HAVE WE REACHED Peak CO_2?

Emitting a total of no more than one trillion tonnes of carbon to the atmosphere will give humanity a 50 percent chance of keeping global warming to 2˚C above preindustrial temperatures. If this is the goal, we have just passed peak CO_2, says **Michael Raupach**.

Perhaps half a million years ago, in the midst of the climatic turmoil of the glacial cycles, a primate species in Africa learned a new trick: the use of fire. This species, destined to become humankind, began to derive energy from the controlled combustion of wood, peat and other detrital carbon left over from the cycling of the carbon-based biosphere all around it.

The ability to use fire would come to give its discoverers a unique evolutionary advantage: energy no longer had to be used as it was gathered or stored within the body of the gatherer. It could be stockpiled, concentrated and used as a transformative agent.

The full potential of this discovery was not realised until an 11,000-year period of relative warmth and calm in the glacial climate cycles (the Holocene), when humankind developed agriculture and started to form towns and cities, supporting specialisation. New economic, social and cultural modes of organisation became possible – all supported by technologies dependent on concentrated energy from the combustion of detrital carbon.

Astonishingly quickly, we are now confronted by finite-Earth vulnerabilities.

Changes were further accelerated by another critical discovery: energy could be derived not only from the carbon in wood but also from a much older source, the huge reserves of fossilised carbon laid down hundreds of millions of years earlier as coal, oil and gas. This ancient detrital carbon provided much more concentrated energy than wood, catalysing yet further forms of organisation which rapidly flowered into industry and advanced technology.

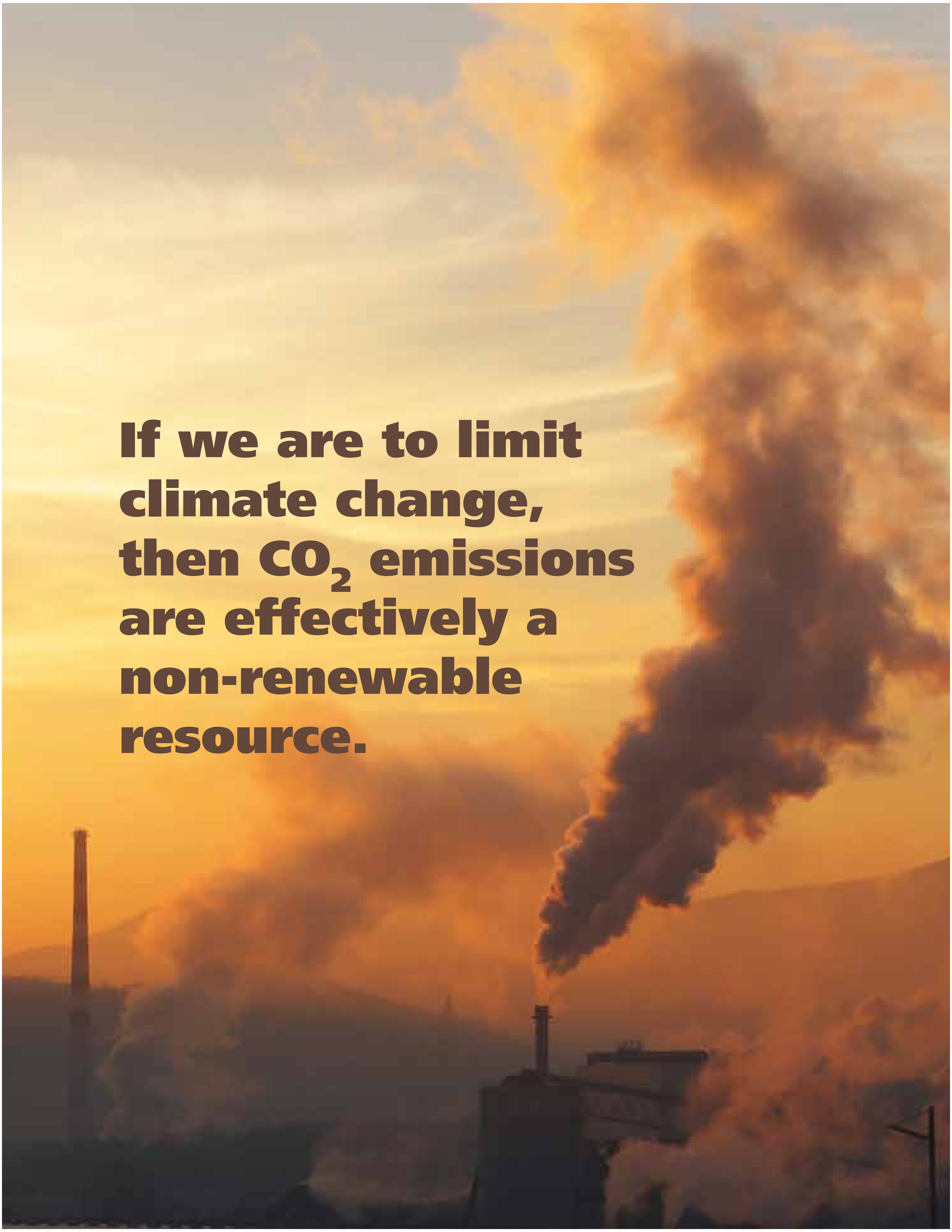
By exploiting this exogenous energy, the human species has come to dominate its planet. Its numbers have swelled to billions, its agriculture has transformed ecosystems, and its appetite for natural resources, including fossil fuels, has become insatiable. Human activities are now at such a scale that they significantly modify the climate, ecosystems and the Earth's great natural cycles of carbon, nutrients, energy and water, signalling the transition from the Holocene to the Anthropocene*.

