4

LIMITS AND THRESHOLDS

Setting global, local and regional safe operating spaces

John Dearing

Limits and thresholds: the context

The roots of this chapter lie in the post-war ideas around systems – entities defined in terms of their different parts interacting through flows of energy, matter or information. A system changes, or adapts, to variations in external influences through negative and positive feedback loops (see Reyers and Selomane, this volume). The book, *Limits to Growth* (Meadows et al., 1972) included a first attempt to use systems models to simulate the global effects of resource depletion and pollution on economic development, and demonstrated how feedback mechanisms could slow or even reverse exponential growth during the twenty-first century. While not universally accepted, the basic ideas in *Limits to Growth* provide the basis for studies on human wellbeing and the natural environment in the context of global economic growth.

Since the 1960s, other scientific approaches have explored systems and how they can become unstable and fail if they cross certain limits or thresholds. The earliest, René Thom's catastrophe theory, introduced mathematical concepts for system instability that later spawned chaos theory and the application of critical transition theory (Scheffer, 2009). Ecologists, including Holling (1973) and May (1972), developed theoretical models for alternate steady states, ecological resilience and food web networks. These early studies of systems fed into the fields now referred to as complexity science and resilience theory.

In parallel, global institutions incorporated these scientific developments into policy statements. The UN Conference on the Human Environment (1972), the UN Rio Earth Summit (1992), the UN Millennium Development Goals (2000), the International Geosphere-Biosphere Amsterdam Declaration (2001), the UN Rio+20 Summit (2012), through to the UN Sustainable Development Goals (2015), brought together the concerns of environmentalists over uncontrolled development, particularly the idea of non-linear, abrupt shifts and a need to recognise the existence of limits. In 2005, the Millennium Ecosystem Assessment (MA) highlighted the dramatic loss of diversity, the degradation of ecosystem services and increased risk of non-linear changes, the consequent barriers to reducing poverty, hunger and disease, and therefore the need for significant changes in policies, institutions and practices (MA, 2005). The ESPA Programme (2009–2018) was designed to provide the interdisciplinary research and evidence base for addressing the MA findings.

Coincident with the start of the ESPA Programme, Johan Rockström and colleagues introduced new concepts: planetary boundaries and safe operating spaces. Rockström et al. (2009a) highlighted global-scale boundaries for nine biophysical processes: climate change, biodiversity loss, biogeochemical flows (N and P cycles), freshwater use, stratosphere ozone, atmospheric aerosol loading, ocean acidification, land use change and chemical pollution. They argued that these planetary life-support systems, and their associated processes, broadly define a safe operating space for human development. Rockström et al. (2009b) developed the conceptual basis for the boundaries. Drawing on Scheffer et al. (2001), they proposed a classification of system changes – from smooth 'linear' changes to 'non-linear' changes that may also be smooth through time, but may also involve abrupt change as thresholds or tipping points are reached.

One particular type of non-linear change that has generated much concern for environmentalists, and increasingly policy-makers, occurs when the system shifts non-linearly and rapidly towards a new steady state but crosses an unstable equilibrium that then represents a barrier to reversibility. Attempts to reverse the system back to its starting point show hysteresis, or a lagged effect, because reversals in the external conditions have little impact on the system until they have gone far beyond the point of the initial threshold. In this last case, Rockström et al.

BOX 4.1 RELATIONSHIPS BETWEEN POVERTY ALLEVIATION AND ECOSYSTEM SERVICES

Many theoretical and empirical relationships between human wellbeing or poverty alleviation (PA) and the quality or abundance of ecosystem services (ES) have been proposed. Here, they are shown using the planetary boundary concepts with PA on the x-axis (control variable) and ES on the y-axis (response variable), but whether they are control or response variables depends on the context. ES may represent aggregated services but, more realistically, a subset of provisioning, regulating, supporting or cultural services. (a) *Linear* – the direction and elasticity (or strength) of direct relationships. Low and high positive elasticity are associated with weakly and strongly coupled social-ecological systems, respectively. Negative elasticity describes situations where PA succeeds even as ES decline, or the reverse where poverty increases as ES improve. (b) *Parabolic non-linear* – the trajectory, often relatively gradual, whereby (i) regulating ES (e.g. water quality) first declines with agricultural

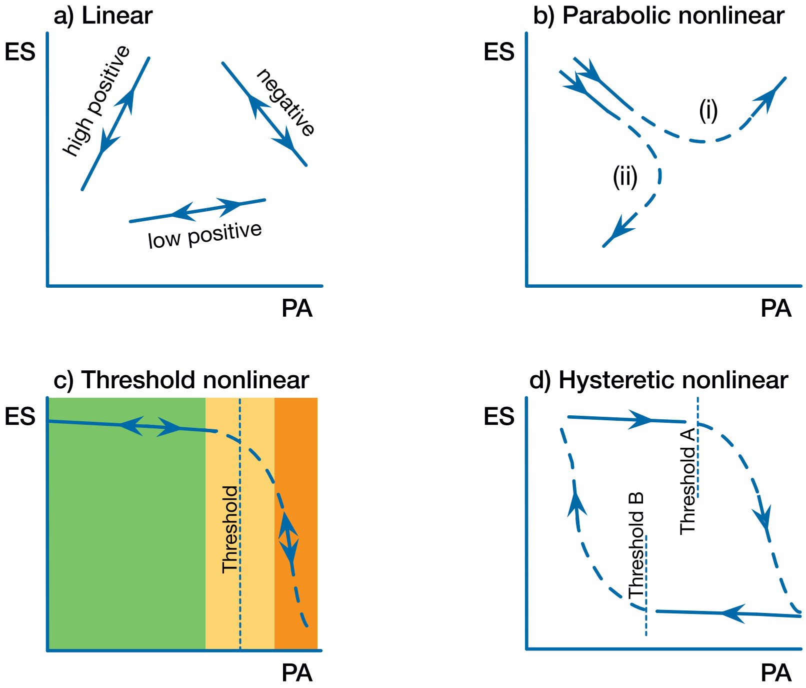


FIGURE 4.1 theoretical and empirical relationships between human wellbeing or poverty alleviation (PA) and the quality or abundance of ecosystem services (ES).

