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When and how did the Anthropocene begin?

Frank Oldfield

In March of this year, *Nature* published a stimulating article by Simon Lewis and Mark Maslin entitled 'Defining the Anthropocene' (Lewis and Maslin, 2015). In it, they proposed criteria for determining the formal onset of the Anthropocene Epoch and from these, derived new starting dates. They proposed two alternatives, AD 1610 and AD 1964. The former date lies some two centuries before the date proposed by Crutzen and Stoermer (2000) in their paper introducing and providing both a definition and a starting point for the Anthropocene. The latter date is over a decade later than an alternative and increasingly discussed onset date arising from Steffen et al.'s paper (2007) identifying a 'Great Acceleration' in detectable human impact on the Earth System beginning in the mid 20th century. These new proposals have provoked a great deal of interest and debate. In this issue of *The Anthropocene Review*, we have tried to provide a timely account of this debate. The first four papers comprise contrasted 'comments' on the *Nature* article, followed by 'replies' from its authors. The issues raised are far from forming a sterile debate on starting dates. They are full of, and indeed go well beyond, the engaging scientific basis upon which the contrasted points of view rest. For this reason, I have taken the decision to regard them as 'comments' and 'replies' despite their length. As well as making it possible to view them as a linked set in the present volume of the *Review*, it has also allowed their appearance online before the provocative impact of the original *Nature* paper fades. I hope readers will enjoy the debate and find the ideas put forward and issues raised every bit as stimulating as I have as Editor.

References

Crutzen PJ and Stoermer EF (2000) The Anthropocene. *IGBP Global Change Newsletter* 41: 17–18.
Lewis SL and Maslin MA (2015) Defining the Anthropocene. *Nature* 519: 171–180.
Steffen W, Crutzen PJ and McNeill JR (2007) The Anthropocene: Are humans now overwhelming the great forces of nature? *Ambio* 36: 614–621.

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Perspectives and controversies

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Getting the Anthropocene so wrong

Clive Hamilton

Abstract

Rather than clarifying it, a recent paper by Simon Lewis and Mark Maslin (2015), 'Defining the Anthropocene', adds to the confusion about the new epoch. The paper does not recognise that a paradigm shift has occurred, one in which environmental science has been displaced by Earth System science. The story tells of an Anthropocene beginning in 1610. It is not credible, as it is not based on an accurate understanding of the Earth System. In addition, in its determination to find a 'golden spike' the paper confuses stratigraphic markers for the epoch itself. It finds a marker when there is no event and ignores an event when it cannot find a marker.

Keywords

Anthropocene, Earth System science, new paradigm

'Defining the Anthropocene', written by Simon Lewis and Mark Maslin (2015) and recently published in *Nature*, does nothing to advance the definition of the new epoch. Each of the paper's misinterpretations can be reduced to two essential mistakes.

The first is soon apparent: Lewis and Maslin's text fails to recognise that a paradigm shift has occurred, one in which ecology or environmental science has been displaced by Earth System science. Ecology is the science of the relationship between organisms and their local environments, whereas Earth System science is the science of the whole Earth as a complex system beyond the sum of its parts. The gulf between the two remains, even if the local environments of ecological thinking are aggregated up to the 'global environment'. The global environment is not the Earth System.

In the paper the object in question is variously described as 'the environment', 'the Earth', 'geology' (as in 'human geology') and 'the Earth system'. When considering the Anthropocene only the last is correct, yet it is used in the paper as if it were synonymous with 'the environment',

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which itself takes on various forms, from 'vegetation' to 'biogeochemical cycles'. So when Lewis and Maslin begin their paper by reviewing 'human geology', summarizing 'geologically important human-induced environmental impacts', we suspect instantly that they are on the wrong track.

The Earth System is not the environment

Let me spell this out because it is the fundamental point that most commentators on the Anthropocene, including Lewis and Maslin, have not grasped. The Anthropocene concerns human impacts on the Earth System, not on the environment, and one cannot understand the emergence of the concept of the Anthropocene without an understanding of the radically new conception of the Earth System that emerged with Earth System science in the 1980s and 1990s.[1] This is explained in a recent paper by Jacques Grinevald and myself (Hamilton and Grinevald, 2015). In their recent textbook, Charles Langmuir and Wally Broecker provide a concise definition of the Earth System.

> The various parts of the Earth system – rock, water, atmosphere – are all involved in interrelated cycles where matter is continually in motion and is used and reused in the various planetary processes. Without interlocked cycles and recycling, Earth could not function as a system. … In the last fifty years or so we have come to recognize the movements in all Earth's layers, including the plates at the surface, the mantle and the core as well as the atmosphere and ocean. (Langmuir and Broecker, 2012: 20, 22)

It is worth rereading this definition carefully. The Earth System is not 'the landscape', it is not 'ecosystems', and it is not 'the environment'.

When we read the seminal works of the early advocates of the Anthropocene as a new geological epoch it is plain that they are all steeped in Earth System science. They always speak of the Earth as a total system, and humans as a 'force of nature' like the other great forces of nature that determine the evolution of the Earth System. They speak of humans as a force of nature because we have changed the *functioning* of the Earth System.

It is significant that, in the year 2000, Paul Crutzen first blurted out the word 'Anthropocene' at a meeting of the International Geosphere-Biosphere Programme (IGBP), the institutional heart of Earth System science, of which he was Vice-Chair (Steffen, 2013: 486).[2] Crutzen linked his advocacy of the Anthropocene explicitly to human-induced climate change, and he nominated the end of the 18th century as its starting point because, and only because, ice core data show 'the beginning of growing global concentrations of carbon dioxide and methane' (Crutzen, 2002).[3]

Before others began to appropriate and distort its meaning, the standard-bearers of the Anthropocene – mainly Paul Crutzen, Will Steffen, John McNeill and Jan Zalasiewicz –repeatedly reminded us that the Anthropocene concept holds water only if it can be shown that humans have had a detectable impact on the functioning of the Earth System. Yet this seems to have passed by most published authors, including Lewis and Maslin, who persistently write the new concept into the old concepts of environmental science.

It is necessary to belabour the point: the fundamental test of the Anthropocene is whether human activity *affects the Earth's global functioning*, does so *discernibly* and *is outside the range of natural variability* (Steffen et al., 2007). It is on this basis, and this basis alone, that Steffen, Crutzen and McNeill have reassessed the evidence to conclude that the beginning of the new epoch is better set at the beginning of the Great Acceleration.

> Only beyond the mid-20th century is there clear evidence for fundamental shifts in the state and functioning of the Earth System that are beyond the range of the Holocene and driven by human activities. (Steffen et al., 2015)

Nothing happened to the Earth System in 1610

It is a clear statement whose words are judiciously chosen. Yet many scientists who have leapt into the Anthropocene debate fail to grasp its simple but fundamental lesson. As a result, Lewis and Maslin develop a story that is a patchwork of dubious claims leading to the conclusion that the new epoch ought to be dated from 1610.

Although the paper's storyline was striking enough to generate extensive media coverage, the 1610 Anthropocene starting date is an arbitrary one without scientific basis. So how did they come up with it? The authors noticed a small (7–10 ppm) dip in the global concentration of CO_2 then wove around it a complex story about colonization of South America, depopulation, forest regrowth, trade, species exchange and pollen counts. It is an explanation that does not meet the criteria of correlation let alone causation. No attempt is made to show numerically that the dip changed the functioning of the Earth System or was caused by human activity, other than the mention of some historical events that occurred at roughly the same time.

The dip was, in all likelihood, the result of natural variability[4] and the fact that it ended after a few decades is not explained in the paper. The argument for 1610 is no more than speculation built on speculation. When other scientists and historians begin to examine more closely the historical correspondences and the scales of the various claims about colonization, population decline, the spread of crop varieties from Europe to South America and back the other way, pollen in marine sediments, rates of forest regeneration, atmospheric CO_2 and the course of the 'Little Ice Age', the Lewis–Maslin story will surely fall apart.

Yet the authors believe that this small, temporary and unexplained dip in atmospheric CO_2, which was not enough to change the functioning of the Earth System and was probably not due to human activity, should trump the 120 ppm increase in CO_2 emissions since the Industrial Revolution, an increase that is very large, is definitely caused by human activity and is virtually certain to be the cause of rapid global warming that will last for many centuries.

In order to defend it Lewis and Maslin must engage in some intellectual gymnastics to dismiss the other main contenders for the start date. There are only two that are robust, the onset of the Industrial Revolution[5] and the beginning of the Great Acceleration. They reject the Industrial Revolution by arguing that 'humans have long been engaging in industrial-type production'. This is a gross distortion of the argument. The point about nominating the Industrial Revolution is not that there was more industry but that it marked the beginning of the burning of coal on an industrial scale, which had a discernible effect on the functioning of the Earth System. As I will show, this is another example of Lewis and Maslin's persistent confusion of an event in Earth history with a historical marker for it.

After pointing out that the Industrial Revolution did not happen everywhere at once they go on to claim that the rise in CO_2 concentrations was slow in the 19th century and the absence of an abrupt change rules out the Industrial Revolution as a Global Stratotype Section and Point (GSSP) marker. Well, yes, and this is the reason that Earth System scientists are now inclined to nominate the beginning of the Great Acceleration as a more decisive and unambiguous start date (Zalasiewicz et al., 2014). To compound the confusion Lewis and Maslin later claim that one advantage of their 1610 date is that the colonization of South America made possible industrialization in Britain 150 years later! Many events made industrialization possible, including the Enclosure Laws, the rise of the British merchant class and the invention of the Spinning Jenny, so to pick out colonization of South America is mere fancy. To repeat, what matters in locating the beginning of the Anthropocene is the time at which human activity changed the functioning of the Earth System.

The golden spike fetish

For consistency we would expect the unambiguously rapid increase in CO_2 emissions from the end of the Second World War to persuade Lewis and Maslin to accept, say, 1945 as a suitable start date. But to dismiss this contender they go down a different track, one that causes them to reject 1945 and pick out the date of 1964. To understand what they are doing I need to comment on their second big mistake, their misplaced preoccupation with the GSSP or the golden spike.

The fixation arises not, as before, because Lewis and Maslin confuse Earth System science with environmental science but because they confuse Earth System science with traditional geology or, more precisely, with stratigraphy. They write: 'Defining the beginning of the Anthropocene as a formal geological unit of time requires the location of a global marker of an event in stratigraphic material, such as rock, sediment, or glacier ice, known as a Global Stratotype Section and Point (GSSP) …'. Typically, the marker is the global emergence of new species uncovered as fossils in rock strata. Lewis and Maslin ignore the new species requirement but cling to the idea that we must have a global marker in rock strata; for them, no GSSP means no new epoch.

Dropping the new species test is an obvious move (and not just to Lewis and Maslin) as there are no new species appearing with the arrival of the Anthropocene, although plenty are disappearing. This ought to signal that identification of the new geological epoch can be like no previous one and the conventions will have to change (something the Anthropocene Working Group is wrestling with). From the viewpoint of traditional geology, the Anthropocene markers have to be imagined or 'backcast' by projecting oneself forward a million years or so. Lewis and Maslin, however, are not happy with a GSSP that *will be* apparent; they must be able to find one now.

Short of stratigraphers turning their traditions upside down, the Anthropocene Working Group (AWG) will also have to provide a clear, datable marker for the new epoch if it is to persuade the International Commission on Stratigraphy to accept the proposed addition to the Geological Time Scale. Jan Zalasiewicz and others (including several members of the AWG) have recently published a paper nominating 1945 as the Anthropocene's starting date because 'it was from the mid-20th century that the worldwide impact of the accelerating Industrial Revolution became both global and near-synchronous' (Zalasiewicz et al., 2014). They argue that this is an appropriate year because the first nuclear bomb tests at Alamogordo, New Mexico were staged then and the effects will show up in the rock strata as a layer of radionuclides.

However, Zalasiewicz and his co-authors understand that *the marker is not the epoch*; it is just a marker. The Anthropocene is defined not by nuclear blasts but by a human-induced change in the functioning of the Earth System, one mainly due to climate change from the burning of fossil fuels. The nuclear explosions did not in any way change the functioning of the Earth System; the layer of radionuclides that geologists in a million years will detect are merely a signifier, and have nothing directly to do with the Anthropocene. They do, however, have a great deal to do with it indirectly, because they signalled unambiguously the dawn of the era of global economic domination by the United States of America, which was intimately tied to the economic boom of the post-war years and so the rapid increased in greenhouse gas emissions and associated warming.

Lewis and Maslin, however, are fixated on the marker at the expense of what is marked. And so they play around with data on nuclear isotopes and pick out 1964 as the beginning of the Anthropocene – it was, apparently, the year in which ^{14}C shows up as a maximum in some tree ring data[6] – completely forgetting what this 'golden spike' is supposed to signify, a change in the functioning of the Earth System due to human activity. In fact, that change is *detectable* 20 years (if not 120 years) before their arbitrary selection. The 1964 peak in ^{14}C may 'provide an unambiguous global change in a number of stratigraphic deposits', but it has absolutely nothing to do with the Anthropocene. The marker is not the epoch. It makes no sense to replace 1945 with 1964 as the start date of the Anthropocene when 1964 cannot be linked in any way to any point of inflection in the functioning of the Earth System, human-induced or otherwise.

It is worth noting here that to support their claim of a 1610 start date Lewis and Maslin write that the transoceanic movement of species is ‘an unambiguously permanent change to the Earth system’. In support they cite a paper by Zalasiewicz et al. (2011). Zalasiewicz et al. do not suggest that species movement at that time changed the Earth System. The paper simply lists biostratigraphy as one of the kinds of evidence used to determine transitions in the Geological Time Scale. The referencing of Zalasiewicz et al. is used by Lewis and Maslin to defend their choice of a 1610 start date ‘because the transoceanic movement of species is a clear and permanent geological change to the Earth system’, a crucial claim for which they adduce no evidence. Yet it nicely encapsulates the dual misconceptions that underpin their paper – a lack of understanding of what the Earth System is, and the ‘spike fetish’ that causes them to find a marker when there is no event and to ignore an event when they cannot find a marker.

A paradigm shift

All of this raises the question of why *Nature* would publish the Lewis-Maslin paper. The short, and rough, answer is that the Earth sciences are undergoing a paradigm shift, from environmental science to Earth System science. Historically, this kind of shift is rare and takes a long time to take hold because it requires communities of scientists to change radically the way they think about the world. Against sustained resistance, it took some 40 years before the theory of plate tectonics became accepted (Oreskes, 1999). The problem is that those who have not made the shift do not accept that a shift is needed either because the evidence contradicts their firmly held theory or principles (as in the ‘Wegener revolution’) or because they absorb the new paradigm into the existing one, reinterpreting it so that it seems to fit into familiar concepts (as in this case). The elision of the Earth System and the environment is the first sign of this failure to understand. Attempting to shoehorn the Anthropocene into changes in the landscape or ecosystems is the second.

By applying a different, and outdated, paradigm, various geographers, archaeologists and ecologists have ‘falsified’ the claims about the Anthropocene put forward by the Earth System scientists (Hamilton, 2014). For their part, the Earth System scientists have not argued that the old paradigm is ‘wrong’, only limited and now superseded, because it cannot properly understand and explain how the Earth is changing. The problem is that the ‘war’ between the old paradigm and the new one has not yet been declared, because only a handful of scientists have become aware that there is one underway, a hidden battle now unwittingly being fought through the journals.

In mitigation of Lewis and Maslin’s paper and the editors of *Nature*, the idea that human beings could be responsible for changing the trajectory of the Earth System presents a profound challenge to the conventions of the Geological Time Scale, a challenge that everyone is trying to come to grips with, some more consciously than others. The truth is that traditional stratigraphy is unsuited to making a judgement about the Anthropocene. Finding new species (or other signs) in rock strata is not the same as identifying a change in the functioning of the Earth System. (A retrospective examination of the correspondence between the transitions from one interval to the next in the Geological Time Scale and episodic changes in the functioning of the Earth System is an important study yet to be done.[7]) Moreover, while geologists will find markers of the Anthropocene in the rock strata in a million years’ time, they cannot do so now. A range of above-ground indicators is needed and that is why the membership of the AWG includes not only geologists and palaeontologists but, among others, an atmospheric chemist, a climate modeller, an Earth System modeller and a forest ecologist. It was bold of the International Commission on Stratigraphy to create the

Anthropocene Working Group. The question now is whether it can accept the consequences of its decision to appoint such an eclectic mix of expertise.

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Notes

1. I agree with Will Steffen that both words in ‘Earth System’ should be capitalized. The Earth System is a unique entity, like the Sun, and deserves a proper noun.
2. The role of the IGBP in the development of the Anthropocene concept is discussed by Hamilton and Grinevald (2015).
3. It is true that Crutzen opens himself up to misinterpretation by referring to ‘the effects of humans on the global environment’.
4. This is the argument made by Waters et al. (2015) in a brief response to Lewis and Maslin by Earth System scientists.
5. By which I mean the first period of industrial transformation in Britain in which coal became the dominant source of energy gradually in the 19th century.
6. A fact already noted by Zalasiewicz et al. (2014).
7. A point made by Jan Zalasiewicz in an email to the author.

References

Crutzen PJ (2002) Geology of mankind. *Nature* 413: 23.

Hamilton C (2014) Ecologists butt out: You are not entitled to redefine the Anthropocene. *The Anthropocene Review*. Available at: http://anthropocene55.rssing.com/browser.php?indx=33080809&item=13.

Hamilton C and Grinevald J (2015) Was the Anthropocene anticipated? *The Anthropocene Review* 2(1): 59–72.

Langmuir C and Broecker W (2012) *How to Build a Habitable Planet*. Revised and expanded edition. Princeton, NJ: Princeton University Press.

Lewis S and Maslin M (2015) Defining the Anthropocene. *Nature* 519: 171–180.

Oreskes N (1999) *The Rejection of Continental Drift: Theory and Method in American Earth Science*. Oxford: Oxford University Press.

Steffen W (2013) Commentary on Crutzen and Stoermer. In: Robin L, Sörlin S and Warde P (eds) *The Future of Nature*. New Haven, CT: Yale University Press.

Steffen W, Crutzen P and McNeill J (2007) The Anthropocene: Are humans now overwhelming the great forces of nature? *Ambio* 36(8): 614–621.

Steffen W, Broadgate W, Deutsch L et al. (2015) The trajectory of the Anthropocene: The Great Acceleration. *The Anthropocene Review* 2(1): 81–98.

Waters C, Zalasiewicz J, Barnosky AD et al. (2015) Colonization of the Americas, Little Ice Age climate, and bomb-produced carbon: Their role in defining the Anthropocene. *The Anthropocene Review*, forthcoming. DOI: 10.1177/2053019615587056.

Zalasiewicz J, Williams M, Fortey R et al. (2011) Stratigraphy of the Anthropocene. *Philosophical Transactions of the Royal Society A* 369: 1036–1055.

Zalasiewicz J, Waters CN, Williams M et al. (2014) When did the Anthropocene begin? A mid-twentieth century boundary level is stratigraphically optimal. *Quaternary International*. Available at: http://dx.doi.org/10.1016/j.quaint.2014.11.045.

Perspectives and controversies

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Anthropocene: Earth System, geological, philosophical and political paradigm shifts

Mark A Maslin[1] and Simon L Lewis[1,2]

Abstract

The concept of the Anthropocene has created a profound paradigm shift within the scientific community that may well create equally important changes in philosophy and politics. There is general scientific agreement that human activity has been a geologically recent, yet profound, influence on the Earth System. The magnitude, variety and longevity of human-induced changes, to the lithosphere, hydrosphere, cryosphere, biosphere and atmosphere, suggests that we should refer to the present, not as within the Holocene Epoch (as it is currently formally referred to), but instead as within the Anthropocene Epoch. Hamilton (2015) argues that many commentators fail to acknowledge this paradigm shift and suggests the discussion of when the Anthropocene Epoch started is a distraction and irrelevant. Earth System scientists, such as ourselves, would argue that the evidence for the Anthropocene is already accepted and that the paradigm shift has already occurred. The current discussion has moved forward and is now centred on defining the start of the epoch using the fundamental principles of stratigraphy. We explain how geological time is divided up and the fundamental role of Global Stratotype Section and Points (GSSPs). We go beyond Hamilton's (2015) limited discussion and argue that the Anthropocene is creating paradigm shifts beyond the natural sciences. We also argue that there are multiple definitions of the Anthropocene and even if a formal definition of the Anthropocene Epoch is agreed by geoscientists, this would in no way invalidate other definitions or uses. It is the utility and wide appeal that makes the Anthropocene such an important concept.

Keywords

Anthropocene, Earth System, global environmental change, golden spikes, GSSP, paradigm shift

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Introduction

The Anthropocene as an idea is extremely powerful and therefore provokes powerful emotions. An example of this is Hamilton (2015) who argues that many scientists, including ourselves, have failed to recognise the Anthropocene as a fundamental shift in an underlying scientific paradigm. At the heart of his argument is that the 'global environment' is not the same as the 'Earth System', though many scientists use them interchangeably (Lewis and Maslin, 2015a). However, we hoped that we had been clear about this, given that the opening line of Lewis and Maslin (2015a) stated 'Time is divided by geologists according to marked shifts in Earth's state'. To move between the Earth in one state to another requires a change to the Earth System. Geologists have long considered the Earth as an integrated system as they have uncovered the major events in Earth's 4.6 billion year history, which form the basis of the Geologic Time Scale within which the Anthropocene may, or may not, be included in the future. Moreover Hamilton's (2015) definition of the 'Earth System' leaves much to be desired. The quote he uses from Langmuir and Broecker (2012) contains no mention of biology. But Earth scientists and Earth System scientists all agree that the biosphere has a huge influence on the Earth System; ranging from the speed of tectonic plate movements to chemical composition of the atmosphere, from the rate of mountain erosion to the intensity of the hydrological cycle. Indeed, life is what separates Earth and its functioning from other planets. Hamilton (2015) also asserts that human activity has changed the functioning of the Earth System. True, but it should also be noted that the fundamental processes governing the Earth System are the same now as in the past. The only difference is that human activity is a major force influencing the trajectory of the Earth System instead of all the usual non-human forces of nature.

