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POLICY PERSPECTIVE

Meeting the Global Ecosystem Collapse Challenge

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Abstract

Natural systems are declining at an unparalleled rate. To prompt conservation of ecosystems, the IUCN has developed a framework to assess ecosystem threat. By 2025, the IUCN aims to assess the collapse risk of *all* the world's ecosystems using this framework. This increases the pressure to refine tractable methods to predict collapse. However, there has been no *systematic* review of whether predicting collapse is *possible* and *practical*, which is impeding consistent and comparable assessments of ecosystem threat. Here, we conduct such a review and highlight six areas of concern – stemming from the findings of our review – in need of immediate attention to progress work on assessing ecosystem collapse and the application of such assessments to the management of at-risk ecosystems. These are: (1) better conceptualizations of ecosystems, (2) better conceptualizations of ecosystem collapse, (3) improved integration of theory, experimentation, and practice, (4) improved surrogates and early warning indicators of ecosystem collapse, (5) the implementation of management experiments to enhance understanding of ecosystem stability, and (6) ensuring IUCN Red List of Ecosystems listings result in the conservation of biodiversity.

Assessing risks of ecosystem collapse

Globally, anthropogenic pressures are forcing ecosystems outside of safe operating spaces (*sensu* Rockström *et al.* 2009), increasing their likelihood of collapse. The IUCN aims to assess the risk of collapse of *all* of the world's ecosystems by 2025, using the Red List of Ecosystems (RLE) assessment framework (Keith *et al.* 2013). Ecosystem collapse (see Table 1 for glossary) is a hot topic in ecology, receiving increasing treatment in the scientific and popular literature – with several recent articles reviewing potential early warning indicators of collapse (Dakos *et al.* 2014; Kéfi *et al.* 2014; Scheffer *et al.* 2015; see Table 1 for glossary and examples of early warning indicators). We address the broad overarching question: *Is ecosystem collapse predictable*? The importance of answering this question is underscored by the fact that the concept is now formally codified under five criteria (A-E) in the IUCN RLE (Box 1), with Criterion E specifically seeking a quantification of collapse risk (Keith *et al.* 2013). This significantly raises the stakes in identifying and refining tractable methods to predict collapse, especially because collapse assessments inform listings in threat categories along a continuum from Least Concern to Critically Endangered according to the risks that they face (Keith *et al.* 2013; IUCN 2016). Here, we explored the challenges associated with predicting ecosystem collapse, providing commentary on the considerable implications those challenges have on numerically predicting collapse under Criterion E of the IUCN RLE. We conduct a formal systematic review to provide a detailed assessment of the ability to predict ecosystem collapse – and identify six key concerns and unresolved issues (stemming from the findings of our review) that must be addressed for researchers and practitioners to promote assessments of ecosystem collapse risk based on robust and objective predictions of ecosystem collapse. Robust predictions of ecosystem collapse are important if Criterion E of the IUCN RLE is to be successfully established and rigorously applied.

Within the growing literature on ecosystem collapse, we found that: (1) definitions of ecosystems, and what constitutes ecosystem collapse, are scant; (2) experimental tests of theory are rare – just four distinct experiments have been conducted; and (3) there is a mismatch

Table 1 Glossary of terms

Terminology	Definition	Reference
Early warning indicator	A general term for dynamic patterns ("signals") in ecosystem behavior that precede ecosystem collapse, e.g., increasing variance, increasing autocorrelation, or the presence of "flickering" in temporal or spatial data; see Kéfi *et al.* (2014) and Dakos *et al.* (2012) for a full summary of temporal and spatial indicators	Boettiger *et al.* (2013)
Ecosystem	A dynamic complex of plant, animal, and microorganism communities and their nonliving environment interacting as a functional unit	UN (2014)
Ecosystem collapse	A transition beyond a bounded threshold in one or more variables that define the identity of the ecosystem	Keith *et al.* (2013)
Empirical study	Studies that collect and/or use observational and experimental data to answer ecological questions	Haller (2014)
Mean maximum prediction	Average of the maximum number of years advance warning of ecosystem collapse reported in 21 articles	This article
Narrative review	A comprehensive narrative synthesis of previously published information, but does not employ rigorous and explicit literature search methods	Lortie (2014)
Surrogate	A component of an ecosystem that can be more easily measured or managed than others and that is used as an indicator of the attribute/trait/characteristic/quality of that ecosystem.	Lindenmayer *et al.* (2015)
Systematic review	A type of literature review that employs detailed, rigorous, and explicit methods to answer a specific question	Lortie (2014)
Theoretical study	Studies that use conceptual, mathematical, or simulation methods, often *parameterized* with real data, to answer ecological questions	Haller (2014)