intensification and then improves as regulatory frameworks improve with PA; (ii) PA causes regulating ES (e.g. forest cover/biodiversity) to decline, eventually feeding back to reduce provisioning ES (e.g. forest products) and increase poverty, and where regional resource exploitation leads to growing inequalities in wellbeing. (c) *Threshold non-linear* – crossing a threshold causes a relatively rapid decline in ES – for example, the loss of wheat yield (provisioning ES) as investment in larger shrimp farms causes widespread soil salinisation. The example uses the definition of 'safe, cautionary and dangerous operating spaces' (green, yellow and orange), which in theory may be reversible. (d) *Hysteretic non-linear* – in contrast to (c), threshold responses between ES and PA may be irreversible or time-lagged – for example, the loss of fish stocks (provisioning ES) as technological investment in fish catch methods transgresses threshold A; fish stock recovery requires fishing efforts to be reversed beyond threshold A to threshold B, with losses of income or livelihoods (after Daw et al., 2016; Dearing unpublished; Scheffer et al., 2001; Steffen et al., 2015; Zhang et al., 2015).

(2009a) tapped into real fears that continued degradation of biophysical conditions could result in global change that was not only unanticipated and rapid but would be effectively irreversible. This led to the authors defining a 'safe' space where the risk of transgressing a potentially damaging biophysical threshold, as defined scientifically, was minimised (see Figure 4.1, (c) and (d)). Boundaries of safe spaces are not defined at the threshold value but by the lower end of the range of driving conditions (Figure 4.1 (c)). In theory, this allows time for society to react to early warning signals of an imminent tipping point. Expert judgement and literature reviews in 2009 concluded that three systems, climate change, biodiversity loss and biogeochemical flows, already exceeded safe boundaries.

The planetary boundaries concept includes key processes that have relevance to the ESPA programme: the paths taken by the linked human–environment system or its components over time; the effects of changes in external conditions on single process or on the interaction of processes; and the risk of crossing thresholds and moving to alternate steady states (Willcock et al., 2016). This chapter reviews recent relevant research and draws conclusions relevant to ecosystem services and poverty.

Extending and updating the planetary boundaries

The planetary boundaries work has been immensely influential but not without critics, who have pointed to the treatment of the nine control variables as independent when several are clearly interdependent; to the lack of social or economic context; and to the non-explicit determination of the boundaries (e.g. Nordhaus et al., 2012).

As anticipated, a number of more recent studies have updated the key boundaries (Carpenter and Bennett, 2011; Running, 2012). Mace et al. (2014) focused on biodiversity and showed that extinction rates and species richness are weak metrics for biodiversity loss as it affects humanity. Instead, their analysis points to genetic diversity, functional diversity and biome integrity as more useful indicators of ecosystem conditions that underlie persistent and productive life-support systems, such as forest biomes and biogeochemical cycling. While challenges remain, particularly in understanding the drivers or control variables of biome change and the presence of thresholds, they proposed taking a stronger systems-based approach and considering the role of biodiversity in moderating other boundaries and understanding the cross-scale relationship between sub-global biomes and biodiversity.

Steffen et al.'s (2015) planetary boundaries update did adopt a more systems-based approach, recognising the interdependence of boundaries and the importance of spatial scale. They discuss the links to societal needs, especially in terms of UN Sustainable Development Goals, which imply the need for a stable functioning Earth System.

A major innovation in Steffen et al.'s (2015) paper was to link global and regional scales through sub-global dynamics that are important for global functioning. Where they can be mapped, certain regions have already exceeded a safe boundary (Figure 4.2). For phosphorus and nitrogen, these include many of the agricultural

