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ABSTRACT

Humanity faces a major global challenge in achieving wellbeing for all, while simultaneously ensuring that the biophysical processes and ecosystem services that underpin wellbeing are exploited within scientifically informed boundaries of sustainability. We propose a framework for defining the safe and just operating space for humanity that integrates social wellbeing into the original planetary boundaries concept (Rockström et al., 2009a,b) for application at regional scales. We argue that such a framework can: (1) increase the policy impact of the boundaries concept as most governance takes place at the regional rather than planetary scale; (2) contribute to the understanding and dissemination of complexity thinking throughout governance and policy-making; (3) act as a powerful metaphor and communication tool for regional equity and sustainability. We demonstrate the approach in two rural Chinese localities where we define the safe and just operating space that lies between an environmental ceiling and a social foundation from analysis of time series drawn from monitored and palaeoecological data, and from social survey statistics respectively. Agricultural intensification has led to poverty reduction, though not eradicated it, but at the expense of environmental degradation. Currently, the environmental ceiling is exceeded for degraded water quality at both localities even though the least well-met social standards are for available piped water and sanitation. The conjunction of these social needs and environmental constraints around the issue of water access and quality illustrates the broader value of the safe and just operating space approach for sustainable development.

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1. Introduction

1.1. Rationale and motivation

The planetary boundaries framework (Rockström et al., 2009a,b) has significantly influenced the international discourse on global sustainability. In short, it proposes nine interlinked biophysical (hereafter referred to as ecological) boundaries at the planetary scale (Fig. 1a) that global society should remain within, if it is to avoid "disastrous consequences for humanity". The proposition of planetary boundaries has provoked discussion in the science and policy communities. Recently published commentaries include refinement of the boundaries for phosphorus (Carpenter and Bennett, 2011), nitrogen (de Vries et al., 2013) and freshwater use (Rockström and Karlberg, 2010); the proposal of a potential state shift in the global biosphere (Barnosky et al., 2012); a new approach to defining land-related boundaries using net primary plant production (Erb et al., 2012; Running, 2012); analyses of the governance implications (Biermann, 2012; Galaz, 2012; Nordhaus et al., 2012); and critical assessment of the nature of the proposed planetary boundaries (Brook et al., 2013). Raworth's (2012) extension of the planetary boundary concept to include social objectives in the context of sustainability policy and practice has produced a framework that has become known as the 'Oxfam doughnut', with an explicit focus on the social justice requirements underpinning sustainability (Fig. 1b). This allows multi-metric 'compasses' to be elaborated for directing decision-making. In this paper, we develop the 'doughnut' idea at the regional scale in terms of the levels of societal wellbeing and conditions of ecological processes that co-exist within regional social-ecological systems, using the terms 'social foundation' and 'environmental ceiling' to represent the social and ecological boundaries. In doing so, we define the regional safe and just operating space (RSJOS).

Our main motivation is to show how the concept of ecologically safe and socially just planetary boundaries can be adapted and applied at regional levels, for example: watersheds, national parks, sub-national administrative divisions, and nation states. Because critical transitions can occur at any scale (Scheffer et al., 2001; Folke et al., 2004; Lenton, 2013), the original planetary boundaries framework recognized that the effects of crossing multiple thresholds at regional scales can aggregate to become a global concern (Rockström et al., 2009a,b). But the cascading effects of environmental degradation (Peters et al., 2011) can have critical consequences for the sustainability of regional systems themselves, well before the effects are obvious at the global scale. This means that global sustainability requires both regional and planetary dimensions to be addressed. Hence our view is that concepts sharpened by consideration of regional scales can feed back iteratively to help refine or redefine planetary boundaries.

The argument for considering regional-scale boundaries is reinforced by an equally strong equity and governance rationale. In the planetary boundaries framework, protecting human wellbeing is the rationale for the scientific assessment of how to limit the use and degradation of natural resources in order to avoid critical transitions in Earth system processes. At the same time, human wellbeing depends fundamentally upon each person having claim to the natural resources required to meet their physiological needs such as food, water, shelter and sanitation (Folke et al., 2011). It follows from these fundamental equity considerations that social foundations (sensu Raworth, 2012) should be considered alongside planetary and regional boundaries. Traversing the scales to regional boundaries requires explicit attention to both the human drivers of change and social distributional issues, bringing new transdisciplinary, conceptual and ethical challenges to the planetary boundaries concept.

Many nations and regions face significant and urgent challenges in ensuring that available resources are used to meet the needs of all, emphasizing the sustainable use of regional resources for human wellbeing. In particular, while agricultural intensification in developing countries is widely seen as promoting rapid economic growth and poverty alleviation, evidence exists to show that the associated degradation of ecosystem processes may be unsustainable (e.g. Tilman et al., 2002; Dearing et al., 2012a). Natural resource management takes place predominantly at regional scales as part of national and regional development planning. Therefore, analytical tools that map the condition of ecological processes at these scales are more likely to have relevance and traction for policy design and resource governance.

Above all, there is a need to counter the limitations of current political-strategic timeframes that are too often aligned with short term 'discounting' perspectives that place emphasis on near future decisions. An ability to identify and stay within ecological boundaries over longer timescales would help to ensure intergenerational sustainable resource use. A longer timeframe is also in tune with "perfect storm" projections for converging trends by mid-century (Godfray et al., 2010; Dearing et al., 2012b). For communities in regions that already occupy dangerous operating spaces, a new framework that captures multiple timescales could provide a scientifically informed prioritization of restorative action.

1.2. A regional framework

A regional boundaries framework can be designed in alternative ways, depending on its motivation. One approach would be to calculate the regional share of global resource use (e.g. water) and

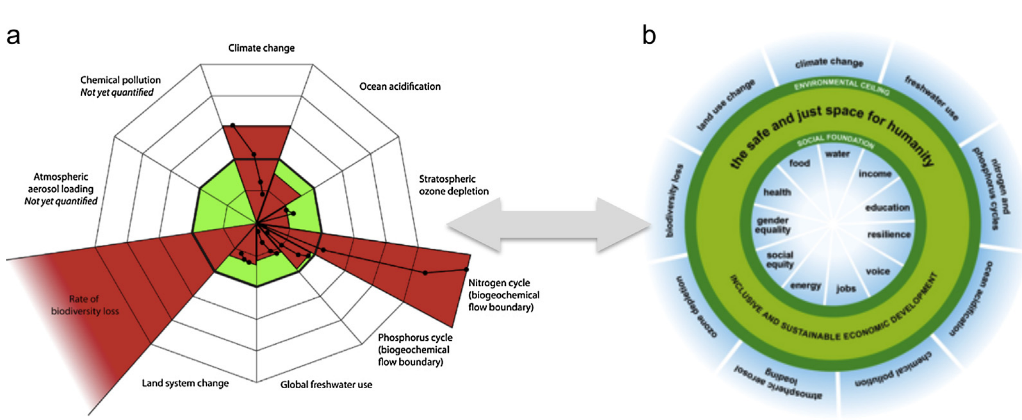

Fig. 1. Merging (a) the planetary boundary framework (Rockström et al., 2009a,b) and (b) the social 'doughnut' framework (Raworth, 2012) into a new framework and tool for defining safe and just operating spaces for sustainable development at regional scales.

