribution of the possible outcomes. For such situations of true uncertainty, Arrow and Hurwicz (1972) showed that only extreme strategies could be consistent with rational behaviour. This could motivate choosing the policy for which the worst possible outcome is the least bad (Arrow and Hurwicz, 1972; Bishop, 1978; Gilboa and Schmeidler, 1989; Woodward and Bishop, 1997). When irreversible damage can occur and utilitarian calculus is inapplicable, Safe (Minimum) Standards have also been traditionally discussed as something morally or ethically right to do even if the resulting policy is not necessarily maximizing social welfare (Bishop, 1978; Randall, 1991; Crowards, 1998).

Regarding the stability of the Earth system, two strategies materialize. We could choose to stay in the safe zone within the planetary boundary as defined in Figure 1. An immediate welfare loss may result from the costs of remaining within the boundaries but the benefits of the current regime of the biosphere could be enjoyed for a long time. These

[5]For example a search (December 10, 2014) through the American Economic Association's electronic database (Econlit), the world foremost source of references to economic literature, hits only 16 titles of which most concern governance and political science issues, one of the few exceptions being an article on growth by van den Bergh and Kallis (2012). In contrast, Web of science core collection reports 989 citations for Rockström *et al.* (2009a) and 194 for Rockström *et al.* (2009b). Of these, 72 are attributed to economic journals and among these most are either in political sciences or not addressing the issue as a central part like Hepburn (2010).

costs and benefits should be put in relation with enjoying a higher level of well-being in the short run at the price of possible future catastrophic welfare losses if the biosphere leaves its current stability domain. Recent studies of climate change favour remaining within the climate boundary (IPCC, 2014). Entering an alternative regime of the biosphere is likely to have large impacts on well-being and the threshold for this occurring is surrounded with large uncertainties. Hence, Arrow and Hurwicz's (1972) rationality argument and the ethical argument would certainly legitimate not wanting to trespass the planetary boundaries although the cost in foregone development opportunities could be substantial.

In addition to these arguments that pertain when uncertainty is substantial (probability distributions are unknown), Ciriacy-Wantrup (1952) suggested that when damage are highly uncertain, possibly severe and likely to be irreversible, it can be optimal to use a safe minimum standard even from a utilitarian framework. Margolis and Nævdal (2008) picture situations when there are boundaries which divide the state space into sets with different stochastic structures (risk thresholds), for example, no risk of entering a dangerous zone/some risk of entering a dangerous zone. They show formally that safe minimum standards could be optimal if some risk threshold can be identified below which there is no risk of a regime shift and above which the risk is positive. They describe the risk of a regime shift as a hazard rate — some probability that the system will shift under particular conditions and at a particular time. They illustrate that if the change in risk at the risk threshold is relatively abrupt and the potential damage large enough then establishing a safe minimum standard could be an optimal policy. They give a simple condition for when to establish a safe minimum standard before learning more about the risk. While Rockström *et al.* (2009b) argue that "determining a safe distance involves normative judgments of how societies choose to deal with risk and uncertainty", Margolis and Nævdal (2008) define risk thresholds as dividing the state space into risky and non-risky zones. Their calculation of the safe minimum standard hinges on using a utility function with underlying assumptions about risk preferences. This is one way of formalizing the normative judgment about risk that (Rockström *et al.*, 2009b) refer to.

If the Margolis and Nævdal condition (2008, Proposition 2 and below, p. 416) is satisfied a safe minimum standard should be set at the risk threshold. Such policy would be particularly appropriate for dynamic processes with global scale thresholds like climate change, ocean acidification, and to some extent stratospheric ozone (Rockström *et al.*, 2009b). If we can determine the risk threshold and assess that the risk is steeply increasing at this threshold, this should be the limit beyond which society would not want to go. This is very similar to the approach taken in the planetary boundary framework, which is strongly based on observations; the most fundamental one being that the Holocene is the only Earth system regime that we know for sure can support complex human societies. The planetary boundaries define the biophysical limits of the Holocene based on observations about, for example, ice core data and observed limits of eutrophication of freshwaters. No predictions are needed about the nature of the alternative regime; it is enough to know that the zone beyond the boundary is more risky in the sense that more surprises are likely to occur (Steffen *et al.*, 2015). Hence, Figure 2 illustrates how these three measures (planetary boundary, safe minimum standard, and risk threshold) coincide when risk, represented by the yellow curve, is steeply increasing at the risk threshold. In this case, no risk at all is acceptable (Margolis and Nævdal, 2008, Section 5.2).

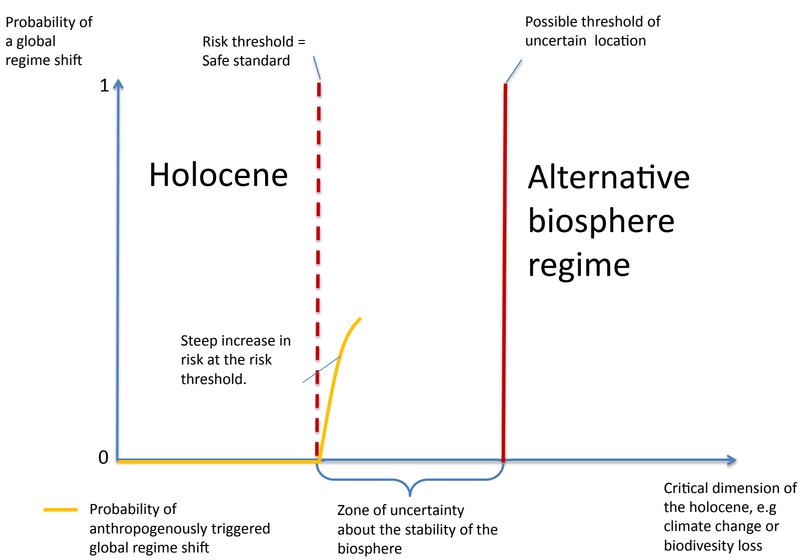

Figure 2: Planetary boundary at a risk threshold.

3.2.2 Precautionary approaches

In other cases, some risk may be acceptable but it could still be optimal to be precautious in the way defined by Polasky *et al.* (2011b) and take actions that lessen exploitation to reduce probabilities of bad future outcome. For example if at the threshold the change in risk is small, Margolis and Nævdal (2008) suggest that it can be optimal to accept some risk. However they argue that it could still be motivated to have a safe standard if the expected cost of the bad outcome is large enough. In such a situation an optimal economic policy could either be to recommend a safe standard, if the average cost is large or to recommend a standard that is not safe anymore but still likely to be somewhere beyond the risk threshold, as illustrated in Figure 3. The planetary boundary as defined in Rockström *et al.* (2009b) and Steffen *et al.* (2015) would coincide with the safe standard or the risk threshold.

Polasky *et al.* (2011b) revisit precautionary approaches in the context of management of a renewable natural resource and regime shifts. They identify four different cases depending on whether management can or

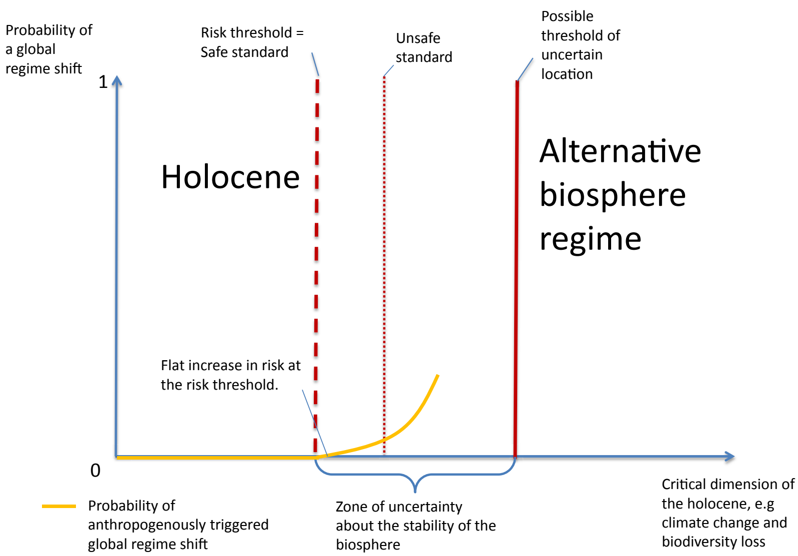

Figure 3: Unsafe standard set beyond the risk threshold when risk increases slowly at the risk threshold.

cannot impact on the risk of a regime shift and whether the regime shift materializes as a change in system dynamics or a stock collapse. They find that precaution is an optimal strategy if management actions can influence the risk of a regime shift and when such shift would result in a substantial reorganization of system dynamics. If the regime shift could lead to a stock collapse and management can influence the risk of a shift then the impact of management on the stock level still implies that precaution is recommended. However, the risk of losing the stock also tends to increase exploitation. This works in the opposite direction making precaution or not unclear. If the potential loss is relatively large compared to the discount rate and the risk of losing the stock, then it may still be optimal to act precautionary (Reed, 1989; Clarke and Reed, 1994; Tsur and Zemel, 1996).