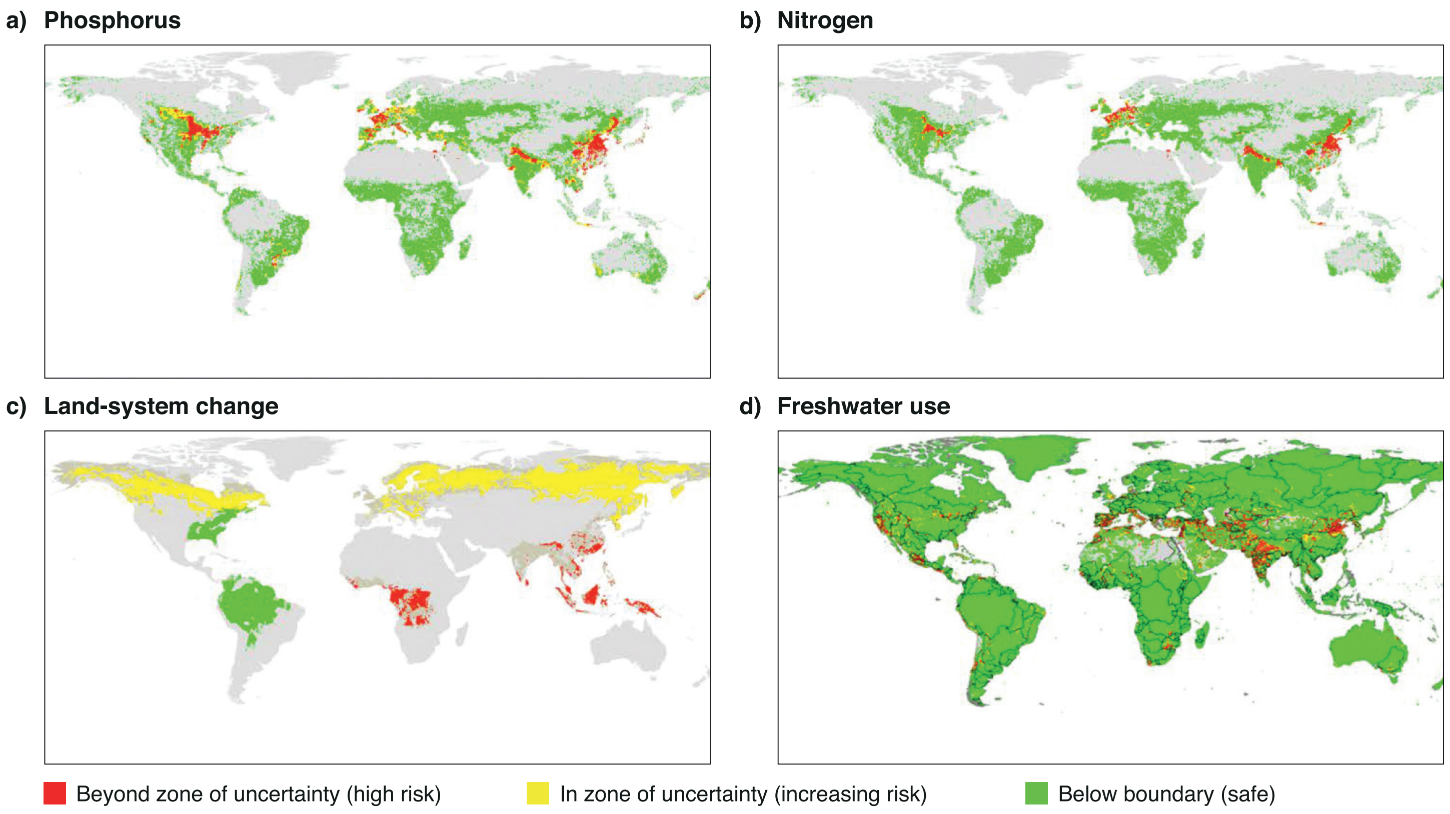


FIGURE 4.2 The global distributions and current status of the planetary boundary control variables for (a) biogeochemical flows – phosphorus (P), (b) biogeochemical flows – nitrogen (N), (c) land-system change and (d) freshwater use. Green areas are within the safe boundary; yellow areas are within the zone of uncertainty (increasing risk); and red areas are beyond the zone of uncertainty (high risk) (see also Figure 4.1). Grey areas in (a) and (b) are areas where P and N fertilisers are not applied, in (c) are areas not covered by major forest biomes, and in (d) are areas where river flow is very low so that environmental flows are not allocated.

Source: After Steffen et al., 2015; reproduced with permission from AAAS.

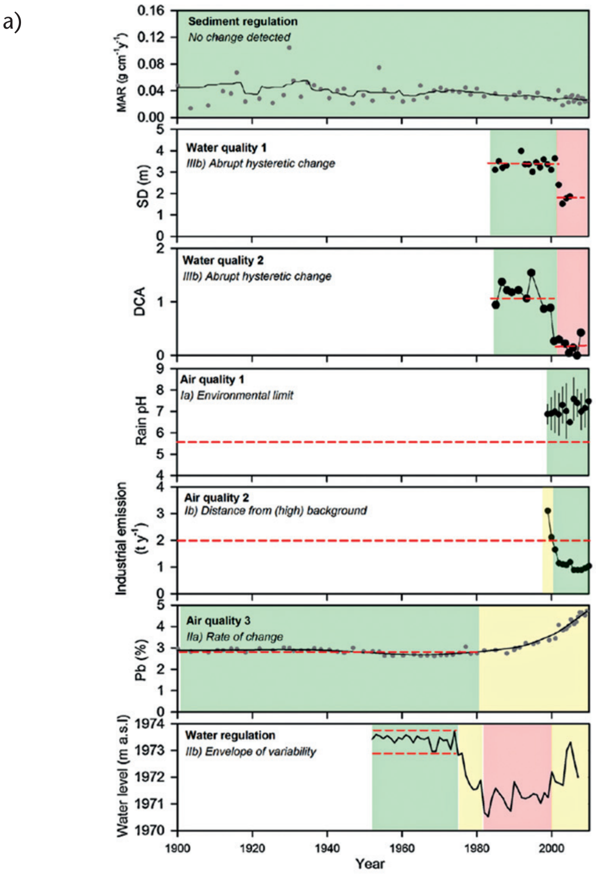
areas of North America, Europe, the Ganges plain and China. For land system change, the high-risk areas are deforested forest biomes in Africa and Southeast Asia. For freshwater use, the high-risk areas are predominantly in California, Central America, the Mediterranean region, the Middle East, South Asia and north-east China. While the planetary boundaries framework was not designed to be downscaled or disaggregated to smaller levels, the ‘planetary boundary thinking’ is clearly relevant to achieving development goals at the smaller scales/levels (e.g. regions, catchments) where most policy actions are designed and implemented.

Regional safe and just operating spaces

The first planetary boundary study to ‘think’ in a regional development context (Dearing et al., 2014) argued that the sustainability of local ecosystem services is often a more urgent socio-environmental need than understanding the cumulative effects of environmental degradation at the planetary scale. Raworth (2012) had already extended the planetary boundary concept to include a normative ‘social foundation’, which together with the scientifically defined ‘environmental ceiling’ created by the boundaries, defined a doughnut-shaped operating space that was both ‘safe’ and ‘just’. Dearing et al. (2014) applied this to two Chinese rural lake-catchment systems in Yunnan Province and the lower Yangtze basin (Erhai and Shucheng) where multi-decadal time-series for several ecosystem services were available. The classification of system behaviours (linear, non-linear, threshold and early warning signals) allowed safe, cautionary and dangerous spaces to be defined in real time-series (Figure 4.3(a)). Published data for local social conditions (e.g. access to education, health care, piped drinking water) were used to assess the extent to which regional social norms had been achieved.