Hamilton (2015) falls into two traps. The first one is the trap of *Anthropocentrism*, as he sees the Anthropocene as geologically different because it involves humans. He invokes the image that humans have taken the Earth's global functioning outside of natural variations. This is, however, simply a matter of timescale. For example, the natural Earth System without humans has been a lot warmer and colder than the present day (Maslin, 2013). Greenhouse gas concentration in the atmosphere has been a lot higher in the geological past than today, and there have been five mass extinctions that likely exceeded the present extinction rate. The second trap that Hamilton (2015) falls into is misunderstanding the difference between the evidence that we are in the Anthropocene and the formal definition of when this epoch may have started. The former, as we suggested at the beginning of Lewis and Maslin (2015a), and argue below, has been accepted and that is why most of the discussion is now related to defining the start of the new epoch, now that it is collectively acknowledged we are in the Anthropocene. In this paper we present our evidence that the Anthropocene is indeed a new geological epoch if we stick to the usual geological rules. We show that the paradigm shift has already occurred in science and we go beyond Hamilton (2015) and argue that it is a major conceptual jump in philosophy, history and geopolitics (e.g. Castree, 2014; Chakrabarty, 2009, 2015a, 2015b; Clark, 2012; Dalby, 2007; Harari, 2014; Johnson and Morehouse, 2013; Latour, 2015; Vidas, 2014; Yusoff, 2013). We also discuss that there should be multiple definitions of the Anthropocene and the formal geological definition of the Anthropocene Epoch should just be one of them.

Scientific paradigm shift

We disagree with Hamilton (2015) that there is a general ongoing Earth System science paradigm shift occurring. It has already happened. In 2001 the Amsterdam Declaration on Earth System Science stated, 'The Earth system behaves as a single, self-regulating system comprised of physical, chemical, biological and human components'. This was signed by four different research programmes – the International Geosphere-Biosphere Programme (IGBP), the International Human Dimensions Programme on Global Environmental Change (IHDP), the World Climate Research Programme (WCRP) and the international biodiversity programme DIVERSITAS. Specifically on the Anthropocene, Lewis and Maslin (2015a) summarised the scientific evidence showing that the Earth System has been fundamentally altered by humans. But it is worth repeating this evidence again, as Hamilton (2015) argues that we and other commentators have distorted this view. If we start with the atmosphere there is clear evidence that human actions have released 555 petagrams of carbon (where 1 Pg = 10^{15} g = 1 billion metric tonnes) to the atmosphere since 1750, increasing atmospheric CO_2 to a level not seen for at least 800,000 years, and possibly several million years (IPCC, 2013), thereby delaying Earth's next glaciation event (Tzedakis et al., 2012). The released carbon dioxide has also increased ocean water acidity at a rate probably not exceeded in the last 300 million years (IPCC, 2013). Despite the focus on greenhouse gases because of concerns about climate change, humans have also profoundly affected other parts of the Earth System, for example the nitrogen cycle. The early-20th-century invention of the Haber–Bosch process, which allows the conversion of atmospheric nitrogen to ammonia for use as fertiliser, has altered the global nitrogen cycle so fundamentally that the nearest suggested geological comparison refers to events about 2.5 billion years ago (Canfield et al., 2010).

There is clear evidence that humanity is changing Earth's climate through anthropogenic greenhouse gas emissions (IPCC, 2013). These changes include a 0.85°C increase in average global temperatures and sea-level rise of over 20 cm over the last 100 years. There is also evidence for significant shifts in the seasonality and intensities of precipitation, changing weather patterns, and the significant retreat of Arctic sea ice and nearly all continental glaciers. It is estimated that Greenland is losing over 200 gigatonnes of ice per year, a six-fold increase since the early 1990s (IPCC, 2013), while Antarctica is losing about 150 gigatonnes of ice per year, a five-fold increase since the early 1990s and most of this loss is from the northern Antarctic Peninsula and the Amundsen Sea sector of West Antarctica (IPCC, 2013).

Human action also affects non-human life. Over recent decades, global net primary productivity appears to be relatively constant (Running, 2012); however, the appropriation of 25%–38% of net primary productivity for human use (Krausmann et al., 2013; Running, 2012) reduces the amount available for millions of other species on Earth. This land-use conversion to produce food, fuel, fibre and fodder, combined with targeted hunting and harvesting, has resulted in species extinctions some 100 to 1000 times higher than background rates (Barnosky et al., 2011), and probably constitutes the beginning of the sixth mass extinction in Earth's history (Barnosky et al., 2011). Species removals are non-random, with disproportionate removal of animals with larger body size from both the land and the oceans. Organisms have been transported around the world, including crops, domesticated animals and pathogens on land. Similarly, boats have transferred organisms among once-disconnected oceans. Such movement has led to a small number of extraordinarily common species, new hybrid species (Thomas, 2013), and a global homogenisation of Earth's biota. Ostensibly, this change is unique since Pangaea separated about 200 million years ago (Baiser et al., 2012), but Lewis and Maslin (2015a) argue that such trans-oceanic exchanges probably have no geological analogue.

Furthermore, human actions may well constitute Earth's most important evolutionary pressure (Darimont et al., 2009; Palumbi, 2001). The development of diverse products, including antibiotics, pesticides and novel genetically engineered organisms, alongside the movement of species to new habitats, intense harvesting and the selective pressure of higher air temperatures resulting from greenhouse gas emissions, are all likely to alter evolutionary outcomes (Darimont et al., 2009; Palumbi, 2001; Stuart et al., 2014; Tabashnik et al., 2014). Considered collectively, there is no geological analogue (Lewis and Maslin, 2015a; Palumbi, 2001). Furthermore, given that the average species occurrence is 1–10 million years, the rates of anthropogenic environmental change in the near future may exceed the rates of change encountered by many species in their evolutionary history. Human activity has clearly altered the lithosphere, hydrosphere, cryosphere, atmosphere and biosphere, and thus the Earth as an integrated system, including its future trajectory.

Kuhn (1962) defines a paradigm shift as a change in the basic assumptions within the ruling theory of science. We would contend that within the field of Earth System science the Earth's functioning as an integrated system is entirely uncontroversial, and the evidence for humans being a major geological power has been accepted and the paradigm shift has occurred (Lewis and Maslin, 2015a; Steffen et al., 2015; Zalasiewicz et al., 2011, 2015). That human activity has altered Earth fundamentally is rarely questioned within scientific publications. What is now being discussed is exactly how to formally define the Anthropocene Epoch so this paradigm shift can be ratified as part of the Geologic Time Scale, and more easily discussed and debated within and beyond the scientific community. In many ways the theory of plate tectonics example (Oreskes, 1999) presented by Hamilton (2015) is a false one, as we and many other Earth System scientists would argue that the basic science relating to the Anthropocene is already accepted after only a few years on from Crutzen and Stoermer's (2000) recent highlighting of the concept.

Philosophical paradigm shift

The paradigm shift in science to recognise that humanity is a power of geology is profound and influences fields beyond Earth System science. But we should be clear that this shift in the scientific paradigm, through complex social processes, is *a better*, not just different understanding of the world. This is because a common misinterpretation of paradigms is the belief that the discovery of paradigm shifts and the dynamic nature of science is a case for relativism, i.e. that science only has subjective value according to differences in perception, consideration or beliefs. Kuhn (1962, 1977) vehemently denied this as rational assessment of the weight of scientific evidence means the new paradigm, if evidence-based, is always superior to the previous theory. However, to be able to discuss and translate the new scientific concept of the Anthropocene it needs to be defined. All previous periods of geological time have been defined through the process outlined in the *Geologic Time Scale* (Gradstein et al., 2012; also see Smith et al., 2014) and hence the same scientific process is being followed for the Anthropocene. Thus, the comment that it is 'bold' that the International Commission on Stratigraphy set up a working group on the Anthropocene is incorrect. It is normal practice. Some commentators such as Ruddiman et al. (2015) wish to keep the term Anthropocene vague and undefined. This is partly because they are concerned that a formal definition of the Anthropocene would not include the early effects of human agriculture on both the landscape and atmospheric greenhouse gases. However, we see these and even earlier influences can be easily acknowledged as described as the 'palaeoanthropocene' (Foley et al., 2013). Others such as Hamilton (2015) and Zalasiewicz et al. (2015) are convinced that the Anthropocene must be formally defined as 1945 or 1950 to coincide with the early part of the Great Acceleration (Steffen et al., 2015). However, these studies neglect the fact that epochs typically last millions of years, and many of the changes they describe may be ephemeral changes to the Earth System. The need for clear long-term irreversible changes in the Earth System is also the reason why the discussion is only about defining the Anthropocene as an epoch and not a period on the same level as the Quaternary, as we do not currently know whether human impacts will stop the glacial–interglacial cycles which define the current Quaternary Period.

We argue that acknowledging and defining the Anthropocene would be a major shift in the way that we see the world, but the tools for deciding the definition will be the usual ones. The key difference geologically between the Anthropocene and other epochs is the cause of the change in the state of the Earth System. Thus Hamilton's claim that the Anthropecene 'can be like no previous one and the conventions will have to change' is incorrect. However, in terms of the way we see the world the shift is profound because adopting the Anthropocene Epoch reverses 500 years of scientific discoveries, which have continually moved humans to ever-increasing insignificance. The Copernicus 16th century revolution put the Sun at the centre of the solar system, downgrading the Earth. Modern cosmology suggests our Sun is one of 10^{24} stars in the Universe, each one with the potential to have planets. Darwin's 19th-century discoveries and the development of evolutionary science established that humans are merely a twig on the tree of life with no special origin. In the 21st century, adopting the Anthropocene reverses this insignificance: humans are not passive observers of Earth. *Homo sapiens* are central because the future of the only place where life is known to exist is being determined by the actions of humans. In fact, we would argue that humanity has become a geological superpower.

Defining geological time

There are currently two different Anthropocenes, and two different debates. One debate concerns informal use of the Anthropocene concept to recognise the influence of humans on the global environment or the Earth System. The second debate focuses on the formal definition of the Anthropocene Epoch by geoscientists. Hamilton (2015) mixes and twists these two debates, which is not helpful. It is the second debate, which Hamilton (2015) rather patronisingly refers to as the 'golden spike fetish', which was the focus of Lewis and Maslin (2015a). We certainly agree with Hamilton (2015) that the 'marker is not the epoch'; the marker is just the boundary that fits with geological conventions. The epoch is the Anthropocene, a change in the state of the Earth driven by humans. This failure to understand the importance and role of such markers appears to be due to a lack of understanding of the detailed work that goes into defining and refining the understanding of geological time.

In practice, the formal definition of any geological stage is a long and bureaucratic process that has been followed for every single geological boundary definition (Smith et al., 2014). It is worth summarising how geological time is understood so that similar confusion does not arise in future discussion. Geological time is divided into a hierarchical series of ever-finer units, the finest being stages, with stages nested within epochs, and so on (Smith et al., 2014). The present, according to the *Geologic Time Scale* (Gradstein et al., 2012), is in the Holocene Epoch (Greek for 'entirely recent'; started 11,650 BP, where present is defined as 1950), within the Quaternary period (started 2.588 million years ago), within the Cenozoic era ('recent life'; started 66 million years ago) of the Phanerozoic eon ('revealed life'; started 541 million years ago). Divisions represent differences in the functioning of Earth as a system and the concomitant changes in the resident life-forms. Larger differences result in classifications at higher unit-levels.

Formally, geological time units are defined by their lower boundary, that is, their beginning. Boundaries are demarcated using a GSSP (Global Stratotype Section & Point), or by an agreed date, termed a GSSA. For a GSSP, a 'stratotype section' refers to a portion of material that develops over time (rock, sediment, glacier ice), and 'point' refers to the location of the marker within the stratotype. These 'golden spikes' are a single physical manifestation of a change recorded in a stratigraphic section, often reflecting a global-change phenomenon. These are then complemented by other stratigraphic records showing a global change to the Earth System (Smith et al., 2014). Thus for a long-term change to the Earth from one state to another a single boundary time is chosen at a specific point within that long-term change. The definition of each GSSP differs and combines these requirements depending upon the time period, sediment types that are available and the types of change occurring at that point within Earth's history. Importantly, markers themselves are not required to encompass the complete change in the Earth from one state to another, nor, as Hamilton (2015) incorrectly suggests, are they chosen relative to some parameter exceeding some prior bounds of variability. Critically, it has been decided that within the Phanerozoic (last 541 million years) GSSPs define the boundaries, with a major scientific effort to define these under way. Currently 65 of the likely 102 Phanerozoic GSSPs have been ratified by the International Commission on Stratigraphy (ICS) while several others await ratification or selection from competing candidate locations (Smith et al., 2014). We should note that there is no requirement, as Hamilton (2015) suggests, that new species are required to define an epoch. There is a strong move over the past decade or more to define boundaries with chemical markers, as these are less diachronous than biostratigraphic markers (Smith et al., 2014). The Holocene Epoch was formally ratified in the absence of new species (Walker et al., 2009).

It is also possible, following a survey of the stratigraphic evidence, that a GSSA date may be agreed by committee to mark a time unit boundary. GSSAs are common in the Precambrian (>630 million years ago) because well-defined geological markers and clear events are less obvious further back in time. Regardless of the marker type, formally ratifying a new Anthropocene Epoch into the GTS would first require a positive recommendation from the Anthropocene Working Group (AWG) of the Subcommission of Quaternary Stratigraphy. This would be followed by a supermajority vote of the International Commission on Stratigraphy (ICS), and finally ratification by the International Union of Geological Sciences (see Finney, 2014, for full details).

In Lewis and Maslin (2015b) we respond to the specific concerns of Hamilton (2015) about our two suggestions for possible boundaries to define the inception of the Anthropocene Epoch: the irreversible exchange of species following the collision of the Old and New Worlds, coupled with the decline in CO_2 at 1610 CE (Orbis spike), which marks Earth's last synchronous cool period before the long-term warmth of the Anthropocene; and the accelerated changes to the Earth System in the second half of the 20th century, conveniently marked by the 1964 peak in radionuclide fallout (Bomb spike).

There has been no decision about the formal definition of the Anthropocene Epoch as yet. Moreover, even if there were a formal definition of the Anthropocene Epoch this definition should in no way prevent authors from understanding the Anthropocene in other ways, as long as they define how they are using the informal term. Indeed geological convention allows both to be easily discussed; formal names have capitalised designation, informal terms do not. Anthropocene Epoch is a formal geological term, while Anthropocene epoch or just the Anthropocene can be used as the informal term.

Anthropocene confusion

Confusion has arisen over the Anthropocene because of the assumption that defining the Anthropocene Epoch is *the* definition of the Anthropocene. In fact it is just the definition of a geological stage by geologists who have a long scientific tradition and institutions to investigate the major events in Earth's history and define geological time. Any formal definition of the Anthropocene Epoch does not invalidate other definitions. Geoscientists would never claim to have the ability nor legitimacy to define the beginning of historic periods, the emergence of important changes to economic or political systems. It may well be that the specific date associated with the geological definition of the Anthropocene, following the usual GSSP criteria, does not make a major contribution to the understanding of history or political science or philosophy. But the fact that we are today in the Anthropocene may well be important to these fields. We would therefore argue it is incumbent on other subjects such as history, political science, geography, etc., to have their own definitions of the Anthropocene, if these are useful within these domains. Moreover if the term Anthropocene is not fit for purpose within the disciplines then other terms, such as Capitalocene or Anglocene (Bonneuil and Fressoz, 2013), should of course be used if they are helpful to our understanding of the human influence on the Earth System. Nevertheless, for the AWG, the final report to the ICS must be based on the fundamental principles of stratigraphy and be able to be defended scientifically against accusations of political bias or agenda. If the AWG does not follow these principles it would be unlikely that the ICS will ratify the Anthropocene Epoch and the discussion and debate will continue. We would suggest that Hamilton (2015) and many other commentators must separate the argument for defining the Anthropocene Epoch from both the general agreement that humans are rapidly changing the Earth as an integrated system, and the more fluid and broader use of the Anthropocene concept.

Conclusion

The discussion of the Anthropocene concept both as an informal and a formal definition has changed the way we think about the relationship between humans and the Earth System. No longer are humans easily considered 'other' or 'outside nature' but rather now can be seen as one of the most powerful driving forces of change 'within' and 'part of' the Earth System. It is clear that scientists have already accepted the Anthropocene (Lewis and Maslin, 2015a; Rose, 2015; Steffen et al., 2015; Zalasiewicz et al., 2015), so Hamilton's (2015) claims that we, and others, are ignoring the paradigm shift is simply wrong. The slow careful bureaucratic approach of geoscientists to defining distinct periods of time is one of the great advantages in the discussion of the Anthropocene. Because it conforms to Stengers' (2010) call for 'slow science', it allows for the full discussion of the currently available evidence, it can identify, as do Lewis and Maslin (2015a, 2015b), gaps in our knowledge that need to be addressed and it can consider evidence from a wide range of disciplines. The definition of any formally ratified Anthropocene Epoch will be based on the fundamental principles of stratigraphy and the selection of a GSSP (Smith et al., 2014). Hamilton (2015), unfortunately rather ignorantly dismisses this process as 'golden spike fetish', despite the fact that geologists have spent decades painstakingly undertaking careful work to define and refine stage boundaries within the Geological Time Series (Gradstein et al., 2012). The result is an increasingly clear history of the major events in Earth's history, itself a major scientific achievement. We do feel this work should not be so lightly dismissed.

We also stress that the definition of the Anthropocene Epoch should not be seen as the only useful definition of the Anthropocene. The Anthropocene is emerging as an extremely useful concept in other disciplines such as history, geography, anthropology, political science and philosophy. Therefore there must be room for the formally stratigraphically defined Anthropocene Epoch and the more fluid and broader use of the Anthropocene concept. Of course, in many ways it does not matter which definition of the Anthropocene Epoch is used, so long as it is clearly stated, because it is the debate and discussion within and beyond science about human impact of the Earth System, which is the true paradigm shift in our thinking.

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References

Baiser B, Olden JD, Record S et al. (2012) Pattern and process of biotic homogenization in the New Pangaea. *Proceedings of the Royal Society London, B* 279: 4772–4777.

Barnosky AD et al. (2011) Has the Earth's sixth mass extinction already arrived? *Nature* 471: 51–57.

Bonneuil C and Fressoz J-B (2013) *Fressoz L'événement anthropocène: La Terre*. l'histoire et nous. Paris: Seuil, 304 pp.

Canfield DE, Glazer AN and Falkowski PG (2010) The evolution and future of Earth's nitrogen cycle. *Science* 330: 192–196.

Castree N (2014) Geography and the Anthropocene 2: Current contributions. *Geography Compass* 8(7): 450–463.

Chakrabarty D (2009) The climate of history: Four theses. *Critical Inquiry* 35(Winter): 197–222.

Chakrabarty D (2015a) The Anthropocene and the convergence of histories. In: Hamilton C, Bonneuil C and Gemenne F (eds) *The Anthropocene and the Global Environmental Crisis: Rethinking Modernity in a New Epoch*. Abingdon: Routledge, 204 pp.

Chakrabarty D (2015b) 'Anthropocene'. In: Wenzel J and Szeman I (eds) *Fuelling Culture: Energy, History, Politics*. New York: Fordham University Press, forthcoming.

Clark N (2012) Everything but the Earth? *Progress in Human Geography* 36(5): 685–687.

Crutzen PJ and Stoermer EF (2000) The Anthropocene. *IGBP Newsletter* 41(17): 17–18.

Dalby S (2007) Anthropocene geopolitics: Globalisation, empire, environment and critique. *Geography Compass* 1(1): 103–118.

Darimont CT et al. (2009) Human predators outpace other agents of trait change in the wild. *Proceedings of the National Academy of Sciences USA* 106: 952–954.

Finney SC (2014) The 'Anthropocene' as a ratified unit in the ICS International Chronostratigraphic Chart: Fundamental issues that must be addressed by the Task Group. *Geological Society of London, Special Publication* 395: 23–28.

Foley SF et al. (2013) The Palaeoanthropocene: The beginnings of anthropogenic environmental change. *Anthropocene* 3: 83.

Gradstein FM, Ogg JG, Schmitz MD et al. (eds) (2012) *Geologic Time Scale*. Oxford: Elsevier, pp. 1175.

Hamilton C (2015) Getting the Anthropocene so wrong. *Anthropocene Review*. DOI: 10.1177/2053019615584974.

Harari YN (2014) *Sapiens: A Brief History of Humankind*. London: Harvill Secker, 443 pp.

Intergovernmental Panel on Climate Change (IPCC) (2013) *Climate Change 2013: The Physical Science Basis*. Working Group I Contribution to the IPCC Fifth Assessment Report. Available at: http://www.ipcc.ch/report/ar5/wg1/.

Johnson E and Morehouse H (2013) After the Anthropocene: Politics and geographic inquiry for a new epoch. *Progress in Human Geography* 38(3): 439–456.

Krausmann F et al. (2013) Global human appropriation of net primary production doubled in the 20th century. *Proceedings of the National Academy of Science USA* 110: 10,324–10,329.

Kuhn T (1962) *The Structure of Scientific Revolutions*. Chicago, IL: University of Chicago Press.

Kuhn T (1977) *The Essential Tension: Selected Studies in Scientific Tradition and Change*. Chicago, IL: University of Chicago Press.

Langmuir C and Broecker W (2012) *How to Build a Habitable Planet*. Revised and Expanded Edition. Princeton, NJ: Princeton University Press.

Latour B (2015) Telling friends from foes in the time of the Anthropocene. In: Hamilton C, Bonneuil C and Gemenne F (eds) *The Anthropocene and the Global Environmental Crisis: Rethinking Modernity in a New Epoch*. Abingdon: Routledge, 204 pp.

Lewis SL and Maslin MA (2015a) Defining the Anthropocene. *Nature* 519: 171–180.

Lewis SL and Maslin MA (2015b) A transparent framework for defining the Anthropocene. *Anthropocene Review*. DOI: 10.1177/2053019615588792.

Maslin M (2013) *Climate: A Very Short Introduction.*Oxford: Oxford University Press, 159 pp.

Oreskes N (1999) *The Rejection of Continental Drift: Theory and Method in American Earth Science*. Oxford: Oxford University Press.

Palumbi SR (2001) Humans as the world's greatest evolutionary force. *Science* 293: 1786–1790.

Rose NL (2015) Spheroidal carbonaceous fly ash particles provide a globally synchronous stratigraphic marker for the Anthropocene. *Environmental Science and Technology* DOI: 10.1021/acs.est.5b00543.

Ruddiman WF, Ellis EC, Kaplan JO et al. (2015) Defining the epoch we live in. *Science* 348: 38–39.

Running SW (2012) A measurable planetary boundary for the biosphere. *Science* 337: 1458–1459.

Smith AG et al. (2014) GSSPs, global stratigraphy and correlation In: Smith DG, Bailey RJ, Burgess PM et al. (eds) Strata and time: Probing the gaps in our understanding. *Geological Society, London, Special Publications* 404: 37–67. Available at: http://dx.doi.org/10.1144/SP404.8.

Steffen W et al. (2015) The trajectory of the Anthropocene: The Great Acceleration. *The Anthropocene Review* 2(1): 81–98.

Stengers I (2010) *Cosmopolitics I*. Minneapolis, MN: Minnesota University Press.

Stuart YE et al. (2014) Rapid evolution of a native species following invasion by a congener. *Science* 346: 463–466.