At this time – the peak of human supremacy over its planet – the dependence of humanity on fossil fuels suddenly exposes a pair of vulnerabilities. First, the supply of natural resources is limited: among the fossil fuels, oil and gas are the most vulnerable.

Second, the planet has a limited capacity to metabolise the waste products from human activities without suffering damage – a major threat being climate change induced by the build-up in the atmosphere of CO_2 from fossil-fuel burning and land clearing. These two "finite-Earth" vulnerabilities respectively impose constraints on the inputs to and the outputs from human activities. Humans can consume a limited amount of natural resources and produce a limited amount of waste.

Peak oil

A widely used approach for assessing the first vulnerability – resource limitation – is the "Hub-



If we are to limit climate change, then CO_2 emissions are effectively a non-renewable resource.

Credit: Istockphoto

bert curve". In 1956, the American geoscientist M. King Hubbert predicted that oil extraction in the US would peak in the early 1970s and then begin to decline.

At the time, not many geologists believed Hubbert, preferring to think of oil as a resource so great that it would last into some distant future. But Hubbert was proved correct, and his theory is now widely applied to predict reserves of non-renewable resources such as oil, gas and coal in specified areas or for the planet as a whole.

The basic idea, of which there are many variants, is that the extraction rate of a non-renewable resource follows a roughly bell-shaped curve. Extraction starts slowly as the resource is discovered, accelerates to a peak as exploitation of the resource increases, and then declines as the resource is depleted and further discovery and extraction become progressively more difficult. This means that the point at which half of the total resource is consumed coincides approximately with the point at which production is greatest.

Estimates of the Earth's fossil fuel resources vary widely. In 2008, the World Energy Outlook of the International Energy Agency put the ultimately recoverable resource for oil at about 410 Gigatonnes (GtC, one billion tonnes of carbon), including production to date (130 GtC), proven reserves (140 GtC) and estimated unproven and undiscovered reserves (140 GtC). For conventional gas, the ultimately recoverable resource is estimated as about 217 GtC, of which 28 GtC has been used. The ultimately recoverable resource for coal is much larger, probably over 1000 GtC, including 165 GtC of past production, 620 GtC of proven reserves and a conservative estimate of undiscovered reserves.

These conventional fossil fuel resources are supplemented by a large (though very uncertain) reserve of unconventional resources, including shale oils, tar sands and methane hydrates, which collectively may contain over 1000 GtC. Hence the world probably has a total fossil-fuel resource of over 2500 GtC, of which about 320 GtC have been used. Of the three major conventional resources (coal, oil and gas), oil is the one for which peak production is being reached first.

It would seem from these figures that the world has a large endowment of fossil fuels, enough to last for centuries. However, the second finite-Earth vulnerability, the limit on output, imposes another critical constraint.

Peak warming above preindustrial temperatures would be limited to 2°C if cumulative CO_2 emissions are kept to 1000 GtC.