In both locations, a social foundation was found to be close to fully met except for access to piped water (Erhai and Shucheng), energy (Erhai) and modern sanitation (Shucheng). Yet the regulating services that had already crossed a safe boundary into cautionary or dangerous spaces included water quality (Figure 4.3(b)). The findings underline the massive challenge for water and soil management in achieving the complete alleviation of poverty while protecting or restoring water resources. Indeed, at Erhai, a previous study (Wang et al., 2012) showed that the aquatic ecosystem passed a critical transition in 2001 as it changed from a relatively clear water, mesotrophic state to a turbid water eutrophic state in a matter of months (Figure 4.3(a)), water quality 1 and 2). More than fifteen years on, and despite implementation of measures to reduce nutrient loading from farming and sewage plants, the lake shows no evidence (Wang, personal communication) of tipping back to the initial state: a real-world example of a system undergoing hysteresis (Figure 4.1(d)).

An assessment of safe and just operating spaces in South Africa (Cole et al., 2014) took a different approach, combining global boundaries, national limits and local thresholds to create a national ‘barometer’ of sustainable development. Climate change, freshwater use, marine harvesting and biodiversity loss all exceeded their



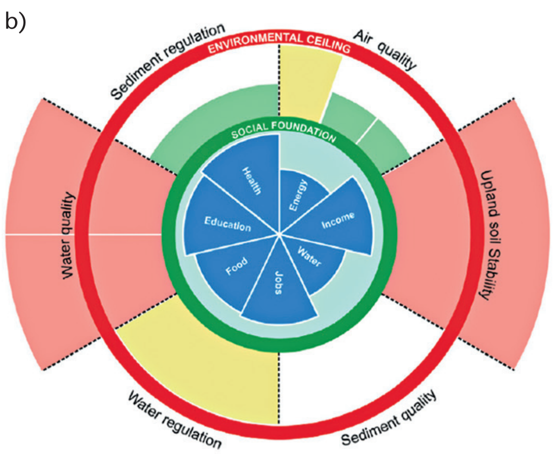


FIGURE 4.3 Setting a safe and just operating space for the Erhai lake-catchment, Yunnan Province, China. (a) seven individual time-series for four regulating services (sediment regulation, water quality, air quality, water regulation) classified as safe (green), cautionary (yellow) and dangerous (red) according to different criteria: environmental limits, distance from background, envelopes of variability, rates of change, abrupt change and increased variability; (b) the current status of regulating services (drawn from (a) with additional data for upland soil stability from Dearing, 2008) defines an environmental ceiling, and local authority data (percentage of households with a specific facility, e.g. access to pipe water) show deficits from a social foundation set by locally defined social norms. Water quality and upland soil stability have already moved outside the environmental ceiling into dangerous spaces, and provision of household water and energy are furthest from achieving a social foundation.

Source: After Dearing et al., 2014; CC-BY-3.0 licence.

safe boundaries, while the greatest social deprivations were personal safety, income and jobs. Disaggregated results showed that environmental stress varies significantly but is generally increasing (Cole et al., 2017). In contrast, social deprivation is generally decreasing but with notable exceptions, such as food security in six provinces. Historically disadvantaged provinces show the most deprivation overall. The 'barometers' and trends help communicate the range of challenges for provincial governments as they try to implement the UN Sustainable Development Goals.

More research is needed to develop a universal approach to setting, and then delivering, local and regional safe and just operating spaces. Even accepting Rockström et al.'s (2009b) stance that 'ecological and biophysical boundaries should be non-negotiable' (2009b SI, p.5), there is much scope for how the social foundations for just spaces are configured socially and economically through governance. In this respect, the issue of ecosystem governance may be less about equity and more about justice (Sikor et al., 2014). Empirical justice analysis takes a broad scan of moral concerns and ethical positions, and pays attention to the roles of all stakeholders today and across generations (see also Dawson et al., this volume). Configuring new spaces may require transformative changes in social norms, behaviours, governance and management. Pereira et al. (2015) promote several principles for multi-stakeholder learning and collaboration: emancipation and empowerment, ensuring reflexivity, knowledge co-creation, transformative learning and nurturing innovations. But a major challenge, and one that goes to the heart of the ESPA programme, is to understand how social and biophysical factors depend upon each other.

Interactions between ecosystem services and poverty

These configurations of planetary boundaries and safe and just operating spaces are valuable for communicating the risks of transgressing biophysical limits and thresholds. But they all fail to define limits and thresholds in terms of a social-ecological system (SES) and fall short of providing a basis for designing policy that can adapt or transform the whole system to a more sustainable or desirable state. Thus the challenge is to find metrics of SES behaviour that define the paths towards limits and thresholds. Such an approach has been previously recognised as 'syndromes' (e.g. Schellnhuber et al., 1997), 'archetypes' (e.g. Eisenack, 2012) and 'green-loop' to 'red-loop' transitions (Cumming et al., 2014). These functional descriptions all aim to provide a level of generality about the key interactions that determine a system's path. For example, the Sahel syndrome (Schellnhuber et al., 1997) describes a dysfunctional SES defined by positive feedbacks that drive overgrazing and soil erosion; the archetypes of Moral Hazard or Poverty Trap (Eisenack, 2012) define barriers to climate adaptation; and different sets of population, technological and ecological feedback mechanisms define transitions in agricultural systems (Cumming et al., 2014). These are clearly valuable for providing static, implicit or conceptual assessments of social-ecological dynamics.