Tabashnik BE, Mota-Sanchez D, Whalon ME et al. (2014) Defining terms for proactive management of resistance to Bt crops and pesticides. *Journal of Economic Entomology* 107: 496–507.

Thomas CD (2013) The Anthropocene could raise biological diversity. *Nature* 502: 7.

Tzedakis PC, Channell JET, Hodell DA et al. (2012) Determining the natural length of the current interglacial. *Nature Geoscience* 5: 138–141.

Vidas D (2014) Sea-level rise and international law: At the convergence of two epochs. *Climate Law* 4: 70–84.

Walker M et al. (2009) Formal definition and dating of the GSSP (Global Stratotype Section and Point) for the base of the Holocene using the Greenland NGRIP ice core, and selected auxiliary records. *Journal of Quaternary Science* 24: 3–17.

Yusoff K (2013) Geologic life: Prehistory, climate, futures in the Anthropocene. *Environment and Planning D: Society and Space* 31: 779–795.

Zalasiewicz J et al. (2011) Stratigraphy of the Anthropocene. *Philosophical Transactions of the Royal Society A* 369: 1036–1055.

Zalasiewicz J et al. (2015) When did the Anthropocene begin? A mid-twentieth century boundary level is stratigraphically optimal. *Quaternary International* http://dx.doi.org/10.1016/j.quaint.2014.11.045.

Perspectives and controversies

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Colonization of the Americas, 'Little Ice Age' climate, and bomb-produced carbon: Their role in defining the Anthropocene

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Abstract

A recently published analysis by Lewis and Maslin (Lewis SL and Maslin MA (2015) Defining the Anthropocene. *Nature* 519: 171–180) has identified two new potential horizons for the Holocene−Anthropocene boundary: 1610 (associated with European colonization of the Americas), or 1964 (the peak of the excess radiocarbon signal arising from atom bomb tests). We

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discuss both of these novel suggestions, and consider that there is insufficient stratigraphic basis for the former, whereas placing the latter at the peak of the signal rather than at its inception does not follow normal stratigraphical practice. Wherever the boundary is eventually placed, it should be optimized to reflect stratigraphical evidence with the least possible ambiguity.

Keywords
Anthropocene, 'Little Ice Age', radiocarbon fallout, stratigraphy

Introduction

Since the initial proposal of the Anthropocene as a new interval of geological time (Crutzen, 2002; Crutzen and Stoermer, 2000), the term has become widely used, both within the natural sciences (e.g. Waters et al., 2014; Williams et al., 2011; and references therein) and those of the social sciences, humanities and arts (e.g. Chakrabarty, 2015; Latour, 2015; Vidas, 2010, 2011, 2014). It is also currently under analysis as a potential formal addition to the Geological Time Scale. A key question – one that needs to be established whether the Anthropocene is to be formalized or not – is when it may be said to have begun. If it is to be regarded as a geological (chronostratigraphic) time unit, it needs to have a defined beginning, be synchronous around the world, and be effectively traceable in geological strata using a range of evidence (fossil, chemical, physical) that expresses changes as clearly as other major boundaries in the stratigraphic record. Other possibilities exist, for instance Edgeworth et al. (2015) suggested an alternative interpretation of the Anthropocene as an archaeology-based time unit with a diachronous lower boundary.

The Anthropocene was initially suggested by Crutzen (2002) as beginning with the Industrial Revolution in the late 18th century, along with the initial rise of atmospheric CO_2 and CH_4 concentrations above the Holocene baseline, and James Watt's steam engine, patented in 1776. At this time, the global human population surpassed 1 billion (it is now over 7 billion). The first stratigraphic analysis associated with the term proposed a numerical age of 1800 or associated with the 1815 eruption of Mount Tambora (Zalasiewicz et al., 2008).

There has been a wide range of suggested 'Anthropocene' beginning dates, ranging from ideas of an 'early Anthropocene' linked to early human impacts on the globe associated with hunting and, particularly, the changes to landscape and, arguably, to CO_2 levels associated with the origin and spread of farming (e.g. Ruddiman, 2003, 2013; Ruddiman et al., 2015; Smith and Zeder, 2013), to a number of suggestions based on the large changes to the Earth System in the mid-20th century 'Great Acceleration' (Steffen et al., 2007, 2015; Syvitski and Kettner, 2011; Syvitski et al., 2005) and associated stratigraphic signals (Corlett, 2015; Rose, 2015; Waters et al., 2014 and references therein, 2015; Wolfe et al., 2013; Zalasiewicz et al., 2015).

A recently published Perspective in *Nature* (Lewis and Maslin, 2015) advanced two other dates, 1610 and 1964, to potentially begin the Anthropocene, with the first of these being favoured. Lewis and Maslin's second, 1964, proposal is chronologically close to, but conceptually distinct from, other mid-20th century proposals. Their wide-ranging study brings valuable insights to the issues involved with selecting an Anthropocene boundary, focuses attention on key historical intervals in Earth history, and brings new logic and ideas to the process of boundary selection. Here we consider the new boundary suggestions of Lewis and Maslin critically, in order to examine whether they show promise to effectively define the Anthropocene.

Events of the 16th and 17th centuries, and the 'Orbis' hypothesis

The 1610 'Orbis' date, the preferred option of Lewis and Maslin, reflects a short-lived decline in atmospheric CO_2 of ~10 ppm identified in two Antarctic ice cores and 'the most prominent feature, in terms of both rate of change and magnitude, in pre-industrial atmospheric CO_2 records over the past 2,000 years' (MacFarling Meure et al., 2015). Like other postulates (Faust et al., 2006), they associated this CO_2 dip with depopulation in the Americas following European colonization: thus, Lewis and Maslin regard it as an anthropogenic marker of 'transoceanic movement of species [that] is a clear and permanent geological change to the Earth system'. However, the magnitude of the CO_2 fluctuation cited by Lewis and Maslin (2015) is not outside the range of natural Holocene variability (Figure 1). Furthermore, the anthropogenic origin of the brief CO_2 transient is not conclusively established, making the 1610 date problematic for marking an epoch's beginning. The salient points are:

- *The '1610 CO_2 downturn' is not an ideal stratigraphic marker*. The CO_2 concentration curve in the NGRIP ice core (Monnin et al., 2001) reveals many 'sharp and brief dips' in CO_2 of comparable amplitude before 1610. Thus, the 1610 dip seems not a large enough anomaly to stand out as an epoch marker, particularly when compared with post-industrial changes in atmospheric CO_2, not least because the signal is only detectable in select ice core localities. Even then, its precise timing is uncertain because of the lag between snow deposition and closure of air bubbles in ice, which can be allowed for, but not quantified precisely: any 'golden spike' is different for air and the surrounding ice by decades to centuries (Ahn et al., 2012). The chosen 1610 date hence combines aspects of a Global Boundary Stratotype Section and Point (GSSP or golden spike) and Global Standard Stratigraphic Age (GSSA), without fully satisfying either one.
- *The 1610 event is not significant with respect to the entire Holocene record*. Atmospheric CO_2 concentrations vary naturally during interglacial periods by about 20–25 ppm. During the pre-industrial Holocene, it varied between 260 and 285 ppm and during the previous interglacials it has varied between 262 and 287 ppm (Barnola et al., 1987, 2003; Etheridge et al., 1996, 1998; Indermühle et al., 1999). Much of this variation may reflect fluctuations in ocean circulation (e.g. Intergovernmental Panel on Climate Change (IPCC), 2013: chapter 3 (Observations: Ocean) and chapter 5 (Information from paleoclimate archives)). The carbon stored in the ocean exceeds that stored in land systems by a factor of 20. Therefore, small changes in the marine storage of carbon can significantly change atmospheric CO_2 levels. Hence, the dip of about 10 ppm in the CO_2 curve at ~1610 (enhanced by the scale chosen for Lewis and Maslin, 2015: figure 2c) may well fall within natural variation.
- *The 1610 dip does not match the suggested regional anthropogenic trigger*. The loss of population in the Americas (in aggregate terms) continued until about 1650 (Cook, 1998). If the proposed model is correct, this depopulation should have resulted in forest regrowth and attendant CO_2 uptake until the mid-17th century at least, especially as trees stock carbon fastest at maturity, not as saplings. If depopulation in the Americas drove the downturn in atmospheric CO_2, concentrations should have continued to decline until 1650–1680, which is not seen in the ice core data. The link between depopulation and greenhouse gas declines is further complicated by other factors. With Amerindian depopulation, farmed and burned-over land did not necessarily revert to forest ecosystems, as large herbivores locally underwent population explosions, affecting vegetation dynamics. Furthermore, reduced soil respiration may have resulted from the low temperatures of the 'Little Ice Age', adding an

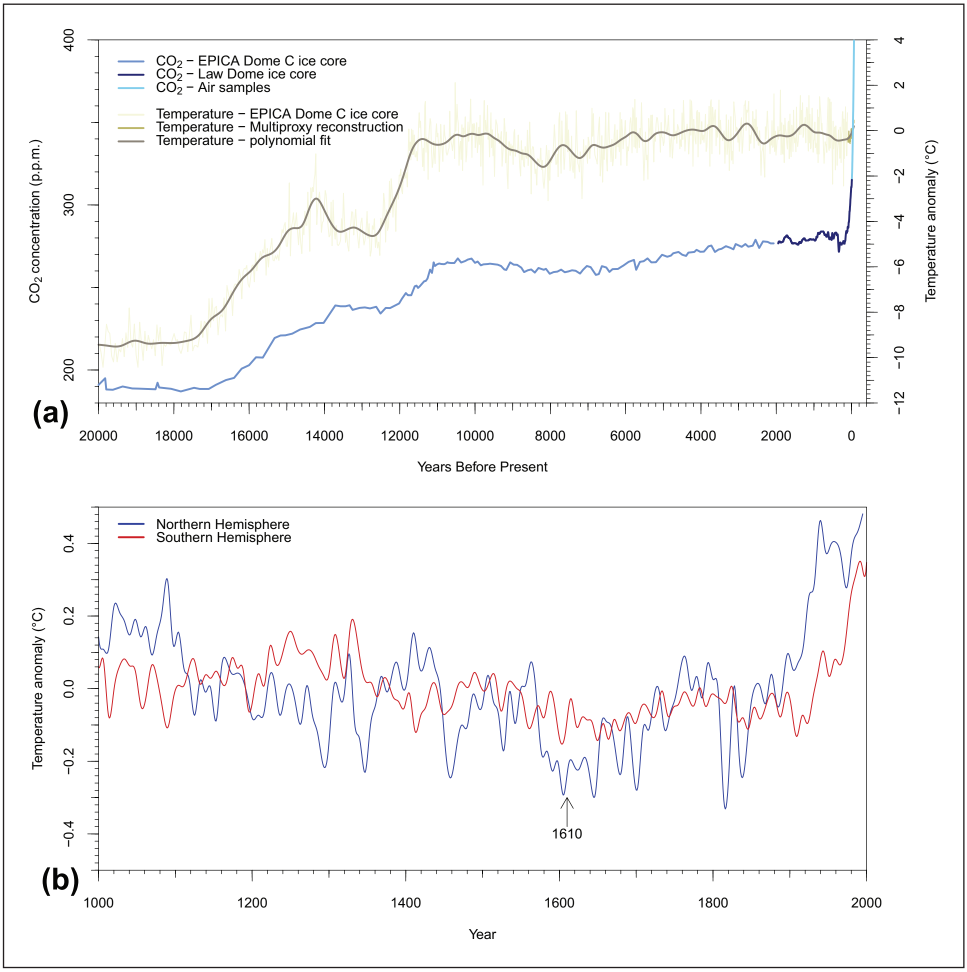

Figure 1. (a) Atmospheric CO_2 and temperature based upon proxy information from the Law Dome and EPICA Dome C ice cores (Jouzel et al., 2007; MacFarling Meure et al., 2006; Monnin et al., 2001) combined with data from observed measurements (Jones et al., 2013; Keeling et al., 2005); (b) Southern (red) and Northern (blue) Hemisphere temperature anomaly reconstructions from Neukom et al. (2014) showing the temporal and geographical complexity of climate history through the last millennium.

additional complicating factor (Rubino et al., 2015). The peak cold of the ‘Little Ice Age’ occurred after the CO_2 event, during the sunspot Maunder Minimum between 1645 and 1715 (Eddy, 1976).

- *The 1610 dip does not match global trends*. Conceptually, the 1610 date is underpinned by linking the minor downturn of CO_2 with the loss of ~50 million people in the Americas (1492–1650) (Cook, 1998). That link may be questioned, as noted above, and in any case the resulting land-cover changes need be interpreted in a global context. While both regional and global population figures are inexact, outside of the Americas, population was probably rising for most of the 1500s until 1600 or 1620, with consequent deforestation potentially muting the American trend towards forest regrowth and CO_2 uptake. Various large-scale

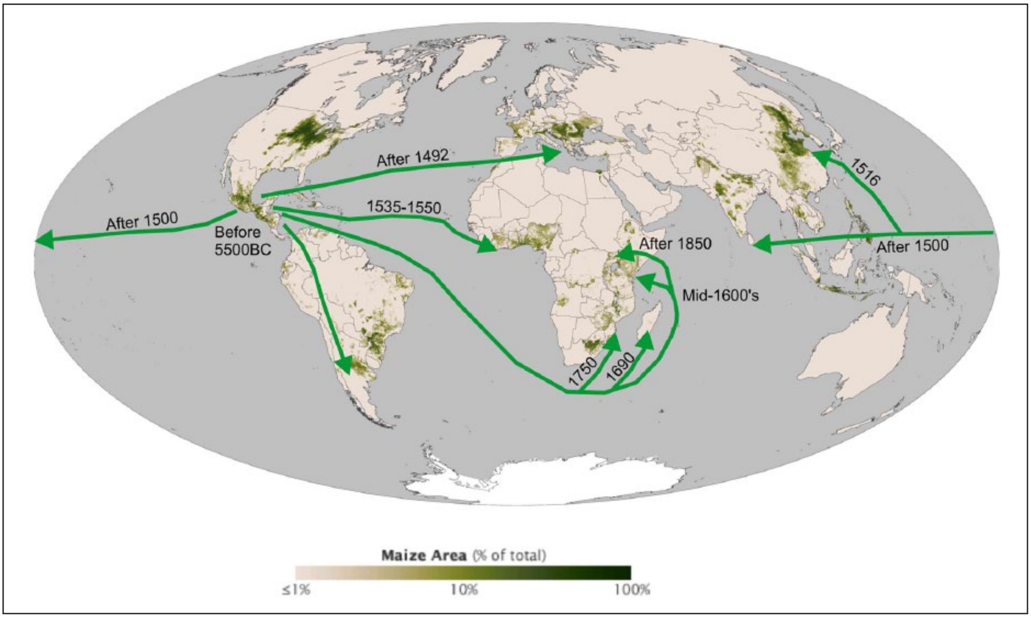

Figure 2. Maize distribution map sourced from NASA: Visible Earth (http://visibleearth.nasa.gov/view.php?id=47250); the timing of maize transfer and spread sourced from Natural History Museum (http://www.nhm.ac.uk/nature-online/life/plants-fungi/seeds-of-trade/page.dsml?section=crops&page=spread&ref=maize).

events, including wars, famines and epidemics probably reduced global population ~1600–1660 (Parker, 2013). Loss of population in north China and Germany (two hard-hit places ~1620–1670) may not have the same implications for forest regrowth and atmospheric CO_2. But, as a first approximation, considering population and forest cover as key CO_2 drivers, and taking an integrative global perspective, one would predict the CO_2 nadir to occur later than 1610. The correlation between native human depopulation in the Americas and the CO_2 dip of 1610 therefore lacks an unambiguous causal link.

- *The associated global temperature change does not form a distinct stratigraphic marker.* Lewis and Maslin cite the analysis by Neukom et al. (2014) of climate in the last millennium in indicating, within the 'Little Ice Age', 'a relatively synchronous cold event noted in geologic deposits worldwide'. It is not clear, though, that an obvious stratigraphic event marker exists here. Neukom et al. (2014) do recognize within the 'Little Ice Age' an interval of a little under a century (1594–1677) as a cold period affecting both hemispheres. However, their reconstruction (Figure 1b) shows an indistinct interval around the late 16th and early 17th centuries where, although both hemispheres show, unusually for the 'Little Ice Age', a similar temperature trend, there seems little otherwise to distinguish this from other earlier and later minor climate oscillations. The 'Little Ice Age' overall (~1300–1870) shows considerable geographic variations in climate history (IPCC, 2013; Mann et al., 2008).
- *The global biostratigraphic signal from colonizing the Americas remains incompletely documented*. The two-way spread of invasive/transported species from and to the Americas has considerable biostratigraphic potential, but needs further study to show just how closely these particular signals approximate to globally detectable time planes, and how they compare with the plethora of other invasive-related signals, both earlier and later. Maize, the

example quoted by Lewis and Maslin (2015), did become a major crop plant worldwide. However, the spread took place over a few centuries (Figure 2), making the resulting biostratigraphic signal diachronous at the time scale relevant to defining the Anthropocene.

1964 and peak excess radiocarbon

The alternative 1964 date suggested by Lewis and Maslin (2015) is, in contrast to the *dip* (in atmospheric CO_2 in 1610), based rather upon a *peak* in atmospheric radiocarbon recorded in annual tree rings from pines in the park by Niepołomice Castle, Poland (Rakowski et al., 2013). Such a reference point would be precise – a desirable feature of setting epoch boundaries – and accessible. However, a living tree may not be universally accepted to be 'geological stratigraphical material such as rock, glacier ice or marine sediments', as Lewis and Maslin (2015) note. Other difficulties with this suggestion include:

- *The boundary is not ideally placed relative to the signal*. It is more conventional, and usually more practical in terms of worldwide correlation, to place a boundary based on chemical or isotopic excursion at the beginning, rather than at the peak, of such a major geochemical change in strata. That is the case with the iridium spike at the Cretaceous–Palaeogene boundary (Molina et al., 2006) and the negative $\delta^{13}C$ excursion for the Paleocene–Eocene boundary (Aubry et al., 2007), for instance. In this way one captures the whole signal and not just part of it, making the interval being defined more easily recognizable, especially in geological situations where the record is incomplete. For the Anthropocene, for instance, another potential boundary-defining isotope curve is the $^{13}C/^{12}C$ anomaly produced by the burning of fossil fuels (Dean et al., 2014), which has a clear inception, but which has not yet reached its peak. The onset of the globally significant fallout signature occurred in 1952 (Waters et al., 2015), which brings this GSSP suggestion closer in line to recent suggestions of a boundary associated with the mid-20th century 'Great Acceleration' (Zalasiewicz et al., 2015). In the Niepołomice pine, $\Delta^{14}C$ measurements were only conducted to 1960 (Rakowski et al., 2013), and so a more extended record is needed to capture the beginning of the signal. There is a conceptual issue concerning use of radioisotopes as a marker for the base of the Anthropocene. As the radioisotopes decay the first inception of a signal will, with time, fall below resolvable detection limits and ultimately (50,000 years for ^{14}C) only the peak signal will be recognizable. Therefore, a peak signal would be better recognized when nearly decayed, but for immediate use the inception is clearly preferable.
- *The excess radiocarbon signal is diachronous and inconsistent*. The 1964 ^{14}C bomb spike is recorded from atmospheric measurements, and tree rings will suitably record that peak in an annual growth ring for that year. However, the tree-ring radiocarbon curve (Rakowski et al., 2013) is representative of the Northern Hemisphere only, rather than capturing a global signal, with the equivalent but lower bomb peak evident in the Southern Hemisphere ~1–2 years later (see Zalasiewicz et al., 2015: figure 2 and references therein). Also, there will be a mixed inventory of the ocean's native carbon inventory and the bomb peak, so that the excess radiocarbon signal is likely to be suppressed in marine sedimentary deposits, the typical setting within which most, though not all, GSSPs are defined.
- *Other components of the 'bomb spike' are likely to give a clearer signal than ^{14}C*. Plutonium ($^{239, 240}Pu$) is likely to sorb better to clays and organic compounds within marine sediments and moreover has the advantage of being a mostly artificial radionuclide suite with a longer half-life (24,110 years as opposed 5730 years for ^{14}C) that will be detectable in sedimentary deposits for some 100,000 years (Waters et al., 2015).

Should choice of human narrative influence boundary selection?

A key factor that lies behind the proposal of Lewis and Maslin (2015) for 1964 as a suggested Anthropocene boundary relates to arguments regarding nuclear weapons, their testing, and the related international treaties. They note that this proposed 'boundary' was when atmospheric nuclear tests – upon reaching their peak in 1963 – began to fall, citing the *reason* behind 'rapid decline in atmospheric testing' as the 1963 Partial Test Ban Treaty. They present this to 'highlight the ability of people to collectively successfully manage a major global threat to humans and the environment' (Lewis and Maslin, 2015: 178). In other words, the onset of the Anthropocene according to Lewis and Maslin (2015) is not when nuclear powers started to detonate nuclear weaponry, but rather when humanity demonstrated collectively the ability to manage this through means of international law.

However, neither is the collective will of people shown in a stratigraphic marker nor was the decrease of atmospheric nuclear tests the result of the 1963 Partial Test Ban Treaty. On the contrary, different interpretations suggest that the Treaty itself resulted from the fact that the three nuclear powers of the time – USA, USSR and UK – by then had reached the technological level allowing them to reduce atmospheric nuclear tests, and to agree on an international treaty hampering other states from developing nuclear weapons to reach the same level (Andrassy, 1978; Mastny, 2008).

By a fluke of timing, the publication of the Lewis and Maslin paper in *Nature* on 12 March 2015 almost exactly coincided with a milestone in a recent legal case at the International Court of Justice (ICJ): the submission of the Memorandum by Marshall Islands against the UK, scheduled for 16 March 2015 (ICJ, 2014a, 2014b). The case relates to accusation of all nuclear states for not fulfilling their obligations with respect to the cessation of the nuclear arms race and to nuclear disarmament (and the unique position of the UK as respondent is related to jurisdictional reasons under international law). Overall, however, this case is also a reminder that the prevention of future stratigraphic 'bomb peaks' is still aspiration, and not yet reality.

Lewis and Maslin (2015) observe that the date chosen to begin the Anthropocene will affect perceptions of the narrative of humans on, and affecting, the Earth. There is certainly some truth in this. Hence 1610 may be said to reflect colonialism and indeed genocide (http://avidly.lareviewofbooks.org/2015/03/22/the-inhuman-anthropocene/) and global trade expansion, while the use of their second choice, the atmospheric bomb spike of 1964 may symbolize control of great technological power and destructive potential.