impacts on planetary boundaries (e.g. CO_2 emissions) in the light of social conditions (e.g. in a less developed country). Another approach could focus on the links between social wellbeing (e.g. food security) and the sustainable management of resources (e.g. sustainable fish farming) within a particular region. Both demand the integration of social and ecological data with equity issues placed centrally. In this paper we focus on the latter approach: developing a RSJOS conceptual framework that allows, as a first step, setting and assessing performance against boundaries on both environmental and social fronts in two rural case studies from China. This approach is complementary to, and equally important as, evaluating the impact of human actions at the global scale because staying within regional boundaries is a prerequisite for reducing the aggregated effects on six of the proposed planetary boundaries. Ongoing work is exploring alternative frameworks for national levels (Nykvist et al., 2013) where the focus is on burden sharing, fairness and national responsibility for planetary boundaries.

2. Theory and methods

2.1. Environmental ceilings

The scientific logic of defining environmental limits and boundaries for regional social-ecological systems draws on relevant theoretical insights from other systems approaches (Dearing et al., 2012a, 2010) and links to current policy discourses (Cornell, 2012). In particular, it is generally agreed that critical transitions and early warning signals of impending thresholds need to be better defined (Lenton, 2011; Dakos et al., 2012; Scheffer et al., 2012) in order to allow a more robust assessment of environmental risk. Similarly, ecosystem services have become central to the discourse in current environmental assessment and policy (Millennium Ecosystem Assessment, 2005, The Economics of Ecosystems and Biodiversity, 2010 and United Kingdom National Ecosystem Assessment, 2011) but, with the exception of global services such as climate regulation, are more appropriate for regional scales where natural resources and processes are managed, such as within land (or water) use planning sectors (Cowling et al., 2008; Reyers et al., 2009). Balmford et al. (2011) argue that the human benefits from ecosystems can usefully be broken down into three groupings: (1) core ecosystem processes; (2) beneficial ecosystem processes; and (3) ecosystem benefits. Ecosystem benefits have a direct impact on human welfare, and they arise from beneficial ecosystem processes (i.e. water provisioning) that in turn are part of core ecosystem processes (i.e. nutrient or water cycling); analogous to regulating and supporting services in the Millennium Ecosystem Assessment (2005). In our framework, we focus on environmental ceilings for core and beneficial ecosystem processes and conditions because they: (1) represent the ultimate constraints or boundaries on social activities within the region; and (2) link directly to the biogeochemical cycles that underpin global boundaries.

Rockström et al. (2009b) argued that boundaries should be defined through an understanding of nonlinear systemic change and focused particularly on ecological thresholds and dangerous aggregate effects. We agree on the priority to have criteria that recognize dynamic change and seek to widen the two categories used for defining boundaries at the planetary scale by drawing upon theory for early warning signals. We also include information on environmental regulatory limits that are widely used in regional management. Taking a wider range of metrics obviates the need to make sharp distinctions between ‘environmental limits’ and ‘environmental thresholds’ (Haines-Young et al., 2006) because, in practice, these represent two end members of the scheme.

Our aim is to develop a pragmatic guide for identifying regional boundaries *from observations of system dynamical behaviour in real world time series* drawn from monitoring, survey, remote sensing and sediment analysis covering the multi-decadal timescales that capture most social-ecological system behaviour, while bearing in mind the narrow lens of system behaviour afforded by human timescales (Dearing et al., 2010). A practical classification of ecological boundaries with reference to environmental limits and the dynamical properties of ecological variables is shown in Fig. 2 and Table 1. The different types of boundary (Fig. 2) are not necessarily mutually exclusive in theoretical terms but rather are set according to the analysis of the actual observed system behaviour. Each type of boundary may demand a particular resolution of time series, involving specific statistical analyses. The regional boundary may be relevant to a whole system (e.g. extent of forest ecosystem), a system condition (e.g. water quality) or a process (e.g. soil erosion). Setting boundaries according to the observed record of system behaviour provides new evidence, *based on current complex system theory*, for accepting a business-as-usual policy, applying constraints on the continuation of the system or taking remedial action.

Type I boundaries refer to linear trending data, where a regional regulatory limit on a particular ecosystem process is set by scientific, expert or public opinion, through negotiation and trade-offs between the benefits and damages arising from particular activities. This type of boundary is commonly used for management of degraded landscapes and ecosystems (e.g. quality targets, critical loads), but it is only weakly linked to system dynamical properties and generally assumes stationarity in the trend. Type II boundaries can be placed on nonlinear trends, but unlike Type I boundaries, they need to be set in ways that recognize the dynamics of the system described by trend and variability. Type III boundaries describe threshold-dependent transitions in a system or condition towards new states that are considered abrupt *within human timescales* (decades and shorter). The causes of transitions may be the gradual erosion, or more stochastic forcing, of system resilience. But beyond a point, changes in the internal system structure and the transition to positive feedback loops produce relatively rapid changes until the system settles into a new attractor. Such transitions are observed in mathematical models for many ecological systems (Scheffer, 2009), but in real systems can only be observed after they are crossed (Groffman et al., 2006). A key distinction between two types of threshold change is the existence of different degrees of reversibility or hysteresis. Type IV boundaries refer to the rapidly developing area in dynamical theory of early warning signals where the sensitivity of a system to impacts grows disproportionally as a system loses resilience prior to a threshold. A number of new analytical techniques defined by changes in magnitude-frequency, variability, skewness or auto-correlation metrics (Lenton, 2013; Dakos et al., 2012; Carstensen and Weydmann, 2012) offer the promise of providing Type IV early warning signals. Types I–IV represent guides to defining boundaries and are not necessarily mutually exclusive (see also Table 1).

The challenges of communicating complexity concepts in real world situations are significant. In this initial attempt, we use a colour-coded scheme to identify ‘safe’, ‘cautious’ and ‘dangerous’ categories of operating space (Fig. 2) with the environmental ceiling set between the safe/cautious and dangerous categories. This simple imagery condenses powerful complexity concepts and time-series analyses into an easily understood qualitative basis of assessment. At this stage, it is important to set down a generic and dynamical basis for the definition of boundaries. It is easier to define ecological boundaries retrospectively when they have already been crossed. Where they have not been crossed, the process of setting boundaries needs to utilize all possible ways of defining systemic change: observation of Type IV early warning signals, model simulations, and expert judgement (Balmford et al., 2011; Moss and Schneider, 2000), which together represent an important research priority.

