Planetary boundaries

In the latest issue of *Nature*, a group of leading academics argue that humanity must stay within defined boundaries for a range of essential Earth-system processes to avoid catastrophic environmental change (*Nature* **461**, 472–475; 2009). In proposing the concept of 'planetary boundaries', Johan Rockström of the Stockholm Resilience Centre and co-authors present a new framework for measuring stress to the Earth system and define a safe operating space for human existence on this planet.

Rockström and co-authors suggest preliminary boundaries for the following indicators of environmental change: climate, ocean acidification, stratospheric ozone depletion, freshwater use, biodiversity, the global cycles of nitrogen and phosphorus, and land-use change. They propose that for three of these — the nitrogen cycle, the rate of loss of species and anthropogenic climate change — the maximum acceptable limit has already been transgressed. In addition, they say that humanity is fast approaching the boundaries for freshwater use, for converting forests and other natural ecosystems to cropland and urban areas, and for acidification of the oceans. Crossing even one of these planetary boundaries would risk triggering abrupt or irreversible environmental changes that would be very damaging or even catastrophic for society. Furthermore, if one boundary is transgressed, then there is a more serious risk of breaching the other boundaries.

In this series of Commentaries, seven renowned experts respond to the planetary boundaries concept. Though collectively they represent a broad spectrum of interests across Earth and environmental sciences, each author brings specific expertise to evaluating one aspect of the proposed framework. They ask whether we can currently define, even roughly, the acceptable upper bounds for indicators of environmental degradation, and whether doing so would ultimately help or hinder efforts to protect the planet.

Thresholds risk prolonged degradation

WILLIAM H. SCHLESINGER

For nitrogen deposition as for other pollution, waiting until we approach the limits of environmental degradation merely allows us to continue our bad habits until it's too late to change them.

Thresholds are comforting for decision-makers. There is no controversy when a high-jumper makes the bar, in contrast to a figure-skater who wins based on form and execution. When the skater doesn't make the grade, there is endless debate about whether the judges were too harsh and what revisions are needed in scoring procedures.

In personal health, as long as we are alive we can be pretty sure we haven't crossed a threshold of dire consequence. But in many cases, identifying and waiting for thresholds also allows misbehaviour that might be better nipped in the bud. Humans don't die of the first cigarette they inhale, but the slow cumulative effects of smoking can hasten the journey towards one's ultimate personal threshold.

Ecologists believe there are numerous thresholds in nature (*Nature* **413,** 591–596; 2001). As we see anthropogenic changes in the Earth system, we need to decide whether we want to allow human activities to disrupt Earth's life-support processes, or whether to begin now to sustain something that is pleasant and potentially more healthful for humans and the other species that share this planet with us. Ongoing changes in global chemistry should alarm us about threats to the persistence of life on Earth, whether or not we cross a catastrophic threshold anytime soon.

Rockström *et al.* (*Nature* **461,** 472–475; 2009) guess that an acceptable human impact on the global nitrogen cycle should not exceed 25 per cent of the current anthropogenic transfer of nitrogen from the atmosphere to the land surface. This threshold for nitrogen seems arbitrary and might just as easily have been set at 10 per cent or 50 per cent. Since nitrogen can also be denitrified by soil bacteria and ecosystem remediation is theoretically possible, greater human impacts might potentially be tolerated with proper management (*Proc. Natl Acad. Sci. USA* **106,** 203–208; 2009).

But is a threshold really a good idea at all? In areas of excess nitrogen deposition from the atmosphere — for example, in pastures in Great Britain — species decline linearly as a function of increasing nitrogen inputs to the land (*Science* **303,** 1876 –1879; 2004). Some experimental studies with nitrogen fertilizer show a greater loss of species at low levels of excess nitrogen deposition, with diminishing incremental effects thereafter (*Nature* **451,** 712–715; 2008). Waiting to cross the threshold allows much needless environmental degradation.

Rockström *et al.* set a lenient limit for acceptable human perturbation of the global phosphorus cycle, suggesting it should not exceed ten times the background weathering of phosphorus. But if we cross a threshold for phosphorus that leads to deep oceanic anoxia, we risk a truly dire situation. And lower levels of phosphorus input have well-documented effects on fresh water, which led regulators to set limits on the phosphorus content of detergents nearly 40 years ago.