We are aware of the narratives that may be built around the Anthropocene, and how these may be influenced by boundary choice. However, we suggest that the positioning of a stratigraphic boundary should simply be pragmatically and dispassionately chosen, by the same manner in which all earlier stratigraphic boundaries were chosen, to allow the most effective practical division between what would then become (by definition) Anthropocene and pre-Anthropocene strata and history. Such a choice would, we consider, be the best guarantee that wider discussion is solidly founded on the best factual basis available.

Discussion

The study of Lewis and Maslin (2015) is important in stimulating debate on a significant transition in Earth history, which has brought what is now being termed the Anthropocene world into being. However, the stratigraphic evidence for a '1610 Orbis event' as an epoch-scale boundary is not compelling in our view. It is clear that interchange between the Americas and the rest of the world was an event of historic significance with global consequences. It is clear also that,

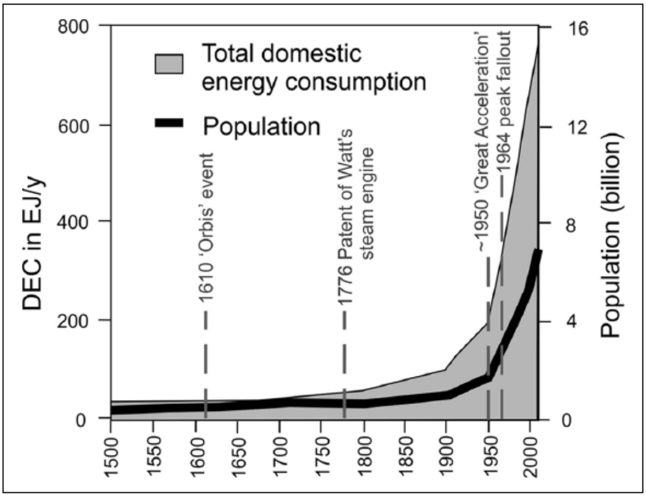

Figure 3. Population and energy use over the last two millennia, modified from Fischer-Kowalski et al. (2014), showing the steep climb in energy use of the mid-20th century 'Great Acceleration'. DEC = Domestic Energy Consumption.

around this time, the world was beginning its trajectory towards its modern, largely fossil fuel-powered, state of operation (Fischer-Kowalski et al., 2014). However, the historic significance is in itself insufficient to allow stratigraphic subdivision as effectively as may be done in the mid-20th century, where the energy use and impact are far greater (Figure 3) and their impacts unquestionably global.

With respect to 1964, the 'Great Acceleration' was already well under way, the beginnings of which, a little over a decade earlier, exhibit greater synchrony in the upward inflections of many physical and socio-economic trends and their respective stratigraphic signals, than at the proposed 1964 date (Steffen et al., 2007, 2015). Considerations of the symbolism of the Partial Test Ban Treaty, related to this peak, are understandable, but emphasis should be placed on the actual stratigraphic evidence in making the boundary selection process as pragmatic as possible. Hence, the beginning of the upsurge in bomb-produced radiocarbon recorded in such tree rings might form a plausible candidate GSSP to be compared with other potential GSSPs around this level.

The discussions of the Anthropocene Working Group are currently working towards defining the Anthropocene. The paper by Lewis and Maslin adds new perspectives and ideas to the debate, which will stimulate inquiry into the nature of Earth System change that saw the world change from its Holocene to its Anthropocene state, but we consider that their specific suggestions are not as stratigraphically effective as others that have been proposed. A suggestion to downgrade the Holocene from epoch to stage, shown in Option 2 of Lewis and Maslin's Figure 1, is not realistically tenable, given that the term is fully ratified.

Author contributions

The authors are members of the Anthropocene Working Group (AWG) of the Subcommission on Quaternary Stratigraphy, in turn a component body of the International Commission on Stratigraphy. Correspondence should be addressed to CNW, Secretary of the AWG (cnw@bgs.ac.uk).

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References

Ahn J, Brook EJ, Mitchell L et al. (2012) Atmospheric CO_2 over the last 1000 years: A high-resolution record from the West Antarctic Ice Sheet (WAIS) Divide ice core. *Global Biogeochemical Cycles* 26: GB2027.

Andrassy J (1978). *On the Judgment of the International Court of Justice on Nuclear Tests*. Rad 375, Zagreb: Yugoslav Academy of Sciences and Arts (in Croatian), pp. 5–105.

Aubry M-P, Ouda K, Depuis C et al. (2007) The Global Standard Stratotype-section and Point (GSSP) for the base of the Eocene Series in the Dababiya section (Egypt). *Episodes* 30: 271–286.

Barnola J-M, Raynaud D, Korotkevich YS et al. (1987) Vostok ice core provides 160,000-year record of atmospheric CO_2. *Nature* 329: 408–414.

Barnola J-M, Raynaud D, Lorius C et al. (2003) Historical CO_2 record from the Vostok ice core. In: *Trends: A Compendium of Data on Global Change*. Oak Ridge, TN: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy.

Chakrabarty D (2015) The Anthropocene and the Convergence of Histories. In: Hamilton C, Bonneuil C and Gemenne F (eds) *The Anthropocene and the Global Environmental Crisis: Rethinking Modernity in a new epoch*. Abingdon: Routledge, pp. 46–56. In press.

Cook ND (1998) *Born To Die: Disease and New World Conquest, 1492–1650*. New York: Cambridge University Press.

Corlett RT (2015) The Anthropocene concept in ecology and conservation. *Trends in Ecology and Evolution* 30: 36–41.

Crutzen PJ (2002) Geology of Mankind. *Nature* 415: 23.

Crutzen PJ and Stoermer EF (2000) The 'Anthropocene'. *Global Change Newsletter* 41: 17–18.

Dean JR, Leng MJ and Mackay AW (2014) Is there an isotopic signature of the Anthropocene? *The Anthropocene Review* 1(3): 276–287. DOI: 10.1177/2053019614541631.

Eddy J (1976) The Maunder Minimum. *Science* 192 (4245): 1189–1202.

Edgeworth M, Richter DDeB, Waters CN et al. (2015) Diachronous beginnings of the Anthropocene: The lower bounding surface of anthropogenic deposits. *Anthropocene Review* 2(1): 1–26. DOI: 10.1177/2053019614565394.

Etheridge DM, Steele LP, Langenfelds RL et al. (1996) Natural and anthropogenic changes in atmospheric CO_2 over the last 1000 years from air in Antarctic ice and firn. *Journal of Geophysical Research* 101: 4115–4128.

Etheridge DM, Steele LP, Langenfelds RL et al. (1998) Historical CO_2 records from the Law Dome DE08, DE08–2, and DSS ice cores. In: *Trends: A Compendium of Data on Global Change*. Oak Ridge, TN: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy.

Faust FX, Gnecco C, Mannstein H et al. (2006) Evidence for the postconquest demographic collapse of the Americas in historical CO_2 levels. *Earth Interactions* 10: 1–14.

Fischer-Kowalski M, Krausmann F and Pallua I (2014) A sociometabolic reading of the Anthropocene: Modes of subsistence, population size and human impact on Earth. *The Anthropocene Review* 1(1): 8–33.

Indermühle A, Stocker TF, Fischer H et al. (1999) High-resolution Holocene CO_2-record from the Taylor Dome ice core (Antarctica). *Nature* 398: 121–126.

Intergovernmental Panel on Climate Change (IPCC) (2013) *Climate Change 2013: The Physical Science Basis*. Working Group I contribution to the IPCC Fifth Assessment Report. Available at: http://www.ipcc.ch/report/ar5/wg1/.

International Court of Justice (ICJ) (2014a) *Application Instituting Procedures against the United Kingdom*. Submitted 24 April 2014. Available at: http://www.icj-cij.org/docket/files/160/18296.pdf

International Court of Justice (ICJ) (2014b). *Obligations Concerning Negotiations Relating to Cessation of the Nuclear Arms Race and to Nuclear Disarmament (Marshall Islands* v. *United Kingdom), Order: Fixing of Time Limits*. 16 June 2014. Available at: http://www.icj-cij.org/docket/files/160/18342.pdf

Jones PD, Parker DE, Osborn TJ et al. (2013) Global and hemispheric temperature anomalies – Land and marine instrumental records. In *Trends: A Compendium of Data on Global Change*. Oak Ridge, TN: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy. DOI: 10.3334/CDIAC/cli.002.

Jouzel J, Masson-Delmotte V, Cattani O et al. (2007) Orbital and millennial Antarctic climate variability over the past 800,000 years. *Science* 317: 793–797.

Keeling CD, Piper SC, Bacastow RB et al. (2005) Atmospheric CO_2 and $^{13}CO_2$ exchange with the terrestrial biosphere and oceans from 1978 to 2000: Observations and carbon cycle implications. In: Ehleringer JR, Cerling TE and Dearing MD (eds) *A History of Atmospheric CO_2 and its Effects on Plants, Animals, and Ecosystems*. New York: Springer Verlag, pp. 83–113.

Latour B (2015) Telling friends from foes in the time of the Anthropocene. In: Hamilton C, Bonneuil C and Gemenne F (eds) *The Anthropocene and the Global Environmental Crisis: Rethinking Modernity in a new epoch*. Abingdon: Routledge, pp. 145–155. In press.

Lewis SL and Maslin MA (2015) Defining the Anthropocene. *Nature* 519: 171–180.

MacFarling Meure C, Etheridge D, Trudinger C et al. (2006) Law Dome CO_2, CH_4 and N_2O ice core records extended to 2000 years BP. *Geophysical Research Letters* 33: L14810.

Mann ME, Zhang Z, Hughes MK et al. (2008) Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia. *Proceedings of the National Academy of Sciences of the United States of America* 105: 13,252–13,257.

Mastny V (2008) The 1963 Nuclear Test Ban Treaty: A missed opportunity for détente? *Journal of Cold War Studies* 10(1): 3–25.

Molina E, Alegret L, Arenillas I et al. (2006) The Global Boundary Stratotype Section and Point for the base of the Danian Stage (Paleocene, Paleogene, 'Tertiary', Cenozoic) at El Kef, Tunisia – Original definition and revision. *Episodes* 29: 263–273.

Monnin E, Indermühle A, Dällenbach A et al. (2001) Atmospheric CO_2 concentrations over the last glacial termination. *Science* 291: 112–114.

Neukom R, Gergis J, Karoly DJ et al. (2014) Inter-hemispheric temperature variability over the past millennium. *Nature Climate Change* 4: 362–367.

Parker G (2013) *Global Crisis: War, Climate Change, and Catastrophe in the Seventeenth Century*. New Haven, CT: Yale University Press.

Partial Test Ban Treaty (1963) *Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer Space and under Water*. Signed on 5 August 1963 by the Original Parties: The Union of Soviet Socialist Republics, the United Kingdom of Great Britain and Northern Ireland and the United States of America at Moscow, entered into force 10 October 1963. *United Nations Treaty Series* vol. 480.

Rakowski AZ, Nadeau M-K, Nakamura T et al. (2013) Radiocarbon method in environmental monitoring of CO_2 emission. *Nuclear Instruments and Methods in Physics Research B* 294: 503–507.

Rose NL (2015) Spheroidal carbonaceous fly ash particles provide a globally synchronous stratigraphic marker for the Anthropocene. *Environmental Science and Technology* 49(7): 4155–4162. DOI: 10.1021/acs.est.5b00543.

Rubino M, Etheridge D, Trudinger C et al. (2015) Atmospheric CO_2 and $\delta^{13}C$–CO_2 reconstruction of the Little Ice Age from Antarctic ice cores. *Geophysical Research Abstracts* 17: EGU2015–9747–2.

Ruddiman WF (2003) The anthropogenic greenhouse era began thousands of years ago. *Climatic Change* 61: 261–293.

Ruddiman WF (2013) Anthropocene. *Annual Review of Earth and Planetary Sciences* 41: 45–68. DOI: 10.1146/annurev-earth-050212–123944.

Ruddiman WF, Ellis EC, Kaplan JO et al. (2015) Defining the epoch we live in. *Science* 348: 38–39.

Smith BD and Zeder MA (2013) The onset of the Anthropocene. *Anthropocene* 4: 8–13.
Steffen W, Broadgate W, Deutsch L et al. (2015) The trajectory of the Anthropocene: The Great Acceleration. *The Anthropocene Review* 2(1): 81–98.
Steffen W, Crutzen PJ and McNeill JR (2007) The Anthropocene: Are humans now overwhelming the great forces of Nature? *Ambio* 36: 614–621.
Syvitski JPM and Kettner AJ (2011) Sediment flux and the Anthropocene. *Philosphical Transactions of the Royal Society* A 369: 957–975.
Syvitski JPM, Harvey N, Wollanski E et al. (2005) Dynamics of the Coastal Zone. In: Crossland CJ, Kremer HH, Lindeboom HJ et al. (eds) *Coastal Fluxes in the Anthropocene*. Berlin: Springer, pp. 39–94.
Vidas D (2010) Responsibility for the seas. In: Vidas D (ed.) *Law, Technology and Science for Oceans in Globalisation*. Boston, MA: Martinus Nijhoff Publishers/Brill, pp. 3–40.
Vidas D (2011) The Anthropocene and the international law of the sea. *Philosophical Transactions of the Royal Society A* 369: 909–925.
Vidas D (2014) Sea-level rise and international law: At the convergence of two epochs. *Climate Law* 4: 70–84.
Waters CN, Syvitski JPM, Gałuszka A et al. (2015) Can nuclear weapons fallout mark the beginning of the Anthropocene Epoch? *Bulletin of the Atomic Scientists* 71(3): 46–57.
Waters CN, Zalasiewicz J, Williams M et al. (eds) (2014) *A Stratigraphical Basis for the Anthropocene*. London: Geological Society. Special Publications, 395, pp. 321.
Williams M, Zalasiewicz J, Haywood A et al. (2011) The Anthropocene: A new epoch of geological time? *Philosophical Transactions of the Royal Society A* 369(1938): 833–1112.
Wolfe AP, Hobbs WO, Birks HH et al. (2013) Stratigraphic expressions of the Holocene–Anthropocene transition revealed in sediments from remote lakes. *Earth-Science Reviews* 116: 17–34.
Zalasiewicz J, Waters CN, Williams M et al. (2015) When did the Anthropocene begin? A mid-twentieth century boundary level is stratigraphically optimal. *Quaternary International*. DOI: 10.1016/j.quaint.2014.11.045.
Zalasiewicz J, Williams M, Smith A et al. (2008) Are we now living in the Anthropocene? *GSA Today* 18(2): 4–8.

Perspectives and controversies

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A transparent framework for defining the Anthropocene Epoch

Simon L Lewis[1,2] and Mark A Maslin[1]

Abstract

Lewis and Maslin (2015) applied modern geological requirements to a systematic search for evidence of markers that could be used to define a new geological time unit, the Anthropocene Epoch. These must include (1) a near-permanent change to the Earth System that sets it on to a new trajectory and (2) global changes to the Earth System recorded in a number of stratigraphic deposits worldwide to provide a correlative boundary event or marker called a Global Stratotype Section & Point (GSSP) or 'golden spike'. Using this framework Lewis and Maslin conclude that just two time periods likely adhere to the criteria. These are the irreversible cross-ocean exchange of species alongside the globally synchronous coolest part of the 'Little Ice Age' in the 17th century, marked by the 1610 minima of CO_2 (Orbis Spike), or the accelerating atmospheric, oceanic and terrestrial changes in the second half of the 20th century, conveniently marked by the 1964 peak radionuclide fallout (Bomb Spike). Two recent responses by members of the Anthropocene Working Group (Zalasiewicz, 2015a, 2015b) to Lewis and Maslin (2015) do not dispute the GSSP framework, nor that these are the only two time periods that minimally fit the requirements for a new epoch. Instead they question our selection of two specific 1610 and 1964 GSSP primary markers. We respond to their misconceptions and misunderstandings about geological criteria and relevant evidence required to define a GSSP. Our primary goal, however, is to present a framework to assist the scientific community in objectively and transparently arriving at a robust selection of a GSSP and correlated markers to define the Anthropocene Epoch.

Keywords

Anthropocene, Colombian Exchange, Earth System, fossil pollen, global environmental change, golden spikes, Great Acceleration, nuclear, paradigm shift, phytolith

Introduction

The concept and term 'Anthropocene' has been used with increasing frequency over the last decade. Since the year 2000 the most commonly used definition of the Anthropocene was that it began in the year 1800 (Crutzen, 2002; Crutzen and Stoermer, 2000; Steffen et al., 2011; Zalasiewicz et

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al., 2011a). This date, coincident with the early part of the Industrial Revolution, marks an important moment in human history with eventual global-scale environmental impacts, yet it is not consistent with the geological norms used to define a geological epoch (Gradstein et al., 2012; Smith et al., 2014). Epochs within the Phanerozoic, the last 541 million years, are today defined using a Global Stratotype Section & Point (GSSP), alongside correlated changes in stratigraphic deposits worldwide, to indicate a fundamental change to Earth's state in the time before compared with the time after the marker-event (Gradstein et al., 2012; Smith et al., 2014). That is, a dated globally correlated marker is selected within the long-term change of the Earth from one state to another. The temporal longevity of a typical epoch is on the order of millions of years, and the before-and-after differences may take tens or hundreds of thousand years to complete. Such globally distributed markers do not exist near 1800 (Lewis and Maslin, 2015; Zalasiewicz et al., 2015c). Thus, we reasoned that if a GSSP and correlated markers exist, then they should be chosen to define the Anthropocene Epoch, and therefore its inception.

In 2013 we could find no published comparison of potential GSSP markers with which to formally define an Anthopocene Epoch. At that time there seemed relatively little interest in GSSPs. So with the encouragement of colleagues we worked on a review and submitted it to *Nature* on 26 March 2014. After extensive reviews over almost 10 months, with four reviewers of whom at least one was a member of the Anthropocene Working Group (AWG[1]), the paper was accepted on 12 January 2015 (Lewis and Maslin, 2015). We concluded two dates did likely minimally adhere to the GSSP criteria to define the Anthropocene: 1610 and 1964. Unbeknown to us, on the same day, the majority of the members of the AWG also published a paper discussing how to define the Anthropocene (Zalasiewicz et al., 2015c). They recommended that the Anthropocene should not be defined using a GSSP, but instead by a date chosen by the AWG. However, instead of 1800 they chose 1945 (technically a Global Standard Stratigraphic Age, GSSA, usually reserved for geological time units >541 million years ago; see Gradstein et al., 2012; Smith et al., 2014). This was a landmark paper for the AWG, as it was the first peer-reviewed paper authored by the majority of the group, and garnered much publicity (e.g. Zalasiewicz and Williams, 2015).

An almost identical group of members of the AWG who published the paper recommending a 1945 GSSA (Zalasiewicz et al., 2015c) have then published two responses to Lewis and Maslin (2015), one in *Nature* (Zalasiewicz et al., 2015b), and one in this journal (Zalasiewicz et al., 2015a). We note that AWG members chose not to submit a comment to *Nature* which would have been peer-reviewed, but instead chose to write to the non-peer-reviewed correspondence section of *Nature* (Zalasiewicz et al., 2015b). The second response (Zalasiewicz et al., 2015a), submitted to the Perspectives and Controversies section of this journal, likewise avoided formal peer review.

In response to these three AWG papers (Zalasiewicz et al., 2015a, 2015b, 2015c), we emphasise the need for a transparent framework to objectively assess the existing evidence relevant to a geological definition of the Anthropocene, objective assessments of what further evidence should be sought, and transparent methods to prioritise differing evidence. After stating our framework and its logic we then deal with outstanding specific criticisms in Zalasiewicz et al. (2015a, 2015b).

In this paper we proceed in five parts. First, we discuss why scientists should define the Anthropocene, as understanding the reasons may help with the formal definition. Second, we describe how geologists divide time, which is via GSSP requirements, as this also assists in setting a framework for formally defining the Anthropocene Epoch. Third we describe a two-step process of defining the Anthropocene, for any body of evidence. Fourth, we address the errors and misunderstandings in the AWG responses to the two time periods (Orbis and Great Acceleration) and potential GSSPs (CO_2 in glacier ice and ^{14}C in tree rings) we highlighted in Lewis and Maslin (2015) as promising inception dates for the Anthropocene, alongside their genuine limitations as marker-events. Fifth, we briefly response to Zalasiewicz et al. (2015a) regarding human narratives and the Anthropocene. Taken together we hope this paper assists researchers in moving towards an objective, transparent assessment of the evidence from which to recommend a formal definition of the Anthropocene, including a start date.

Why define the Anthropocene?

One key reason why it is desirable to agree a definition for the Anthropocene Epoch, whether formally ratified by the geological community or not, is because clear and precise definitions aid understanding. Surprisingly, a recent paper argued that scientists should deliberately leave the Anthropocene undefined (Ruddiman et al., 2015). Applied broadly, this route leads to obscurantism and confusion and should be avoided. However, we recognise that differing definitions may be relevant to differing disciplines, particularly outside the physical sciences (Maslin and Lewis, 2015).

Additionally, the likely key reason why geologists should set a formal definition of the Anthropocene Epoch is the integrity and internal consistency of the Geologic Time Scale (GTS). Geologists have uncovered the major events of Earth's 4.6 billion year history, dividing this history into a hierarchical series of ever-finer units, with stages nested with epochs, nested within periods, nested within eras, nested within eons (Gradstein et al., 2012). Divisions represent changes in the functioning of Earth as a system and the concomitant changes in the identity, abundance and composition of the resident life-forms. Larger differences result in classifications at higher unit-levels. The question, in terms of the GTS, is whether human activity has altered the Earth as a system, with permanent or extremely long-lived impacts, to such an extent that defining a unit of geological time is logically obvious. A strict adherence to the previously defined norms of defining epochs and other higher units is thus necessary to ensure that the categorisation of Earth's history is consistent across time. Furthermore, given the clearly contentious nature of the idea of the Anthropocene, strict adherence to the requirements generated *before* the modern usage of the Anthropocene term at the turn of this century, provides a relatively clear and objective geological test of the impact of the human activity on the Earth and its future trajectory. The alternative is to argue that the time closest to the present day within the GTS is somehow in need of exceptions to agreed norms. This would obviously present challenges to the process of defining the Anthropocene as any definition would be open to easy criticism that the process is biased and ideologically driven (see Maslin and Lewis, 2015, for this discussion).

Epochs within the Phanerozoic are defined by GSSPs

Formally, geological time units are defined by their lower boundary, that is, their beginning. New geological time units are defined by multiple stratigraphic records to delimit before-and-after major changes to the Earth as a system (Smith et al., 2014). These divisions represent differences to the functioning of the Earth as a system and the integrated changes manifest in the resident life-forms. Boundaries are demarcated using a GSSP, or by an agreed date, termed a GSSA. Within the Phanerozoic Eon (meaning 'revealed life' that started 541 million years ago), epochs are defined by GSSPs and complemented by other correlated changes to the Earth System documented in other stratigraphic records (Gradstein et al., 2012; Smith et al., 2014). A recent review of GSSPs states as its first major conclusion: 'GSSPs are currently the internationally agreed method of fixing the definitions of stage [and therefore epoch] boundaries in rock sections'. It further notes, '[t]he ultimate aim of the GSSP project is to define a complete and globally correlatable set of lower boundaries for all stages of the Phanerozoic' (Smith et al., 2014).