We could draw on the Polasky *et al.* (2011b) result in the framework of Figure 1 by picturing the resource as the accumulated amount of resources that we derive from the Earth system and the regime shift as a shift out of the Holocene. Such regime shift could result either in a change in system dynamics that would substantially affect the flow of ecosystem goods and services or in a resource collapse in case the shift is so substantial that vital functions for human life cannot be maintained. In such context, the risky zone between the dashed line and the dotted line would be a zone of increased precaution rather than a no go zone. It is likely though that the level of precaution should be increasing as a function of risk and that an additional no go zone may be defined as the risk becomes so high that it is simply not acceptable, beyond the dotted line in Figure 3. It is tempting to equal planetary boundaries with the risk threshold. However, since Rockström *et al.* (2009b) propose that "determining a safe distance involves normative judgments of how societies choose to deal with risk and uncertainty", it is unclear how the risk threshold, safe standard and unsafe standard relate to the concept of planetary boundaries. In addition Steffen *et al.* (2015) specify that a planetary boundary also allows society time to react to early warning signs that it may be approaching a threshold and consequent abrupt or risky change. In contrast, the economic literature typically does not account for such lagged effects and only considers immediate risk.

Margolis and Nævdal deal with safe standards for a single variable. Increasing the chance of maintaining the Holocene involves keeping a complex system within several boundaries that may sometimes interact with each other. Nævdal and Oppenheimer (2007) study a problem with multiple thresholds of unknown locations that they apply to a potential major change in the thermohaline circulation. They show that if the damage following the trespassing of a threshold is high enough, it is then optimal to apply a precautionary principle. In the particular case they study this means putting a limit on global mean temperature and emissions of CO_2. Their model could be generalized to more boundaries and thus complement the planetary boundaries framework. However, none of these approaches envisage multiple thresholds that interact as do the thresholds of many of the global processes discussed.

These approaches focus almost solely on the consequences of reaching a critical threshold and much less on the dynamics of the system below the critical thresholds. The following section discusses the ways to navigate the global social-ecological system within planetary boundaries.

4 Navigating the Global Social-Ecological System

How can we relate to a system with planetary boundaries? Do we need to limit growth in human population and economic growth? Can we trust technological progress to help us overcome the challenges? Section 4.1 addresses these questions while Section 4.2 considers improving resilience — the capacity to deal with change and continue to develop and even transform to alternative development paths as ways to deal with regime shifts and complex dynamics within planetary boundaries.

4.1 Growth Within Planetary Boundaries, A Spectrum of Different Understandings

Exponential human population growth and associated human activities is of concern in a world of biosphere constraints, albeit dynamic. Among the general public and parts of the scientific community, economic growth is often portrayed as the source of many environmental problems and of current unsustainable development trajectories. Others believe that technological change will solve the challenges.

4.1.1 Population Growth

Malthus (1798) suggested that an exponential population growth could not continue forever since food only grew arithmetically while population grew exponentially and this exponential increase would result in a population collapse due to war, starvation, or disease. The current imprint of over 7 billion people and activities on the biosphere and ecosystem services is substantial (Steffen *et al.*, 2011). World population is starting to stabilize with recent projections to reach some 9–9.5 billion people on Earth by 2070 (Lutz *et al.*, 2014). According to predictions, most of the population increase will take place in sub-Saharan Africa and in Asia. The implications for food and water consumption are substantial along with the rise of the middleclass in these regions with altered and increased patterns of consumption (Cleland, 2013; Mora, 2014). Education, future health, quality of governance, the capacity to adapt to climate change, and economic growth are vital in determining future population growth (Lutz *et al.*, 2014). But, even if population growth was to stabilize substantially sooner, this may not help if the amount of resources and ecosystem services appropriated by the current population was to continue to increase as it has in the past (Ehrlich and Ehrlich, 2013). This is tightly linked to the discussion on economic growth and planetary boundaries.

4.1.2 Economic growth

Generally, the economic growth literature tends to explain economic growth independently of environmental concerns, except for availability of non-renewable resources (fossil fuels and minerals).

The environmental Kuznets curve (EKC) literature studies the relationship between economic growth and environmental impacts and suggests that it should have an inverted U shape. This literature builds on many empirical studies showing a positive correlation between growth and environmental impacts, often measured as pollution, for low level of development and a negative correlation for high levels of development. Grossman and Krueger (1995) point to three effects that would explain such dynamics (1) a scale effect, a larger scale economy would use more resources and incur more waste; (2) a composition effect, as the economy grows richer it tends to focus more on activities like services which are less polluting than industries; (3) a technological effect, technological progress in richer countries leads to less polluting processes. Theoretical literature complementing these findings focus on dynamic or static optimization models with environmental considerations, e.g., optimal growth model with pollution and abatement expenditure (Selden and Song, 1995) or with models where pollution increases with growth up to some threshold (John and Pecchenino, 1994; Stokey, 1998; Jaeger, 1998).

While it is tempting to use this literature as evidence that increased economic growth will solve environmental problems, no convincing argument can be made on this point and the approach has been criticized (Arrow *et al.*, 1995; Steffen *et al.*, 2004). Indeed due to lack of appropriate data most of the EKC literature focuses on pollution of particular pollutants involving short term local costs rather than, for example, pollutants involving more long term and dispersed costs (CO_2), resource stocks, provision of ecosystem services or land use change. The environmental improvement observed in a particular country may also be explained to some extent by transfers of polluting activities to other countries (pollution havens, Levinson and Taylor, 2008) or increase in the use of some other pollutants (Lopez, 1994). And importantly, this literature has so far discarded the risk of irreversible environmental regime shifts triggered by increased environmental pressure.

To what extent does economic growth impact on the biosphere? Surprisingly little economics literature focuses on the sources of life-supporting ecosystems as a critical foundation for the economy even though Nordhaus (1974), possibly inspired by Boulding (1966) pictured a “’spaceship economy”, where “great attention must be paid to the sources of life and to the dumps where our refuse is piled” in contrast to “the cow-boy economy” Nordhaus (1974, p. 22) that had been prevailing. Meadows *et al.* (1972) modelled limits to growth but was widely criticized on many aspects including poor empirical support and flawed assumptions about technological progress and population growth.

However, the substantial growth of the economy in terms of consumption and production, or the Great Acceleration that has taken place since the Second World War (Steffen *et al.*, 2007), is to many the root of numerous environmental problems. Ecological economics has long debated economic growth in relation to energy, material flows, ecosystems and natural capital broadly (e.g., Daly, 1968; Norgaard, 1994; Arrow *et al.*, 1995; Costanza *et al.*, 1997; Jackson, 2009). Degrowth has been put forward as a way to decrease the impacts of the human enterprise on the environment by downsizing the economy (e.g. Martinez-Alier, 2009; Schneider *et al.*, 2010; Kallis, 2011). According to this perspective, fixing market imperfections, increasing efficiency and technological progress will not be sufficient to deal with global challenges. van den Bergh (2011) argues though that degrowth may not be an efficient strategy to reduce environmental pressure.

Economic growth is traditionally measured in GDP rather than in social welfare, the focus of economic theory. Only under unrealistic conditions can GDP approximate social welfare (Weitzman, 1976). Individual welfare depends on things like access to basic goods and services, social status, adaptation to change, income, which are unlikely to be well represented by one aggregate measure of GDP.[6] GDP estimates the costs of market-related activities in society but not their benefits and discards all informal or non-market activities (for example, the use of natural resources and the environment). Despite a steady GDP growth in rich countries between 1950 and 1980, some happiness or subjective well-being studies point to a stagnating or even decreasing level of welfare (Layard, 2005; Costanza *et al.*, 2013; Raudsepp-Hearne *et al.*, 2010b).

If GDP is not a good indicator of social welfare, the A-growth theory (van den Bergh, 2011) suggests that we should ignore it. Policy makers should instead focus on correcting market inefficiencies that create environmental problems and develop policies to ensure that human behaviour does not push us outside of a safe operating space (van den Bergh and Kallis, 2012). In many respects, further economic growth based on biophysical expansion is deeply problematic for sustainability. Still there are options for economic growth that do not damage the environment but the potential for redirecting economic development in tune with the life-supporting ecosystems is yet to materialize. Obviously, new approaches and measures of social welfare (e.g. Inclusive Wealth, Dasgupta *et al.*, 2000; Arrow *et al.*, 2003, happiness index, Human Development Index) and institutions that can redirect economic growth from quantity to quality and into active collaborations with the biosphere are urgently needed (Walker *et al.*, 2009; Folke *et al.*, 2011).