However, functional descriptions based largely on contemporaneous interactions are not the best guide for assessing the likelihood of transgressing limits and thresholds in real situations through time. Where the challenge is to assess temporal dynamics explicitly, one approach is to map recent social and ecological changes onto theoretical links between ecosystem services and poverty alleviation.

As a starting point, Daw et al. (2016) mapped out 'elasticity in ecosystem services', a concept akin to 'price elasticity' in economics (Figure 4.1(a)). This represents a set of plausible relationships between human wellbeing and ecosystem quality ranging from predictable, linear ones where human wellbeing is more or less strongly linked either positively or negatively to ecosystem quality, to non-linear ones where human wellbeing may show unpredictable responses to changes in ecosystem services. The authors also developed a framework for understanding the relationships based on a linear flow chain, by which ecosystems are coupled to wellbeing through several steps: ecosystem stocks, flows, goods, value, shared contributions and well-being.

However, although the Daw et al. (2016) framework is designed to underpin the theoretical linear-non-linear elasticities, in practice it is restricted to linear understanding. Feedbacks are not explicitly studied in this ESPA project set in East African coastal communities, and it would have been interesting to see the likely feedbacks (however tentative) added to their comprehensive model of the chain of multiple flows. The lack of a temporal dimension makes this difficult, and means that the empirical application here is limited to qualitative assessments of elasticity.

The inherent weakness of linear frameworks (e.g. Wei et al., 2012) is clear from studies that have used time-series to observe the dynamic coupling between wellbeing and ecosystem services (Box 4.1). An ESPA project set in the lower Yangtze basin (Dearing et al., 2012; Zhang et al., 2015) reconstructed historical regulating ecosystem services from analyses of lake sediments. Combining these with social and economic records illustrated the long-term trade-off between provisioning and regulating (and many cultural) services as a result of actions to alleviate poverty (Figure 4.1(b)). Economic growth over the past 60 years through land intensification and urban development was paralleled by steep rises in provisioning services but steep losses in a range of regulating ecosystem services, mainly since the 1980s (Figure 4.4(a)). Of special concern are water quality services that have already passed critical transitions in several areas. Viewed collectively, the results suggest that the regional social–ecological system passed a tipping point in the late 1970s and is now in a transient phase heading towards a new steady state. Across the region, the long-term relationship between economic growth and ecological degradation (Figure 4.4(b)) shows no sign of decoupling, as demanded by the need to reverse an unsustainable trajectory. Although improved environmental policies and regulation after the late 1980s helped to stabilize losses of biodiversity and regulating services, such as soil stability, agricultural intensification continues to cause widespread pollution of water and air (Zhang et al., 2015).

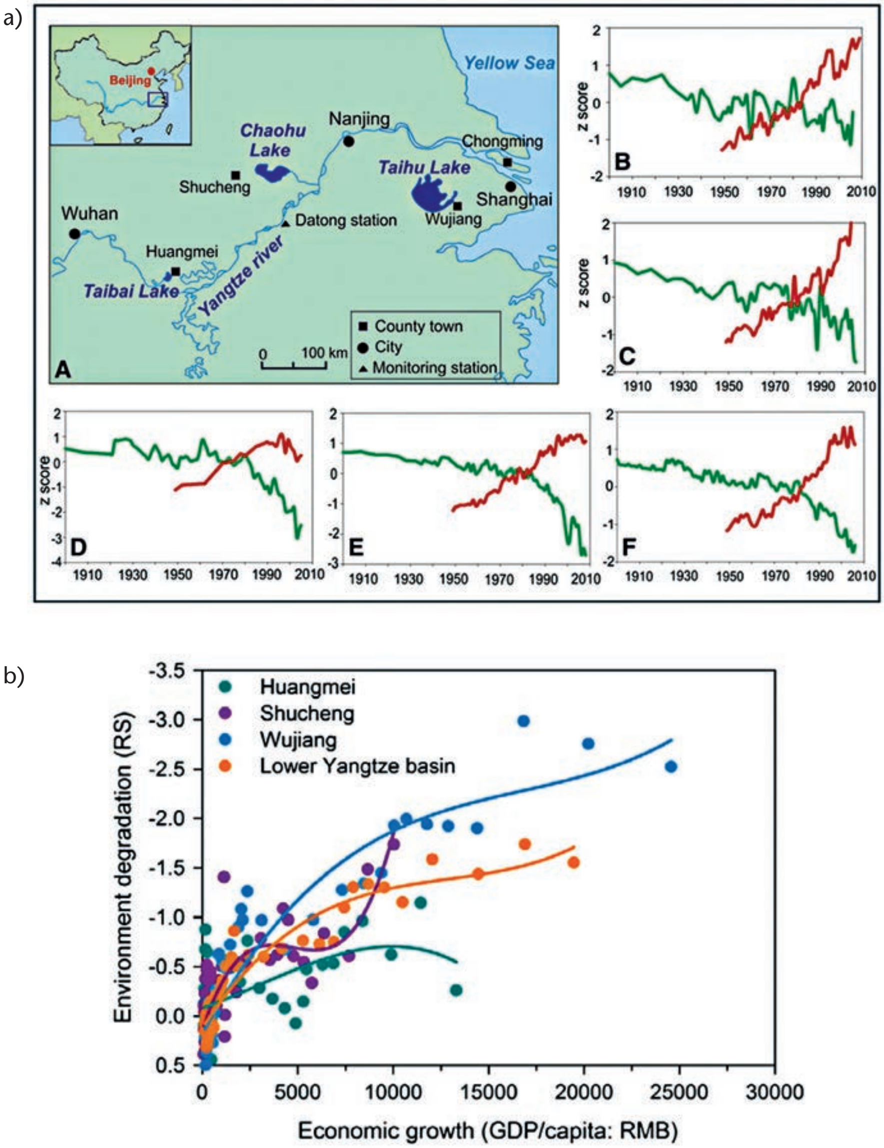


FIGURE 4.4 Poverty alleviation and ecosystem service dynamics in the lower Yangtze basin, eastern China. (a) Relationships between time-series of regulating (green) and provisioning (red) ecosystem services in the twentieth and twenty-first centuries for different locations and aggregated for the whole basin, showing widespread trade-offs between successful land use intensification and environmental degradation; (b) relationship between regional economic wealth and regulating services for the same locations 1950–2010, showing little evidence for a downturn in environmental degradation with greater poverty alleviation.