The usual GSSP selection limitations are largely absent when considering the Anthropocene, as ice cores, marine sediments and other recent records will likely consist of adequate continuous sedimentation, be accurately dated, and several records spanning the globe are likely to exist (see limitations in Smith et al., 2014). Furthermore, GSSPs need not rely on biostratigraphic (fossil) evidence (Smith et al., 2014; the Holocene Epoch is defined without reference to fossils). Thus, there is no practical impediment to defining the Anthropocene the usual way any other epoch would be defined – by a GSSP and correlated stratigraphic markers. Specifically, a proposed GSSP must have (1) a principal correlation event (the marker), (2) other secondary markers (auxiliary stratotypes), (3) demonstrated regional and global correlation, (4) complete continuous sedimentation with adequate thickness above and below the marker, (5) an exact location – latitude, longitude and height/depth – because a GSSP can be located at only one place on Earth, (6) be accessible, and (7) have provisions for GSSP conservation and protection (Gradstein et al., 2012; but also see Smith et al., 2014 for further details).

One further practical argument against the use of a GSSA date chosen by committee is that any date may be challenged as being arbitrary and politically motivated (Lewis and Maslin, 2015; Maslin and Lewis, 2015). It is clear that the Industrial Revolution is a key event in human history. But which date should be chosen: 1760, 1800, 1850? Similarly for the Great Acceleration: 1945, 1950 or later? Furthermore, important events always have precursor events. When should the tracing of dates back from an actual geologically recorded environmental change stop? Watt's refinement of the steam engine? The first prototype working steam engine? Or the first use of coal for cooking or heating? The inevitable arbitrariness in a small group choosing a date is much less likely to be widely accepted compared with a well-justified and evidenced GSSP and correlated stratigraphic data. Data and weight of evidence should define the Anthropocene Epoch.

A framework for defining the Anthropocene Epoch

Our framework is designed to assess all relevant evidence using a transparent and rational approach to assess the potential selection of a GSSP and correlated secondary markers to define the Anthropocene Epoch. It is in two parts: (1) screen the geological evidence against the geological requirements for defining an epoch to assess the evidence that we are in a new epoch, including support for different GSSPs and associated globally correlated markers; then (2) compare those time periods that minimally fit the requirements for a Anthropocene Epoch GSSP against a set of objective, specified, relevant and agreed-upon criteria to enable the selection of one time period and GSSP from the group of time periods that minimally fit the GSSP requirements. Lewis and Maslin (2015) undertook part one, but did not comment on part two stating only '[w]e hope that identifying a limited number of possible events and GSSP markers may assist in focusing research efforts to select a robust GSSP alongside a series of auxiliary stratotypes'. We can only begin the second part here, but suggest it is the role of the AWG to obtain consensus on the criteria.

We use the example of the Holocene Epoch, as it is instructive in terms of defining an Anthropocene Epoch. It was only recently ratified and so follows the newer understanding and recommendations of global correlation among multiple markers, and does not focus solely on biostratigraphic records (Smith et al., 2014; Walker et al., 2009). The transition from the glacial to interglacial was long, with surface air temperature rising for ~8000 years. Within this period of change one much shorter time period had to be chosen within which to place the boundary. An anomalous short-term abrupt change in temperature, which is superimposed on the long-term trend was chosen, because short-term abrupt changes to the Earth System provide the best global correlations in stratigraphic material. Thus, having documented the Earth System change (glacial to interglacial planetary conditions), the selected time period within that long change was at the beginning of a rapid near-global temperature rise following the end of an anomalously cool period. That is, a brief time period with high correlation potential was chosen. Finally, the GSSP was selected, an inflection of 2H excess (deuterium) in a Greenland ice core, because it is the most direct indicator of the abrupt change at that time (specifically sea surface temperature). Though Zalasiewicz et al. (2015b) claim that a GSSP should document changes larger than the variability of the prior epoch, this is not the case for the Holocene Epoch as the changes in 2H excess are well within the changes documented within the prior Pleistocene Epoch (cf. Walker et al., 2009; Solomon et al., 2007: figure 6.2). The Holocene ice-core GSSP is then complemented by changes in sediments from four lakes (Germany, Canada, Japan, Australia), mostly documenting changes in pollen counts, and one oceanic record (off Venezuela) mostly documenting chemical changes (Walker et al., 2009).

The ratified Holocene Epoch GSSP by Walker et al. (2009) provides an excellent template for defining the Anthropocene Epoch, with the key points being (1) a small but clear transition within a very long-term change is all that is required for the boundary placement, and (2) points of inflection in stratigraphic data where the Earth System undergoes a short-term rapid change can provide good markers within overall longer-term and larger trends marking the transition of Earth from one state to another, and (3) only a small number of stratigraphic records, showing consistent changes, are required (six for the Holocene). Although, it is worth noting that the Holocene GSSP occurs towards the end of the long increase in surface air temperature. By comparison the Anthropocene Epoch is not being discussed in the same way – the implicit argument of all work seeking to define the Anthropocene Epoch is that the boundary is placed at the beginning of the long-term change that humans are exerting on the Earth System and its trajectory.

Defining the Anthropocene framework, part I: Screen data against GSSP requirements

The increasing variety and magnitude of impacts of human activity on the Earth System, some of which are schematically represented in Figure 1, require a boundary to be selected. To do this the first part of our framework compares the geological requirements for defining an epoch, moving forward through time to assess each time period, as presented in Lewis and Maslin (2015). Essentially, this is a systematic search for some near-permanent change to the Earth System (as epochs typically last millions of years) coupled with widespread correlated environmental changes that are documented in stratigraphic deposits that collectively indicate a change to the Earth System to provide a globally correlated boundary marker. We note no criticism of this approach in Zalasiewicz et al. (2015a, 2015b).

Lewis and Maslin (2015) concluded from this search that the impacts of the hunter-gatherers on Earth's Megafauna (>10,000 BP), the impacts of early farming (~11,000 BP), the impacts of widespread farming (~5000 BP) and the impacts of the early Industrial Revolution (~1800 CE) did not meet these requirements. Again, we note no criticism from the AWG members that we conclude that each of these time periods did not co-occur with near-permanent changes to the Earth System, *and* changes to the Earth System documented in several stratigraphic deposits worldwide. We further concluded that two time periods, (1) the time following the post-1492 collision of the Old and New Worlds leading to the irreversible exchange of species across continents and ocean basins *alongside* the globally synchronous coolest part of the 'Little Ice Age' in the 17th century captured

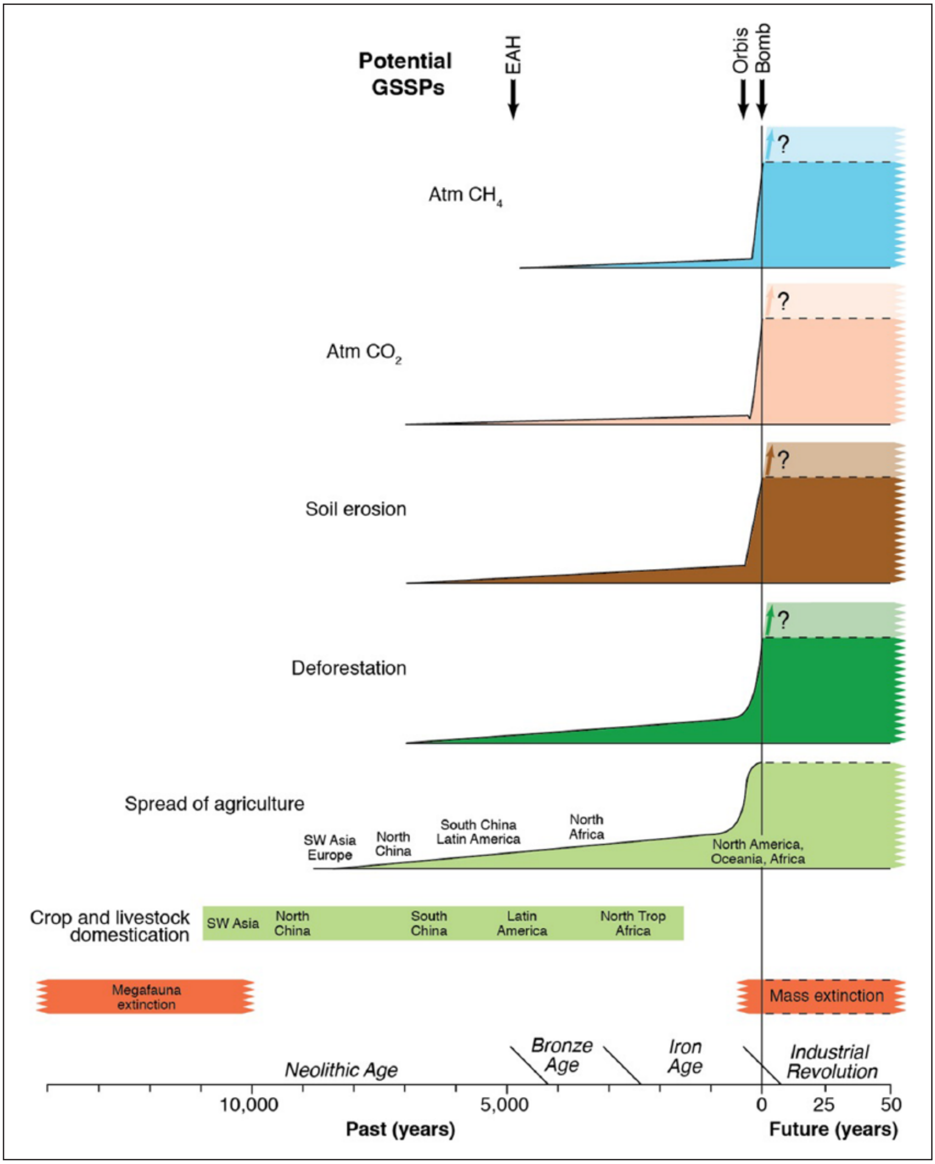

Figure 1. Schematic figure showing the varied and increasing impacts of human activity on the Earth System. Within this long-term change of Earth from one state to another a specific event or date is required to be selected to mark the beginning of the Anthropocene. In contrast to other geological time units the final state of Earth is not known. EAH = Early Anthropogenic Hypothesis.
Source: Adapted, expanded and scaled appropriately from Ruddiman et al. (2015), with three possible GSSP markers reported in Lewis and Maslin (2015).

in stratigraphic deposits worldwide (Orbis Hypothesis; ~1600 onwards), and (2) the accelerating global atmospheric, oceanic and terrestrial changes in the second half of the 20th century captured in stratigraphic deposits worldwide (Great Acceleration; ~1950 onwards) *both* likely adhere to the

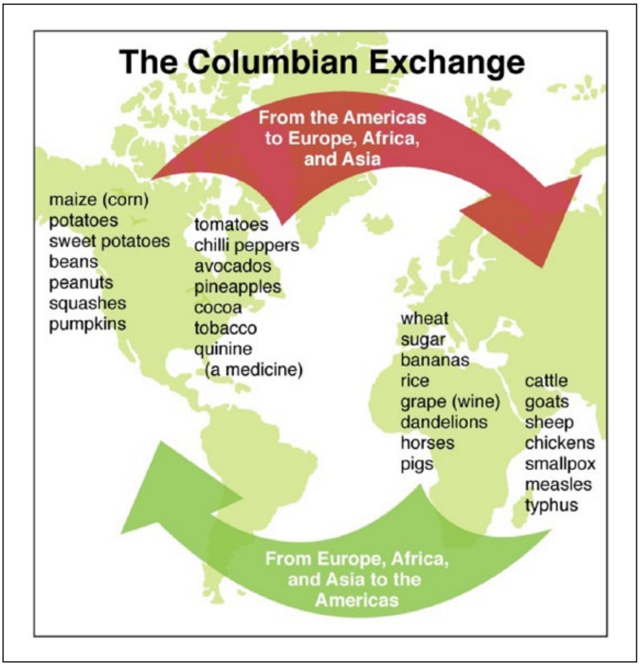

Figure 2. The Colombian Exchange describes the global transfer of crops, domesticated animals, diseases and human commensals between the Old and New Worlds following the arrival of Europeans in the Americas after 1492 and subsequently developed global circuits of trade. The transformation of human diets was a major change in human history.

requirements to define the Anthropocene Epoch using GSSP criteria. We also concluded a broader point, that if the requirements for defining the Anthropocene Epoch are a GSSP with global correlation *and* dated to within a few years or decades, then only those changes associated with well-mixed atmospheric gases can provide such globally correlated signals. Thus, overall, there is evidence that a strict assessment of the evidence compared with the GSSP requirements leads us to the conclusion that a formal definition of the Anthropocene is possible, beginning at one of two possible events/time periods.

Our selection of the 1610 GSSP followed the following logic. The long-term change to the Earth's trajectory is the irreversible cross-continental movement of species, and between disconnected oceans, for example, seen as maize fossil pollen at ~1600 in a European marine sediment (Mercuri et al., 2012). This Colombian Exchange is well known and provides much stratigraphic, archeological and modern material globally (Crosby, 2003; Diamond, 1997; Mann, 2011; Figure 2). However, newer GSSP requirements state that biostratigraphic markers should not be used as the primary GSSP marker, so we chose, identically to the Holocene Epoch GSSP, the parameter in a stratigraphic deposit that most closely allies to the phenomena that is changing the Earth System at that time. For the 17th century period, the likely cause, in part, is the major human population decrease due to the arrival of Europeans in the Americas which killed ~50 million people, mostly via the arrival of the smallpox virus as part of the Colombian Exchange, resulting in the recovery of abandoned farmland to its original vegetation thereby removing 7–14 Pg C from the atmosphere over a few decades, which is captured in a 7–10 ppm decrease in CO_2 measured in the highest-resolution Antarctic ice cores (Dull et al., 2010; Lewis and Maslin, 2015, and references therein; Nevle et al., 2011). Thus, we selected the minima of CO_2 at 1610, captured in the Law Dome ice core to mark a possible beginning of the Anthropocene (Figure 3). Other globally correlated changes, captured in stratigraphic deposits, flow from the change in radiative forcing caused by the change in CO_2 (e.g. $\delta^{18}O$ in speleothems in Chinese caves; Wang et al., 2005). Practically, a 1610 GSSP marks both the irreversible mixing of once-separate biotas setting Earth on a new trajectory and Earth's last globally synchronous cool period before the onset of the long-term warmth of the Anthropocene.

Despite many questions about the Orbis Hypothesis in Zalasiewicz et al. (2015a) the authors do not dispute that species crossed continents and ocean basins, in an essentially permanent change to Earth (see Zalasiewicz et al., 2015a: figure 2). Additionally, the authors also agree that the globally synchronous cool period between 1594 and 1677 was captured in a variety of geological deposits (Neukom et al., 2014). Zalasiewicz et al. (2015a, 2015b) instead note that the drop in atmospheric CO_2 with a minima at 1610 is 'not outside the range of natural Holocene variability', thereby excluding it as a marker. As discussed above, this criticism is easily dismissed as the Holocene Epoch GSSP is defined by and located at an inflection of 2H (deuterium) excess which that falls well within the range documented within the prior epoch, the Pleistocene (cf. Solomon et al., 2007; figure 6.3; Walker et al., 2009). We emphasise that GSSP primary markers selected to be boundaries of geological time units may be modest compared with the changes occurring to the Earth at that time or when compared with the changes before and after the boundary event, as noted by others, for example, see Zalasiewicz and Williams (2014). Thus, despite the criticism of Zalasiewicz et al. (2015a, 2015b), a 1610 boundary adheres to the GSSP criteria for defining an Anthropocene Epoch.

Objectively selecting a boundary for the Great Acceleration is challenging, as it has occurred via varied environmental changes associated with increasing land-use change, mostly in the tropics, increasing numbers of people utilising fossil fuels, directly and indirectly via increased consumption of material goods, and other changes, as shown in the data collation by Steffen et al., (2015; also shown here in Figure 4). In Lewis and Maslin (2015), like Zalasiewicz et al. (2015c), we selected a globally widespread marker, radionuclide fallout. This signal can be interpreted as the equivalent of a major human-created 'volcanic eruption' that merely coincides with the Great Acceleration, but probably gives the best global correlative potential because of the global fallout. For this signal we selected ^{14}C in tree rings from the temperate zone because annual rings give an unambiguous annually dated marker, and despite the ^{14}C half-life (5730 years) the marker can easily be used by many generations of scientists. We chose the peak in fallout based on generic considerations: (1) earliest detectable dates reflects detection technologies, which change over time and affect correlatability; (2) detecting small changes at the earliest detectable date are more likely influenced by natural geochemical background levels; (3) signal decay will affect earliest dates more than peak values (Lewis and Maslin, 2015). Zalasiewicz et al. (2015a, 2015b) do not disagree that the Great Acceleration is a possible beginning of the Anthropocene, but that the first detection of the radionuclide marker ought to be used. We respond that misunderstanding of the GSSP evidence in section '1964 CE Bomb Spike GSSP proposal' below. Regardless of that debate, there is no dispute that the Great Acceleration, including radionuclide fallout, adheres to GSSP criteria to mark the inception of the Anthropocene.

Other choices are certainly possible for the primary marker within each of the two time periods, switching the 1610 CO_2 drop in an Antarctic ice-core, or the 1964 ^{14}C peak in European tree rings, to become secondary markers, but such choices must be evidence-based following a clear logic outlined for the selection of primary GSSP markers.

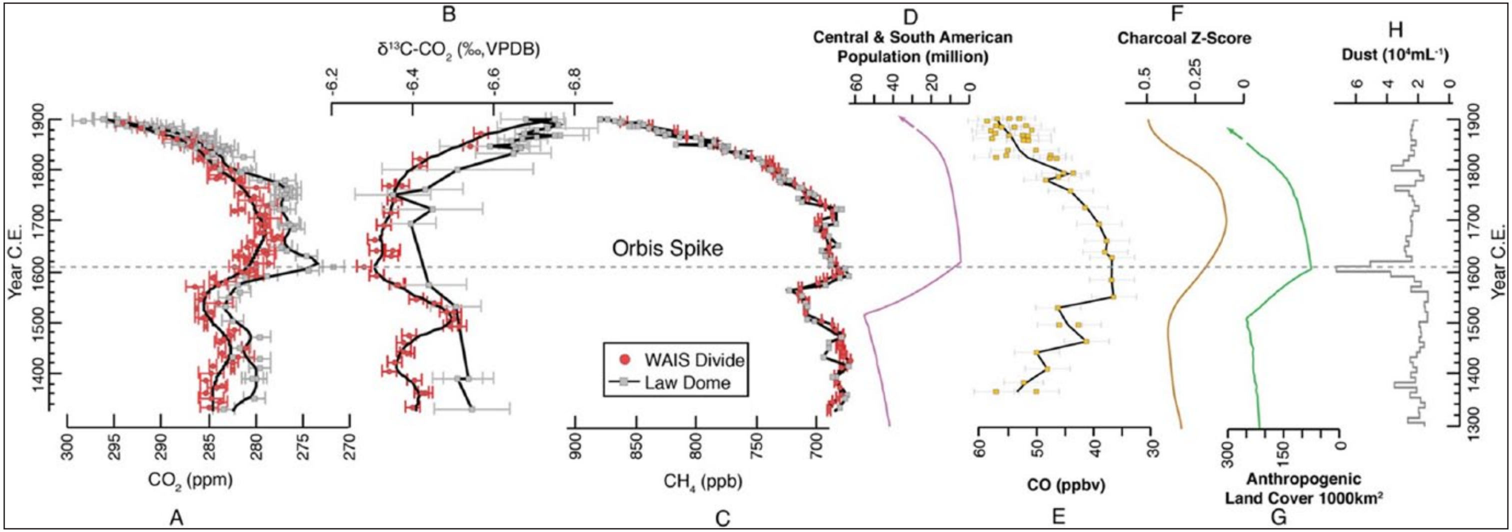

Figure 3. Earth System changes in the 16th and 17th centuries, temporally coincident changes in the population of the Americas, proxies of fire numbers and intensity, estimated anthropogenic land-cover change, and the impacts of the coincident Huaynaputina volcanic eruption that in combination with the irreversible exchange of species via the Colombian Exchange at this time suggest a possible 1610 GSSP to begin the Anthropocene. (A) Atmospheric carbon dioxide concentration from Law Dome and WAIS Antarctica ice cores (Ahn et al., 2012). (B) $\delta^{13}C$–CO_2 from the Law Dome and WAIS core, indicating strong land uptake of CO_2 in the 16th century in the well-sampled WAIS core (Bauska et al., 2015). (C) Methane concentration from Law Dome and WAIS Antarctica ice cores (Ahn et al., 2012). (D) Estimated human population in Central and South America (Krumhardt, 2011). (E) Carbon monoxide from a South Pole ice core, a proxy of Southern Hemisphere biomass burning (Wang et al., 2010). (F) Charcoal composite, indicating biomass burning, using 100-year smoothed Z-score anomalies (Power et al., 2013). (G) Estimated anthropogenic land cover in Central and South America (Kaplan et al., 2011). (H) Dust in a Peruvian ice core from the 1600 Huaynaputina eruption (Thompson et al., 2013).

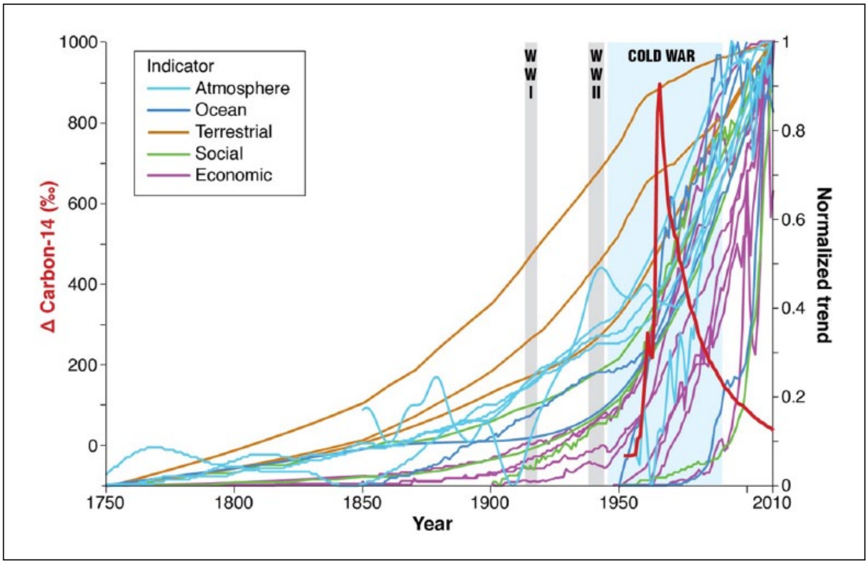

Figure 4. Data representing the Great Acceleration plus superimposed 1964 peak in radionuclide fallout.
Source: All data from Steffen et al. (2015) were normalised, right axis. Radiocarbon from nuclear weapons testing, relative to an international standard, from Rakowski et al. (2013), left axis.