between predicting ecosystem collapse, and predicting ecosystem collapse in time to *implement management* to avert collapse. We found warnings of ecosystem collapse ranged between 1 and 40 years prior to a shift (Contamin & Ellison 2009; Carpenter *et al.* 2011), but sometimes averting collapse was unlikely even if actions were taken *more than* 40 years prior to the onset of a shift in ecosystem state (Biggs *et al.* 2009). In fact, many early warnings of collapse may not be detected by managers as these warnings may precede ecosystem shifts by 2000 years (Spanbauer *et al.* 2014). While this means ecosystem shifts could be detected 2000 years into the future by managers, some imminent ecosystem shifts may have displayed early warning signals in the first century – and are undetectable for managers using early warning signals on contemporary (rather than paleoecological) data sets. Furthermore, a land manager's ability to predict collapse may also be confounded as supposed early warning signals may be detected *after* the collapse of an ecosystem (Carpenter *et al.* 2008).

Experiences and challenges in predicting ecosystem collapse

For Criterion E under the IUCN RLE to work, we need to answer two key questions: Is predicting collapse possible? If so, how much advance warning is needed to avert collapse? Answers are essential to determine the level of threat an ecosystem is under. To answer these questions, we conducted a formal systematic review (see Table 1 for glossary) of the scientific literature in four online databases on August 11, 2015, using a standardized search string (see Supplementary Methods and Table S1 for methodological details). Our search returned 10,696 articles, but only 64 focused on predicting ecosystem collapse (see Table S2 for details). Of these, six narrative reviews (Table S1) examined early warning indicators (Boettiger *et al.* 2013; Dakos *et al.* 2014), regime shifts (deYoung *et al.* 2008) and their application to management (Angeler *et al.* 2016). Of the 58 remaining articles, 29 were theoretical, and 29 were empirical. Nine empirical articles were experimental. In terms of ecosystems, aquatic systems were the focus of 42 studies, while just 13 articles focused on terrestrial systems (Table S3). For the empirical articles exploring these systems, only half provided a detailed description of the ecosystem under study. The number of publications investigating the predictability of ecosystem collapse increased considerably from 2000 to 2015 (no articles in 2000 to a peak of 12 articles in 2013, and 10 articles in 2015; Figure 1).

All but one study indicated that numerical prediction of ecosystem collapse is *possible*, but 21 identified significant practical challenges in predicting collapse – regardless of paper type (i.e., theoretical vs. empirical), ecosystem type (i.e., aquatic vs. terrestrial), surrogate type (i.e., abiotic vs. biotic), or early warning indicator (Figure 2 a-d). Predicting collapse requires intimate understanding of an ecosystem (50/58 studies), knowledge of the type of transition occurring (e.g., gradual, nonlinear, etc., 18/58 studies), and a suitable mathematical model of the

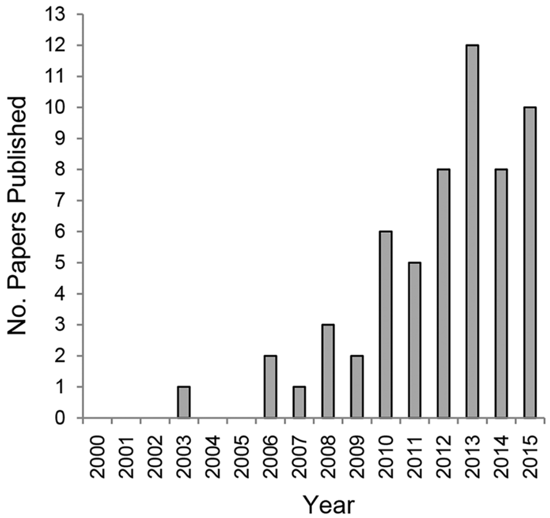

Figure 1 Number of papers predicting ecosystem collapse published each year since 2000.

ecosystem (25/58 studies) to guide the choice of appropriate early warning indicators. Even when these factors are known, reliable prediction is hindered by observation error or environmental variability (27/58 studies), choice of the surrogate that will rapidly display signs of system instability (18/58 studies), and insufficient temporal or spatial sampling of ecosystems (41/58 studies; Table S4).