Peak CO_2

The problem of avoiding dangerous climate change has long been framed as one of stabilising CO_2 and other greenhouse gas concentrations at particular levels such as 550, 450 or even 350 parts per million (ppm) CO_2 equivalent (a concentration measure including CO_2 and other anthropogenic greenhouse gases according to their contributions to global warming). However, several recent papers, including two in *Nature* (Allen et al. 2009, doi:10.1038/nature08019; Meinshausen et al. 2009, doi:10.1038/nature08017) have proposed a different and in many ways preferable view, in which the mitigation challenge is framed as that of putting a cap on total cumulative CO_2 emissions since the start of the industrial revolution. This means that if humankind is to limit climate change, then CO_2 emissions are effectively a non-renewable resource. A small long-term continuing emission may possible in the far future, perhaps 10 percent or less of current emissions, but this is so tiny that a cap on cumulative CO_2 emissions provides a robust guide to the requirements for avoiding dangerous climate change.

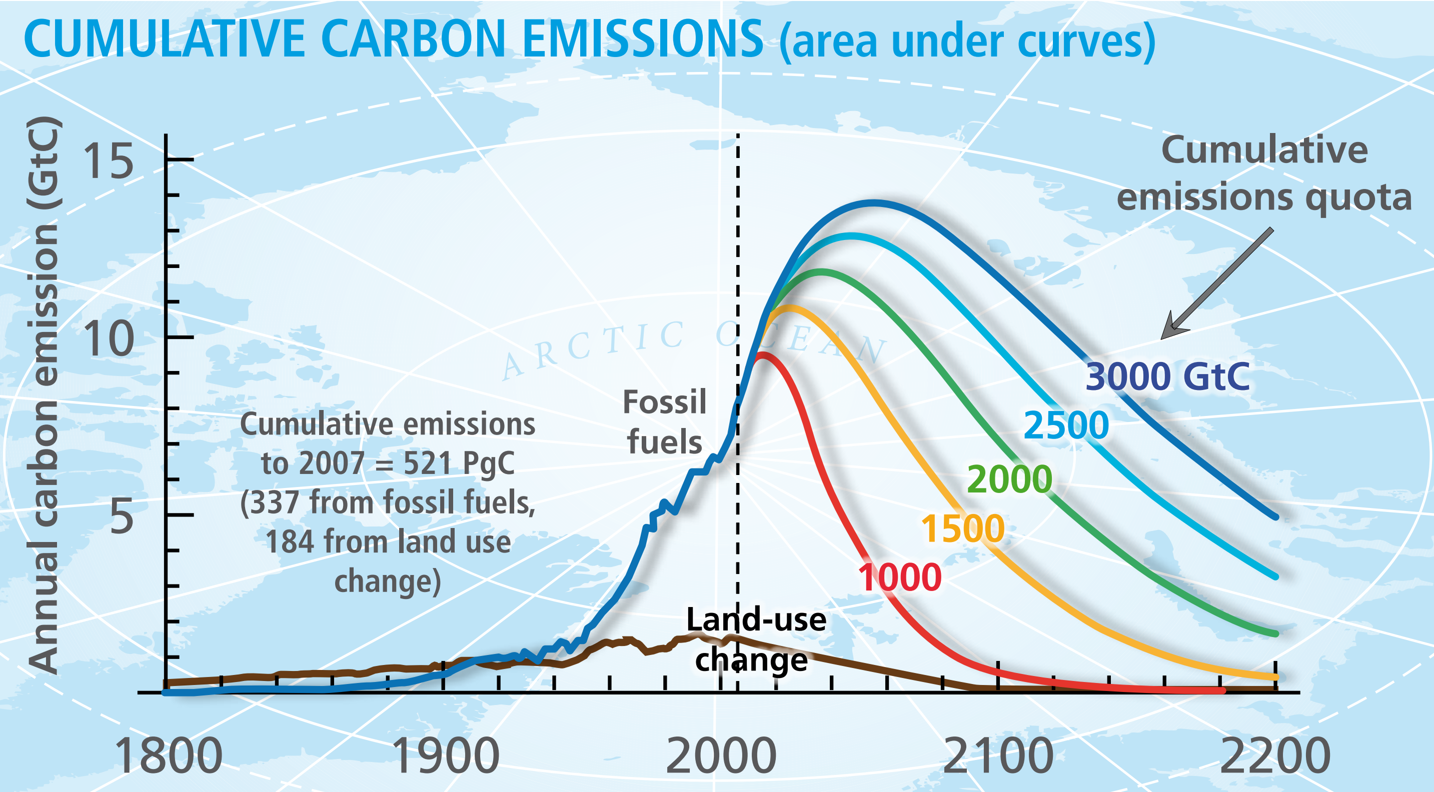
What is the "safe" quota for cumulative CO_2 emissions? Myles Allen from the University of Oxford and colleagues used several models to estimate that the peak warming above preindustrial temperatures would be limited to 2°C with a 50 percent probability of success if cumulative CO_2 emissions, which we will call Q, are capped at 1000 GtC (a trillion tonnes of carbon). Larger caps, $Q = 1500$ GtC and $Q = 2000$ GtC, would keep peak warming below about 2.6 and 3.2°C, respectively, likewise with a 50 percent probability of success.