[6]See van den Bergh, 2009 for an overview of why GDP is a poor approximate of welfare.

4.1.3 The role of technological change

Many economic theories suggest that environmental problems, be it pollution or overuse of resource, will have effects on prices that will trigger technological progress to overcome the original problems and thus support infinite growth.

Neoclassic growth models argue that exogenous factors like the savings rate (Harrod-Domar model) or the rate of technical progress (Solow model) determine the long run rate of economic growth. As resources become scarce and thus expensive, alternative resources become relatively cheap and economically viable; new technologies become more cost effective, which drives technological progress. (Solow, 1956).

In contrast, endogenous growth theory argues that new technologies and human capital play an important part to explain how growth is determined (e.g. the AK model) (Arrow, 1962; Uzawa, 1965). Contributions focus on positive externalities like spillover effects (Romer, 1986; Lucas, 1988; Rebelo, 1991), imperfect markets (Grossman and Helpman, 1990) and research and development (Aghion and Howitt, 1992).

Recent literature has incorporated environmental concerns and claims that sustained growth is not optimal unless resources are devoted to pollution abatement. If emissions are chosen in an optimal way, then constant pollution might be compatible with a growing economy (exogenous growth). If the economy spends resources on abatement and development of clean technology, sustained economic growth is possible if the marginal productivity of capital has a lower bound. The same holds true if intellectual capital has public good characteristics so that output, capital, consumption and knowledge may grow unbounded while environmental quality improves. In some cases, environmental policy may even increase growth (see Xepapadeas, 2005, for a more detailed review of these results).

Meanwhile, these results focus on pollution, rather than humans' use and dependence of the ecosystem services of the biosphere. The endogenous growth literature has developed as an attempt to explain the exogenous growth variable, with different kinds of endogenous growth processes. However, emission growths contribute significantly to output growth and the use of the environment as a not fully compensated factor of production could also explain some share of output growth that is traditionally explained by technical change (Xepapadeas *et al.*, 2007).

More scientific evidence on this issue is needed. Experiences from the past indicate that innovation and technical progress is likely to bring forward improvements to many problems that we are facing today.

While it is essential to account for the important mechanisms by which price adjustments occur and stimulate technological progress (Bretschger, 2005; Vollebergh and Kemfert, 2005), voices in the scientific community have raised two concerns that economists, to our knowledge, have failed to address properly: (1) technological progress may not occur fast enough to prevent humanity trespassing critical thresholds and (2) innovations that solve one problem may also create other environmental and social problems that in the longer run turn out to be of larger scale and even more difficult to solve (Norgaard, 1994; Holling and Meffe, 1996; Sterner *et al.*, 2006). In a world where we are pushing the limits for a safe operating space for humanity and where human actions driven by the search for economic growth may trigger large scale regime shifts, these two concerns should be seriously addressed. Technological change needs to be stimulated to work with the processes of the biosphere rather than further disrupting critical life support services, a path dependence that so far seems to have dominated many innovation, technological change, and development paradigms (Norgaard, 1994; Westley *et al.*, 2011; Galaz *et al.*, 2014).

4.2 Resilience and Long Term Efficiency

We now leave behind what happens at the limits of the stable biosphere zone in which we thrive and focus instead on what can be done to improve management within the current domain of stability of the biosphere. Economics traditionally focuses on welfare improvements, optimization, efficiency, and policies to correct imperfect markets. In contrast, managing resilience of desirable social-ecological regimes has been highlighted as a way forward in the face of complex systems and uncertainty (e.g. Costanza *et al.*, 1993; Levin *et al.*, 2012). Resilience is the capacity of a system to deal with change and continue to develop, using shocks and disturbances to spur renewal and innovation. Resilience thinking embraces learning, diversity and the view that humans and nature are not just linked but intertwined social-ecological systems. (Walker and Salt, 2006; Folke *et al.*, 2010) Short-sighted managers will often find substantial trade-offs between resilience and efficiency. For example specializing in one particular crop that is well adapted to its current environment can improve short term profits and welfare but decreases system resilience as diversity is reduced and the current crop may be poorly adapted to future environmental conditions (Norberg *et al.*, 2001). Hence, specialization may not be an optimal long run strategy if it implies that future profits would drop when environmental conditions change. In a complex evolving world, where regime shifts can occur, investing in resilience is like insurance against unexpected changes. It may also be fruitful to learn more about the underlying mechanisms that maintain the resilience of an unwanted social-ecological regime so as to gain knowledge about how to break out of it, to break out of traps (Durlauf, 2006). Robust management aiming to achieve robust performance and/or stability in the presence of bounded uncertainties could be another strategy. However, increasing robustness to biological variations may result in decreased robustness with respect to economic variations (Anderies *et al.*, 2007; Anderies *et al.*, 2013).

The economic literature has recently started to address issues of ecological thresholds and regime shifts.[7] Beside the results mentioned in Section 2.3.1, Levin *et al.* (2012) review the implications of social-ecological systems as complex adaptive systems and Crépin *et al.* (2012) provide a review of the literature on regime shifts and management. This literature focuses on strategies to avoid a regime shift as well as strategies to deal with a regime shift once it has occurred. Here we go through three avenues to manage resilience: system resilience (Section 4.2.1), policy resilience (Section 4.2.2) and learning and adaptive capacity (Section 4.2.3).

4.2.1 System resilience

Even though some thoughts have been given to the consequences of leaving the Holocene focusing on adaptation and transformation in particular with regard to impending climate change (IPCC, 2014), the main strategy still remains to avoid such regime shifts. The main strategy suggested by the planetary boundary framework is to reduce the probability of a regime shift by releasing pressure on essential biosphere dynamics and thereby remaining in a Holocene-like state.

[7] See Li and Löfgren (1998), Kremer and Morcom (2000), Nævdal (2000), Nævdal (2001), and Nævdal (2003), Muradian (2001), Crépin (2002), Brock and Starrett (2003), Mäler *et al.* (2003), Arrow *et al.* (2003), Wagener (2003) for examples of early work.

This is a global resilience increasing strategy. We find strong support also in the economic literature that remaining below risk thresholds is an optimal policy response (see Section 3.2) when the implications of a planetary regime shift could be catastrophic.

However, negotiations to address global environmental problems like climate change are failing and threshold uncertainty might explain why. Experimental evidence shows that cooperation around the provision of a common public good like improved climate policy breaks down if the threshold for catastrophic climate impacts is uncertain (Barrett and Dannenberg, 2013). Focusing on planetary boundaries identified as risk thresholds rather than on the uncertain thresholds for catastrophic climate change may improve the situation. Indeed the empirical scientific support for defining the planetary boundaries is substantial, thereby limiting the range of uncertainty compared to identifying the thresholds themselves (Rockström *et al.*, 2009a; Rockström *et al.*, 2009b; Steffen *et al.*, 2015). Hence planetary boundaries/risk thresholds have potential to act as focal points and there is substantial evidence that agreeing to remain below planetary boundaries/risk thresholds is an optimal policy (Margolis and Nævdal, 2008).

In addition better knowledge of Earth system dynamics could be useful to figure out ways to alter the system's capacity to absorb change and thus earn time. One possible pathway would be to exploit interactions between Earth system dynamics by temporarily putting more pressure on dynamics that are far from the risk threshold/boundary if that helps release pressure on other dynamics that are closer to the boundaries/risk threshold. For example, keeping high levels of atmospheric aerosol loading may buy time to avoid critical climate warming. (Ramanathan *et al.*, 2005). Figure 4 illustrates two mechanisms for increasing resilience. If a change in risk structure from a to b occurred it may become optimal to set a new standard (which is not entirely safe) symbolized by the dotted red line. A change in risk structure from b to c would instead shift the risk threshold further away and legitimate a new safe standard at the dotted line.