Despite these limitations, 58 articles provided a numerical prediction of collapse: 17 based on disturbance intensity, 33 based on time (in time steps or years), and 8 based on risk/vulnerability. For temporal predictions, early warning indicators provided between 1and 40 years advance warning of collapse (mean maximum prediction $\pm$ SE $= 7.6 \pm 2.1$ years; see Table 1 for glossary). However, if management actions are delayed or acting on "slow" disturbances (e.g., shoreline incursion by rising sea levels), then averting collapse is unlikely – even if actions are taken more than 40 years prior to the onset of the shift (Biggs *et al.* 2009). Given that acting on early warnings may not always avert ecosystem collapse, it is more realistic to use early warning indicators as tools that can identify: (1) the need for intervention, and (2) a timeframe when it may still be *possible to act* to avert collapse, but not necessarily a time when intervention equates with easy or complete reversal of collapse (Donangelo *et al.* 2010).

Toward better predictions of ecosystem collapse

Our formal systematic review demonstrated the limited current ability to apply theoretical methods of predicting collapse to real-world ecosystems, which has substantial implications for conducting robust, quantitative assessments of collapse risk under Criterion E of the IUCN RLE. We therefore identify six unresolved issues and areas of concern that must be addressed to more rapidly progress work on ecosystem collapse, and its application to ecosystem conservation. The unresolved issues and areas of concern we present below are to some extent hierarchical – the first two issues (defining ecosystems and ecosystem collapse) need to be resolved (i.e., consensus reached by researchers and practitioners) to then effectively address the subsequent issues.

First, researchers must better define and conceptualize ecosystems when examining ecosystem collapse. Our review shows that only half of the empirical studies we examined contained a detailed definition of the ecosystem under study; but this is an essential part of the IUCN RLE assessment (Keith *et al.* 2013). Different definitions at different spatial scales can lead to researchers, managers, and policy makers talking about different levels of thematic complexity and – effectively – at cross-purposes. For example, Higgins & Scheiter (2012) found that vegetation shifts driven by changes in atmospheric CO_2 occurred abruptly at local scales, but occurred smoothly when averaged at a continental scale. While it may be desirable to list ecosystems at multiple thematic levels (e.g., if different jurisdictions require different levels of information about an ecosystem), it is critical that researchers, managers and policy makers are clear about the scale at which they are defining an ecosystem and at which they are conducting assessments. Scale-dependent differences in ecosystem response have substantial implications for robust estimates of collapse risk, and timely implementation of appropriate management interventions to avert collapse. Under a global assessment process like that proposed by the IUCN, consistency in definitions – and the scale of those definitions – is essential to minimize multiple listings of "equivalent" ecosystems, to encourage global information sharing between managers and researchers working in similar systems, and to facilitate optimal distribution of funds to conserve globally at-risk ecosystems.

Second, researchers must better define ecosystem collapse. While this issue has been raised by other researchers (e.g., Boitani *et al.* 2015), we underscore it here because our review highlights the extraordinary scarcity of descriptions or conceptualizations of collapsed ecosystems in the reviewed literature (7/58 studies). How ecosystem collapse manifests will be ecosystem specific (Boitani *et al.* 2015), which greatly increases the challenge of defining ecosystem collapse consistently across the globe. However, in understanding what desired ecosystems are *not*, we may begin to develop a general definition of ecosystem collapse