Defining the Anthropocene framework, part II: Select a specific time period/event

Lewis and Maslin (2015) highlighted that it is difficult to objectively select between the Orbis or Great Acceleration GSSP proposals without further research. More generally, some process is required to select between any two or more time periods/events that fit GSSP requirements. What is required is a second part of a framework for defining the Anthropocene: transparent and objective criteria with which to compare events/time periods and relevant markers to assess which, if any, may be considered clearly preferable. In Zalasiewicz et al. (2015c) the AWG members suggest that the Great Acceleration is 'optimal' stratigraphically, yet unfortunately nowhere do they define 'optimal'. We suggest it ought to be a task of the AWG to establish the criteria from which to transparently and objectively compare differing evidence. Here we begin that process.

To fully comply with GSSP requirements more research than that presented in Lewis and Maslin (2015) is required. We propose four possible criteria to potentially distinguish the Orbis Hypothesis, Great Acceleration, and any others that we may have missed in our evidence review.

1. Are there at least six stratigraphic deposits spanning the low-, mid- and high-latitudes, Northern and Southern Hemispheres, and from terrestrial, marine and polar environments, showing globally correlated changes? (Following the example of the Holocene Epoch GSSP ratified proposal, Walker et al., 2009.)
2. Are each of these six or more stratigraphic deposits stratigraphically complete, that is with adequate thickness before and after the event, and show no obvious hiatuses across the boundary? (Following the most important criticism of utilising GSSPs for boundaries: incompleteness of records, see Smith et al., 2014.)

3. Are each of these six stratigraphic deposits preserved and accessible to researchers? (Following a second criticism of some past GSSP decisions; Smith et al., 2014.)
4. Select the boundary that includes the clearest long-term change that is near-permanent on the scale of millions of years (to identify changes on geological timescales relevant to epochs).

While the Earth System changes in the 17th century are obviously smaller than those in the late 20th century we suspect both the Orbis and Great Acceleration time periods will likely pass all of these criteria. One possible exception to this is the correlation in marine environments, as sediments take time to settle, so these may not have adequate thickness after the mid- to late-20th century. This may then exclude the Great Acceleration as a possible beginning of the Anthropocene Epoch, as global correlation would be lacking. This requires more investigation. We suspect the only long-term changes that are near-permanent on the scale of millions of years are species extinctions (not usually used as GSSP markers) and the cross-continental and cross-ocean basin movement of species (analogous to new species) and resulting new hybrid species (Thomas, 2013; often used as GSSP markers, see Smith et al., 2014).

One way of choosing between any two or more qualifying and very close, in geological time, time periods is to return to the question of what the ‘signal’ a boundary such as the beginning of the Anthropocene Epoch is attempting to illustrate. If the view is that human activity represents a force of nature, similar to other forces of nature, such as meteorite strikes, plate tectonic changes or abrupt climate change via sustained volcanic eruptions, and it is this that is driving Earth to a new state, then the signal is the impact of human activity on the Earth System once it reaches a global level. Thus the first time period/event that adheres to GSSP requirements should be used as this captures the *complete* human signal from an Earth System perspective. We therefore strongly believe that the first change that fits the criteria of a GSSP definition of a geological time unit should be chosen.

Another approach is to choose the appropriate time period on ‘practicality’, a rarely defined term, but often meaning better correlation potential. If this is the case – choosing amongst events with global correlation – then all potential time periods should be appraised on an identical basis to assess which has the better correlation potential. However, while correlation is essential in deep-time to match markers, for the near past an emphasis on practicality is itself of limited practical use. Given today’s high-resolution dating techniques and the nearness in the past of both the 17th and 20th centuries such correlative exercises are rarely needed. Scientists will date their stratigraphic record, or use the scientific literature to correlate against local or regional events. They are unlikely to use a GSSP marker for correlation. The desire to improve the dating of sediment over the last decades or few hundred years is not itself an important reason to define the Anthropocene.

Other additional criteria to those we outline could be used, for example, selecting a boundary that fits the GSSP requirements but best fits a profound historical turning point in human history. Whichever criteria are used to distinguish events/time periods that each meet the global correlation and long-term change requirements must, in our view, be specified and published for community discussion.

1610 CE Orbis Spike proposed GSSP

The 1610 Orbis proposal is based on a long-term change to the Earth, due to the irreversible exchange of species across continents and ocean basins following the arrival of Europeans in the Americas and subsequent globalisation of trade (Crosby, 2003; Mann, 2011; Pomeranz, 2000). The key change is the two-way transfer of crop and domesticated animal species and later the establishment of naturalised and new hybrid species (Figure 2). This is geologically unprecedented, and the evolutionary legacy of these species movements unambiguously sets the Earth on a new trajectory. The evolutionary consequences of these changes will be one of the few clearly visible changes to Earth over the typical timescale of an epoch of millions of years that can be recorded today.

However, Zalasiewicz et al. (2015b) suggest that the ‘global biostratigraphic signal from the colonizing of the Americas remains incompletely documented’, and we agree that more research is needed to document the first occurrence of fossil pollen and/or phytoliths or other long-lived fossilised plant remains on a new continent. Yet, we consider that this holds great potential, in the same way that new species have been used to recognise other transitions from one epoch to another. These crop movements are human-caused, near-permanent and geologically unprecedented. For example, after ~1600 maize pollen is found in at least 70 marine and lake sediments in Europe (from the European Pollen database, see Lewis and Maslin, 2015). Similarly, the arrival of cassava/manioc in Africa and banana in the Americas, both likely indicated by the presence of phytoliths, should provide further stratigraphic evidence, as does the later arrival of wheat in North America. Following modern advice we do not suggest maize arrival in Europe as the primary GSSP because, like all biostratigraphic markers, the near-global appearance of a new species is always diachronous (Gradstein et al., 2012; Smith et al., 2014). Lewis and Maslin (2015) proposed a new approach to investigating and documenting one of only a few identified human-induced changes to the Earth System that places it onto a permanently new trajectory. More research will be required to fulfil its potential.

Zalasiewicz et al. (2015b) suggest the global atmospheric CO_2 decline does not match the Americas’ population decline, as some of the population loss continues until 1650, therefore the decline in CO_2 should continue until at least then, ‘which is not seen in the ice core data’. Both the Law Dome and WAIS ice cores in fact show a CO_2 decline from ~1550 to beyond 1650 (Figure 3A). The difference between the two is the superimposed ‘extra’ 3 ppm on the Law Dome core (hence reports of 7–10 ppm declines; Ahn et al., 2012). Zalasiewicz et al. (2015b) also note that as atmospheric CO_2 integrates global changes in population and land cover, the CO_2 minima would occur after 1610. Considering the data in Figure 3(A), the WAIS data conform to a later minima, as does the Law Dome data, aside from the superimposed ‘extra’ 3 ppm drop centred on 1610. Zalasiewicz et al. (2015b) also suggest the decline may be caused by ocean circulation changes. However, changes in $\delta^{13}C–CO_2$ in the high-resolution Antarctic WAIS ice-core indicate that the land and not the oceans are the main driver of atmospheric CO_2 over the period 755–1850, as do other $\delta_{13}C–CO_2$ records (Bauska et al., 2015). This land carbon uptake pattern is in line with global population and the carbon impacts from the resultant land-use change over the period 1500–1650 (Bauska et al., 2015; Kaplan et al., 2011). In Figure 3 we add relevant data showing the coincident Americas population reduction, decline in fire frequency and/or intensity, modelled land-cover change, increase in land carbon storage and resulting decline in atmospheric CO_2 (i.e. each step from population reduction to CO_2 decline). It is therefore difficult to construct an alternative plausible scenario to explain the CO_2 drop without, at least in part, invoking human activity.

Finally, Zalasiewicz et al. (2015b) suggest that the global temperature change at the coolest part of the ‘Little Ice Age’ may not provide stratigraphic markers, but Lewis and Maslin (2015) listed 11 different candidate stratigraphic records. A number of correlated changes can be seen in Figure 3, alongside the coincident Huaynaputina eruption, itself recorded globally, showing this concern is unfounded (space precludes showing more in this paper such as speleothem $\delta^{18}O$ in China, e.g. Wang et al., 2005; and see references in Lewis and Maslin, 2015).

While the case for human activity being at least a contributory factor in the 7–10 ppm decline in CO_2 is fairly clear, a better primary GSSP marker may now be available from more recent research. The record of $\delta^{13}C$–CO_2 from the WAIS Antarctic ice-core becomes less negative, implying a steep increase in land carbon uptake beginning at ~1500 and ending at ~1610 CE (Bauska et al., 2015). This may improve upon CO_2 as the primary GSSP marker as it is more directly related to the uptake of carbon on land. An additional reason for favouring the $\delta^{13}C$–CO_2 record is the currently unexplained difference between the two high-resolution Antarctic ice core CO_2 records (Figure 3A). It was previously considered that the Law Dome record was of higher resolution, hence explaining the discrepancy between the Law Dome and WAIS cores, as noted in Ahn et al. (2012); this motivated our choice of GSSP. However, newer results suggest that both ice cores have similar resolution (Mitchell et al., 2015). Thus while both show an abrupt decrease of ~7 ppm beginning after 1550, the Law Dome presents a further superimposed 3 ppm CO_2 drop at 1610, whereas the WAIS core shows a continuing decline but lacks this feature (Figure 3A). Additional measurements are currently required to ascertain why this 3 ppm difference occurs in one core, and not the other, at that time (S Marcott, L Mitchell and T Bauska, personal communication, May 2015).

To summarise, given the major changes to the Earth System after 1610, including near-permanent changes following the Colombian Exchange, and all the changes associated with the Industrial Revolution, and that no clearly discernable permanent global change to the Earth System is clearly documented prior to this date, 1610 is a reasonable potential GSSP boundary for the Anthropocene. Concerns that the signal is small compared with the entire change from Holocene to Anthropocene are based on a misunderstanding of GSSP boundary markers, while concerns that human activity may not have been at least a partial driver are unfounded (and a surprising argument given Zalasiewicz et al., 2011a state that the cause of any change, in their view, is irrelevant to its use as a marker of change), and queries about the number of other correlated markers are misplaced. However, much more work is clearly required to fully document the stratigraphic legacy of the Colombian Exchange and the homogenisation of Earth's biota.

1964 CE Bomb Spike proposed GSSP

The conditions of the atmosphere, oceans and land-surface in the latter half of the 20th century suggest a likely departure from the bounds of variability within the current interglacial (e.g. Stocker et al., 2013). Some of these conditions represent very long-lived changes of geological import, including accelerated species movement among continents, the delay of the next glacial inception, and the legacy of nuclear explosions. Lewis and Maslin (2015) selected as a potential primary GSSP marker the 1964 peak in radionuclide fallout, specifically ^{14}C in temperate tree rings, as this event has global correlation, can be dated to an unambiguously annual resolution, and provides the best correlation potential with other radionuclide species.

First, Zalasiewicz et al. (2015a, 2015b) disagree with the suggestion that the peak radionuclide can be used as a GSSP marker stating, 'it is more conventional, and usually more practical in terms of worldwide correlation, to place a boundary based on chemical or isotopic excursion at the beginning, rather than at the peak, of such a major geochemical change in strata'. Hence they argue that a GSSP defined boundary should be placed at the beginning of the excursion, which defines the 'golden spike', instead of the suggested peak in radionuclide fallout. However, this is an incorrect interpretation of the two deep-time examples they give, and is false when considering more recent 'non-deep time' GSSP ratifications.

The first example they give is the base of the Cenozoic Era, Paleogene Period, Paleocene Epoch and Danian Stage which is defined at the reddish layer at the base of the ~50 cm thick, dark boundary clay in a tributary of the Oued Djerfane, west of El Kef, Tunisia, where it coincides with the Iridium Anomaly fallout from a major asteroid impact (http://www.stratigraphy.org/GSSP/Danian.html). The boundary is defined by the red clay layer which contains the iridium peak, *not* the start of the rise in iridium as Zalasiewicz et al. (2015a, 2015b, 2015c) claim. Their second example is the base of the Eocene Epoch and Ypresian Stage, which is defined in the Dababiya Section, near Luxor, Egypt, at the base of a lithostratigraphic unit where the initiation of the Carbon Isotope Excursion is recorded (http://www.stratigraphy.org/GSSP/Ypresian.html). In fact it is the base of the lithostratigraphic unit that contains the carbon isotope excursion, *not* the start of the excursion itself that defines the epoch, as Zalasiewicz et al. (2015a, 2015b) claim.

If we then move to the definition of the Quaternary Period, Pleistocene Epoch and Gelasian Stage then this boundary is defined as the *top* of a sapropel called MPRS 250 (http://www.stratigraphy.org/GSSP/Gelasian.html) which is found in the Monte San Nicola Section located on the southern coast of Sicily (Italy). A sapropel is a dark organic-rich layer found in marine sediments, due to a reduction in the oxygen content of the bottom waters. Sapropels are common within Mediterranean marine sediments. The Monte San Nicola sapropel MPRS 250 GSSP is dated at 2.588 Ma and occurs close to the end of a prolonged cooling interval which led to the onset of Northern Hemisphere glaciation (Maslin et al., 1998). The fact that this GSSP occurs in a warm stage (MIS103) has little overall consequence for the widely agreed concept of the Quaternary, namely the onset of major glaciation in the Plio–Pleistocene (Gibbard and Head, 2010). Again, the boundary is not marked by the beginning of an excursion.

The Holocene Epoch GSSP, which is probably the best analogy to any Anthropocene GSSP, is defined as an inflection point, which shows the clearest signal of climatic warming in the North Atlantic region at the end of the Younger Dryas. Overall, the Zalasiewicz et al. (2015b) justification that the boundary of the Anthropocene is located at the start of the Bomb Spike radio-carbon excursion is an incorrect interpretation of how GSSPs have been defined. There is no simple 'convention' in placing GSSP boundaries at the first sign of geochemical change in a stratigraphic deposit. Alternatively, if the Bomb Spike is viewed essentially as a human-induced 'volcanic eruption' the use of peak fallout has obvious precedent.

The real justification for Zalasiewicz et al. (2015b) not agreeing with using the 1964 peak radionuclide fallout as a marker is because 'the year 1964 is later than the near-synchronous upward inflections of many physical and socio-economic trends and their respective stratigraphic signals, which date to around 1950', which for evidence they cite Zalasiewicz et al. (2015c) and Steffen et al. (2015). In Figure 4 we plot the normalised changes for all the physical, biological and socio-economic trends reported in Steffen et al. (2015). It is unclear visually, in the absence of the Bomb Spike, exactly where a data-driven choice of Great Acceleration boundary should be placed. Regarding only those data-sources that derive from stratigraphic records (the five atmospheric records plus ocean acidification), it becomes even less clear, particularly as CO_2 has been rising for ~200 years, global air temperature did not increase in the 1950s and 1960s, and global temperature changes are often key drivers of other changes in stratigraphic deposits. Some clear stratigraphic data-driven procedure for defining the beginning of the Great Acceleration is likely necessary. Alternatively, as we state in Lewis and Maslin (2015), the radionuclide signal is not an Earth-changing event, so either the beginning of the signal in the 1950s or the peak in 1964 is merely a coincidence. In our view the radionuclide fallout ought to be seen akin to a volcanic eruption, a short-term, global and therefore useful marker coincident with the Great Acceleration – but it should be clearly noted that it lacks a causal relationship to the acceleration of changes to the Earth System in the second half of the 20th century.

Additionally, Zalasiewicz et al. (2015b) noted that: ‘living wood may not be universally accepted’ as a stratigraphic material. Crucially, the samples are composed of dead material. Trees in Europe exist from before 1945 so there is no difficulty in sampling them prior to the first nuclear explosion. They can be preserved for thousands of years suggesting they would be accepted just as glacier ice or ocean cores are now used (e.g. see Smith et al., 2014). Next Zalasiewicz et al. (2015b) state that the ‘excess radiocarbon signal is diachronous and inconsistent’, because the fallout in the Northern Hemisphere is generally in 1963–1964 and in the Southern Hemisphere in 1964–1965. This view contradicts the statements in Zalasiewicz et al. (2015c): ‘Some of these signals (e.g. the radionuclides) are in effect globally synchronous’. Furthermore, in the same paper they state, ‘we propose that the beginning of the nuclear age, that led to dispersal of artificial radionuclides worldwide, may be adopted as an effective stratigraphic boundary in Earth history. These radioisotopes appear in ice at both poles and on all continents’. The ‘inconsistency’ noted in Zalasiewicz et al. (2015b), but not in Zalasiewicz et al. (2015c), is related to the possible lack of accurate correlation in extremely young marine sediments. We agree that if there is a lack of any correlation for 70% of the Earth’s surface this would likely mean that a Great Acceleration GSSP proposal could not be completed. However, other radionuclide species such as 239-Plutonium likely persist in marine sediments (Ketterer et al., 2004).

Surprisingly, Zalasiewicz et al. (2015b) state that marine sedimentary deposits are ‘the typical setting within which most, though not all, GSSPs are defined’. This statement is flatly false: almost all ratified primary GSSP markers are on ‘rocky outcrops’ (Smith et al., 2014: figures 2, 3 and 4). Finally, Zalasiewicz et al. (2015b) then suggest that other radionuclide species may be a better choice, based on a longer half-life. Lewis and Maslin (2015) suggested selecting these as secondary markers as they are likely to be less precisely dated than ^{14}C in tree-rings (Fehn et al., 1986; Ketterer et al., 2004). To summarise, we see no compelling reason why the 1964 peak in radionuclide fallout as ^{14}C in annual tree-rings should be discounted as a possible primary marker of a formal definition of an Anthropocene Epoch.

Human narratives

In a section at the end of Lewis and Maslin (2015) termed ‘The wider importance’, we discussed how the choice of either 1610 or 1964 may affect ‘the perception of human actions on the environment’. We did this only *after* completing a review of ‘anthropogenic signatures in the geological record against the formal requirements for the recognition of a new epoch’ as the abstract stated. Zalasiewicz et al. (2015b) assert that the social or political ‘arguments regarding nuclear weapons testing, and the related international treaties’ were a ‘key factor’ in our choice of the peak of ^{14}C in temperate tree-rings as the beginning of the Anthropocene. We reject this. The reasoning behind our choice is clearly stated in Lewis and Maslin (2015) and repeated again, above. Moreover in Maslin and Lewis (2015) we restate the warning given by Lewis and Maslin (2015) that political and other societal considerations ideally should not be part of the decision-making process of defining any formal Anthropocene Epoch, or should be made explicit. Indeed, we noted that such considerations have been deeply problematic in the past, leading to the anomaly that the Holocene Epoch was ratified even though it does not differ in important ways from other Pleistocene interglacials (until the impacts of human activity become apparent).

We are concerned that the AWG publications of Zalasiewicz et al. (2015a, 2015b, 2015c) including the majority of the AWG members marks a change of approach from a facilitator role

Table 1. Results from poll of AWG members when asked when they considered the Anthropocene began conducted in early 2015 (Waters C, AWG secretary, personal communication, 21 April 2015).

	No response	Diachronous boundary	Synchronous: unspecified	Synchronous: Palaeoanthropocene	Synchronous: Industrial Revolution	Synchronous: mid-20th century	1945 age	1945 or mid-century
No. votes	13	2	1	1	1	7*	2	4

Note: *additionally two members stated mid-20th century with a question mark.

encouraging the publication of Anthropocene-relevant material, to an advocacy group publicising certain ideas and attempting hasty dismissal of other ideas. We view this as perplexing and dangerous. Prior to Zalasiewicz et al. (2015c) the AWG had organised the publication of a special issue of *Philosophical Transactions of the Royal Society A* (Zalasiewicz et al., 2011b), and a *Geological Society of London Special Publication* (Waters et al., 2014). They contained 30 papers, some by AWG authors, some not, and no papers had more than four AWG members as authors. None of these publications could be viewed as the 'voice' of the AWG, unlike Zalasiewicz et al. (2015c) where the view of the AWG was made publically explicit (e.g. Zalasiewicz and Williams, 2015). The AWG was convened by the International Commission on Stratigraphy (ICS), like other boundary working groups, to openly and without bias consider all the data and arguments and produce a view within a specified time period. The recent papers by members of the AGW would appear to have strayed away from this remit.

Downsides to a formal grouping of scientists adopting collective advocacy positions are well-known and are described and explained by Realistic Group Conflict Theory, where out-groups are judged to differing criteria compared with the in-group (Baumeister and Vohs, 2007; Whitley and Kite, 2010). The rapid-fire responses (Zalasiewicz et al., 2015a, 2015b) to Lewis and Maslin (2015) appear in line with theoretical expectations from social psychology. Surprisingly, the in-group collective opinion of the AWG, as presented by Zalasiewicz et al. (2015c), of a 1945 GSSA to begin the Anthropocene Epoch is actually far from the collective view of the AWG. Zalasiewicz and Williams (2015) stated: '26 of the 38 members on the panel agreed that July 16, 1945, the date of the world's first nuclear test, is a "practical and effective" choice' to begin the Anthropocene. By contrast, a poll of the AGW *after* the publication of Zalasiewicz et al. (2015c) but *before* Lewis and Maslin (2015), asked the question of when the Anthropocene began: only two members selected 1945, see Table 1. The publication of conclusions that only a small minority of the AWG appear to agree upon ought to be deeply concerning. This is evidence that the recent AWG publications are being judged to differing standards to others' papers, in line with Realistic Group Conflict Theory.

To avoid these types of problems in the future we suggest the AWG return to operating along similar lines to other International Commission on Stratigraphy Boundary working groups and major scientific committees such as the Royal Society or National Academy of Sciences working groups, or the Intergovernmental Panel on Climate Change (IPCC). These collate the scientific evidence and publish definitive reports; they do not publish a commentary every time a group of scientists publish a paper that is not in line with their favoured hypothesis.

Conclusion

Scientists are in general agreement that we live in the Anthropocene, a human-dominated geological time unit. One key question, as the Earth has been altered from a state of being unaffected by human activity towards a different future state, is where to place a boundary maker to separate the old geological time and the new (Figure 1). In many ways this is no different from any other Phanerozoic boundary definition, with rules (GSSPs), scientific evidence, debates and a committee (the AWG) to sift the evidence and arrive at a view.