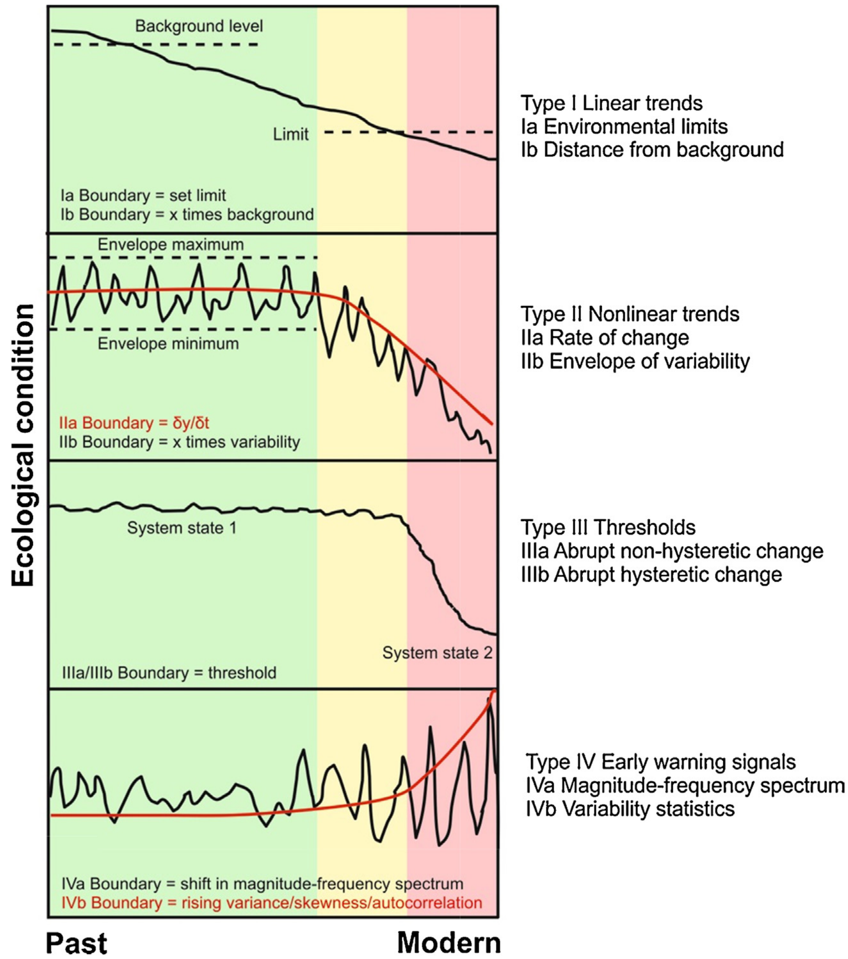

Fig. 2. A classification of possible system behaviour as an ecological boundary is reached showing Types I, II, III and IV, with colour coded categories (green, yellow and red) for attributed 'safe', 'cautious' and 'dangerous' status of key ecological services/processes and respectively (see also text and Table 1 for detailed explanation).

2.2. Social foundations

In direct contrast to environmental ceilings, social foundations are not defined by social dynamics but by nationally or internationally agreed minimum standards for human outcomes (Raworth, 2012). While some social standards have been established at the global scale, such as through the Universal Declaration of Human Rights and subsequent human rights law, their governance is enforced at the regional/national level with supranational governance continuing to be the exception for the foreseeable future. Therefore to have most policy impact, our framework must be applicable to regional governance systems, their practicalities and motivations. For example, the management of water resource catchments to provide adequate water and sanitation for all is typically a regional issue. Political and administrative boundaries shape where governance happens and consequently will determine how the framework can be made operational, how flows of materials in and out of the social-ecological system may be delineated, and how trade-offs can be agreed.

Data are available for many social indicators. In this initial demonstration, we follow Raworth (2012) and use national governments' stated social priorities, as set out in their national and regional submissions to the Rio + 20 Earth Summit. Analysis of those submissions (Raworth, 2012) reveals strong global consensus on eleven social priorities, including: food security, income, water and sanitation, health care, education, energy, gender equality, social equality, voice, employment and resilience (Table A.1). These priorities are used as the basis for selecting indicators within regions to define a social foundation. In practice, data are often available through the Millennium Development Goals (a suite of global human development targets set by the United Nations) that are adjusted to provide national and sub-national level data for poverty and health (United Nations, 2012a). Illustrative indicators include the percentage figures for: population undernourished; population living below \$1.25 (PPP) per day; population without access to an improved drinking water source; and population without access to improved sanitation.

2.3. Case-study methods

Ecological time series were drawn from a combination of monitored instrument records and lake sediment proxy records. Sediment cores were sampled from the deepest zones of lakes with intact modern sediment-water interfaces and analyzed at 0.5 cm intervals to obtain proxy records of water quality, soil stability, air quality, sediment quality, and sediment regulation. Sediment dating was based on ^{210}Pb and ^{137}Cs analyses that provide timescales covering roughly the last century. The analytical techniques used are published in detail elsewhere (Dearing et al., 2012a; Wang et al., 2012). Each time series was examined for trends, nonlinear system behaviour and proximity to environmental limits (Fig. 2 and Table 1). Social data, other environmental data and relevant environmental regulatory limits were collected from official Chinese statistical yearbooks and government reports. The main interactions between the different ecosystem service/process records and the human welfare categories recorded at each

Table 1
Types of ecological boundaries based on environmental limits and dynamical properties of time series.