Economics provides policy recommendations that could help address problems in relation to pressure on biosphere stability. Policy instruments addressing incremental change are well studied and selection matrices depending on different criteria and conditions are available (Xepapadeas, 1997; Sterner and Coria, 2012). However, evidence sug-

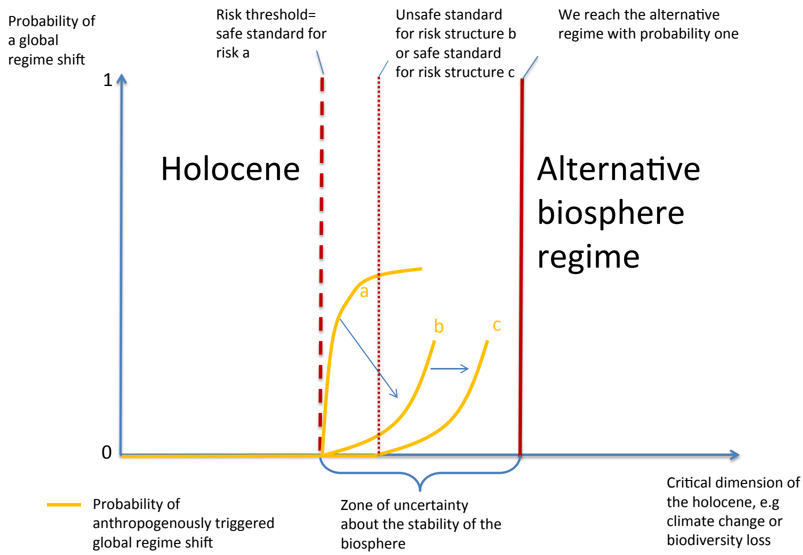

Figure 4: Examples of how policies that affect risk structures can help increase resilience: (a) shift in risk threshold and (b) change in risk structure.

gests that these recommendations need to be revisited for problems dealing with phenomena that involve regime shifts or catastrophic change. For example, it may sometimes be useful to combine price and quantity regulations to regulate regime shifts. If a shift to a less desirable regime has occurred, a quantity instrument could be used to push the system back into a more favourable regime, while once the system is back in that regime, a price instrument may be better to help keep the system within the desirable regime (Heijdra and Heijnen, 2013). While some progress has been made recently (Pizer, 2003; Crépin *et al.*, 2011; Heijdra and Heijnen, 2013), more research is needed in that direction.

Improving system resilience is only one side of a set of policy reforms. It is at least as important to also improve policy resilience so that society is prepared and can react adequately if a crisis occurs.

4.2.2 Policy resilience

When possible, society can monitor early warning signals. A successful signalling system must build on knowledge about what may happen, a good monitoring system of essential variables and critical changes should trigger a warning signal followed up by an action plan ready to use. These require substantial system knowledge and capacity to respond adequately to such signals. Even so, some warning signals may actually come too late to allow for a successful response that would help avoid a regime shift (Biggs *et al.*, 2009). Developing indicator systems focusing on system resilience and potential regime shift could be the first step in the direction of a good early warning signals system (e.g., Scheffer *et al.*, 2012).

Even if society cannot avoid an impending regime shift, it can still prepare to better handle it. Regime shifts and policies to address them might impact people's welfare unevenly making it more difficult to reach agreements about how to address regime shifts (Crépin *et al.*, 2012). Hence, balancing the unfair welfare impacts that regime shifts or policies to address them generate would improve the chance of success. This could be achieved by putting in place good legitimate systems for wealth redistribution so that at least the worst welfare impacts on the most vulnerable can be avoided. Policy resilience also involves a substantial governance capacity enhancing good governance practices to deal with change in a welfare enhancing way. For example, strengthened institutional linkages can help society react more quickly in an adequate way (Folke *et al.*, 2007; Young *et al.*, 2008). Reducing inequalities and building social capital and trust also increases the chance that society will mobilize in a positive way in times of crisis rather than collapse (Wilkinson and Pickett, 2006). A satisfying policy for the decision maker will often result in a portfolio of measures that can handle different aspects of potential regime shifts.

There are substantial intergenerational differences regarding regime shifts too. The costs to avoid must be taken now while future generations will benefits. This is problematic because future generations do not have a voice in the debate. In addition, regime shifts create history dependency in the sense that what has happened in the past affects what the future looks like. If a regime shift has occurred it may not be possible to go back to the original regime, which can substantially decrease the range of options available to future generations. Irreversible decisions taken today can redistribute wealth among generations (Crépin *et al.*, 2012).

Policy resilience also requires substantial amount of flexibility to use windows of opportunities. The new stage set by the Anthropocene creates the need to stimulate social-ecological innovations to help maintain the geophysical conditions of the Holocene while also promoting human development (Westley *et al.*, 2011).

4.2.3 Learning and adaptive management

Good system knowledge and capacity to handle the unknown are essential prerequisites for system and policy resilience. Society's learning potential should become more focused than it is now on monitoring and learning about social-ecological changes. More science is needed to do so and particularly science that studies the interactions of global processes, which have traditionally been studied in very separate clusters, and also how those processes play out across levels and scales.

Given the seriousness of the issues involved it is essential to strike the right balance between action and learning. Waiting to learn everything before acting could be disastrous if regime shifts are triggered at the global scale as a result. However, acting for the sake of doing something, without having any idea of the consequences is no good either. Carefulness must be prioritized to ensure that actions taken do not have dramatic consequences that could have been avoided. However, the trade-off is that short term opportunities to increase welfare may be foregone.

Adaptive management is a structured and iterative process of optimal decision making under uncertainty, aiming to reducing uncertainty over time via system monitoring. While managing the system according to best practices, the manager also gathers information to improve future management. Learning and experimenting can be used to test hypotheses and improve long-run management outcomes (Holling, 1978; Walters, 1986). However, it may be challenging to balance the perspective of increased knowledge to improve management in the future and the wish to achieve the best short-term outcome based on current knowledge (Allan and Stankey, 2009). In particular, experiments at the scale of the planet like geoengineering require substantial caution (Barrett *et al.*, 2014).

5 Concluding Remarks

Traditional economics provides a wide set of conceptual tools necessary to analyse the role of the biosphere in relation to human well-being but these tools have been built in response to other kinds of problems and are often relying on too restrictive assumptions to encompass the essential challenges posed by the Anthropocene. Very little of the economics literature has focused directly on a human-dominated planet, and particularly not on the significance of the biosphere for social welfare. This is also true for work on planetary boundaries and where socialecological interactions form a complex dynamic system. However, the economics literature on precautionary approaches and safe minimum standards indicates almost unanimously that for the global scale problems we are facing it is optimal to apply a precautionary approach and often it is optimal to stay safe below a risk threshold. We suggest that planetary boundaries can be interpreted as risk thresholds, which they already are to a large extent (Rockström *et al.*, 2009b; Steffen *et al.*, 2015). This would help create consensus around them. Individual preferences about how to deal with risk will impact how society chooses to relate to planetary boundaries, for example whether no risk or some risk is acceptable may depend on risk aversion. However, preferences should not impact on the location of the boundaries themselves.

In line with the proposition of operating within a safe space (Rockström *et al.*, 2009a), economic growth needs not be limited, but redirected towards biosphere collaboration and certainly with reduced physical growth. This becomes quite obvious in relation to further population growth, and in the light of poor measures, like GDP, that still dominate measures of economic progress. Finally, resilience thinking could help improve management, and counteract short term efficiency goals that do not incorporate the risk of regime shift. This could help navigate systems prone to regime shifts towards long term efficiency and avoid unwanted and costly collapses of ecosystem services and welfare losses.

The planetary boundaries framework has literally exploded since the concept was minted 2009. Current planetary boundaries research focuses on refining the boundaries as some of those had been very coarsely approached in the seminal articles. Recent contributions include Carpenter and Bennett (2011), Anderies *et al.* (2013) and Steffen *et al.* (2015), with a strong focus on improving understanding of the dynamic biophysical limits of the Holocene. Drawing on Section 3, we suggest that it would be useful to also assess the risk structure of the planetary boundaries by attempting to gather more information about how risk may change beyond the boundary/risk threshold. This would help refine policy recommendation about how to relate to the boundaries following Margolis and Nævdal (2008).

Another focus of planetary boundaries research concerns planetary boundaries interactions. As already stated in the seminal articles, several of the planetary boundaries are likely to interact with each other. This implies that the planetary boundaries are highly dynamics and must be assessed and used as such. Steffen *et al.* (2015) have initiated work on planetary boundaries interactions.

While the planetary boundaries are concerned with phenomena linked to biosphere dynamics, the need for more social and economic boundaries in the form of minimum livelihood requirements and for examples millennium development goals have been explored earlier. The "doughnut" concept defining a safe and just space for humanity between a floor of social foundations based on human rights and an environmental ceiling consisting of planetary boundaries (Raworth, 2012) takes some steps towards defining social-ecological boundaries and similar work on Southern Africa and elsewhere is emerging (Leach *et al.*, 2012; New, 2014), but more is needed.