Zalasiewicz et al. (2015c) state, 'As members of the Anthropocene Working Group, we contend that the proposed new geological epoch should reflect a unique stratigraphic unit that is characterized by unambiguous, widespread and essentially permanent anthropogenic signatures …'. We agree: our two-step framework operationalises that sentiment. Step one is to screen the available evidence against current GSSP requirements (Gradstein et al., 2012; Smith et al., 2014) to identify time periods that likely comply with geological GSSP boundary markers in a similar way to recently ratified GSSP boundaries such as the Holocene Epoch (Walker et al., 2009). In our view this includes the identification of required research to improve the evidence base for potential candidate time periods. Step two is then to generate and agree on objective criteria with which select a single GSSP time period to become the GSSP boundary of the Anthropocene.

Our review in Lewis and Maslin (2015) noted that the Colombian Exchange – the irreversible cross-ocean movement of species – is one of the very few human-induced changes that is likely captured today in stratigraphic records and is a near-permanent change to Earth (Figure 2). The evolutionary repercussions will be obviously visible for the millions of years, as the Earth System is now on a new trajectory. We consider this and the associated drop in CO_2, less negative $\delta^{13}C$–CO_2, and stratigraphic impacts of the Huaynaputina eruption all near 1610 CE are worthy of further investigation as a possible GSSP boundary (Figure 3). Zalasiewicz et al. (2015a, 2015b) state their primary concern that the drop in CO_2 is 'not outside the range of natural Holocene variability'. This concern is easily dismissed: the Holocene Epoch is defined by 2H (deuterium) excess, in which neither the value or absolute range change across the inflection is outside the range of 2H values in the prior epoch, the Pleistocene.

We also noted that the second half of the 20th century, with the great number, scale and variety of long-lived changes to the Earth System, likely fits the GSSP requirements, with the 1964 peak in radionuclide fallout from weapons testing being a useful marker (Figure 4). Surprisingly, Zalasiewicz et al. (2015a, 2015b) state their primary concern with this marker is that the beginning rather than peak fallout should be utilised as a marker, based on an assertion of geological convention. However, this is based on a misreading of the GSSP literature: there is no such convention.

Overall, there is no evidential reason why both the 1610 and 1964 proposals should not be further developed. As the AWG is mandated to review all the evidence that may contribute to a formal proposal for an Anthropocene Epoch in a critical, open and transparent way, we hope the AGW will fulfil this role.

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Note

1. The AWG was initiated by the International Commission on Stratigraphy to collate, assess and evaluate the evidence for recommending (or not) the formal definition of the term ‘Anthropocene’ for possible incorporation into the Geologic Time Scale.

References

Ahn J, Brook EJ, Mitchell L et al. (2012) Atmospheric CO_2 over the last 1000 years: A high-resolution record from the West Antarctic Ice Sheet (WAIS) Divide ice core. *Global Biogeochemical Cycles* 26: GB2027.

Baumeister RF and Vohs KD (2007) Realistic group conflict theory. *Encyclopedia of Social Psychology* 2: 725–726.

Bauska TK, Joos F, Mix AC et al. (2015) Links between atmospheric carbon dioxide, the land carbon reservoir and climate over the past millennium. *Nature Geoscience* 8: 383–387.

Crosby AW (2003) *The Columbian Exchange: Biological and Cultural Consequences of 1492*. 30 Year Edition. Westport, CT: Preager.

Crutzen PJ (2002) Geology of mankind. *Nature* 415: 23.

Crutzen PJ and Stoermer EF (2000) The Anthropocene. *IGBP Global Change Newsletter* 41: 17–18.

Diamond J (1997) *Guns, Germs and Steel: A Short History of Everybody for the Last 13,000 Years*. London: Chatto & Windus.

Dull RA, Nevle RJ, Woods WI et al. (2010) The Columbian encounter and the ‘Little Ice Age’: Abrupt land use change, fire, and greenhouse forcing. *Annals of the Association of American Geographers* 100: 755–771.

Fehn U, Holdren GR, Elmore D et al. (1986) Determination of natural and anthropogenic I-129 in marine-sediments. *Geophysical Research Letters* 13: 137–139.

Gibbard PL and Head MJ (2010) The newly-ratified definition of the Quaternary System/Period and redefinition of the Pleistocene Series/Epoch, and comparison of proposals advanced prior to formal ratification. *Episodes* 33: 159–163.

Gradstein FM, Ogg JG, Schmitz MD et al. (2012) *The Geologic Time Scale 2012*. Oxford: Elsevier, pp. 1175.

Kaplan JO, Krumhardt KM, Ellis EC et al. (2011) Holocene carbon emissions as a result of anthropogenic land cover change. *The Holocene* 21: 775–791.

Ketterer ME, Hafer KM, Link CL et al. (2004) Resolving global versus local/regional Pu sources in the environment using sector ICP-MS. *Journal of Analytical Atomic Spectrometry* 19: 241–245.

Krumhardt KM (2011) Methodology for worldwide population estimates: 1000BC to 1850. *ARVE Technical Report* 3. Available at: http://arve.unil.ch/pub/ARVE_tech_report3_pop_methods_2010.pdf.

Lewis SL and Maslin MA (2015) Defining the Anthropocene. *Nature* 519: 171–180.

Mann CC (2011) *1493: How the Ecological Collision of Europe and the Americas Gave Rise to the Modern World*. London: Granta.

Maslin MA and Lewis SL (2015) Earth system, geological, philosophical and political paradigm shifts. *The Anthropocene Review*. DOI: 10.1177/2053019615588791.

Maslin MA, Li X-S, Loutre M-F et al. (1998) The contribution of orbital forcing to the progressive intensification of Northern Hemisphere glaciation. *Quaternary Science Reviews* 17: 411–426.

Mercuri AM, Mazzanti MB, Torri P et al. (2012) A marine/terrestrial integration for mid–late Holocene vegetation history and the development of the cultural landscape in the Po valley as a result of human impact and climate change. *Vegetation History and Archaeobotany* 21: 353–372.

Mitchell LE, Buizert C, Brook EJ et al. (2015) Observing and modeling the influence of layering on bubble trapping in polar firn. *Journal of Geophysical Research: Atmospheres* 120: 2558–2574.

Neukom R, Gergis J, Karoly DJ et al. (2014) Inter-hemispheric temperature variability over the past millennium. *Nature Climate Change* 4: 362–367.

Nevle RJ, Bird DK, Ruddiman WF et al. (2011) Neotropical human–landscape interactions, fire, and atmospheric CO_2 during European conquest. *The Holocene* 21: 853–864.

Pomeranz K (2000) *The Great Divergence: China, Europe, and the Making of the Modern World Economy.*, Princeton, NJ: Princeton University Press.
Power MJ, Mayle FE, Bartlein PJ et al. (2013) Climatic control of the biomass-burning decline in the Americas after AD 1500. *The Holocene* 23: 3–13.
Rakowski AZ, Nadeau M-J, Nakamura T et al. (2013) Radiocarbon method in environmental monitoring of CO_2 emission. *Nuclear Instruments & Methods in Physics Research Section B-Beam Interactions with Materials and Atoms* 294: 503–507.
Ruddiman WF, Ellis EC, Kaplan JO et al. (2015) Defining the epoch we live in. *Science* 348: 38–39.
Smith AG, Barry T, Bown P et al. (2014) GSSPs, global stratigraphy and correlation. *Geological Society, London, Special Publications* 404: 37–67. Available at: http://dx.doi.org/10.1144/SP404.8.
Solomon S, Qin D, Manning M et al. (2007) *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.
Steffen W, Broadgate W, Deutsch L et al. (2015) The trajectory of the Anthropocene: The Great Acceleration. *The Anthropocene Review* 2(1): 81–98.
Steffen W, Grinevald J, Crutzen P et al. (2011) The Anthropocene: Conceptual and historical perspectives. *Philosophical Transactions of the Royal Society A: Mathematical Physical and Engineering Sciences* 369: 842–867.
Stocker TF, Qin D, Plattner G-K et al. (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.
Thomas CD (2013) The Anthropocene could raise biological diversity. *Nature* 502: 7.
Thompson LG, Mosley-Thompson E, Davis ME et al. (2013) Annually resolved ice core records of tropical climate variability over the past ~1800 years. *Science* 340: 945–950.
Walker M, Johnsen S, Rasmussen SO et al. (2009) Formal definition and dating of the GSSP (Global Stratotype Section and Point) for the base of the Holocene using the Greenland NGRIP ice core, and selected auxiliary records. *Journal of Quaternary Science* 24: 3–17.
Wang Z, Chappellaz J, Park K et al. (2010) Large variations in Southern Hemisphere biomass burning during the last 650 years. *Science* 330: 1663–1666.
Wang Y, Cheng H, Edwards RL et al. (2005) The Holocene Asian monsoon: Links to solar changes and North Atlantic climate. *Science* 308: 854–857.
Waters CN, Zalasiewicz JA, Williams M et al. (2014) *A Stratigraphical Basis for the Anthropocene*. Geological Society, London, Special Publications, Vol. 395.
Whitley BE and Kite ME (2010) *The Psychology of Prejudice and Discrimination*. Belmont, CA: Wadsworth.
Zalasiewicz J and Williams M (2014) The Anthropocene: A comparison with the Ordovician–Silurian boundary. *Rendiconti Lincei-Scienze Fisiche E Naturali* 25: 5–12.
Zalasiewicz J and Williams M (2015) First atomic bomb test may mark the beginning of the Anthropocene. *The Conversation* 30 January. Available at: https://theconversation.com/first-atomic-bomb-test-may-mark-the-beginning-of-the-anthropocene-36912.
Zalasiewicz J, Waters CN, Barnosky AD et al. (2015a) Colonization of the Americas, 'Little Ice Age' climate, and bomb-produced carbon: Their role in defining the Anthropocene. *The Anthropocene Review*. DOI: 10.1177/2053019615587056.
Zalasiewicz J, Waters C, Barnosky AD et al. (2015b) Epochs: Disputed start dates for Anthropocene. *Nature* 520: 436.
Zalasiewicz J, Waters CN, Williams M et al. (2015c) When did the Anthropocene begin? A mid-twentieth century boundary level is stratigraphically optimal. *Quaternary International*. Available at: http://dx.doi.org/10.1016/j.quaint.2014.11.045.
Zalasiewicz J, Williams M, Fortey R et al. (2011a) Stratigraphy of the Anthropocene. *Philosophical Transactions of the Royal Society A: Mathematical Physical and Engineering Sciences* 369: 1036–1055.
Zalasiewicz J, Williams M, Haywood A et al. (2011b) The Anthropocene: A new epoch of geological time? *Philosophical Transactions of the Royal Society A: Mathematical Physical and Engineering Sciences* 369: 835–841.

Perspectives and controversies

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The emergency framing of solar geoengineering: Time for a different approach

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Abstract

Solar geoengineering has been proposed as a possible response measure in the event of a 'climate emergency'. Scientific evidence for climate emergencies in the form of tipping points, however, is contested and unsettled. Furthermore, declarations of emergency entail authoritarian political tendencies that historically have given rise to repression and abuse. By definition, an emergency must exhibit a combination of high risk, urgency and necessity; no plausible climatic tipping point displays all these attributes simultaneously. A weak scientific basis together with genuine societal peril argues against the continued emergency framing of solar geoengineering.

Keywords

climate engineering, emergency framing, geoengineering

Over the past several years, solar geoengineering, also known as solar radiation management (SRM), has been presented to the public as a possible last-ditch response option in the event of a 'climate emergency' (Blackstock et al., 2009; Long et al., 2011). Many technical and scientific uncertainties remain, but the available evidence suggests that methods such as stratospheric aerosol injection (SAI), which theoretically would reflect a small but significant amount of incoming shortwave radiation sufficient to restore global mean temperatures to approximately preindustrial values, would act relatively quickly, possibly within months (Royal Society, 2009). The fast-acting nature of such measures would seem to make them especially suitable for urgent situations requiring quick action. In the climate context, such scenarios are commonly referred to as 'climate emergencies'.

Within the geoengineering research community itself, however, framing SRM in terms of a climate emergency has drawn increasing criticism from both opponents and advocates of more research. This criticism has been fragmented and disparate, originating from natural scientists,

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social scientists, philosophers and others. Yet while skepticism toward emergency framing has become increasingly uniform within the research community – even across otherwise contrasting disciplinary orientations and normative outlooks – viewing SRM through the lens of climate emergencies remains a primary mode of talking about geoengineering in both mainstream media and popular science accounts of this emerging field. In this brief article, I will bring together and consider the key objections to the emergency framing of solar geoengineering, and argue that this framing should be dropped from future public policy debates on managing climate risks.

Defining climate emergencies

In assessing the soundness and utility of the emergency framing, the starting point is an examination of the concept of 'climate emergency'. Put simply, climate scientists have no agreed definition of what would constitute a climate emergency, and are nowhere close to reaching consensus on the issue. When discussing 'emergencies', scientists and other researchers tend to have one of two physical phenomena in mind. The first of these is the so-called runaway greenhouse scenario, in which an atmosphere supersaturated with greenhouse gases (GHGs) restricts the emission of long-wave radiation to space, triggering positive feedbacks, boiling the oceans and transforming the Earth into a planet more like Venus. All available evidence indicates that such a scenario is squarely implausible (Goldblatt and Watson, 2012).

The second, more plausible 'emergency' scenario entails crossing a climate tipping point and thereby pushing a planetary subsystem into a qualitatively different state (Lenton et al., 2008). A number of possible tipping points have been identified, and indeed paleoclimatic data show multiple instances of abrupt, nonlinear changes in the climate system, for example, Dansgaard-Oeschger events (sudden, short-lived temperature increases) and Heinrich events (extreme, rapid declines in temperature). However, the Intergovernmental Panel on Climate Change (IPCC) in its Fifth Assessment Report (AR5) judged that few if any currently known potential tipping points are simultaneously abrupt, irreversible, and likely to be crossed this century (IPCC Working Group II, 2013). Another recent study put the related concept of 'planetary' tipping points in serious doubt (Brook et al., 2013). Even those researchers most closely associated with theorizing about tipping points stress the limitations of their models and the multitude of questions remaining to be answered (Lenton, 2013). In sum, scientific research into tipping points remains at an early stage, and existing evidence provides a decidedly weak foundation from which to argue that an emergency SRM intervention might be required.

Whether envisioned in terms of a runaway greenhouse effect or, more credibly, climate tipping points, what is clear is that the concept of 'climate emergency' is socially constructed. In other words, an emergency (climate or otherwise) is ultimately a shared idea, rather than objective reality. The climate system is of course replete with acute, high-risk events, but whether a given event is regarded as an 'emergency' depends entirely on how society defines 'emergency'. Moreover, a large number of social phenomena, ranging from crop failures and infrastructure collapse to 'climate refugee' crises and 'climate wars', might be blamed on climate change and labeled as 'emergencies' even in the absence of causal evidence. The attribution of physical effects to climate change is already highly contested, and conclusively attributing social outcomes to climate is even more controversial if not impossible. Either case begs the question, who would be empowered to define a climate emergency and determine whether a particular event qualifies as such?

The obvious candidates, as suggested by the above, are climate scientists or other qualified experts. And yet the apparent necessity of ceding some degree of decision-making authority over an issue as critical as planetary emergencies to a select group of specialized experts has led to criticism that emergency framing promotes technocracy (Heyward and Rayner, 2013). On this view, government by experts has the potential to erode democratic practices, and public policy framings that favor rule by technical experts over popular representatives should, at a minimum, be challenged.

Society and the 'state of exception'

A more systematic political objection to the emergency framing of solar geoengineering relates to the risks entailed in any declaration of emergency. Commentators have long noted that when public authorities declare emergencies, power is inevitably concentrated in the hands of a relative few, enhancing opportunities for abuse, at times on a grand scale. The transformation of ancient Rome from a Republic into an Empire stands as a paradigmatic case of this phenomenon. For centuries, the Republic's ordinary political institutions were periodically supplemented by the formal appointment of a dictator, who was granted near-absolute power to repel extraordinary foreign and domestic threats. Despite a system of safeguards intended to minimize the risk of abuse, the supremely powerful dictatorship eventually overwhelmed its institutional rivals in a process that culminated in the establishment of the Empire under Julius Caesar.

The authoritarian tendency inherent in states of emergency has been a point of contention among political theorists, particularly over the past century. Controversial German philosopher Carl Schmitt embraced the potential for decisive state action made possible by a 'state of exception' (Schmitt, 2014). But most liberal theorists, such as Italian philosopher Giorgio Agamben, have criticized emergency modes of government as fundamentally undemocratic (Agamben, 2005). During the Indian Emergency of 1975–1977, for instance, the purported need to quell 'internal disturbance' was used to justify widespread derogations of civil and political rights. Other episodes such as the emergency decrees issued under the Weimar Republic, Egypt's longstanding Emergency Law, and emergency rule under Augusto Pinochet in Chile substantiate concerns about the autocratic propensity of emergency proclamations. Indeed, for some observers, we now live in 'a world of emergencies' requiring constant vigilance in the face of endless invocations of emergency, crisis and catastrophe (Calhoun, 2004).

Many members of the incipient geoengineering research community have criticized the emergency framing of SRM for the socially corrosive ethical and political effects associated with the proclamation of emergency powers (Hulme, 2014). Similarly, researchers have also criticized this framing as based on underdeveloped scientific concepts and insufficient empirical evidence (Keith, 2013). However, as already noted, the climate system does periodically experience abrupt, nonlinear events, and at the same time, solar geoengineering methods such as SAI (*if* proven to work) appear to be the only climate policy tools available that could act effectively to address such risks on short notice. The question, then, is whether SRM should have any role to play in acute, high-risk situations that might be labeled 'climate emergencies'.

Conditions for emergency deployment

To answer this question, it is vital to specify exactly what is meant by 'emergency'. The concept of emergency is arguably composed of three key attributes:

1. *High risk*, or the possibility of significant loss – The stakes must be high, with a reasonable likelihood of occurrence and damages of potentially substantial magnitude.
2. A sense of *urgency* or immediacy – Circumstances must call for a rapid response.
3. A feeling of *necessity* – The response in question must be viewed as essential to avoiding loss.

Each of these attributes has an inescapably subjective element: what is 'significant' is in the eye of the beholder, while 'senses' and 'feelings' depend entirely on individual points of view. To repeat from above, the idea of emergency is ultimately a social construct. In the climate policy context, social construction and therefore subjective judgments about what constitutes an emergency encompass both the climatic phenomenon in question and possible responses to it.

As has been discussed, the most compelling scientific case for a phenomenon that might be regarded as a climate emergency is found in the literature on tipping points. Commentators have suggested many possible climate tipping points, but only about ten critical regional thresholds are regarded as plausible by the scientific community; these include collapse of the Atlantic Meridional Overturning Circulation, collapse of the Greenland or West Antarctic ice sheets, permafrost carbon release, clathrate methane release, tropical forest dieback, boreal forest dieback, disappearance of summer Arctic sea ice, long-term droughts and disruptions to monsoonal circulations (IPCC Working Group II, 2013). Among these potential tipping points, none is considered to be likely, highly damaging *and* abrupt (IPCC Working Group II, 2013). (The closest candidate is Arctic summer sea ice loss, but associated damages are seen as manageable.)

The climate system is, of course, unpredictable, and critical elements remain poorly understood. The possibility of a dangerous, previously unidentified tipping point or other climatic phenomenon cannot be ruled out completely, in which case solar geoengineering might still be an appropriate response strategy. Even in this situation, however, a number of additional questions must be answered satisfactorily in order to treat SRM as a viable emergency response option. Most importantly, and most obviously, is SRM feasible in terms of its efficacy and risks? Researchers have raised serious doubts regarding the very possibility of testing SRM short of full-scale deployment. However, micro- and meso-scale field trials involving process, scaling and climate response experiments should be capable of providing answers to many key questions about the intended and unintended impacts of solar geoengineering (MacMynowski et al., 2011).

Beyond this, and assuming SRM is shown to be viable, is SRM the only feasible tipping point response option and hence necessary to avoid significant loss, or are other options such as robust adaptation available? Has a critical tipping point threshold already been crossed? If so, is the ensuing change reversible? If not, are early warning signs of approaching tipping points available? Can they be detected? Only if convincing answers were provided to *all* these questions would it be appropriate for policymakers to consider solar geoengineering as a serious climate emergency response option. In practice, of course, answers to these questions will likely be difficult to provide, frustratingly imprecise and strongly contested.

Even if these hurdles were overcome, the acute sociopolitical risks associated with declarations of emergency would remain, and might well argue against emergency action despite the real dangers involved. These risks are not insurmountable, as a variety of institutional solutions are available to restrain concentrations of power, mitigate the risk of abuse and strengthen the liberal democratic underpinnings of otherwise unavoidable emergency government (Ferejohn and Pasquino, 2004). As a standard frame through which to consider the possible application of solar geoengineering techniques, however, a broad array of scientific and societal concerns counsels strongly against viewing SRM as a possible response to a climate emergency.

Better approaches

Other forms of deployment offer better rationales for the possible use of SRM in the future. The most common alternative, known as 'peak shaving', would entail application of SAI or some other type of solar geoengineering to reduce the worst effects of peak GHG emissions while implementing an ambitious program of mitigation and adaptation. One variant of peak shaving would involve a gradual ramp-up of solar geoengineering until a modest plateau is reached; as emissions declined, so too would injections of stratospheric aerosols (Keith, 2013). Another potential approach would utilize SRM on a regional scale, for example in the Arctic, in order to address specific, localized damages from climate change.

These and other deployment scenarios contemplate taking advantage of SRM's unique combination of high-leverage, fast-acting and low-cost (at least in direct terms) characteristics within well-defined limits, while avoiding reliance on unsubstantiated science, appeals to political expediency and the slippery slope of emergency rule. As Mike Hulme writes, 'Climate emergencies are made, not discovered, and what matters most is who announces them and for what purpose' (Hulme, 2014: 134–135). Based on current understanding, framing solar geoengineering as a possible a response to climate emergencies is both unwarranted and unwise. The time has come for the geoengineering research community and other interested parties to abandon this approach.

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References

Agamben G (2005) *State of Exception*. Chicago, IL: University of Chicago Press.

Blackstock JJ, Battisti DS, Caldeira K et al. (2009) *Climate Engineering Responses to Climate Emergencies*. Santa Barbara, CA: Novim.

Brook BW, Ellis EC, Perring MP et al. (2013) Does the terrestrial biosphere have planetary tipping points? *Trends in Ecology & Evolution* 28(7): 396–401.