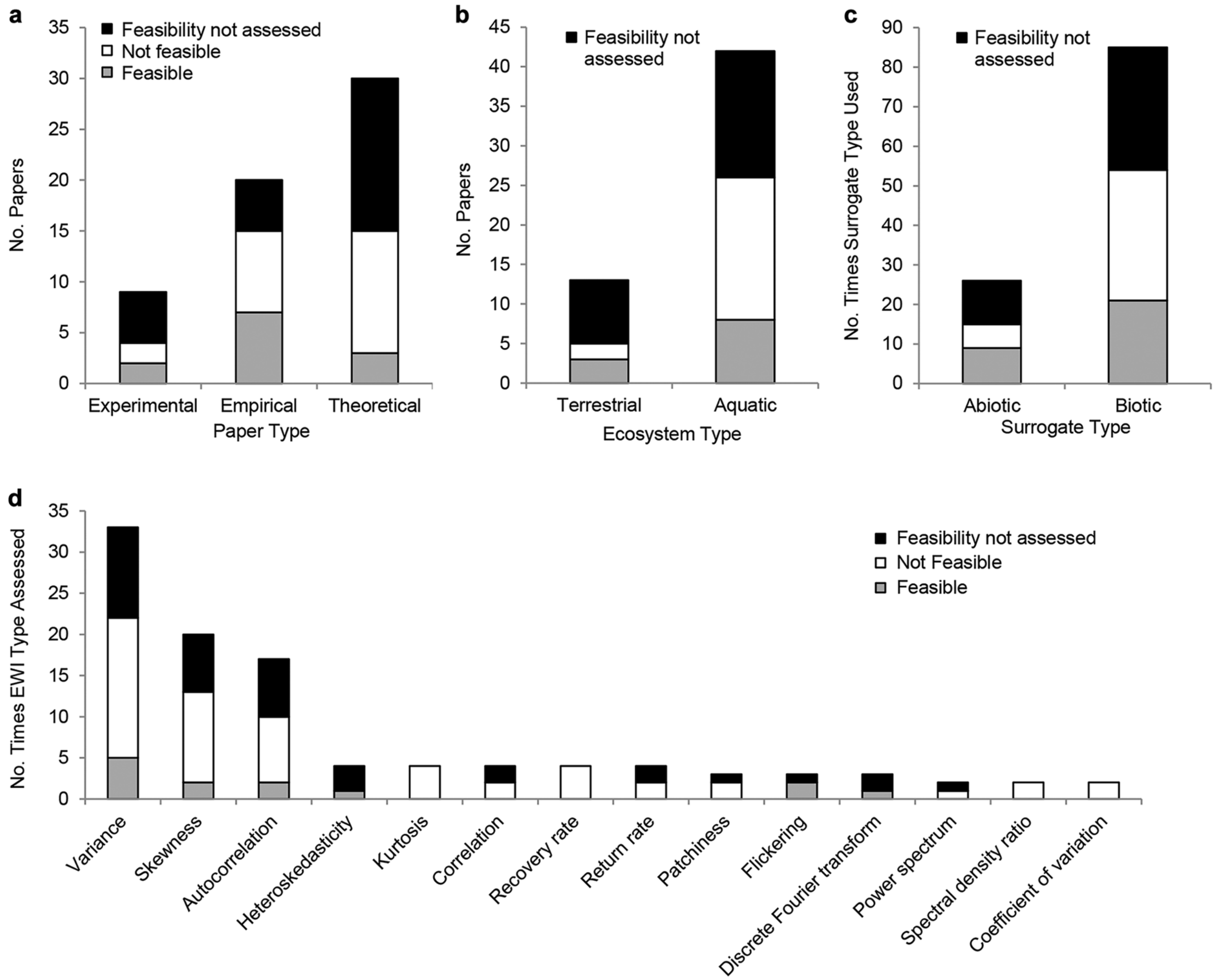

Figure 2 Practicality of predicting ecosystem collapse by (a) paper type (theoretical, empirical, or experimental), (b) ecosystem type (aquatic or terrestrial), (c) surrogate type (abiotic or biotic), and (d) early warning indicator type (only including early warning indicators [EWI] tested at least twice across all papers reviewed). Numbers may add up to more than the number of articles reviewed (58), as individual articles may have examined more than one ecosystem type, surrogate type, or early warning indicator type.

