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Innovations and limits in methods of forecasting global environmental change

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Abstract

Environmental science has developed a diverse set of theories, analytical tools and models to understand and predict ecological responses to human impacts. We review recent innovations in the family of methods used to forecast global environmental change, and offer constructive critiques of five common approaches: phenomenological projections, storyline scenarios, integrated assessment models, decomposition-identity approaches, and global climate simulations. Overall, there is a lack of coherent, empirically based validation for many methods and their assumptions, and only partial incorporation of underlying uncertainties in both parameter estimates and interrelationships of model components. The greatest improvements in global environmental forecasting will likely come from a more systemic approach to quantifying the aggregate socio-economic drivers of the agents of change, along with better integration of multi-disciplinary approaches.

Zusammenfassung

Die Umweltwissenschaft hat vielfältige Theorien, analytische Methoden und Modelle entwickelt, um ökologische Reaktionen auf anthropogene Einflüsse zu verstehen und vorherzusagen. Wir untersuchen hier jüngste Innovationen aus der Familie der Methoden zur Vorhersage von globalen Umweltveränderungen und unterbreiten konstruktive Kritik zu fünf

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verbreiteten Forschungsansätzen: phänomenologische Projektion, “storyline”-Szenarien, integrierte Schätzmodelle, Ansätze zur Zerlegungsidentität, und Simulationen des globalen Klimas. Insgesamt herrscht ein Mangel an kohärenter Empirie-gestützter Validierung bei vielen Methoden und ihren Annahmen. Und die zugrunde liegenden Unsicherheiten, was sowohl. Parameterschätzung als auch Beziehungen zwischen den Modellkomponenten angeht, werden nur teilweise eingearbeitet. Die größten Verbesserungen für globale Umweltvorhersagen werden wahrscheinlich mit einem mehr systemischen Ansatz zur Quantifizierung der aggregierten sozio-ökonomischen Treiber der bestimmenden Kräfte des Wandels erreicht werden, in Verbindung mit einer engeren Integration von multi-disziplinären Forschungsansätzen.

Keywords: Projection; Scenario; Integrated assessment; Decomposition; Multi-criteria decision making analysis; Climate models; Decoupling

Introduction

How might the activities of human civilization drive changes in the Earth system during the 21st century and beyond? Projections of future environmental states are inherently constrained by imperfect knowledge and systemic uncertainties in the drivers of change (Clark et al., 2001). As the famous aphorism goes, all models are wrong, but some are useful (Box, 1979). Forecasts of environmental change are useful in helping planners trade off the consequences of, and opportunities offered by, alternative future scenarios (Loftus, Cohen, Long, & Jenkins, 2015). Forecasts offer decision makers a way to anticipate the response of complex systems to chronic stressors or disturbance, and can permit the evaluation of realistic development pathways to improve conservation benefit (Ausubel, 2000; Leadley, Pereira, & Alkemade, 2010; Sala et al., 2000). There are many uses for scenarios: here we focus primarily on their application to conservation management, ecology, and their relation to other planning outcomes such economic development. In this context, the development of ‘what if?’ scenarios can aid in identifying critical ‘pressure points’ and flexible ‘levers’ for policy, thereby expanding the design space and opportunities for global conservation while balancing the concessions between the drive towards equitable human prosperity and the vital need to conserve as much of our rich natural history and biodiversity as possible.

Forecasting should be based on a robust causal framework. One useful heuristic for conceptualising the linkages between human activities and environmental transformation is the driver-pressure-state-impact-response (DPSIR) framework (Omann, Stocker, & Jäger, 2009). Drivers, including population, consumption, and technology, determine the aggregate amount of ‘pressures’ (although such a structure lacks explicit consideration of the role of governance and other aspects of institutional behaviour that influence the drivers in this framework). Pressures are defined as physical interventions in the environment, and include, for example, land-use change (due to expanding areas of cropland, pasture, biofuels, plantation forests, and built-up land), emissions of greenhouse gases, water extraction, and pollution of air and water (Foley et al., 2005; MEA, 2005; Rands et al., 2010). These pressures alter the state of environmental variables (like the distribution of habitats, or the concentration of greenhouse gases in the atmosphere), with attendant impacts on biodiversity (species and populations), in the form of changing abundance, altered geographical distributions, and extinctions (Brook, Sodhi, & Bradshaw, 2008). Responses are the actions taken by humans to address these problems.

Forecasting possible future pathways of biodiversity change (impacts) requires understanding – and modelling – each prior step in this causal chain. Conservation science has developed and validated a rich set of theories and methods to understand and predict the impacts of various human pressures, including population viability analyses, species-area relationships and coupled niche-population models (Brook et al., 2000; Ibáñez et al., 2006; Botkin et al., 2007; Lacy et al., 2013). Conservation science has, however, made less progress on modelling the connections between drivers and pressures. By contrast, in the physical sciences, computer simulations of the Earth System are now routinely used to project emissions of greenhouse gases, the resultant climate change, and its associated risks and impacts (Hansen et al., 2007; Lenton et al., 2008; Fordham, Wigley, & Brook, 2012). And in the socio-economic realm, integrated assessment models are used to summarize diverse inputs on complex problems such as multi-regional energy projections (Ostrom, 2009; Golub et al., 2012).

Despite the progress outlined above, there remains considerable work to do in developing the theoretical and applied tools needed to project and optimize human development pathways to minimize biodiversity loss from climate change, land-use change, and other pressures. Local interventions like protected areas and payments for ecosystem services can safeguard some of the most valuable elements of biodiversity and ecosystem integrity (Mace, Norris, & Fitter, 2012). Yet they do little to mitigate the overall level of human pressures, since this is governed primarily by changing patterns of consumption (e.g., demand for material resources) and implementation of new technology (e.g., affecting environmental impacts per unit of production) (Ausubel, 2000; Andam, Ferraro, Pfaff, Sanchez-Azofeifa, & Robalino, 2008; Butchart et al., 2010; Clark, Boakes, McGowan, Mace, & Fuller, 2013). If the hypothesis that technology is a driver (rather than simply a consequence) of social/governance pressures holds true, then the success of biodiversity