Type I Linear trends
(Ia) Environmental limits. These are quantitative measures of the state of beneficial ecosystem processes that, once exceeded, significantly constrain conventional resource use (Haines-Young et al., 2006). For example, exceeding a given level of dissolved sodium in soil water means that the beneficial ecosystem process of water purification is lost, leading to losses of an ecosystem benefit (e.g. healthy grain production). Such values are often empirically determined from local experiments and can often be applied throughout a region.
(Ib) Distance from a baseline or background/low impact state. Setting these boundaries involves defining relative measures linked to beneficial ecosystem processes. For example, the European Union Water Framework Directive (http://ec.europa.eu/environment/water/water-framework/) requires member countries to restore or manage water quality to a ‘good ecological status’, defined as a slight deviation from a reference condition with no, or only very minor, anthropogenic disturbance.
Type II Nonlinear trends
(IIa) Rate of change. A boundary can be set where there is an unacceptable acceleration in a harmful effect or a decline in a beneficial ecosystem process. The change in rate may be caused by the cumulative effect of smaller scale changes on a process or condition, corresponding directly to the ‘dangerous aggregated effect’ category used by Rockström et al. (2009). For example, soil erosion may continue for centuries without major impact on crop yields. Yet a maximum soil erosion rate may be determined from observations and modelling that acknowledges unsustainable losses of soil over soil formation, and off-site effects like increased sediment delivery to rivers.
(IIb) Envelope of variability. A regional boundary can be defined by the point at which the system moves outside of the long-term normal envelope of variability, or is statistically different from the long-term quasi-stationary mean. By this definition, extreme events like ‘1 in 100 years floods’ are deemed part of normal variability. This idea is the basis of arguments for the existence of contemporary anthropogenic global warming (Mann et al., 1998). A regional scale example is an analysis of river discharge data that show recent divergence from stationary time-series (Milly et al., 2008). Such changes may imply that system boundary conditions may be changing and equilibrium-models for medium-term forecasting are probably invalid.
Type III Thresholds
(IIIa) Abrupt non-hysteretic changes. Some systems oscillate easily between different states (e.g., predator/prey populations, El Niño/La Niña cycles). These relatively fast and reversible (from historical evidence) transitions can be disruptive to both ecosystems and society but are non-catastrophic (Scheffer, 2009).
(IIIb) Abrupt hysteretic change. Some systems exhibit catastrophic shifts that are hard to reverse because they involve the forced loss of stability of one system state and abrupt switch to an alternative state. The metaphor employed to visualize these systems is of neighbouring valleys with a hill in-between them. The bottom of the valleys are attractors. Driving a ball from the bottom of one valley, over the hill and then releasing it would roll the ball down to the bottom of a different attractor. The transition from one attractor to another may only require a very small input if the ball is near the top of the hill. However reversing a transition could require significant input into the system. Although such fold bifurcations with hysteresis are widely discussed in the literature the evidence in real systems is quite limited (Bascompte et al., 2005; Wang et al., 2012; Lenton, 2013).
Type IV Early warning signals
(IVa) Shifts in magnitude and frequency. The time-series of many human-affected biophysical phenomena show pronounced changes that can be viewed as a shift in the ‘risk spectrum’ (Dearing et al., 2010). Bivariate frequency-magnitude log-log plots may show evidence for power law behaviour that defines naturally evolved system properties, giving a possible baseline for judging the impacts of human activities (Dearing and Zolitschka, 1999). Examples include the increasing frequency of extreme weather events at regional scales associated with anthropogenic climate change (e.g., Webster et al., 2005), and altered fire regimes in southwestern USA to larger, less frequent fires as a result of fire suppression measures (Swetnam et al., 1999).
(IVb) Variability metrics. Changes in statistical properties of mathematical model output and empirical data offer possible early warning signals of regime shifts in systems (Scheffer et al., 2012). This has been shown for changes in time-series of lake ecosystems (Wang et al., 2012) and also in spatial patterns of vegetation cover (e.g., Hirota et al., 2011). Analysis of mathematical systems suggests that these early warning signals are not specific to either catastrophic or non-catastrophic transitions (Kéfi et al., 2012). We interpret such statistical signals as signs of decreasing system stability, loss of resilience, and the start of a path towards a relatively rapid (though not always catastrophic) transition, especially where independent metrics mutually corroborate (Dakos et al., 2012; Lindegren, 2012).
From a human time perspective, a Type I linear trend in the short term may prove to be part of the forward limb of a Type IIIb fold bifurcation in the long term. A change in the rate of a system variable (Type II) over several years may be part of increasing system variability (that could be detected through Types IVa and IVb) or the beginning of a regime shift (Type III) when viewed over a multi-decadal timescale. Transitions are often referred to as abrupt, but many transitions unfold slowly after transgressing a threshold (Fischer-Kowalski and Haberl, 2007; Hughes et al., 2012). Thus, both Type IIa and IIb changes could represent a relatively slow transition towards a new state (Type III). The different boundaries could also be ranked according to their severity, with well-understood Type Ia boundary setting more stringent limits than Type III.

site are (at least) qualitatively known (Fig. A.1). For example, at Erhai (Fig. A.1a) the first order effects of upland soil instability are on water quality, sediment regulation and food security (crops and fisheries) through flooding, the natural fertilization of paddy fields and lake water quality. Higher order effects create more complex webs of interactions with potential feedback loops. However, our focus at this initial stage is simply to derive the current status of the individual social and ecological conditions. Further work will combine the information on status with known interactions to create dynamic modelling tools for management.

3. Results

Our case studies are represented by two similarly sized low-income rural communities in China, each covering an area of $\sim$2000 km^2 with $\sim$1 M population. In each case we define the ecological boundaries, social standards, environmental ceiling and social foundation from available time series, historical records and survey data. The two areas differ in terms of regional governance, physical landscape and proximity to large economic centres, yet provide similar challenges for sustainable development based largely on agricultural intensification.

3.1. Erhai lake-catchment, Yunnan Province, China

The mountainous Erhai lake-catchment, Yunnan, China ($25^{0}48^{\mathrm{I}}02.38^{\mathrm{II}}$ N $100^{0}11^{\mathrm{I}}33.86^{\mathrm{II}}$ E), including the ancient city of Dali, has a long history of unsustainable pressures on ecosystems (Dearing et al., 2008). Today, the rural community is involved in wet and dry cropping, dairy farming, fishing, aquaculture, and forestry. The southern part of the lake catchment is the focus for targeted industrial development. Documented environmental impacts include deforestation, soil erosion and eutrophication of the lake and inflowing rivers (Wang et al., 2012). The ecological time series (Fig. 3 and Table A.2) show recent changes in dynamical behaviour for water quality, air quality and water regulation. Two measures of water quality describe a hysteretic threshold change around 2001 that have taken the lake into the dangerous category represented by a highly eutrophic state (Wang et al., 2012). Water regulation over the past four decades has shifted the lake water level beyond the long-term envelope of variability but has recently changed from the dangerous to the cautious status. Three measures of air quality show mixed trends but the change in rate for Pb deposition in the sediments indicates a cautious status for emitted heavy metals in the current environment. Much longer

