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

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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.

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