Moreover, the background value for phosphorus is difficult to estimate. Rivers now carry an estimated 22×10^{12} grams of phosphorus per year ($gP\ yr^{-1}$) to the sea, but an unknown fraction of that is derived from human activities (*Treatise on Geochemistry* Vol. 8, 585–643; Elsevier, 2005). Not all phosphorus in rivers is reactive; most is bound to iron and aluminium minerals and is rapidly deposited in marine sediments. The current human contribution to reactive phosphorus in river waters (about

1×10^{12} gP yr^{-1}; *Amer. J. Sci.* **282,** 401–450; 1982) is probably equivalent to the natural background flux, doubling the total reactive phosphorus load and causing difficulties in coastal waters. The total background flux is probably greater than 11×10^{12} gP yr^{-1}, so the suggested tolerable boundary for the human impact would exceed 110×10^{12} gP yr^{-1}, enough to deplete known phosphorus reserves in less than 200 years and certainly not sustainable.

Unfortunately, policymakers face difficult decisions, and management based on thresholds, although attractive in its simplicity, allows pernicious, slow and diffuse degradation to persist nearly indefinitely. Through the Holocene, atmospheric CO_2 was nearly constant; nature mitigated the effects of humans. The human impact on the carbon cycle now exceeds the natural buffering capacity of the Earth system, leading to cumulative changes in the environment for life in every corner of the planet. When these changes are more rapid than evolution, extinctions mount and the ability of the planet to support life is diminished (*Nature* **427,** 145–148; 2004). Setting boundaries is fine, but waiting to act until we approach these limits merely allows us to continue with our bad habits until it's too late to change them.

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Keep off the grass

STEVE BASS

Humanity must learn to live within a stable Holocene environment, but the boundary limit for land use depends on more than the amount of surface covered.

Johan Rockström and colleagues' description of planetary boundaries (*Nature* **461,** 472–475; 2009) is a sound idea. We need to know how to live within the unusually stable conditions of our present Holocene period and not do anything that causes irreversible environmental change.

Planetary boundaries build on a long and respectable tradition of research and thinking on ecological limits, such as the 'limits to growth' thesis of 1972, as well as more recent developments, such as the idea of the ecological footprint and the Millennium Ecosystem Assessment — though Rockström and colleagues would have done well to acknowledge these foundations.

Their paper has profound implications for future governance systems, offering some of the 'wiring' needed to link governance of national and global economies with governance of the environment and natural resources. The planetary boundaries concept should enable policymakers to understand more clearly that, like human rights and representative government, environmental change knows no borders.

That said, there is much work to be done before the concept can be used practically — before it can be 'operationalized'. What policymakers need is a clear instruction that says something to the effect of 'keep off the grass'. What the planetary boundaries paper provides is closer to an index of lawn carrying capacity expressed in terms of soil engineering and grass regeneration.

One of the boundaries described is land-use change. The authors say there needs to be a limit on the amount of the world's land surface that is converted for farming or industry. They suggest that no more than 15 per cent of land should be used as cropland. Current crop cover is around 12 per cent.

Rockström and colleagues will be the first to accept that the 15-per-cent figure is not a consensus value that can be validated in the research literature, but rather is based on a sensible — though apparently arbitrary — expansion factor. In that regard, they need to be prepared for at least two critical questions. First, if a figure of 15 per cent cannot be authenticated scientifically, policymakers will want to know why they should pay attention to it. Why shouldn't, say, 20 per cent of land surface be used for farming? Or indeed, why not 10 per cent?

Second, readers will want to know the basis for the authors' contention that land-use change undermines human well-being. If anything, the opposite has probably been more true: converting land for farming and for industry has clearly delivered a great deal of well-being, and populations will continue to find such land-use change both attractive and desirable.

What research does tell us is that the sustainability of land use depends less on percentages and more on other factors. For example, the environmental impact of 15 per cent coverage by intensively farmed cropland in large blocks will be significantly different from that of 15 per cent of land farmed in more sustainable ways, integrated into the landscape.

The boundary of 15 per cent land-use change is, in practice, a premature policy guideline that dilutes the authors' overall scientific proposition. Instead, the authors might want to consider a limit on soil degradation or soil loss. This would be a more valid and useful indicator of the state of terrestrial health. More satisfactory policy guidelines on land use could subsequently be constructed, based on this and other relevant planetary boundaries.

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Tangible targets are critical

MYLES ALLEN

Setting a limit on long-term atmospheric carbon dioxide concentrations merely distracts from the much more immediate challenge of limiting warming to 2 °C.