Source: Zhang et al., 2015; CC-BY-3.0 licence.

Similar results were revealed within the ESPA DELTAS project focused on the Bangladesh coastal zone (Hossain et al., 2016). Since the 1980s, increasing gross domestic product and *per capita* income have mirrored rising levels of food and inland fish production, which has led to a reduction of ~17% in the population below the poverty line. At the same time, non-food ecosystem services such as water availability, water quality and land stability have deteriorated. Conversion of rice fields to shrimp farms is almost certainly a factor in increasing soil and surface water salinity, while water availability, shrimp farming and maintenance of biodiversity appear to have passed tipping points in the 1970s–1980s. As with the lower Yangtze basin, the point at which growing economic wealth might be expected to feed back into effective environmental protection (Zhang et al., 2015 and Figure 4.1(b)) has not yet been reached, at least for water resources.

Using the same methodology, the Belmont Forum DELTAS project produces similar temporal dynamics in the Amazon, Ganges–Brahmaputra–Meghna (GBM) and Mekong deltas (de Araujo Barbosa et al., 2016). Combining these findings with the lower Yangtze basin and the Bangladesh coastal zone (smaller than GBM) provides evidence of a widespread trade-off between rising food production and deteriorating regulating services as poverty is alleviated (Figure 4.5). The recent slowing down in production levels may be linked to the loss of regulating services: an unsustainable trajectory now brought to a head by negative feedback (Raudsepp-Hearne et al., 2010).

Applying Daw et al.'s (2016) elasticity concept to these delta systems classifies them as having high negative (or inverse) elasticity, but with different elasticities (low vs high) through time as local thresholds are transgressed. In contrast, Suich et al. (2015) found ESPA studies tending towards direct elasticities, with impacts on ecosystem services and poverty correlated either positively or negatively. But importantly they noted that the empirical studies were usually incomplete in terms of the range of ecosystem services, with most focusing on provisioning, rather than regulating, services. It will be difficult to apply the elasticity concept in the absence of time-series, or detailed qualitative information over time for multiple ecosystem services. The strong uni-directionality of the empirical relationship between provisioning and regulating services (Figure 4.5) may underline the lack of case studies, but may call into question the validity of elastic and reversible relationships. The priority of paying greater attention to long-term drivers (Fischer et al., 2015) is certainly borne out in these studies.

Can historical perspectives, based on time-series, provide information about whether a threshold change is imminent: essentially providing an early warning signal that the system is moving out of safe space? Much work has been undertaken in the search for properties of real or modelled time-series, such as increased variance, which indicate 'critical slowing down' or 'flickering' of the system as it loses resilience and becomes unstable (e.g. Biggs et al., 2009; Scheffer et al., 2012). But the evidence across the ESPA projects is equivocal. In the Bangladesh coastal system (Hossain et al., 2017a), the results were variable with no clear indication of impending shifts. In Yunnan Province, China, the apparent variability prior to

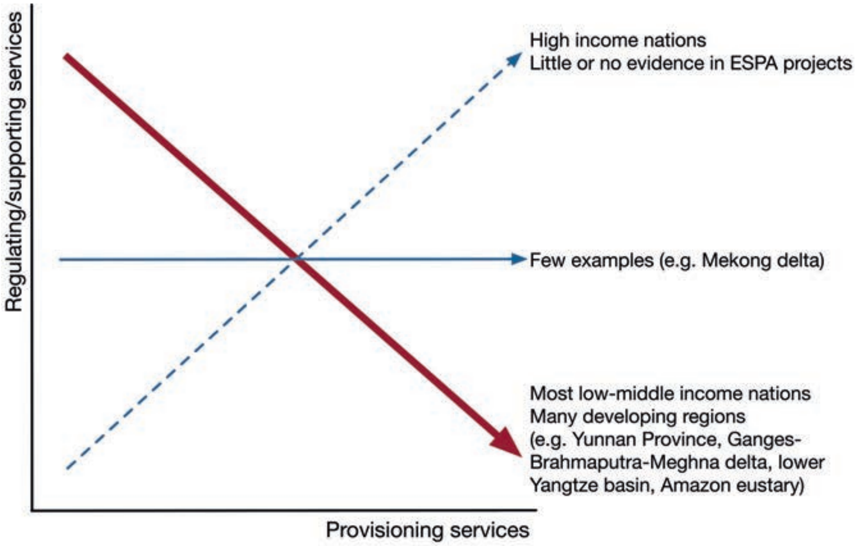


FIGURE 4.5 Schematic empirical relationships between provisioning and regulating/supporting ecosystem services as poverty is alleviated, showing the apparent main direction and prevalence (thick solid line – most common; thin solid line – less common; dotted line – rare or no evidence). The most common and inverse relationship represents a trade-off between poverty alleviation and environmental degradation (e.g. lower Yangtze basin, Bangladesh coastal zone and the Amazon estuary). Data from some regions (e.g. Mekong delta) indicate that poverty alleviation may be linked to a greater extraction of provisioning goods without incurring losses of regulating services. However, on current evidence, there is little or no evidence for provisioning services to be positively associated with regulating/supporting services.

a critical transition in the lake ecosystem owed as much to the quality of the dataset as it did to actual system instability (Wang et al., 2012). Only in the lower Yangtze basin (Zhang et al., 2015) was widespread rising variability in regulating and provisioning services interpreted as a possible signal of regional instability. These findings are driving the search for early warning signals based on the structural properties of the system, such as connectedness (de Araujo Barbosa et al., 2016; Doncaster et al., 2016; Zhang et al., 2015), rather than the frequency properties of time-series.