In addition to planetary boundaries, further work must address the implications of navigating complex social-ecological systems with potential regime shifts (Biggs *et al.*, 2009; Scheffer *et al.*, 2012). In particular, we need to empirically quantify the impacts of regime shifts on people's well-being, enquire about people's behavioural responses to regimes shifts in the resources they use and more systematically assess the implication of regime shifts on optimal policy instrument design. The delayed impacts of human actions due to lagged system dynamics should be of particular concern and the consequences for policy design should be examined.

The intricate relationships and trade-offs between efficiency and resilience should be further studied. It would be particularly useful to learn how resilience thinking can be used to increase long term well-being. Learning how to break the resilience of undesired situation would also contribute to increased management options. The potential and dangers of technical progress for helping societies out of crises should also be studied in a more objective way than today to help clarify under which conditions technical progress can be spurred to trigger desired transitions and under which conditions it might generate new problems in the future.

Climate economics has recently exploded as a branch of economics in the aftermath of impending climate change but climate change is only one particular aspect of global change. Economics research must better address the implications of living in the Anthropocene, in a totally interconnected world where all kinds of dynamics interact in nonlinear ways (Walker *et al.*, 2009; Folke *et al.*, 2011). This includes developing a new class of Earth system/economic models, going far beyond climate economic models. These models should capture implications of interacting biosphere processes and inherent non convexities and surprises associated with the Anthropocene.

We propose 'biosphere economics' as a significant area of investigation that explicitly accounts for the scale, speed, connectivity, of the intertwined social-ecological system and the social welfare challenges of dealing with biosphere capacity and resilience. This perspective has been raised in ecological economics, but now it needs more attention. In other words, the social welfare challenges of the Anthropocene need to be explicitly connected to the role of the biosphere and how it operates with social and economic development as part of it. Hence biosphere economics should build on state of the art empirical foundations of economics and biosphere research (Rockström *et al.*, 2009a; Rockström *et al.*, 2009b; Steffen *et al.*, 2015; IPCC, 2014, are examples of excellent reviews of the latter field). Biosphere economics should use the extensive set of tools developed in economics and adapt and develop them further to meet the particular challenges identified in this article. This article has taken a normative approach focusing mostly on the situation of a social planner asked to give policy advice. However, biosphere economics should also seek a more descriptive approach to better understand why we risk taking harmful decisions. Concepts like externalities, ill-defined property rights, and results from political economy and game theory are particularly relevant due to the global nature of the problems where a social planner does not exist and regulation is minimal.

Finally, it is essential that biosphere economics also borrows tools from other disciplines and builds on essential relevant knowledge available elsewhere, for example, about earth system dynamics and global governance. Current empirical data is scattered across different fields of economics, social and natural sciences that do not traditionally work together. In that respect, it is essential to better link global empirical data in economics, social and natural sciences and analyse it using state of the art statistical and econometric tools in relation to these issues.

References

Aghion, P. and P. Howitt. 1992. "A Model of Growth Through Creative Destruction". *Econometrica*. 60: 323–351.

Allan, C. and G. H. Stankey. 2009. *Adaptive Environmental Management: A Practitioner's Guide*. Dordrecht, Netherlands: Springer — CSIRO.

Anderies, J. M., S. R. Carpenter, W. Steffen, and J. Rockström. 2013. "The Topology of Non-linear Global Carbon Dynamics: From Tipping Points to Planetary Boundaries". *Environmental Research Letters*. 8: 044048.

Anderies, J. M., A. A. Rodriguez, M. A. Janssen, and O. Cifdaloz. 2007. "Panaceas, Uncertainty, and the Robust Control Framework in Sustainability Science". *Proceedings of the National Academy of Sciences*. 104(39).

Ang, F. and S. van Passel. 2012. "Beyond the Environmentalist's Paradox and the Debate on Weak versus Strong Sustainability". *BioScience*. 62: 251–259.

Arrow, K. J. 1962. "The Economic Implications of Learning by Doing". *The Review of Economic Studies*. 29: 155.

Arrow, K. J., P. Dasgupta, and K.-G. Mäler. 2003. "Evaluating Projects and Assessing Sustainable Development in Imperfect Economies". *Environmental and Resource Economics*. 26: 647–685.

Arrow, K. J. and A. C. Fisher. 1974. "Environmental Preservation, Uncertainty, and Irreversibility". *The Quarterly Journal of Economics*. 88: 312–319.

Arrow, K. J. and L. Hurwicz. 1972. "Decision Making Under Ignorance". In: *Expectations in Economics*. Ed. by C. F. Carter and J. L. Ford. New York, United States: Augustus M. Kelley.

Arrow, K., B. Bolin, R. Costanza, P. Dasgupta, C. Folke, C. S. Holling, B.-O. Jansson, S. A. Levin, K.-G. Mäler, C. Perrings, and D. Pimentel. 1995. "Economic Growth, Carrying Capacity, and the Environment". *Ecological Economics*. 15: 91–95.

Ayres, R. U. 2007. “On the Practical Limits to Substitution”. *Ecological Economics*. 61: 115–128.

Barrett, S. and A. Dannenberg. 2013. “Sensitivity of Collective Action to Uncertainty About Climate Tipping Points”. *Nature Climate Change*. 4: 36–39.

Barrett, S., T. M. Lenton, A. Millner, A. Tavoni, S. R. Carpenter, J. M. Anderies, F. S. Chapin III, A.-S. Crépin, G. Daily, P. Ehrlich, C. Folke, V. Galaz, T. Hughes, N. Kautsky, E. F. Lambin, R. Naylor, K. Nyborg, S. Polasky, M. Scheffer, J. Wilen, A. Xepapadeas, and A. J. de Zeeuw. 2014. “Geoengineering Reconsidered”. *Nature Climate Change*: 527–529.

Berkes, F. and C. Folke. 1998. *Linking Social and Ecological Systems — Management Practices and Social Mechanisms for Building Resilience*. Cambridge (UK): Cambridge University Press.

Biggs, R., T. Blenckner, C. Folke, L. J. Gordon, A. Norström, M. Nyström, and G. D. Peterson. 2012. “Regime Shifts”. In: *Encyclopedia of Theoretical Ecology*. Ed. by A. Hastings and L. Gross. Berkeley, United States: University of California Press.

Biggs, R., S. R. Carpenter, and W. A. Brock. 2009. “Turning Back From the Brink: Detecting an Impending Regime Shift in Time to Avert it”. *Proceedings of the National Academy of Sciences of the United States of America*. 106: 826–831.

Bishop, R. C. 1978. “Endangered Species and Uncertainty: The Economics of a Safe Minimum Standard”. *American Journal of Agricultural Economics*. 60: 10.

Bishop, R. C. 1979. “Endangered Species, Irreversibilities, and Uncertainty: A Reply”. *American Journal of Agricultural Economics*. 61(2): 376–379.

Boulding, K. E. 1966. “Economics and ecology”.

Bretschger, L. 2005. “Economics of Technological Change and the Natural Environment: How Effective are Innovations as a Remedy for Resource Scarcity?” *Ecological Economics*. 54(2): 148–163.

Brock, W. A. and D. Starrett. 2003. “Managing Systems with Nonconvex Positive Feedback”. *Environmental and Resource Economics*. 26: 575–602.

Cameron, J. 1991. “Precautionary Principle: A Fundamental Principle of Law and Policy for the Protection of the Global Environment”. *The*

Boston College International and Comparative Law Review. 14(1): 1–28.

Carpenter, S. R. and E. M. Bennett. 2011. "Reconsideration of the planetary boundary for phosphorus". *Environmental Research Letters*. 6: 014009.

Carpenter, S. R., D. Ludwig, and W. A. Brock. 1999. "Management of Eutrophication for Lakes Subject to Potentially Irreversible Change". *Ecological Applications*. 9: 751–771.

Carpenter, S., K. J. Arrow, S. Barrett, R. Biggs, W. A. Brock, A.-S. Crépin, G. Engström, C. Folke, T. P. Hughes, N. Kautsky, C.-Z. Li, G. McCarney, K. Meng, K.-G. Mäler, S. Polasky, M. Scheffer, J. Shogren, T. Sterner, J. R. Vincent, B. Walker, A. Xepapadeas, and A. de Zeeuw. 2012. "General Resilience to Cope with Extreme Events". *Sustainability*. 4(12): 3248–3259.

Ciriacy-Wantrup, S. V. 1952. *Resource Conservation*. Berkeley: University of California Press.

Clarke, H. M. and W. J. Reed. 1994. "Consumption/Pollution Tradeoffs in an Environment Vulnerable to Pollution-Related Catastrophic Collapse". *Journal of Economic Dynamics and Control*. 18(5): 991–1010.

Cleland, J. 2013. "World Population Growth; Past, Present and Future". *Environmental and Resource Economics*. 55: 543–554.