The campaign to establish 350 parts per million (p.p.m.) as a long-term target carbon dioxide concentration has acquired considerable momentum despite relatively little support for this specific number in the scientific literature. As one of the highest-profile scientific endorsements of 350 p.p.m., the essay by Rockström *et al.* (*Nature* **461,** 472–475; 2009) will no doubt be heavily cited in the run-up to the UN climate negotiations in Copenhagen this December. While the underlying argument for limiting anthropogenic warming to below 2 °C is indisputable, attempts to define a 'climate boundary' in terms of long-term CO_2 concentrations represent an unnecessary distraction. The problem is not that 350 p.p.m. is too high or too low a threshold, but that it misses the point. The actions required over the next couple of decades to avoid dangerous climate change are the same regardless of the long-term concentration we decide to aim for.

Rockström *et al.* define planetary boundaries as "scientifically informed values of the control variable established by societies at a 'safe' distance from dangerous thresholds". The 350-p.p.m. boundary fails on at least two counts. First, the concentration of carbon dioxide at some unspecified date in the future is not a "control variable" in any recognizable sense.

GETTY

Keeping temperatures at no more than 2 °C above pre-industrial values, which Rockström *et al.* use as their starting point, will require substantial emissions reductions over the coming decades. Even then, it will probably be many centuries, and possibly millennia, before concentrations return naturally to 350 p.p.m. The time required will partly depend on the long-term behaviour of the carbon cycle, which is highly uncertain. Even more, it will depend on how our descendants manage the carbon budget over the ensuing centuries, which is more uncertain still. Although emissions over the next few decades could commit us to much higher atmospheric CO_2 concentrations in the long term, whether they are 350 p.p.m. or 450 p.p.m. in the year 3000 is not something anyone living in the twenty-first century could meaningfully claim to control.

Second, the scientific justification that carbon dioxide levels must equilibrate at 350 p.p.m. or lower to avoid more than 2 °C of warming appears to depend on a rather questionable estimate of the 'climate sensitivity' — the very long-term warming response to a doubling of atmospheric carbon dioxide. Rockström *et al.* acknowledge that the strength of feedbacks in the present-day climate suggests a most likely value for climate sensitivity of 3 °C, with a 'likely' (one-standard-error) uncertainty range of 2–4.5 °C. Yet they cite evidence from paleoclimate research (*Open Atmos. Sci. J.* **2,** 217–231; 2009) that, in the past, additional feedbacks due to polar ice-sheet melting and poleward shifts in vegetation resulted in a climate sensitivity of 6 °C, with a 'likely' range of 4–8 °C. They invoke this higher number, assuming these additional feedbacks, to justify their 350-p.p.m. target. But is it coherent to include these feedbacks? If stabilizing at 350 p.p.m. would prevent the collapse of the polar ice sheets, why use a value for climate sensitivity that assumes the ice sheets melt?

The same problem applies to the radiative forcing boundary of one watt per square metre (W m^{-2}) suggested by Rockström *et al.* We cannot categorically rule out the possibility that our descendants may need to steer CO_2 levels back below 350 p.p.m. or reduce radiative forcing to less than 1 W m^{-2} to avoid dangerous climate change, but it would be equally wrong to suggest that current evidence indicates this is the most likely course they will have to take.

There is, however, one important respect in which aiming for 350 p.p.m., even without a date attached, may be a helpful target. For reasons that do not depend on carbon-cycle models, 15–20 per cent of CO_2 emissions remain in the atmosphere more or less indefinitely, until removed by chemical weathering or active sequestration (*Proc. Natl Acad. Sci. USA* **106,** 1704–1709; 2009). Because of this lingering CO_2, emitting 1 trillion tonnes of carbon over the entire 'anthropocene' era — half of which has already been released — would increase the long-term equilibrium CO_2 concentration to at least 350 p.p.m. Hence 'target 350' implies, at a minimum, that we limit net anthropogenic carbon emissions to less than one trillion tonnes. But there is no need to invoke a long-term climate sensitivity of 6 °C or to speculate about multi-century draw-down of CO_2 to justify limiting cumulative carbon emissions to less than one trillion tonnes: this is simply what we need to do to keep the most likely peak CO_2-induced warming below 2 °C (*Nature* **458,** 1163–1166; 2009).

The importance of cumulative emissions implies that, as far as climate change is concerned, the atmosphere should be treated as an exhaustible resource, which does not seem to fit into the framework of 'planetary boundaries within which we can safely continue to operate indefinitely' at all. Indeed, attempting to define time-invariant boundaries on atmospheric composition and radiative forcing focuses attention on quantities such as the long-term climate sensitivity that are very difficult to constrain, implying that the science is less certain than it actually is. There is no need to speculate about the behaviour of the climate system into the next millennium to make the case that emission reductions are urgently needed to avoid dangerous climate change.

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Identifying abrupt change

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Five per cent is a reasonable limit for acceptable ozone depletion, but it doesn't represent a tipping point.