Overall, a typology of social-ecological dynamics, supported by both theory and metrics, is becoming better defined; and a language that includes linear, non-linear, feedbacks, thresholds, hysteresis and early warning signals is valuable for taking stock of current conditions and anticipating future changes (see Reyers and Selomane, this volume). The evidence from case-studies points to a need to identify safe and just spaces in purely dynamical terms, asking how society and communities have interacted with the natural environment, and whether the trajectory of interactions is heading towards desirable or undesirable states. To design policy that achieves this, it will be helpful to combine empirical assessments with tools and models that communicate the likely effects of alternative decisions.

Simulating limits, trade-offs and safe spaces

The modelling and simulation of future limits and safe operating spaces for real SES is in its infancy. Verburg et al.'s (2016) review makes the point that models for management often ignore feedbacks and thresholds, while models describing social-ecological dynamics often lack direct relevance to decision making. Nevertheless, a few ESPA projects have made significant advances in the development and use of simulation models that capture both realistic dynamics and management options.

Daw et al. (2015) combined participatory conceptual modelling, ecological modelling, interactive models and qualitative scenarios to explore trade-offs in a Kenyan coastal fishery. The EcoSim fisheries model was used as a conceptual systems model, and a simple mathematical model is used to simulate flows of benefits to different resource users under different scenarios. Comprehensive bivariate outputs (phase plots) map out a range of linear and non-linear relationships that define different kinds of trade-offs (Box 4.1). A classification of the relationships according to strongly held 'sacred' and 'secular' values gives 'routine', 'tragic' and 'taboo' trade-offs depending on which groups of stakeholders are involved. For example, a socially acceptable win-win for the whole community between conservation of fish stocks and profitability gained from fewer, larger fish may mask the trade-off for women who typically rely on small, cheap fish for income. The study introduces a novel approach to capturing the complexities in the biophysical system that produce trade-offs and clearly demonstrates how stakeholders can be brought into the learning process through the application of such simple, 'toy' models (Galafassi et al., 2017). Feedback mechanisms are alluded to in the conceptual model, and it would have been interesting to understand how they are incorporated into the interactive toy models.

Hossain et al. (2017a) used a systems dynamic model to make a first attempt at operationalising the safe operating spaces concept for the Bangladesh coastal zone. Like Daw et al. (2015), a conceptual model produced in collaboration with stakeholders summarised the main social and ecological components including provisioning and regulating services, basic farm economics, land-use shifts between cropping and shrimp farming, and farm incomes as the indicator of wellbeing. The connections between the components were defined from regression analyses of time-series (Hossain et al., 2017b) and from estimated functional relationships where data were sparse or absent. Partial validation of the model was achieved through comparison of outputs against historical trends in subsets of data. Eight 'what if' scenarios produced simulated outputs for different combinations of climate change, subsidy level, sea-level rise and water flows in the Ganges. A dangerous operating space was defined when the system moves outside its historical envelope of variability. The overarching message is that a safe operating space requires a temperature rise of less than 2°C, as agreed within the 2015 Paris Agreement, but there are still risks to regulating services, especially increasing soil salinity. In this respect, the model illustrates unintended consequences of farm subsidies in the form of a positive feedback loop, which tends to encourage over-use of fertiliser and irrigation.

The Bangladesh coastal zone model uses only simple social-ecological couplings that restrict its decision-making value. Cooper (2017) built on the approaches used