Costanza, R. 1991. "Assuring Sustainability of Ecological Economic Systems". In: *Ecological Economics: The Science and Management of Sustainability*. Ed. by R. Costanza. New York, p. 525: Columbia University Press. 331–343.

Costanza, R. L., L. Graumlich, W. Steffen, C. Crumley, J. Dearing, K. Hibbard, R. Leemans, C. Redman, and D. Schimel. 2007. "Sustainability or Collapse: What Can We Learn from Integrating the History of Humans and the Rest of Nature?" *Ambio*. 36: 522–527.

Costanza, R., G. Alperovitz, H. Daly, J. Farley, C. Franco, T. Jackson, I. Kubiszewski, J. Schor, and P. Victor. 2013. "Building a Sustainable and Desirable Economy-in-Society-in-Nature". In: *State of the World 2013*. Washington, DC: Island Press/Center for Resource Economics. 126–142.

Costanza, R., C. J. Cleveland, and C. Perrings. 1997. "Introduction to the Development of Ecological Economics". In: *The Development*

of Ecological Economics. Ed. by R. Costanza, C. J. Cleveland, and C. Perrings. Cheltenham: Edward Elgar. xiii–xxix.
Costanza, R. and H. E. Daly. 1992. "Natural Capital and Sustainable Development". *Conservation Biology*. 6: 37–46.
Costanza, R. and C. Perrings. 1990. "A Flexible Assurance Bonding System for Improved Environmental Management". *Ecological Economics*. 2: 57–76.
Costanza, R., L. Wainger, C. Folke, and K.-G. Mäler. 1993. "Modeling Complex Ecological Economic Systems: Toward an Evolutionary, Dynamic Understanding of People and Nature". *BioScience*. 43: 545–555.
Crépin, A.-S. 2002. *Tackling the Economics of Ecosystem*. Stockholm University: Doctoral dissertation on Economics.
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., R. Biggs, S. Polasky, M. Troell, and A. J. de Zeeuw. 2012. "Regime Shifts and Management". *Ecological Economics*. 84: 15–22.
Crépin, A.-S., J. Norberg, and K.-G. Mäler. 2011. "Coupled Economic-Ecological Systems with Slow and Fast Dynamics — Modelling and Analysis Method". *Ecological Economics*. 70(8): 1448–1458.
Crowards, T. M. 1998. "Safe Minimum Standards: Costs and Opportunities". *Ecological Economics*. 25: 303–314.
Crutzen, P. J. 2002. "Geology of Mankind". *Nature*. 415(6867): 23.
Daily, G., ed. 1997. *Nature's Services*. Washington D.C, Covelo, CA: Island Press.
Daly, H. 1968. *On Economics as a Life Science. Valuing the Earth: Economics, Ecology, Ethics*. Cambridge, MA: MIT Press.
Dasgupta, P., S. Levin, and J. Lubchenco. 2000. "Economic Pathways to Ecological Sustainability". *BioScience*. 50: 339–345. i.
Dasgupta, P. and K.-G. Mäler. 2003. "The Economics of Non-Convex Ecosystems". *Special Issue Environmental and Resource Economics*. 26(4).
Durlauf, S. 2006. "Groups, Social Influences, and Inequality". *Poverty Traps*: 141–175.

Ehrlich, P. R. and A. H. Ehrlich. 2013. "Can a Collapse of Global Civilization be Avoided?" *Proceedings of the Royal Society B: Biological Sciences*. 280: 20122845.

Ekins, P., S. Simon, L. Deutsch, C. Folke, and R. De Groot. 2003. "A Framework for the Practical Application of the Concepts of Critical Natural Capital and Strong Sustainability". *Ecological Economics*. 44(2): 165–185.

Foley, J. A., R. Defries, G. P. Asner, C. Barford, G. Bonan, S. R. Carpenter, F. S. Chapin, M. T. Coe, G. C. Daily, H. K. Gibbs, J. H. Helkowski, T. Holloway, E. A. Howard, C. J. Kucharik, C. Monfreda, J. A. Patz, I. C. Prentice, N. Ramankutty, and P. K. Snyder. 2005. "Global Consequences of Land Use". *Science*. 309: 570–574.

Folke, C., S. R. Carpenter, B. H. Walker, M. Scheffer, T. Elmqvist, L. Gunderson, and C. S. Holling. 2004. "Regime Shifts, Resilience, and Biodiversity in Ecosystem Management". *Annual Review of Ecology, Evolution, and Systematics*. 35: 557–581.

Folke, C., S. R. Carpenter, B. Walker, M. Scheffer, T. Chapin, and J. Rockström. 2010. "Resilience Thinking: Integrating Resilience, Adaptability and Transformability". *Ecology and Society*. 15(4).

Folke, C., Å. Jansson, J. Larsson, and R. Costanza. 1997. "Ecosystem Appropriation by Cities". *Ambio*. 3: 167–172.

Folke, C., Å. Jansson, J. Rockström, P. Olsson, S. R. Carpenter, F. S. Chapin, A.-S. Crépin, G. Daily, K. Danell, J. Ebbesson, T. Elmqvist, V. Galaz, F. Moberg, M. Nilsson, H. Österblom, E. Ostrom, Å. Persson, G. Peterson, S. Polasky, W. Steffen, B. Walker, and F. Westley. 2011. "Reconnecting to the Biosphere". *Ambio*. 40: 719–738.

Folke, C., L. Pritchard, F. Berkes, J. Colding, and U. Svedin. 2007. "The Problem of Fit Between Ecosystems and Institutions: Ten Years Later". *Ecology and Society*. 12(1).

Galaz, V., H. Österblom, Ö. Bodin, and B. Crona. 2014. "Global Networks and Global Change-Induced Tipping Points". *International Environmental Agreements: Politics, Law and Economics*: 1–33.

Gilboa, I. and D. Schmeidler. 1989. "Maxmin Expected Utility with Non-Unique Prior". *Journal of Mathematical Economics*. 18: 141–153.

Grossman, G. M. and E. Helpman. 1990. "Trade, Innovation, and Growth". *American Economic Review*. 80: 86–91.

Hartwick, J. M. 1977. "Intergenerational Equity and the Investing of Rents from Exhaustible Resources". *The American Economic Review*. 67: 972–974.

Hartwick, J. M. 1978a. "Investing Returns from Depleting Renewable Resource Stocks and Intergenerational Equity". *Economics Letters*. 1: 85–88.

Hartwick, J. M. 1978b. "Substitution Among Exhaustible Resources and Intergenerational Equity". *The Review of Economic Studies*. 45: 347.

Heijdra, B. and P. Heijnen. 2013. "Environmental Abatement and the Macroeconomy in the Presence of Ecological Thresholds". *Environmental & Resource Economics*. [0924-6460] 55(1): 47–70.

Henry, C. 1974. "Investment Decisions Under Uncertainty: The "Irreversibility effec"". *The American Economic Review*: 1006–1012.

Holling, C. S. 1973. "Resilience and Stability of Ecological Systems". *Annual Review of Ecology and Systematics*. 4: 1–23.

Holling, C. S. 1978. *Adaptive Environmental Assessment and Management*. Chichester, United Kingdom: John Wiley & Sons. 377.

Holling, C. S. and G. K. Meffe. 1996. "Command and Control and the Pathology of Natural Resource Management". *Conservation Biology*. 10(2): 328–337.

IPCC. 2013. "Climate Change 2013: The Physical Science Basis". In: *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Ed. by T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. 1535.

IPCC. 2014. "Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A:Global and Sectoral Aspects". In: *Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Ed. by C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, and L. L. White. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. 1132.

Jackson, T. 2009. *Prosperity Without Growth? Economics for a Finite Planet.* London: Earthscan/Sustainable Development Commission.

Jaeger, W. 1998. *Growth and Environmental Resources: A Theoretical Basis for the U-shaped Environmental Path.* Williams College: Mimeo.

Jansson, A., M. Hammer, C. Folke, and R. Costanza. 1994. *Investing in Natural Capital: The Ecological Economics Approach To Sustainability.* Island Press.

John, A. and R. Pecchenino. 1994. "An Overlapping Generations Model of Growth and the Environment". *The Economic Journal.* 104: 1393.

Kallis, G. 2011. "In Defence of Degrowth". *Ecological Economics.* 70: 873–880.

Kremer, M. and C. Morcom. 2000. "Elephants". *American Economic Review*: 212–234.

Layard, R. 2005. "Rethinking Public Economics: The Implications of Rivalry and Habit". In: *Economics and Happiness: Framing the Analysis.* Ed. by L. Bruni and P. L. Porta. Oxford University Press. 147–170.