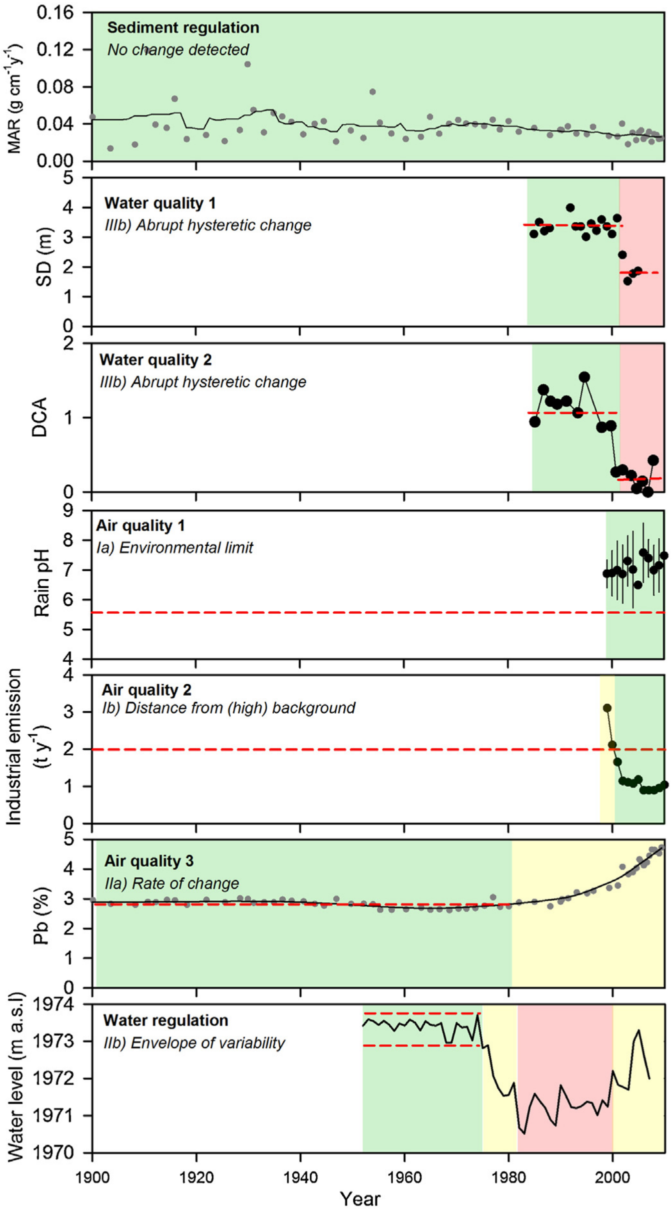

Fig. 3. Erhai lake-catchment, Yunnan Province: ecological boundaries (top to bottom panels) for sediment regulation, two measures of water quality, three measures of air quality and water regulation based on time series extending back from 2006 over one to eleven decades. The time series are illustrated with red dashed lines, where appropriate, to show the basis for defining the different types of dynamical behaviour and boundary (Fig. 2) described in each panel (italicized). Colour coded segments show historical changes in the safe (green), cautious (yellow) and dangerous (red) status of each ecological process (Fig. 2). The status shown for 2006 is used in the social and environmental integrated plot (Fig. 5a). Details of data and the categorization of boundaries are given in Table A.2. (For interpretation of the references to color in this text, the reader is referred to the web version of the article.)

sediment records (Dearing, 2008) show that the upland land use-soil system currently sits in the dangerous category, having settled into an alternate degraded steady state about 850 years ago. The social foundation (Table A.3) is virtually met in terms of health care but provision of food, water and sanitation falls short by substantial margins. Mapping the ecological boundaries with respect to the regional environmental ceiling and social foundation (Fig. 5a) highlights the importance of water quality management. Taking these preliminary findings together suggests that the process of economic development, particularly through agricultural intensification largely based on increasing fertilizer applications, has reduced but not eradicated poverty. There is a clear trade-off in terms of deterioration of key ecological processes and conditions that have led to dangerous threshold changes in lake water quality.

3.2. Shucheng County, Anhui Province, China

Shucheng County ($31^{0}27^{I}43.29^{II}$ N $116^{0}56^{I}55.20^{II}$ E) is situated in eastern China in the lower Yangtze basin about 200 km W of Nanjing City. It is a ‘poverty-stricken county’ as defined by the central government, and previous research has shown that the region has undergone serious environmental degradation due to intensive agricultural activities during the last 60 years (Dearing et al., 2012a). The ecological records from Shucheng (Fig. 4, and Table A.4) show that water quality, sediment quality and air quality have moved into the dangerous status, with soil stability given cautious status in response to the increasing volatility in the recent records. Given the findings from Erhai about alternate soil stability states, it is feasible that the farmed Shucheng soils have also passed into an alternate degraded state, meaning that the designated cautious status based on recent observations should be regarded as a minimum status. Like Erhai, the lake water quality transition is probably hysteretic (Wang et al., 2012) implying a high degree of irreversibility. Levels of sediment-associated P from intensive farming and deposited Pb from local fossil fuel powered industries are not only very high by international standards but also 80–100% higher than pre-1960s levels. Mapping these boundaries with respect to the regional environmental ceiling (Fig. 5b) highlights the importance of soil, water and air management. The social foundation is virtually met in terms of food security, health care and minimum income (Fig. 5b and Table A.5) implying that the government strategy of providing extra resources to ‘poverty-stricken’ counties is relatively successful. But like Erhai, access to piped water and sanitation still lags behind other poverty alleviation measures.

There are huge challenges in these Chinese regions for the local governments to harness the momentum of economic growth to reduce poverty while reconciling growth with the need to restore badly damaged ecosystems and ecological processes, and to avoid further irreversible and costly environment damage. Managing the two regions as social-ecological systems that remain within a RSJOS now needs, particularly, to prioritize the challenge of reducing nutrient loadings to the rivers and lakes whilst improving the rural access to water and sanitation. Air quality and water regulation are also in need of continuous environmental monitoring and evidence-based management if they are to stay within the regional environmental ceilings. Soils in both regions need targeted conservation measures.

4. Discussion

These case studies demonstrate proof-of-concept and validity of a new conceptual framework that may help raise the standards of social conditions while reducing the likelihood of moving into dangerous operating spaces with respect to ecological boundaries. Our framework offers a clear visual image for making comparisons between different regions and, potentially, provides a basis for assessing a region’s impact on planetary boundaries. The outputs could usefully inform the Post-2015 UN Development Agenda and new Sustainable Development Goals (United Nations, 2012b). Although these are good reasons to advocate its use, particularly in rural regions within developing nations, there are a number of caveats and remaining challenges.