The use of planetary boundaries to estimate a safe operating space for humanity is a very interesting and useful concept. In this week's issue of Nature, Rockström *et al.* (*Nature* **461,** 472–475; 2009) define acceptable limits for Earth-system processes in such a way that crossing a boundary would risk triggering abrupt or irreversible environmental changes that would be very damaging or even catastrophic for society.

As a boundary for stratospheric ozone depletion, they choose a five-per-cent decrease in column ozone levels — that is, in the total amount of ozone in the atmospheric column — for any latitude, with respect to 1964–1980 levels. Their choice is reasonable, but a bit arbitrary.

NASA

Although Rockström *et al.* also identify the appearance of the Antarctic ozone hole as a tipping point, it is not connected to this five-per-cent boundary, which is still well within the bounds of linear behaviour for global ozone loss.

Arguably, a more relevant tipping point is reached when certain substances containing chlorine and bromine trigger massive ozone depletion at all latitudes. This abrupt change results from the same non-linear behaviour of ozone-depleting chemical reactions that causes the Antarctic ozone hole. Such potential change was referred to early on as the 'chlorine catastrophe' and has been more recently analyzed by Newman *et al.* (*Atmos. Chem. Phys. Discuss*. **8,** 20565–20606; 2008). They show that if chlorofluorocarbons (CFCs) had not been regulated by the Montreal Protocol, ozone-hole chemistry would appear in the tropical lower stratosphere in about 2052, leading to complete lower-stratospheric ozone loss by 2058, assuming growth of three per cent per year in the manufacture of CFCs. This corresponds to about a 60-per-cent decrease in column ozone levels, triggered by an atmospheric concentration of effective equivalent stratospheric chlorine (EESC) of about 30 parts per billion (p.p.b.). EESC is calculated by summing total stratospheric chlorine and bromine levels, and it quantifies their combined effect on ozone depletion in the stratosphere. The Montreal Protocol limited EESC to about 4 p.p.b., leading to a maximum total ozone loss of roughly five to six per cent.

So while the choice of a five-per-cent decrease in column ozone levels as the boundary for stratospheric ozone depletion appears reasonable, one could argue that a more realistic boundary is 10 or even 20 p.p.b. of EESC. Either of these boundaries would still maintain a safe distance from the 30-p.p.b. tipping point that would lead to massive ozone loss; a 10-p.p.b. EESC boundary, for example, would lead to about 15 per cent total stratospheric ozone loss.

World leaders decided to ban the industrial production of CFCs early enough that the decrease in stratospheric ozone was limited to about five per cent. Although the non-linear behaviour of lower-stratospheric ozone loss was not even a consideration in the discussions that led to the CFC ban, the decision was well-justified in light of the potential damage to human health and to ecological systems from an ozone loss greater than five per cent. It also made sense because of the CFC ban's relatively small cost to society, given that replacement compounds could be developed.

In summary, the planetary boundary concept is a very important one, and its proposal should now be followed by discussions of the connections between the various boundaries and of their association with other concepts such as the 'limits to growth'. Importantly, this novel concept highlights the risk of reaching thresholds or tipping points for non-linear or abrupt changes in Earth-system processes. As such, it can help society to reach the agreements required for dealing effectively with existing global environmental threats, such as climate change. Stratospheric ozone depletion was properly dealt with well before crossing the boundary that would trigger an abrupt change of global proportions, but well after reaching the tipping point that caused the Antarctic ozone hole — a regional, episodic event. A five-per-cent decrease in ozone might be appropriate as a planetary boundary, but that's only true if the concept is expanded to include limits that are well within the linear regime for that Earth-system process.

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The devil is in the detail

DAVID MOLDEN

A global limit on water consumption is necessary, but the suggested planetary boundary of 4,000 cubic kilometres per year is too generous.

Planetary boundaries are a welcome new approach in the 'limits to growth' debate. For one thing, they shift our attention to the scale of planetary systems being altered by human activity. As a scientific organizing principle, the concept has many strengths. What scientists persistently ignore is the unpleasant fact that a good scientific concept isn't necessarily a good communications platform. In that sense, it will take much more than the presentation of a novel concept to spur action. It is imperative that we act now on several fronts to avert a calamity far greater than what we envision from climate change alone.