Leach, M., J. Rockström, P. Raskin, I. C. Scoones, A. C. Stirling, A. Smith, and P. Olsson. 2012. "Transforming Innovation for Sustainability". *Ecology and Society.* 17(2): 11.

Levin, S. A. 1999a. *Fragile Dominion — Complexity and the Commons.* Cambridge, United States: Perseus Publishing.

Levin, S. A. 1999b. "Towards a Science of Ecological Management". *Conservation Ecology.* 3: 6.

Levin, S. A., T. Xepapadeas, A.-S. Crépin, J. Norberg, A. de Zeeuw, C. Folke, T. P. Hughes, K. J. Arrow, S. Barrett, G. C. Daily, P. R. Ehrlich, N. Kautsky, K.-G. Mäler, S. Polasky, M. Troell, J. Vincent, and B. H. Walker. 2012. "Social-Ecological Systems as Complex Adaptive Systems: Modeling and Policy Implications". *Environment and Development Economics.* 18: 111–132.

Levinson, A. and M. S. Taylor. 2008. "Unmasking the Pollution Haven Effect". *International Economic Review.* 49(1): 223–254.

Li, C.-Z. and K.-G. Löfgren. 1998. "A Dynamic Model of Biodiversity Preservation". *Environment and Development Economics.* 3: 157–172.

Lopez, R. 1994. "The Environment as a Factor of Production: The Effects of Economic Growth and Trade Liberalization". *Journal of Environmental Economics and Management*. 27(2): 163–184.

Lucas, R. E. 1988. "On the Mechanics of Economic Development". *Journal of Monetary Economics*. 22: 3–42.

Lutz, W., W. P. Butz, and S. KC, eds. 2014. *World Population & Human Capital in the 21st Century*. Oxford, UK: Oxford University Press.

Mäler, K.-G., A. Xepapadeas, and A. de Zeeuw. 2003. "The Economics of Shallow Lakes". *Environmental and Resource Economics*. 26(4): 603–624.

Malthus, T. 1798. *An Essay on the Principle of Population*. Ed. by J. Johnson. London: United Kingdom.

Margolis, M. and E. Nævdal. 2008. "Safe Minimum Standards in Dynamic Resource Problems: Conditions for Living on the Edge of Risk". *Environmental and Resource Economics*. 40: 401–423.

Martinez-Alier, J. 2009. "Socially Sustainable Economic De-growth". *Development and Change*. 40: 1099–1119.

McNeill, J. R. 2000. *Something New Under the Sun: An Environmental History of the Twentieth-Century World (The Global Century Series)*. WW Norton & Company.

Meadows, D. H., G. L. Meadows, J. Randers, and W. W. Beherens III. 1972. *The Limits to Growth*. Universe Books.

Millennium Ecosystem Assessment (MA). 2005. "Synthesis Report". Millennium Ecosystem Assessment.

Mora, C. 2014. "Revisiting the Environmental and Socioeconomic Effects of Population Growth: A Fundamental But Fading Issue in Modern Scientific, Public, and Political Circles". *Ecology and Society*. 19(1): 38. http://dx.doi.org/10.5751/ES-06320-190138.

Muradian, R. 2001. "Ecological Thresholds: A Survey". *Ecological Economics*. 38: 7–24.

Nævdal, E. 2000. "Essays in Environmental and Resource Economics". In: *Environmental Problem Solving for the Naughties*. Doctor Scientiarum Theses (Norway): Agricultural University of Norway.

Nævdal, E. 2001. "Optimal Regulation of Eutrophying Lakes, Fjords, and Rivers in the Presence of Threshold Effects". *American Journal of Agricultural Economics*. 83: 972–984.

Nævdal, E. 2003. "Optimal Regulation of Natural Resources in the Presence of Irreversible Threshold Effects". *Natural Resource Modelling*. 16(3): 305–333.

Nævdal, E. and M. Oppenheimer. 2007. "The Economics of the Thermohaline Circulation — A Problem with Multiple Thresholds of Unknown Locations". *Resource and Energy Economics*. 29: 262–283.

New, M. 2014. "Water Scarcity on a Blue Planet". *Is the Planet Full?*: 121.

Norberg, J., D. P. Swaney, J. Dushoff, J. Lin, R. Casagrandi, and S. A. Levin. 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. P. 1974. "Resources as a Constraint on Growth". *American Economic Review*. 64: 22–26.

Norgaard, R. B. 1994. "The Process of Loss: Exploring the Interactions between Economic and Ecological Systems". *American Zoologist*. 34(1): 145–158.

Odum, E. P. 1989. "Ecology and Our Endangered Life-Support Systems".

Ostrom, E. 1994. "Constituting social capital and collective action". *Journal of Theoretical Politics*. 6: 527–562.

Partha, D. and I. Serageldin. 1999. *Social Capital a Multi Faceted Perspective*. Washington D.C.: The World Bank.

Pearce, D., K. Hamilton, and G. Atkinson. 1996. "Measuring Sustainable Development: Progress on Indicators". *Environment and Development Economics*. 1(01): 85–101.

Pizer, W. A. 2003. "Climate Change Catastrophes". Resources for the Future, Discussion Paper RFF DP 03-31. Washington DC, United States.

Polasky, S., S. R. Carpenter, C. Folke, and B. Keeler. 2011a. "Decision-Making Under Great Uncertainty: Environmental Management in an Era of Global Change". *Trends in Ecology & Evolution*. 26.

Polasky, S., A. de Zeeuw, and F. Wagener. 2011b. "Optimal Management with Potential Regime Shifts". *Journal of Environmental Economics and Management*. 62: 229–240.

Putnam, R. D. 1995. "Bowling Alone: America's Declining Social Capital". *Journal of Democracy*. 6(1): 65–87.

Ramanathan, V., C. Chung, D. Kim, T. Bettge, L. Buja, J. T. Kiehl, W. M. Washington, Q. Fu, D. R. Sikka, and M. Wild. 2005. "Atmospheric Brown Clouds: Impacts on South Asian Climate and Hydrological Cycle". *Proceedings of the National Academy of Sciences*. 102: 5326–5333.

Randall, A. 1991. "The Value of Biodiversity". *Ambio*. 20: 64–68.

Raudsepp-Hearne, C., G. D. Peterson, and E. M. Bennett. 2010a. "Ecosystem Service Bundles for Analyzing Tradeoffs in Diverse Landscapes". In: *Proceedings of the National Academy of Sciences of the United States of America*. Vol. 107. 5242–5247.

Raudsepp-Hearne, C., G. D. Peterson, M. Tengö, E. M. Bennett, T. Holland, K. Benessaiah, G. K. MacDonald, and L. Pfeifer. 2010b. "Untangling the Environmentalist's Paradox: Why Is Human Well-being Increasing as Ecosystem Services Degrade?" *BioScience*. 60: 576–589.

Raworth, K. 2012. "A Safe and Just Space for Humanity". Can we Live within the Doughnut? — Oxfam Discussion Papers.

Rebelo, S. 1991. "Long-Run Policy Analysis and Long-Run Growth". *Journal of Political Economy*. 99: 500.

Reed, W. J. 1989. "Optimal Investment in the Protection of a Vulnerable Biological Resource". *Natural Resource Modeling*. 3: 463–480.

Reyers, B., R. Biggs, G. S. Cumming, T. Elmqvist, A. P. Hejnowicz, and S. Polasky. 2013. "Getting the Measure of Ecosystem Services: A Social-Ecological Approach". *Frontiers in Ecology and the Environment*. 11(5): 268–273.

Rockström, J., W. L. Steffen, K. Noone, Å. Persson, F. S. I. Chapin, E. F. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. J. Schellnhuber, B. Nykvist, C. A. de Wit, T. P. Hughes, H. R. S. van der Leeuw, S. Sörlin, P. K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B. H. Walker, D. M. Liverman, K. Richardson, P. J. Crutzen, and J. A. Foley. 2009a. "A Safe Operating Space for Humanity". *Nature*. 461: 472–475.

Rockström, J., W. L. Steffen, K. Noone, Å. Persson, F. S. I. Chapin, E. F. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. J. Schellnhuber, B. Nykvist, C. A. de Wit, T. P. Hughes, H. R. S. van der Leeuw, S. Sörlin, P. K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B. H. Walker, D. M. Liverman, K. Richardson, P. J. Crutzen, and J. A. Foley.

2009b. "Planetary Boundaries: Exploring the Safe Operating Space for Humanity". *Ecology and Society*. 2: 32.

Romer, P. M. 1986. "Increasing Returns and Long-Run Growth". *Journal of Political Economy*. 94: 1002.