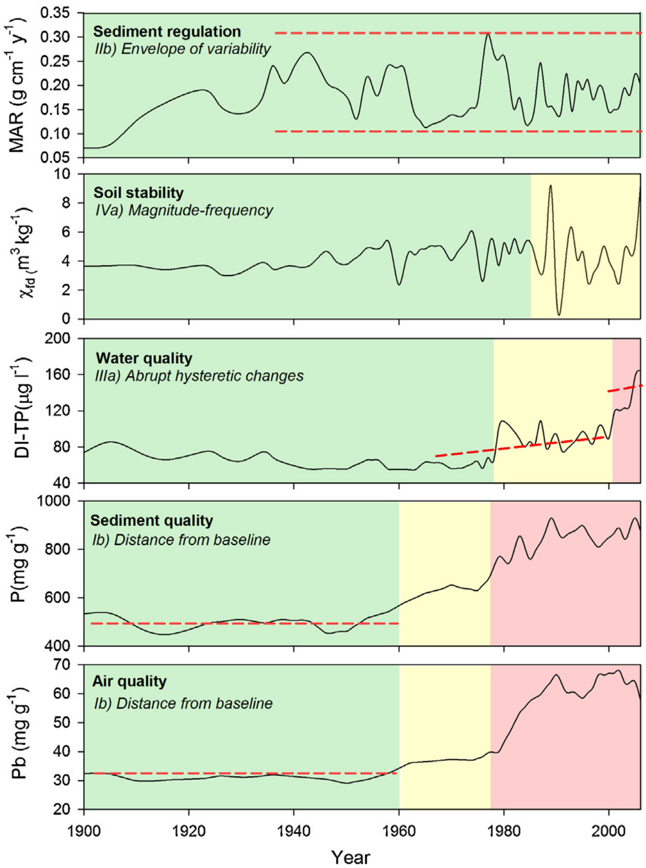

Fig. 4. Shucheng County, Anhui Province: ecological boundaries (top to bottom panels) for sediment regulation, soil stability, water quality, sediment quality and air quality based on time series extending back from 2006 over one to eleven decades. The time series are illustrated with red dashed lines, where appropriate, to show the basis for defining the different types of dynamical behaviour and boundary (Fig. 2) described in each panel (italicized). Colour coded segments show historical changes in the safe (green), cautious (yellow) and dangerous (red) status of each ecological process (Fig. 2). The status shown for 2006 is used in the social and environmental integrated plot (Fig. 5a). Details of data and categorization of boundaries are given in Table A.4. (For interpretation of the references to color in this text, the reader is referred to the web version of the article.)

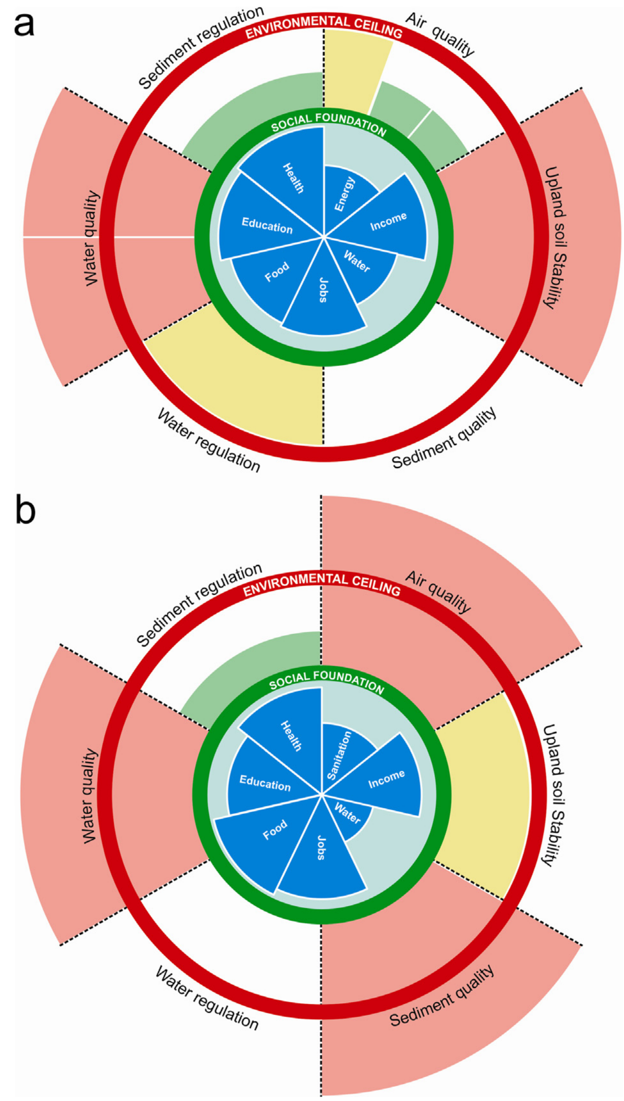

Fig. 5. Safe and just operating spaces mapped for two Chinese regions in 2006. (a) Erhai lake-catchment system, Yunnan Province; (b) Shucheng County, Anhui Province. The figures show the extent to which each region currently meets expected social standards (blue sectors) for an acceptable social foundation (green circle), and the current status of key ecological services/processes (from Figs. 3 and 4): safe (green sectors), cautious (yellow sectors) and dangerous (red sectors). The environmental ceiling (red circle) defines the approximate boundary between sustainable and unsustainable use of ecological processes. The RSJOS exists as a 'doughnut' between the environmental ceiling and social foundation. Data for sediment quality (a) and water regulation (b) unavailable. Note that the relative sizes of green, yellow and red sectors are illustrative: they are not plotted to any scale and are not plotted from the centre of the circles (see text for further explanation). Blank sectors indicate unavailability of data. Ecological data are shown in Figs. 3 and 4, and Tables A.2 and A.4; social data in Tables A.3 and A.5. An additional sector for upland soil stability at Erhai (a) is based on assessment of centennial records (see text and Dearing, 2008). (For interpretation of the references to color in this text, the reader is referred to the web version of the article.)

4.1. Complex interactions

While systems dynamic theory is used to help define ecological boundaries, as with the original planetary boundaries framework (Rockström et al., 2009a,b), the framework does not provide a systems dynamic analysis of the relationships between any of the social and environmental conditions. Rather, it provides a basis for judging the relative state of current environmental viability and societal wellbeing within a region. Clearly, caution must be exercised in considering causative links between the different variables because interactions within and between a social foundation and environment ceiling are likely to be complex, nonlinear and difficult to confirm. The analyses of biophysical time-series alone underline the need to consider the full range of timescales (annual-centennial) embedded within the social-ecological dynamics when assessing the environmental outcomes from a specific social policy or land management decision. There are likely to be important lags in the feedback effects of excessive resource use and resource stress (such as from climate change, eutrophication, biodiversity loss, and so on) on human health, income, food and water availability and resilience. These lagged environmental feedbacks may be related to hysteretic processes with potentially irreversible effects meaning that early warnings of direct stress on those ecological systems, as provided by the RSJOS methodology, is essential.