The capped quota Q is the total cumulative CO_2 emission since the start of the Industrial Revolution (around 1750) to the far future. Hence, CO_2 emissions – like fossil fuels themselves – are a non-renewable resource.

A temperature rise of 2°C is often identified as the point at which the risk of "dangerous" climate change becomes significant (a concept necessarily involving a value judgement). Therefore, $Q = 1000$ GtC is the cap on CO_2 emissions required to give a 50 percent probability of avoiding "dangerous" climate change.

The 50 percent probability caveat is very important because there are great uncertainties in the prediction of future climate change in response to a given greenhouse gas emission trajectory. These arise from the difficulty in quantifying the reinforcing feedbacks in the Earth system associated (for example) with decreasing snow and ice cover, release of additional greenhouse gases from natural pools which are vulnerable under climate change (such as the carbon presently locked in permafrost), and a decrease in the fraction of CO_2 taken up by land and ocean carbon sinks. These sinks now absorb over 50 percent of all CO_2 emitted by human activities, but will absorb less in future if emissions continue to grow rapidly.

The uncertainties imply that if we want a higher probability of staying below a nominated peak



Past and future cumulative carbon emissions (area under curves) including emissions trajectories based on setting cumulative human emissions quotas of between 1000 and 3000 tons of carbon for combined emissions from fossil fuels and land use change.

warming, then the cap *Q* must be lower. For example, to stay below 2°C peak warming with 70 percent rather than 50 percent probability, *Q* must be 800 GtC rather than 1000 GtC.

Avoiding catastrophe

Cumulative CO_2 emissions to date are about 520 GtC (320 from fossil fuels and 200 from land-use change). So, we've used up more than half of the 1000 GtC allowance. The halfway mark (a cumulative emission of 500 GtC) was passed around 2006. In this sense, the world has just passed "peak CO_2" if it is to avoid dangerous climate change. The halfway point in use of the global CO_2 emission quota *Q* also corresponds approximately with the point at which emissions must peak and thereafter decline, as in the red curve in the figure.

There is an important difference between peak CO_2 and peak oil. Non-renewable natural resources such as oil and coal will run out, imposing a hard constraint on their use, whereas the cap *Q* associated with peak CO_2 is the result of a value judgement by humankind about the degree of climate protection that it wishes to give to the global climate commons. If this value judgment is made differently – by changing either the maximum warming to be allowed or the risk level that is tolerated – then a different cap *Q* will result, as in the example trajectories in the figure. Unlike the limit on the use of a finite resource, which is inexorable, the cap *Q* must be decided with a long lead time because technical, institutional and cultural inertias prevent emissions trajectories from changing rapidly.

From the time that our distant forebears discovered fire until a few decades ago, the finiteness of our planet was not a consideration. Astonishingly quickly, we are now confronted by finite-Earth vulnerabilities arising from both the inputs to and the outputs from human activities. Of the two, the output vulnerability is the more acute. We have reached peak CO_2 – a cumulative emission of 500 GtC – before reaching peak oil, and long before exhausting half of the total fossil-fuel reserve of 2500 GtC or more. To allow the input limit to determine future fossil-fuel consumption is to invite climate catastrophe. ■

The 50 percent probability caveat is important because there are great uncertainties in predicting future climate change.

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*Anthropocene: a term first coined by Nobel laureate Paul Crutzen. Crutzen first used the term in print in IGBP's newsletter (No. 41, 2000).