formation will slow substantially. Strong evidence that this can happen has come from many laboratory CO_2-manipulation experiments, but there are few comparable field observations of a decline in the growth of large corals at reduced pH.

In fact, many animals form calcareous shells in waters that are well under-saturated with aragonite; the existence of freshwater pearls and deep-sea corals attests to this. These animals have the ability, at a modest physiological cost, to work against the temperature and pressure gradient for dissolution of aragonite.

It is not well-known whether such abilities are latent in reef-forming corals faced with a slow change in pH over many decades. But the chances are that the species familiar to the reefs we marvel at today will not survive, and we can ill afford to try this global experiment. The limit given by Rockström *et al.* — an aragonite-saturation state equivalent to at least 80 per cent of the average global pre-industrial level of 3.44 — therefore seems reasonable.

But is it truly useful to create a list of environmental limits without serious plans for how they may be achieved? Without recognition of what would be needed economically and politically to enforce such limits, they may become just another stick to beat citizens with. Disruption of the global nitrogen cycle is one clear example: it is likely that a large fraction of people on Earth would not be alive today without the artificial production of fertilizer. How can such ethical and economic issues be matched with a simple call to set limits? Although peak-oil concerns could be allayed by 'clean' coal technologies, among other solutions, the same cannot be said of phosphate — and food is not optional.

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Rethinking biodiversity

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A boundary that expresses the probability of families of species disappearing over time would better reflect our potential impacts on the future of life on Earth.

The story of life on Earth has unfolded over more than 3 billion years, from the earliest unicellular organisms, through the explosion of diversity in the Cambrian period 530 million years ago, to the amazing diversity of species found on the planet today.

As the paleontological record has improved in recent decades, it has become evident that there have been many periods of mass extinction and that the majority of life on Earth has already become extinct (*Extinction: How Life of Earth Nearly Ended 250 Million Years Ago*; Princeton University Press, 2006). In comparison, modern humans are relative newcomers to the world stage, dating back just 200,000 years. In that time we have demonstrated a remarkable capacity to transform our environment while needing to adapt to it at the same time.

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The planetary boundaries concept presented by Johan Rockström and colleagues (*Nature* **461,** 472–475; 2009) addresses an important question: are there particular thresholds or tipping points beyond which non-linear change would affect the planet?

They believe that one such threshold applies to biological diversity. In their view, extinction of species should not exceed ten species per million per year. If this is exceeded, they argue, we risk irreversible environmental change. Rockström and colleagues conclude that the current rate of extinction — 10 to 100 times the average rate — clearly exceeds the proposed boundary.

The first thing to note is that many of the boundaries being proposed are individual physical and chemical variables, which makes them more amenable to measurement over time. The same cannot be said for biodiversity. Interactions among species and ecosystems are extraordinarily complex. Moreover, the data on abundance and distribution for species today are limited, which makes contemporary rates of extinction difficult to estimate for most groups. There are, for example, good data on extinction of groups such as birds going back a couple of centuries, but no reliable data on rates of extinction for insects or most marine invertebrates.

Second, the relationship between species extinction and global environmental change is also not well understood. Rates of extinction (and of speciation) have been highly variable through time (*Proc. Natl Acad. Sci. USA* **105,** 11536–11542; 2008). Indeed, the extinction rate has almost certainly been much higher than the proposed boundary in previous times, such as the massive Permian-Triassic extinction (*Extinction: How Life of Earth Nearly Ended 250 Million Years Ago*; Princeton University Press, 2006).

Third, the usefulness of a single variable for all of biodiversity is not clear. This is because the rates of speciation and extinction can change across different groups of organisms and habitats. For example, we know that the rates of extinction for trilobites and ammonites are ten times higher than for marine gastropods or marine bivalves (*Phil. Trans. R. Soc. Lond. B* **353,** 315–326; 1998). In modern times, we know that amphibians are disappearing much faster than birds (*Science* **306,** 1783–1786; 2004 and *2004 IUCN Red List of Threated Species*; IUCN, Gland, Switzerland, 2004). So coming up with a single biodiversity boundary across all taxa and habitats may not be useful.

Given these limitations of the system being proposed, how else might a biodiversity boundary be constructed? Instead of recording extinction rates, an alternative method could be to construct a measure of how population size, distribution and threat levels are changing for specific groups. Much of this data already exists and has been recorded over time in reports such as the International Union for Conservation of Nature's *Red List of Threatened Species*.

An alternative approach to developing a biodiversity boundary could be to express species extinction as a probability based on evolutionary history and the tree of life, instead of a range of values.

There are some 8,000 families and 175,000 genera of living organisms that have been described to date (*Catalogue of Life: 2009 Annual Checklist*; Species 2000 and Itis, 2009). There is no question that mass extinctions in the past have resulted in the loss of large groups of organisms. There have been moments in time when major branches of the tree of life have disappeared and the planet has undergone dramatic changes. A boundary that estimates the likelihood of families disappearing over time would better reflect our potential impacts on the future of life on Earth.

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