Thus the framework is best used to formulate hypotheses about links and interactions for further testing and investigation. For example, a new family of integrative social-ecological models (e.g. ARIES http://www.ariesonline.org) might help to identify critical points in the flows of ecosystem processes/services that could be used in highlighting vulnerable areas at risk from development. The framework provides a strong basis for designing systems dynamics models that capture feedback mechanisms (e.g. using multi-agent modelling tools, such as STELLA, Matlab-Simulink) in order to explore the ecological impacts of alternative social futures. Multivariate analyses within pressure-state-response frameworks (OECD, 1993) may be able to estimate future probabilities of extreme events as a result of co-occurring drivers (Denny et al., 2009; Rounsevell et al., 2010). Drawing on econometric methods, it may also be possible to aggregate individual time-series signals to give a region-wide assessment of growing connectivity (Wang et al., 2011) and causality (Sugihara et al., 2012) between variables, and the associated risk of systemic failure (Billio et al., 2012). The growing numbers of long term social-ecological reconstructions (Singh et al., 2013) will provide new material for extending the RSJOS framework to embrace the interactions between social foundations and environmental ceilings. But until these opportunities are realized, the RSJOS images presented are essentially informative, teleological devices providing a regional barometer of sustainable development for policy traction and strategic scientific studies.

4.2. Inter-regional fluxes

To a lesser or greater extent, all regions are connected to all other regions. The use of natural resources and ecosystem services within a region is frequently driven by larger scale motivations, resulting in flows of energy, people, money, and goods between regions. This means that the social and ecological variables within many regions are not necessarily strongly linked to local resource availability. Proximity to dangerous ecological boundaries may drive imports (Seto et al., 2012) but conversely regional environmental degradation may be driven by production for export (Muradian and Martinez-Alier, 2001). Thus the welfare data produced in the social foundation are focused on deprivations to be avoided, and do not indicate the extent to which other parts of a society may be engaged in excessive consumption patterns that directly affect the ecological conditions of a region. The rise in the global urban population, in particular, is tied to the sustainability of human and natural resources in both proximal and distant regions (Seitzinger et al., 2012). Whiteman et al. (2012) argue that corporate sustainability should include the impact of companies on the planetary boundaries but, as they also state, there is a need to include collective targets at local/regional scales to avoid problem-shifting among actors and geographic regions. In representing the fundamental limits to impacts on regional ecosystems, from whatever combination of drivers, the RSJOS framework outlined here is a first, and necessary, bottom-up step in improving our understanding of multi-scale interconnections (cf. Nilsson and Persson, 2012) in setting local or regional boundaries.

4.3. Tradeoffs

The impacts of regional resource scarcities (e.g. limits to food production) or overexploitation of regional resources (e.g. overuse of forests) may be overcome by switching to alternative resources, often resulting in new sustainability challenges. For example, Erb et al. (2008) describe a typical pattern in their analysis of historic tradeoffs in land use in Austria. Fossil fuel based yield increases in agriculture and the substitution of fossil fuels for biomass as the main energy source resulted in the recovery of previously degraded forests. From 1830 to 2000, local food supply multiplied and forests increased substantially in both area and stocking density. These regional gains were accomplished without substantially raising the net import of food and other land-based resources, but at the expense of increased greenhouse gas emissions (Folke et al., 2007) and, most likely, unsustainable soil use (Winiwarter and Gerzabeck, 2012). While the latter would be detected within the proposed RSJOS framework, the former would require a global framework with complementary indicators capable of showing unsustainably high levels of regional contributions to global problems. Methods to construct such nested indicators are available for problems such as fossil fuel related emissions 'embodied' in traded products (Peters et al., 2012) and in regards to biodiversity pressures (Haberl et al., 2012) and land-use impacts (Lenzen et al., 2012) related to trade. These underline the need and challenge to extend the RSJOS framework presented to include regional contributions to the pressures on planetary boundaries.

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Appendix A

See Fig. A.1 and Tables A.1–A.5.

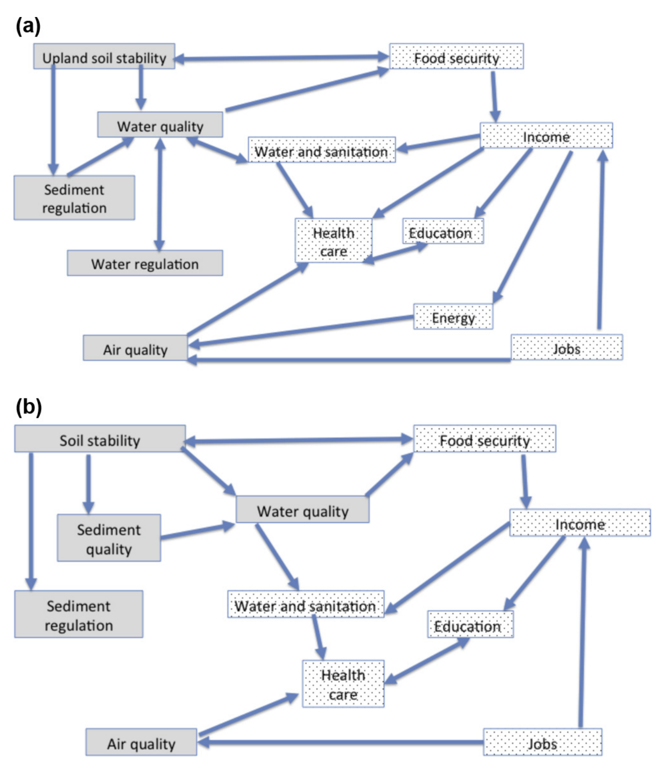

Fig. A.1. Known interactions between ecosystem service/processes (shaded boxes) and social indicators (dotted boxes) for (a) the Erhai lake-catchment system and (b) Shucheng County.

Table A.1
Eleven indicators of a social foundation based on national governments' social priorities for Rio+20 (Raworth, 2012).

Social foundation	Indicators
Food security	Population undernourished 13% 2006–2008
Income	Population living below $1.25 (PPP) per day 21% 2005
Water and sanitation	Population without access to an improved drinking water source
Population without access to improved sanitation	
Health care	Population estimated to be without regular access to essential medicines
Education	Children not enrolled in primary school
Illiteracy among 15–24-year-olds	
Energy	Population lacking access to electricity
Population lacking access to clean cooking facilities	
Gender equality	Employment gap between women and men in waged work (excluding agriculture)
Representation gap between women and men in national parliaments	
Social equity	Population living on less than the median income in countries with a Gini coefficient exceeding 0.35
Voice	E.g. Population living in countries perceived (in surveys) not to permit political participation or freedom of expression
Jobs	E.g. Labour force not employed in decent work
Resilience	E.g. Population facing multiple dimensions of poverty

Table A.2
Erhai lake-catchment: ecological boundaries.