The key element in the planetary boundary framework is the provision of numerical target values for process variables that represent the boundaries. Rockström *et al.* (*Nature* **461,** 472–475; 2009) provide first estimates for seven of nine environmental parameters by synthesizing available knowledge. It could be argued that with our limited understanding it is impossible to present reasonable numbers, or that the borders are much more malleable than the boundaries suggest, and with better or worse management, boundaries can be moved. Moreover, global values mask important issues at regional and local scales and conceal variability. On the other hand, the numbers are important because they provide targets for policymakers, giving a clear indication of the magnitude and direction of change. They also provide benchmarks and direction for science. As we improve our understanding of Earth processes and complex inter-relationships, these benchmarks can and will be updated.

So what are we to make of the water boundary suggested by the authors? Here at the International Water Management Institute, experience tells us that there are physical limits to human intervention into natural processes. We can also confirm that water limits have been reached or breached in many major river basins across the world, and the consequences are already manifest. For example, there is little or no additional streamflow or groundwater for further development remaining in the Murray–Darling River in Australia, the Yellow River in China, the Indus in Pakistan and India, the Amu and Syr Darya in central Asia, the Nile River, and the Colorado River in the United States and Mexico. All of these are important food-producing areas. These basins suffer from excessive pollution, river desiccation, competition for supplies and ecosystem degradation. The drying of the Aral Sea is one of the most infamous examples of ecosystem damage caused by breaching the limits of freshwater withdrawals. Freshwater biodiversity has plummeted as a result of the massive hydraulic construction era beginning in the 1960s. The main driver has been agricultural water use to meet the rising food demands of a growing population.

Johan Rockström and colleagues are suggesting that consumption of 'blue water' sources — evaporation and transpiration from rivers, lakes, groundwater reservoirs and irrigation — should not exceed 4,000 cubic kilometres per year. At present, blue water consumption is estimated at 2,600 cubic kilometres per year. The first thing to say is that the 4,000 figure is based on an analysis of a relatively small number of studies on the global supply and demand of water. When extrapolated (beyond the intentions of the original studies), they lead to a range of 4,000 to 6,000 cubic kilometres. If anything, this 4,000-cubic-kilometre value may well be too high.

Water for agriculture is one of the forces pushing us beyond our boundary limits. In many areas, dense concentrations of people living on arable land are using water at a rate that has exhausted supplies. In other parts of the world, there is ample water but its use is limited because the land or climate is not suitable for agriculture. In yet other places, such as sub-Saharan Africa, more water could be withdrawn, but expansion in water use is limited by financial and institutional capacity. These variations were not taken into account in the setting of the water boundary.

Another factor not taken into account is the widespread and erroneous assumption that useable water in nature can be readily accessed. In their quest for water and food security, many governments have devised grandiose plans to move massive volumes of water from water-rich to water-poor river basins. Examples include the Interlinking of Rivers Project in India and the South to North Water Diversion Project in China. The ecological consequences of these inter-basin water transfers remain unclear, but they are likely to be immense.

Essentially, the concept of a global limit overlooks the importance of local conditions and the role of management in magnifying or ameliorating problems. For this reason, the water boundary suggested by Röckstrom and colleagues may be too high. That said, the planetary boundaries concept and its first estimate of numeric values give us an important warning call that must be heeded. Rather than get bogged down in detailed arguments about the weaknesses of the approach or the methods of analysis, we now have a tool we can use to help us think more deeply — and urgently — about planetary limits and the critical actions we have to take.

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Consider all consequences

PETER BREWER

Ocean acidification has impacts other than simple changes in pH, and these may need boundaries too.

In their definition of planetary boundaries that humans should not transgress for fear of "deleterious or even catastrophic consequences for large parts of the world's inhabitants", Rockström *et al.* (*Nature* **461,** 472–475; 2009) consider ocean acidification as an essential part of the equation. This may be true whether we consider "inhabitants" to be all life or only humans, for the ocean and its resources are deeply embedded in human culture. But the authors' suggested boundary, based on aragonite saturation — a measure of the extent to which seawater is saturated with the carbonate mineral — needs careful examination.

The term 'ocean acidification' has become the recognizable phrase to encompass the ensemble effects of elevated CO_2 levels on marine life. Much as climate is understood to mean much more than temperature change, so too ocean acidification means more than simple changes in pH. Other consequences of warming and the great CO_2 invasion of the ocean also need consideration as boundaries. All aerobic life in the sea, not just calcareous animals, will be affected to some degree by the 'acidification' challenge as oxygen levels fall and carbon dioxide levels rise.

Aragonite is the most common form of calcium carbonate used by coralline animals and is the basic building block of coral reefs. Thus, it might be reasonable to expect that if we transgress the proposed boundary for ocean acidification, so that waters at increasingly shallow depths become depleted of aragonite, coral reef formation will slow substantially. Strong

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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

CRISTIÁN SAMPER

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.

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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