Scheffer, M., S. R. Carpenter, T. M. Lenton, J. Bascompte, W. Brock, V. Dakos, J. van de Koppel, I. A. van de Leemput, S. A. Levin, E. H. van Nes, M. Pascual, and J. Vandermeer. 2012. "Anticipating Critical Transitions". *Science*. 338(6105): 344–348.

Scheffer, M., S. Carpenter, J. A. Foley, C. Folke, and B. Walker. 2001. "Catastrophic shifts in ecosystems". *Nature*. 413(6856): 591–596.

Schneider, F., G. Kallis, and J. Martinez-Alier. 2010. "Crisis or Opportunity? Economic Degrowth for Social Equity and Ecological Sustainability. Introduction to This Special Issue". *Journal of Cleaner Production*. 18: 511–518.

Selden, T. M. and D. Song. 1995. "Neoclassical Growth, the J Curve for Abatement, and the Inverted U Curve for Pollution". *Journal of Environmental Economics and Management*. 29: 162–168.

Solow, R. M. 1956. "A Contribution to the Theory of Economic Growth". *Quarterly Journal of Economics*. 70(1): 65–94.

Solow, R. M. 1974a. "Intergenerational Equity and Exhaustible Resources". *Review of Economic Studies*. 41: 29–45.

Solow, R. M. 1974b. "The Economics of Resources or the Resources of Economics". *The American Economic Review*. 64: 1–14.

Steffen, W. L., A. Sanderson, P. D. Tyson, J. Jäger, P. A. Matson, B. Moore III, F. Oldfield, K. Richardson, H. J. Schellnhuber, B. L. Turner II, and R. J. Wasson. 2004. *Global Change and the Earth System– - A Planet Under Pressure. Global Change — The IGBP Series*. Berlin (DEU): Springer-Verlag.

Steffen, W., P. J. Crutzen, and J. R. McNeill. 2007. "The Anthropocene: Are Humans Now Overwhelming the Great Forces of Nature". *AMBIO: A Journal of the Human Environment*. 36: 614–621.

Steffen, W., Å. Persson, L. Deutsch, J. Zalasiewicz, M. Williams, K. Richardson, C. Crumley, P. Crutzen, C. Folke, L. Gordon, M. Molina, V. Ramanathan, J. Rockström, M. Scheffer, H. J. Schellnhuber, and U. Svedin. 2011. "The Anthropocene: From Global Change to Planetary Stewardship". *AMBIO*. 40: 739–761.

Steffen, W., K. Richardson, J. Rockström, S. Cornell, I. Fetzer, E. M. Bennett, R. Biggs, S. R. Carpenter, W. de Vries, C. A. de Wit, C. Folke, D. Gerten, J. Heinke, G. M. Mace, L. M. Persson, V. Ramanathan, B. Reyers, and S. Sörlin. 2015. "Planetary Boundaries: Guiding Human Development on a changing planet". Science, 1259855.

Sterner, T. and J. Coria. 2012. *Policy Instruments for Environmental and Natural resource Management.* 2nd. Routledge: RFF Press.

Sterner, T., M. Troell, J. Vincent, S. Aniyar, S. Barrett, W. Brock, S. R. Carpenter, K. Chopra, Kanchan, P. Ehrlich, M. Hoel, S. A. Levin, K.-G. Mäler, J. Norberg, L. Pihl, T. Söderqvist, J. Wilen, and A. Xepapadeas. 2006. "Quick Fixes for the Environment: Part of the Solution or Part of the Problem?" *Environment: Science and Policy for Sustainable Development.* 48(10): 20–27.

Stokey, N. L. 1998. "Are There Limits to Growth?" *International Economic Review*: 1–31.

Timothy, O. and A. Jordan. 1995. "The Precautionary Principle in Contemporary Environmental Politics". *Author(s): Source: Environmental Values.* 4(3): 191–212.

Tsur, Y. and A. Zemel. 1996. "Accounting for Global Warming Risks: Resource Management Under Environmental Uncertainty. Journal of Economic Dynamics and Control". 20: 1289–1305.

Turner, B. L., ed. 1990. *The Earth as Transformed by Human Action: Global and Regional Changes in the Biosphere Over the Past 300 Years.* Cambridge University Press.

Turner, R. K., C. Perrings, and C. Folke. 1997. "Economy and Ecosystems in Change: Analytical and Historical Perspectives". In: ed. by J. van den Bergh and J. van den Straaten. London: Edward Elgar. 25–49.

Uzawa, H. 1965. "Optimum Technical Change in An Aggregative Model of Economic Growth". *International Economic Review.* 6: 18.

van den Bergh, J. C. 2007. "Sustainable Development in Ecological Economics". In: *Handbook of Sustainable Development.* Edward Elgar Publishing. 489.

van den Bergh, J. C. J. M. 2011. "Environment Versus Growth — A Criticism of "Degrowth" and a Plea for "A-Growth"". *Ecological Economics.* 70(5): 881–890.

van den Bergh, J. C. and G. Kallis. 2012. "Growth, A-Growth or Degrowth to Stay within Planetary Boundaries?" *Journal of Economic Issues*. 46: 909–920.

Vollebergh, H. R. and C. Kemfert. 2005. "The Role of Technological Change for a Sustainable Development". *Ecological Economics*. 54(2): 133–147.

Walker, B., S. Barrett, S. Polasky, V. Galaz, C. Folke, G. Engström, F. Ackerman, K. Arrow, S. Carpenter, K. Chopra, G. Daily, P. Ehrlich, T. Hughes, N. Kautsky, S. Levin, K.-G. Mäler, J. Shogren, J. Vincent, T. Xepapadeas, and A. J. de Zeeuw. 2009. "Looming Global-Scale Failures and Missing Institutions". *Science*. 325(5946): 1345–1346.

Walker, B. and D. Salt. 2006. *Resilience Thinking: Sustaining Ecosystems and People in a Changing World*. Island Press.

Walters, C. J. 1986. *Adaptive Management of Renewable Resources*. Blackburn Press. 374.

Weitzman, M. L. 1976. "On the Welfare Significance of National Product in a Dynamic Economy". *The Quarterly Journal of Economics*. 90: 156.

Weitzman, M. L. 2009a. "Additive Damages, Fat-tailed Climate Dynamics, and Uncertain Discounting". *Economics: The Open-Access, Open-Assessment E-Journal*. 3(2009–39): 1–29.

Weitzman, M. L. 2009b. "On Modeling and Interpreting the Economics of Catastrophic Climate Change". *Review of Economics and Statistics*. 91(1): 1–19.

Westley, F., P. Olsson, C. Folke, T. Homer-Dixon, H. Vredenburg, D. Loorbach, J. Thompson, M. Nilsson, E. Lambin, J. Sendzimir, B. Banerjee, V. Galaz, and S. van der Leeuw. 2011. "Tipping Toward Sustainability: Emerging Pathways of Transformation". *Ambio*. 40(7): 762–780.

Wilkinson, R. G. and K. E. Pickett. 2006. "Income Inequality and Population Health: A Review and Explanation of the Evidence". *Social Science & Medicine*. 62(7): 1768–1784.

Woodward, R. T. and R. C. Bishop. 1997. "How to Decide When Experts Disagree: Uncertainty-Based Choice Rules in Environmental Policy". *Land Economics*. 73: 492–507.

Xepapadeas, A. 1997. *Advanced Principles in environmental Policy*. UK: Edward Elgar Publishing Limited.

Xepapadeas, A. 2005. “Economic Growth and the Environment”. In: *Handbook of Environmental Economics*. Ed. by K.-G. Mäler and J. R. Vincent. Vol. 3. Elsevier, Amsterdam, Netherlands.

Xepapadeas, A., E. Tzouvelekas, and D. Vouvaki. 2007. “Total Factor Productivity Growth and the Environment: A Case for Green Growth Accounting”. Working Papers. Fondazione Eni Enrico Mattei.

Young, O. R., E. F. Lambin, F. Alcock, H. Haberl, S. I. Karlsson, W. J. McConnell, T. Myint, C. Pahl-Wostl, C. Polsky, P. S. Ramakrishnan, H. Schroeder, M. Scouvart, and P. H. Verburg. 2006. “A Portfolio Approach to Analyzing Complex Human-Environment Interactions: Institutions and Land Change”. *Ecology and Society*. 11(2): 31.

Young, O. R. and W. Steffen. 2009. *The Earth System: Sustaining Planetary Life-Support Systems. Principles of Ecosystem Stewardship*. New York: Springer. 295–315.

Young, O., L. A. King, and H. Schroeder, eds. 2008. *Institutions and Environmental Change: Principal Findings, Applications, and Research Frontiers*. Cambridge, Boston: MIT Press.