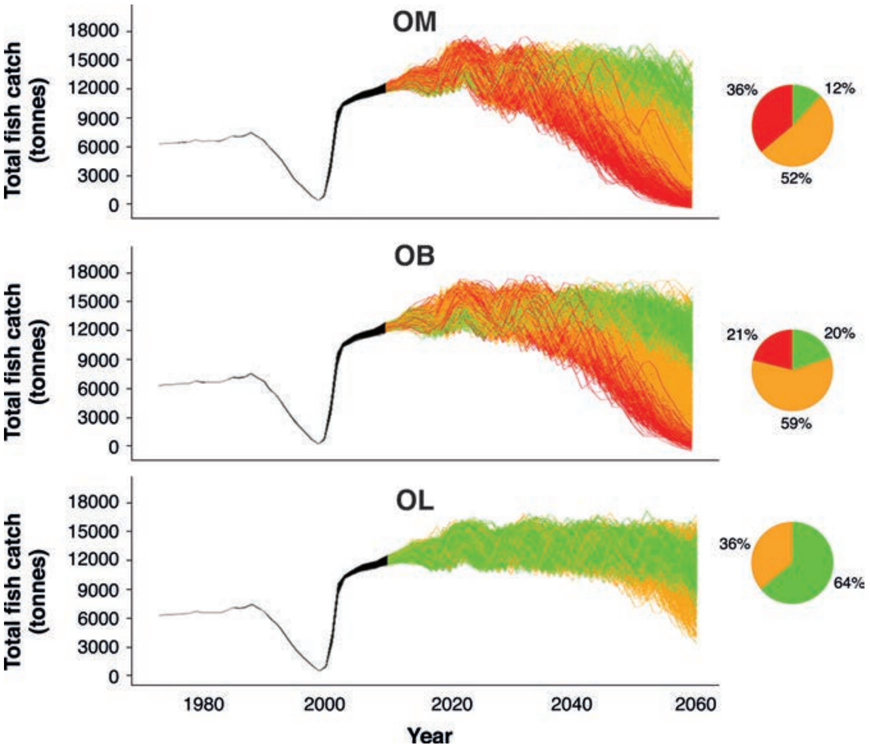


FIGURE 4.6 Simulating future annual catches in the Chilika lagoon fishery, eastern India, using a systems dynamic model with each trajectory defined as safe and just (green), cautionary (yellow) or dangerous (red) with respect to the maximum sustainable yield in 2050–2060. Annual fish catch time-series (N = 1000 per scenario) produced by spectrums of driver interactions under three governance scenarios: OM – only the tidal outlet maintained by dredging; OB – as OM with fishing bans in the tidal outlet; OL – as OM with limits on the number of new fishers allowed to join each fishing fleet. The historical record of fish catch, 1973–2009 (black), shows the fluctuating values caused by a lack of dredging. The findings illustrate the increasing probability of long-term safe and just trajectories (percentages shown in the pie-charts) from OM to OL, as governance becomes stronger.

Source: Cooper, 2017, reproduced with permission.

by both Daw et al. (2015) and Hossain et al. (2017a), embedding a process-based fisheries model within a comprehensive SES dynamic model that allows assessment of future safe spaces as boundary conditions, like climate change (cf. Scheffer et al., 2015). Application to the Chilika lagoonal fishery in eastern India showed that the model can simulate previous abrupt shifts in fish catch. Forward modelling from 2010 to 2060 (Figure 4.6) for three sets of management options determined by stakeholders generated alternative future trajectories, defined as safe, cautionary or dangerous with respect to fishery yield. A further step analysed all the trajectories that end in safe spaces and determined a 'core' set of management options, such as the number of fishers and motorboats that, if implemented today, give good probabilities for desirable outcomes.

Conclusions

By definition, the sustainable management of ecosystem services for poverty alleviation must confront both the natural limits imposed by environmental systems and the implications for the wellbeing of people. Thus, setting limits and defining safe and just spaces for complex SES are powerful and potentially durable concepts. But they necessitate theorising, observing, analysing and simulating system dynamics in ways that are inevitably challenging. These concepts, and the findings that flow from their application, also require a means to be delivered effectively to policymakers. Thus, important questions are: how well have ESPA projects risen to these challenges and what have we learned?

In terms of theorising, the classification of the temporal relationships between poverty alleviation and ecosystem services is a major advance, and could go further by matching the range of elasticities to the many social-ecological theories that exist. Where social-ecological dynamics have been explored empirically, there is a contrast between those that focus on contemporary conditions and those that utilise time-series. The former tend to produce a deep understanding of the coupling between wellbeing and ecosystem services embedded in current circumstances, especially in terms of cultural and governance factors. The latter produce clear representations of trade-offs, thresholds and phase transitions over recent history, but usually at the expense of understanding the causal nature, or otherwise, of the relationships portrayed.

Future studies will benefit from combining the two approaches within the same regional context: on their own, neither is sufficient. Nevertheless, where concepts and theory have been supported by empirical data there are clear conclusions. Many regions in Africa and Asia are deemed to have exceeded safe limits for phosphorus, nitrogen, land use or freshwater use, and smart water management is vital in the two rural communities in China where safe limits have been downscaled. The elasticity concept clearly provides a powerful descriptor of past and present dynamics, and potentially a new means for determining trade-offs and safe regional boundaries. On current evidence, several large tropical deltaic systems with negative elasticity lie in transient phases beyond safe operating spaces, moving towards potentially undesirable or dangerous zones. Similarly, multi-decadal trends in indicators of ecosystem services and human wellbeing point to widespread non-stationary dynamics governed by slowly changing variables, declining resilience (for example to anticipated changes in climate) and with an increased likelihood of systemic instability or threshold changes.

In terms of delivering the results to policy-makers, the evidence is less clear because few studies in this field have covered the full 'science-discovery' to 'solution-driven' spectrum. Developing visual communication tools that can convey limits, trade-offs and safe spaces to policy-makers has been helpful at global, regional and local scales, and outputs from simulation models have been portrayed figuratively. However, a new challenge will be to communicate information derived from system dynamics where visual expression alone is insufficient. Participatory approaches, with stakeholders involved in knowledge co-production, are essential for creating appropriate policy (see Dawson et al.; Buytaert et al., this volume), but where vital knowledge stems from understanding the meaning and implications of system dynamics, it may be necessary to accept that local communities do not have sufficient capacity to ask all the necessary questions, for example, about thresholds and limits. Attempts to raise intellectual capacities through, for example, complexity workshops (ESPA, 2014) and dedicated bi-lingual websites (e.g. www.complexity.soton.ac.uk) are valuable but in their infancy.

The relatively short timescale for ESPA research is necessarily limiting the scale of findings in this area. But there may also be a certain reluctance to pursue systems-based methods to achieve solutions to development problems. It has been argued that systems-based resilience theory should be central to sustainable development thinking (Brown, 2016; Leach et al., 2010; Ramalingam, 2013), but it is perhaps not as dominant as its advocates would like. As Redman (2014: 3) says: 'Simply put, sustainability prioritizes outcomes; resilience prioritizes process'. It's the difference between goal- or path-orientated approaches and open-ended, emergent perspectives. Researchers may still be viewing outcomes against future scenarios as more beguiling than providing process-based advice to stakeholders on being resilient and sustainable over coming years and decades. Outputs from the ESPA and related programmes have now demonstrated the value of studying process-based limits and thresholds within a development context – laying down the challenge for new studies.

Acknowledgements

The author wishes to thank Dr Gregory Cooper, Dr Craig Hutton and the editors for providing feedback on earlier versions of the manuscript, and to Alix Dearing for proofreading. Gregory Cooper also gave his permission to reproduce Figure 4.6 from his PhD thesis.

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