(e.g., Tozer *et al.* 2015). Consistency in defining ecosystem collapse is essential to gauge the relative level of threat faced by different ecosystems (Boitani *et al.* 2015) under the IUCN RLE, and is critical to rigorous assessment under all criteria – including Criterion E (Rodríguez *et al.* 2015). To move toward a workable definition, we suggest that ecosystem collapse be defined relative to a benchmark or reference condition – as suggested by the IUCN RLE (Rodríguez *et al.* 2015). An appropriate reference condition should consider the existing and recent composition (species assemblages), structure (complexity and configuration), and function (processes and dynamics) of an ecosystem (McDonald *et al.* 2016). Moreover, we recommend that explicit definitions of reference conditions as well as explicit definitions of collapse for different ecosystems used by researchers be included in published research – particularly research concerning collapse (including literature on regime shifts, alternative stable states, tipping points, etc.). This will help to expedite consensus on what collapse looks like in different ecosystems and, indeed, what defines specific ecosystems.

Third, there is an unprecedented demand for a far stronger meld of theory, experimentation, and practice to advance work on ecosystem collapse, and its application to initiatives like the IUCN RLE. Since 2009, the IUCN RLE has undergone extensive development, characterizing threat levels based on risk of ecosystem collapse (Keith *et al.* 2013; Box 1). Yet, for Criterion E, published RLE documentation (e.g., Keith *et al.* 2013, 2015;

IUCN 2016) indicates that this process has evolved mostly independently from theoretical research on the same topic. In fact, there is almost no literature from the two areas in common – recent theoretical articles that explore early warning indicators of collapse are rarely cited within RLE documentation (except four articles published in the early 2000s including Scheffer *et al.* 2001), and RLE documentation has not been referenced in any theoretical ecosystem collapse articles. Yet, our review highlights the recognition in theoretical literature that in-field testing of collapse predictors is required (11/29 studies), and empirical literature recognizes the need for further theoretical development of collapse predictors that take into consideration constraints on practical implementation (10/29 empirical studies identified significant challenges with implementing current collapse predictors). It is clear that greater integration of theory and practice is needed not only to advance the practical application of early warning indicators, but also to ensure theoretical advancements in early warning indicators are applied to ecosystem collapse concepts within Criterion E of the IUCN RLE assessment.

Fourth, early warning indicators of collapse must be more practical as current indicators (such as increasingly variable or flickering time series; see Kéfi *et al.* 2014 and Dakos *et al.* 2012 for a full summary of temporal and spatial indicators) are often difficult for managers to apply (10/29 studies). This must be rectified given that conclusions drawn by managers can be strongly influenced by the early warning indicator used (Seekell & Dakos 2015), the variable monitored (Batt *et al.* 2013), and the presence of false positive or negative warning signals (Burthe *et al.* 2016). Given the complexity associated with interpreting current early warning indicators, simpler ecosystem-specific indicators may be more practical for collapse assessments as they increase the chance that end-users (i.e., land managers) can interpret them. Applying an adaptive surrogacy framework (Lindenmayer *et al.* 2015) to early warning indicators will help in identifying tractable early warning indicators for managers that are sensitive, cost-effective, consistent, and that have realistic data requirements. This framework also could be used to evaluate the appropriateness of variables, such as remotely sensed data, for monitoring as surrogates for ecosystem collapse. The reviewed literature repeatedly recommended using remotely sensed data for the application of spatial early warning indicators (16/58 studies), but its surrogacy value has not been adequately evaluated. Remotely sensed data may meet the high-frequency data demands of proposed early warning indicators (Carpenter *et al.* 2011; Burthe *et al.* 2016), but may also yield conservative estimates of collapse risk. For example, Burns *et al.* (2015) used structural features (i.e., hollow-bearing trees, an important resource for many unique fauna) to determine IUCN threat status of south-eastern Australian forests. As remote sensing of tree hollows is not currently feasible, using remotely sensed data may overestimate the availability of these *structural* features, in turn underestimating collapse risk. Such erroneous estimates may have dire consequences for ecosystems (Biggs *et al.* 2009). However, we recognize that remote sensing encompasses many variables, and some remotely sensed applications may be useful as direct monitoring variables (Pereira *et al.* 2013), and therefore have potential for use in predicting ecosystem collapse.