Ecological process or condition	IIndicator (measurable variable)	IEcological boundary (type)	IEcological boundary (definition)	Current status	Boundary value	Current state	IKnown drivers
Air quality 1	Acidity of precipitation (monitored pH)	Type Ia Linear *Environmental limit*	Limit pH = 5.6 according to national regulatory standards	Safe	pH 5.6	pH 7.5	Fossil fuel power generation/industrial emissions
Air quality 2	Industrial soot/ particulate emission (monitored >0.1 μm particle emissions)	Type Ib Linear trends *Distance from a (high) background state*	Emission regulatory standards for Dali prefecture (<2 t/yr)	Safe	2 t/yr	1 t/yr	Fossil fuel power generation
Air quality 3	Heavy metals (lake sediment deposited sediment Pb)	Type Ib Linear trends *Distance from baseline*	Baseline Pb concentration before 1980s	Cautious	3%	5%	Industrial emissions
Water regulation	Lake water volume (monitored lake level)	Type IIb Nonlinear *Envelope of variability*	Earlier low lake levels <1972 m triggered lake eutrophication	Cautious	1973	1972	Dam construction/ hydroelectric power station demands/ climate change
Sediment regulation	Sediment delivery from catchment (lake sediment mass accumulation rate)	No detectable change	Long-term trend and variability indicate no major changes in driver-responses	Safe			Land use change/dam constructions
Water quality 1	Water transparency (monitored secchi depth)	Type IVb Thresholds *Abrupt hysteretic change*	Relative steady state values before 2000. Critical transition ~2001 with evidence for fold bifurcation. (Wang et al., 2012)	Dangerous	3 m	2 m	Nutrients enrichment from fertilizers and untreated sewage/fish farming
Water quality 2	Algal growth (lake sediment diatom community expressed through detrended correspondence analysis (DCA axis 1)	Type IVb Thresholds *Abrupt hysteretic change*	Relative steady state values before 2000. Critical transition ~2001 with evidence for fold bifurcation (Wang et al., 2012)	Dangerous	1.0	0.2	Nutrients enrichment from fertilizers and untreated sewage/fish farming
Upland soil stability	Eroded soil and substrate indicative of gullying on steep slopes (lake sediment record of topsoil and subsoil fingerprints frequency dependent magnetic susceptibility and low field susceptibility)	Type IVb Thresholds *Abrupt hysteretic change*	Steady non-degraded state before ~AD 520. Critical transition to modern degraded state lasted ~600 years until ~AD 1150. Evidence for fold bifurcation with strong hysteresis and irreversibility (Dearing et al., 2008)	Dangerous	n/a	n/a	Upslope movement of farming and ineffective terracing

Sources: Anhui Province Statistical Yearbooks (1989–2011), Dearing et al. (2008), Dearing et al. (2012a,b), Li (2008), Wang et al. (2012), Yan et al. (2005), Yunnan Digital Village (2013).

Table A.3
Erhai lake-catchment: social foundation.

Social foundation	Indicator	Current deficit from 100% (year)
Food security	Children undernourished (0–5 years old)	>5% (2012)
Income	Population living below $1.25(PPP)/day	2% (2010)
Water and sanitation	Households with piped water (Cibihu)	9% (not known)
Health care	Children (0–5 years old) mortality rate	>1% (2012)
Education	Illiteracy rate (Eryuan)	2% (2010)
Energy	Households with clean energy	17% (not known)
Gender equality	To be determined	
Social equity	To be determined	
Voice	To be determined	
Jobs	Urban unemployment	2% (2005)
Resilience	To be determined	

Sources: Bai (2003),), Eryuan County Bureau of Statistics (2011), Dali Environmental Protection Bureau (1999–2010) and Dali Bai Autonomous Perfecture (2012).

Table A.4
Shucheng County: ecological boundaries.

Ecological process or condition	Indicator (measurable variable)	Ecological boundary (type)	Ecological boundary (definition)	Current status	Boundary value	Current state	Known drivers
Air quality	Heavy metals (lake sediment deposited sediment Pb)	Type Ib Linear trends *Distance from baseline*	Baseline Pb concentration before 1960s. Modern values now ×2 baseline	Dangerous	~30 mg/g	~60 mg/g	Industrial emissions
Sediment regulation	Sediment delivery from catchment (lake sediment mass accumulation rate)	Type IIb Nonlinear No detectable change	Low absolute values, stationary data and reducing variability indicate increasing stability or no major changes in driver-responses.	Safe			Land use change/dam constructions
Water quality	Algal growth (lake sediment diatom inferred transfer function)	Type IIIb Thresholds *Abrupt hysteretic change*	Critical transition ~1980 with assumed fold bifurcation as shown in similar contexts (Wang et al., 2012).	Dangerous	100 μg/l	160 μg/l	Nutrient enrichment from fertilizers/ untreated sewage/lake reclamation
Soil stability	Topsoil erosion (lake sediment record of topsoil fingerprint frequency dependent magnetic susceptibility)	Type IVa Early warning signal *Magnitude-frequency*	Relative steady state before 1985. Increasing magnitude and frequency since the 1960s and especially after 1985 suggests growing topsoil instability	Cautious	$2–6 \times 10^{-6}$ m^3/kg	$2–8 \times 10^{-6}$ m^3/kg	Land use change/ deforestation/ cultivated slopes
Sediment quality	Sediment-associated nutrients and contaminants (lake sediment records of bound total P)	Type Ib Linear *Distance from baseline*	*P* concentration increase after 1960s to a high level. Mean value in 1960s taken as a baseline condition.	Dangerous	~500 mg/g	~900 mg/g	Excess fertilizer/soil erosion

Source: Dearing et al. (2012a,b).

Table A.5
Shucheng County: social foundations.

Social foundation	Indicator	Current deficit from 100% (year)
Food security	Children undernourished (0–5 years old)	1% (2009)
Income	Population living below $1.25(PPP)/day	6% (2010)
Water and sanitation	Households with piped water	55% (2011)
	Households with lavatories (Anhui)	42% (2010)
Health care	Children (0–5 years old) mortality (Anhui)	2% (2010)
Education	Illiteracy rate	8% (2010)
Energy	To be determined	
Gender equality	To be determined	
Social equality	To be determined	
Voice	To be determined	
Jobs	Urban unemployment rate (Anhui)	4% (2010)
Resilience	To be determined	

Source: Anhui Province Statistical Yearbooks (1989–2011).

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