Fifth, if there are significant challenges in predicting collapse in practice, management needs to focus on improving understanding of ecosystems (as recognized by 50/58 studies in our review), particularly determining the relationship between variability and stability. Some researchers suggest that ecosystems become increasingly variable prior to collapse (Donangelo *et al.* 2010; Batt *et al.* 2013). Yet, environmental variability can enhance the stability of some ecosystems (Borgogno *et al.* 2007), as well as increase population growth rates and viability (Lawson *et al.* 2015). Actions designed to reduce variability may therefore have perverse outcomes (Lawson *et al.* 2015). Hence, manipulative experiments that push subsets of ecosystems beyond the bounds of natural variability are essential to enhance understanding of ecosystems and ecosystem thresholds – as already demonstrated with "extreme" manipulations of precipitation and temperature variability in tall grass prairies in North America (Hoover *et al.* 2014).

Finally, we must ensure listing ecosystems under an IUCN framework and subsequent practical ecosystem management results in the conservation of biodiversity – as highlighted by Keith *et al.* (2015). This is because biodiversity plays critical roles in ecosystem function, dynamics, and stability (Reich *et al.* 2012). To know if this occurs, we recommend that IUCN ecosystem assessments be revisited regularly (e.g., bidecadally) to quantify: (1) the status of knowledge for the system: whether this has improved, declined, or stagnated – and how (e.g., through experimentation, lack of funding), (2) the effectiveness of monitoring for predicting collapse and improving understanding of ecosystem trajectories – and how this has come about (e.g., data collection or management, change of monitoring protocol, etc.), and (3) the efficacy of collapse surrogates (both monitored variables and early warning indicators) used.

Caveat

We present a review of the global, peer-reviewed literature available to date on predicting ecosystem collapse, providing commentary on the implications our findings have on numerically predicting collapse under the IUCN RLE. While this review provides new and important insight into the challenges associated with implementing the IUCN RLE – it has focused attention on Criterion E only. Further research – and review – of the ecological literature is required to assess each of the other IUCN RLE criteria, and to provide a comprehensive evaluation of the merits and potential challenges associated with conducting a global assessment of ecosystem threat levels using this new framework.

Concluding remarks

There is strong empirical evidence for ecosystem collapse in recent history (Scheffer *et al.* 2001), but anticipating collapse is complex. We found that while there is evidence to suggest that numerically predicting collapse is possible, *at present, early warning indicators cannot predict collapse reliably across all ecosystems*. This means we are currently limited in our ability to provide reliable and robust quantitative predictions of ecosystem collapse using Criterion E of the RLE framework. Existing early warning indicators need refinement for general practical application. Improving the robustness of predictions demands an intimate, long-term understanding of ecosystem dynamics and drivers. This, in turn, requires experimentation with, and long-term monitoring of, ecosystems. Given the growing evidence for collapsed ecosystems and the formal codification of ecosystem collapse in the IUCN RLE, there is an *immediate* need for robust, generally applicable predictors of ecosystem collapse. Thus, the time for researchers, managers, and policy makers to collaborate is now. Never before has it been more important to bring theory, experimentation, and practice together to further the global conservation of ecosystems, and the biodiversity therein.

BOX 1: Summary of the IUCN RLE criteria

In May 2014, the IUCN ratified the criteria for a Red List of Ecosystems assessment framework at the 83rd session of the Council of the International Union for Conservation of Nature (Decision C/83/22; IUCN 2014). Criteria A to D are based on a decline in the spatial or functional attributes of ecosystems, while Criterion E focuses on a quantitative analysis of collapse risk. The summary of the criteria provided is based on Keith *et al.* (2013) and IUCN (2016).

Criterion A: Requires an assessment of the past, present, or future decline in spatial extent of a defined ecosystem.

Criterion B: Requires an assessment of the extent or area of occupancy of a defined ecosystem.

Criterion C: Requires an assessment of the past, present, or future degradation abiotic variable(s) critical to the functioning of a defined ecosystem.

Criterion D: Requires an assessment of the past, present, or future disruption of biotic processes or interactions critical to the functioning of a defined ecosystem.

Criterion E: Requires a quantitative analysis of the collapse risk of a defined ecosystem.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Table S1. Literature review proforma
Table S2. Articles retained from the literature surveys
Table S3. Qualitative and quantitative article summaries from the literature surveys
Table S4. Quantitative article summaries from the literature surveys

This material is available as part of the online article from:
http://www.blackwell-synergy.com/doi/full/10.1111/j.1755263X.2008.00002.x

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