Calhoun C (2004) A world of emergencies: Fear, intervention, and the limits of cosmopolitan order. *Canadian Review of Sociology/Revue canadienne de sociologie* 41(4): 373–395.

Ferejohn J and Pasquino P (2004) The law of the exception: A typology of emergency powers. *International Journal of Constitutional Law* 2(2): 210–239.

Goldblatt C and Watson AJ (2012) The runaway greenhouse: Implications for future climate change, geoengineering and planetary atmospheres. *Philosophical Transactions of the Royal Society A* 370(1974): 4197–4216.

Heyward C and Rayner S (2013) Apocalypse nicked! *Climate Geoengineering Governance Working Paper Series*. Oxford: ESRC.

Hulme M (2014) *Can Science Fix Climate Change?* Cambridge: Polity Press.

Intergovernmental Panel on Climate Change Working Group II (2013) *Climate Change 2013: The Physical Science Basis*. Cambridge: Cambridge University Press.

Keith D (2013) *A Case for Climate Engineering*. Cambridge, MA: MIT Press.

Lenton TM (2013) Can emergency geoengineering really prevent tipping points? *Geoengineering Our Climate Working Paper and Opinion Article Series*. Available at: http://geoengineeringourclimate.com/2013/06/25/can-emergency-geoengineering-really-prevent-climate-tipping-points-opinion-article/.

Lenton TM, Held H, Kriegler E et al. (2008) Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences* 105(6): 1786–1793.

Long J, Rademaker S, Anderson JG et al. (2011) *Geoengineering: A National Strategic Plan for Research on the Potential Effectiveness, Feasibility, and Consequences of Climate Remediation Technologies*. Washington, DC: Bipartisan Policy Center.

MacMynowski DG, Keith DW, Caldeira K et al. (2011) Can we test geoengineering? *Energy & Environmental Science* 4: 5044–5052.

Royal Society (2009) *Geoengineering the Climate: Science, Governance and Uncertainty*. London: Royal Society.

Schmitt C (2014) *Dictatorship: From the Origin of the Modern Concept of Sovereignty to Proletarian Class Struggle*. Cambridge: Polity Press.

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Anthropocene futures: People, resources and sustainability

Jasper Knight

Abstract

The sustainable use of environmental resources is an important tenet guiding future governance and management in the Anthropocene. However, the concept of sustainability is based on underlying assumptions of how sustainable development policies are formulated and applied. This commentary describes some of the flaws of 'sustainability' which are that (1) it requires full knowledge of the workings of Earth's multiple physical systems and their sensitivities; and (2) the structures and management tools used by societal actors have low adaptive capacity to address ongoing changes to the physical environment. This commentary considers that societal actors and their future roles are likely to emerge from changing economic patterns, community structures and geopolitical contexts over coming decades. This providing an alternative Anthropocene future to that which is commonly posited, and emphasizes the use and limitations of sustainable development and the societal actors that are concerned with it.

Keywords

Anthropocene, climate change, environmental governance, environmental management, resources, sustainability

Introduction

Although the Anthropocene is widely acknowledged as a new epoch of both Earth's geologic history and in the ongoing narrative of humankind's relationship with the Earth (Zalasiewicz et al., 2011), there are significant problems in the ways in which these relationships can be framed and then evaluated. In part this is because different types of human activity intersect with different components of Earth's wider system, and in different ways, which yields complex spatial and temporal patterns with significant feedbacks (Knight and Harrison, 2012; Rosenzweig et al., 2008). It is also due in part to the different ways in which different institutions and communities, termed societal actors, develop and enact policies that deal with the use and

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management of different types of environmental resources (Kim and Oki, 2011; Miller et al., 2014). Often, these societal actors use inappropriate methods or unfounded assumptions in the evaluation of environmental resources, and in identifying the best ways to sustainably develop these resources (Haasnoot et al., 2011; Springett, 2013).

These uncertainties mean that there are significant limitations in the extent to which societal actors can respond to the challenges of environment resource management and sustainability in the Anthropocene. For example, Berkhout (2014) argues that societal actors and international structures and institutions can respond adequately to these challenges through capacity-building and increasing resilience. However, whilst people by definition are at the heart of the Anthropocene, the viewpoint that capacity-building by present societal structures is outdated in its approach and conservative in its framing of the future (e.g. Benessia et al., 2012; Lozano, 2014). This is because this viewpoint does not consider in an integrated way the likely changes taking place in the physical and human environments over coming decades. For example, predicted futures patterns of water resource availability and use is dependent on climate, hydrological and ecological model outputs; yet this is seldom matched with predicted future patterns of population growth, socio-economic changes, geopolitical context and land-use change (cf. Bhullar, 2013; Haasnoot et al., 2011; Haie and Keller, 2012). As a consequence, this viewpoint of societal capacity-building does not effectively frame the future contexts of both sustainable development and international governance, or present alternative viewpoints of the future trajectory and management of the Anthropocene world. Framing the future through the scientific and political norms of the past (Benessia et al., 2012) may therefore not offer the best way of understanding and managing this future Anthropocene world.

This present commentary takes a different approach to considering Anthropocene futures, by (1) critiquing the viewpoint that sustainability and existing governance structures are capable of framing such futures, and (2) by proposing alternative ways by which to frame the organization of society(ies) in the Anthropocene and thus who future 'societal actors' may be.

Sustainability and Earth Systems

The concept of sustainability is central to many viewpoints of human–environment relationships and in the context of emerging climate adaptation strategies in the Anthropocene (Hirvilammi and Helne, 2014; Jerneck et al., 2011; Springett, 2013). This concept is based on the assumption that resources used directly or indirectly by humans are knowable, quantifiable and finite; that resource use (i.e. the rate of resource depletion) is quantifiable; and that the mechanisms by which resources are used are capable of management or regulation. In practice, none of these things is true (Zaccai, 2012). As a result, the application of the concept of sustainability to issues of resource use and management is fundamentally flawed (Arias-Maldonado, 2013; Benson and Craig, 2014). Despite this, sustainability science still lies at the heart of issues of resource use in the Anthropocene (e.g. Jerneck et al., 2011; Miller et al., 2014; Springett, 2013), in particular within the context of adaptation to changing resource patterns under climate change (Eakin and Patt, 2011; Wise et al., 2014).

The science of sustainability (as opposed to sustainability science) must be grounded in the workings of the physical world, which can be conceptualized most usefully in the context of Earth Systems. This latter term refers to the organizational structure and processes through which different component systems of Earth's physical world work (Knight and Harrison, 2012; von Elderfeldt, 2012). These component systems include the water (hydrological) cycle, weather and climate system, biogeochemical cycles (including carbon, nitrogen, phosphorus, sulphur), biosphere and sediment system (Rockström et al., 2009). All of these components are driven through the movement of mass and energy over different spatial and temporal scales, and the net result of this movement can be measured and monitored indirectly though the biological, chemical and physical changes that take place in the environment. A complicating factor is the set of properties that characterizes all types of systems and the ways in which systems operate. These properties include equifinality, equilibrium, feedback, hysteresis, relaxation time and thresholds (defined in Knight and Harrison, 2014). These properties are important because they help account for why individual Earth Systems, such as those named above, are characterized by nonlinearity and complexity (i.e. have low predictability), which make them inherently difficult to manage, either individually or in combination. This is relevant to the issue of sustainability because it means that we cannot be sure that any one way of managing a resource, such as water flow in a river, is inherently 'better' than any other way. For example, although rates of groundwater depletion can be calculated with some precision, calculating the rate at which extraction can take place 'sustainably' is more difficult because there are multiple variables involved which have different spatial and temporal contexts (e.g. Liebminger et al., 2007). In other cases, such as with soil erosion, management options are clearer to identify, their impacts can be better measured, and thus over some scales 'sustainability' of these resources can be achieved (Montgomery, 2007).

In addition, anthropogenic intervention in the workings of different Earth Systems, and the feedbacks between and within these systems and with human activity, show that not all systems work in the same way, and that some systems are inherently more sensitive to be affected by human pressure and/or climate change in the Anthropocene epoch than others (Rockström et al., 2009; Rosenzweig et al., 2008). Although this provides the justification for why sustainable management of Earth resources is needed, it also shows why 'sustainable management' is flawed in practice.

Several recent studies have argued that (un)sustainable development in the exploitation of environmental resources poses issues with respect to how such resources are managed by societal actors (Berkhout, 2014; Chin et al., 2014; Miller et al., 2014). Whilst it is true that many different societal actors can impact on the ways in which environmental resources are managed and on different scales, these management frameworks can only be as good as our knowledge of the entity that is being managed. Thus, a poor conception of what sustainability means in different environmental contexts is likely to result in inappropriate management practices being applied, irrespective of how efficient or organized those practices are (Fiksel, 2012; Springett, 2013). This shows that achieving sustainability and/or sustainable development in the Anthropocene requires two separate but related components: (1) a scientific understanding of the dynamics and behaviour of individual Earth Systems from which can be derived an evaluation of what 'sustainability' means in different environmental contexts; and (2) a management framework that is appropriate to the 'systems' context of the resource being managed. Only when these two elements have been achieved and integrated together can it be said that societal actors are managing resources sustainably.

The limitations of sustainability

Sustainability is commonly considered to be a primary goal of the interactions between human activity and the environment (Miller et al., 2014). As discussed above, there are significant limitations in the extent to which we can quantify environmental resources that are used directly and indirectly by human activity, and thus evaluate whether or not these are being used 'sustainably'. This means, as in the case of calculating carbon emissions, a budgetary sleight-of-hand can yield the result that managers or politicians are looking for (see discussion in Knight and Harrison, 2013). To this end, it is important to consider three successive questions:

- Sustainability of what?
- Sustainability for what purpose?
- How do we know if we are being sustainable?

These questions can be considered through the example of sustainable water use, which has been a commonly discussed issue in the literature. Here, the water system at a regional scale has been most commonly viewed as a supply–demand issue (Haasnoot et al., 2011; Walker, 1998) and therefore has a focus on infrastructure development in order to maximize water transfer efficiency (e.g. Haie and Keller, 2012; Margerum and Robinson, 2015). Although it is acknowledged that, to achieve this aim, appropriate governance structures need to be in place (Biggs et al., 2013; Gupta et al., 2013; Schoeman et al., 2014), the mechanisms by which governance can be effective and involve different stakeholders on different scales are still uncertain. For example, water use in the Anthropocene also involves issues of equity of water supply; water security; aquatic ecosystems, biodiversity and ecosystem services; irrigation and food production; river and groundwater pollution; and hydroelectricity production, amongst others. These competing water uses may not always be compatible (Bhullar, 2013; Haasnoot et al., 2011); Gupta et al. (2013: 573) state that 'the water crisis is a crisis of governance'. Set against a background of increased water scarcity in many areas such as Africa (McClain, 2013), sustainable water use in the context of sustainable development will increasingly have to reconcile different viewpoints and require both a 'systems' approach to better understand resource availability, and more adaptive and integrated governance frameworks.

Alternative measures of sustainability

If traditional viewpoints of resource management and sustainability have some limitations, it may be that alternative measures of sustainability could be used (Benessia et al., 2012). These could relate more explicitly to human activities that can be better evaluated and legislated for, rather than the indirect impacts upon human activity of a narrow range of environmental variables. These alternative measures, that are often key narratives for engaging stakeholders (Aylett, 2010; Jerneck, 2014; Thomas and Twyman, 2005), include human health and wellbeing; greenness of urban spaces; environmental ethics; carbon footprint and offsetting; water footprint; food miles; renewable energy sources; and recycling. These measures are quantifiable and studies show that they can increase both environmental awareness and sustainable practices amongst stakeholders (e.g. Aylett, 2010; Bulkeley et al., 2014; Thomas and Twyman, 2005), and facilitate decision-making. Thus, the concept of sustainability may be better applied to societal relationships, whereby the functioning of social or cultural groups or the workings of institutional or organizational frameworks can be considered through the lens of their flexibility or adaptive capacity in the Anthropocene world (e.g. Adger et al., 2009; Jerneck, 2014; Lövbrand et al., 2009).

Managing future change: People, politics and a new world order

Managing future change in order to achieve the sustainable use of environmental resources requires both a better understanding of Earth Systems and societal structures that can manage these resources. Today's political, administrative and sociocultural structures are already struggling to respond to the challenges of climate change (Jerneck, 2014). It is likely that these institutional structures will be increasingly unfit for purpose when faced with a combination of (1) future climatic conditions, including increased frequency and/or magnitude of climatic hazards (e.g. Jongman et al., 2012); and (2) increased urbanization, increased vulnerability, increased food and water insecurity, and geopolitical instability. A possible consequence of climate change over coming decades could be geopolitical crises driven by the collapse of civil order and mass migration in societies with severe water stress and food insecurity. Such events are already happening (O'Loughlin et al., 2012). Geopolitical problems as a consequence of trans-boundary water flows and water trading are also taking place (Haasnoot et al., 2011; Hoekstra, 2011). These issues will significantly hinder any move towards greater sustainable practices, which require greater international collaboration, not fragmented decision-making (Zaccai, 2012). Today, institutional structures charged with managing future change from regional to global scales are top-down, hierarchical and difficult to adapt to changing circumstances (Berman et al., 2012). For the same reasons, these structures significantly limit the extent to which international climate (e.g. Kyoto Protocol) and environmental agreements (e.g. Ramsar sites) can be effective, irrespective of intent. Thus, existing political, administrative and sociocultural structures and today's social actors are becoming increasingly inappropriate to the needs of the Anthropocene (Johnson and Morehouse, 2014; Karlsson, 2013; Lozano, 2014).

This paper argues that managing future change requires a different kind of global socio-politics. This socio-political context can be framed in two ways. (1) Sustainability is a powerful socio-political metaphor in the Anthropocene (Benson and Craig, 2014; Jerneck, 2014), notwithstanding its limitations discussed above, but its narrative context should be widened to include impacts on human wellbeing and environmental and social justice (Arias-Maldonado, 2013; Hirvilammi and Helne, 2014; Houston, 2013; Mauerhofer, 2013; Sessa and Ricci, 2014). This can also be achieved through considering the extent to which human pressure has been exerted on different elements that make up Earth's global system (Dearing et al., 2014; Rockström et al., 2009). These developments can also be facilitated by improved use of technologies in social media, telecommunications, distributed systems and citizen science, all of which can help engage stakeholders and the public, increase transparency and democratic engagement. By such means, today's rigid and hierarchical social and organizational structures may in future become more flexible, fluid in structure (Andersson et al., 2014) and may potentially exhibit greater adaptive capacity. (2) The role of technologies in the areas of gene modification and food production; bioremediation; environmental monitoring through telemetric networks; satellite remote sensing; and climate modelling all have potential to increase future climate resilience. Increased production and/or supply-chain efficiency of environmental resources, aided by technology, can also increase sustainability (Benessia et al., 2012; Zaccai, 2012).

This paper argues that future societal actors and their roles cannot be easily identified, but these are likely to reflect changing economic patterns, community structures and geopolitical contexts over coming decades. The role of these actors in developing future sustainable practices is dependent on both the workings of socio-political systems, as well as an understanding of the physical environment, in combination. For example, management of future global warming through carbon emissions trading and carbon budgeting is as much shaped by geopolitics as by biogeochemical cycling (Knight and Harrison, 2013). Thus, the science of sustainability can be translated into practice only through the mediation of societal and governance frameworks, which often prove not up to task. As such, the future Anthropocene world, whilst controlled by the decisions of societal actors, is dependent on the critical role of science in increasing resource availability and societal resilience to future climatic hazards.

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References

Adger WN, Dessai S, Goulden M et al. (2009) Are there social limits to adaptation to climate change? *Climatic Change* 93: 335–354.

Andersson C, Törnberg A and Törnberg P (2014) Societal systems – Complex or worse? *Futures* 63: 145–157.

Arias-Maldonado M (2013) Rethinking sustainability in the Anthropocene. *Environmental Politics* 22: 428–446.

Aylett A (2010) Participatory planning, justice, and climate change in Durban, South Africa. *Environment and Planning A* 42: 99–115.

Benessia A, Funtowicz S, Bradshaw G et al. (2012) Hybridizing sustainability: Towards a new *praxis* for the present human predicament. *Sustainability Science* 7 (Supplement 1): 75–89.

Benson MH and Craig RK (2014) The end of sustainability. *Society & Natural Resources* 27: 777–782.

Berkhout F (2014) Anthropocene futures. *The Anthropocene Review* 1: 143–159.

Berman R, Quinn C and Paavola J (2012) The role of institutions in the transformation of coping capacity to sustainable adaptive capacity. *Environmental Development* 2: 86–100.

Bhullar L (2013) Climate change adaptation and water policy: Lessons from Singapore. *Sustainable Development* 21: 152–159.

Biggs EM, Duncan JMA, Atkinson PM et al. (2013) Plenty of water, not enough strategy. How inadequate accessibility, poor governance and a volatile government can tip the balance against ensuring water security: The case of Nepal. *Environmental Science & Policy* 33: 388–394.

Bulkeley H, Edwards GAS and Fuller S (2014) Contesting climate justice in the city: Examining politics and practice in urban climate change experiments. *Global Environmental Change* 25: 31–40.

Chin A, Florsheim JL, Wohl E et al. (2014) Feedbacks in human–landscape systems. *Environmental Management* 53: 28–41.

Dearing JA, Wang R, Zhang K et al. (2014) Safe and just operating spaces for regional social-ecological systems. *Global Environmental Change* 28: 227–238.

Eakin HC and Patt A (2011) Are adaptation studies effective, and what can enhance their practical impact? *WIREs Climate Change* 2: 141–153.

Fiksel J (2012) A systems view of sustainability: The triple value model. *Environmental Development* 2: 138–141.

Gupta J, Pahl-Wostl C and Zondervan R (2013) ‘Glocal’ water governance: A multi-level challenge in the Anthropocene. *Current Opinion in Environmental Sustainability* 5: 573–580.

Haasnoot M, Middelkoop H, van Beek E et al. (2011) A method to develop sustainable water management strategies for an uncertain future. *Sustainable Development* 19: 369–381.

Haie N and Keller AA (2012) Macro, meso, and micro-efficiencies in water resources management: A new framework using water balance. *Journal of the American Water Resources Association* 48: 235–243.

Hirvilammi T and Helne T (2014) Changing paradigms: A sketch for sustainable wellbeing and ecosocial policy. *Sustainability* 6: 2160–2175.

Hoekstra AY (2011) The global dimension of water governance: Why the river basin approach is no longer sufficient and why cooperative action at global level is needed. *Water* 3: 21–46.

Houston D (2013) Crisis is where we live: Environmental justice for the Anthropocene. *Globalizations* 10: 439–450.

Jerneck A (2014) Searching for a mobilizing narrative on climate change. *Journal of Environment & Development* 23: 15–40.

Jerneck A, Olsson L, Ness B et al. (2011) Structuring sustainability science. *Sustainability Science* 6: 69–82.

Johnson E and Morehouse H (organizing editors) (2014) After the Anthropocene: Politics and geographic inquiry for a new epoch. *Progress in Human Geography* 38: 439–456.

Jongman B, Ward PJ and Aerts JCJH (2012) Global exposure to river and coastal flooding: Long term trends and changes. *Global Environmental Change* 22: 823–835.

Karlsson R (2013) Ambivalence, irony, and democracy in the Anthropocene. *Futures* 46: 1–9.

Kim J and Oki T (2011) Visioneering: An essential framework in sustainability science. *Sustainability Science* 6: 247–251.

Knight J and Harrison S (2012) Evaluating the impacts of global warming on geomorphological systems. *Ambio* 41: 206–210.

Knight J and Harrison S (2013) The impacts of climate change on terrestrial Earth surface systems. *Nature Climate Change* 3: 24–29.

Knight J and Harrison S (2014) Limitations of uniformitarianism in the Anthropocene. *Anthropocene* 5: 71–75.

Liebminger A, Haberhauer G, Papesch W et al. (2007) Footprints of climate in groundwater and precipitation. *Hydrology and Earth System Sciences* 11: 785–791.

Lövbrand E, Stripple J and Wimand B (2009) Earth System governmentality: Reflections on science in the Anthropocene. *Global Environmental Change* 19: 7–13.

Lozano R (2014) Creativity and organizational learning as means to foster sustainability. *Sustainable Development* 22: 205–216.

McClain ME (2013) Balancing water resources development and environmental sustainability in Africa: A review of recent research findings and applications. *Ambio* 42: 549–565.

Margerum RD and Robinson CJ (2015) Collaborative partnerships and the challenges for sustainable water management. *Current Opinion in Environmental Sustainability* 12: 53–58.

Mauerhofer V (2013) Social capital, social capacity and social carrying capacity: Perspectives for the social basics within environmental sustainability. *Futures* 53: 63–73.

Miller TR, Wiek A, Sarewitz D et al. (2014) The future of sustainability science: A solutions-oriented research agenda. *Sustainability Science* 9: 239–246.

Montgomery DR (2007) Soil erosion and agricultural sustainability. *Proceedings of the National Academy of Sciences* 104: 13,268–13,272.

O'Loughlin J, Witmer FDW, Linke AM et al. (2012) Climate variability and conflict risk in East Africa, 1990–2009. *Proceedings of the National Academy of Sciences* 109: 18,344–18,349.

Rockström J, Steffen W, Noone K et al. (2009) A safe operating space for humanity. *Nature* 461: 472–475.

Rosenzweig C, Karoly D, Vicarelli M et al. (2008) Attributing physical and biological impacts to anthropogenic climate change. *Nature* 453: 353–357.

Schoeman J, Allan C and Finlayson CM (2014) A new paradigm for water? A comparative review of integrated, adaptive and ecosystem-based water management in the Anthropocene. *International Journal of Water Resources Development* 30: 377–390.

Sessa C and Ricci A (2014) The world in 2050 and the New Welfare scenario. *Futures* 58: 77–90.

Springett D (2013) Editorial: Critical perspectives on sustainable development. *Sustainable Development* 21: 73–82.

Thomas DSG and Twyman C (2005) Equity and justice in climate change adaptation amongst natural-resource-dependent societies. *Global Environmental Change* 15: 115–124.

von Elderfeldt K (2012) *System theory in geomorphology. Challenges, epistemological consequences and practical implications*. Springer Theses, Dordrecht, 139 pp.

Walker S (1998) Sustainable water resources management beyond the 1995–96 drought. *Proceedings of the Institution of Civil Engineers-Water Maritime and Energy* 130: 207–216.

Wise RM, Fazey I, Stafford Smith M et al. (2014) Reconceptualising adaptation to climate change as part of pathways of change and response. *Global Environmental Change* 28: 325–336.

Zaccai E (2012) Over two decades in pursuit of sustainable development: Influence, transformations, limits. *Environmental Development* 1: 79–90.

Zalasiewicz J, Williams M, Haywood A et al. (2011) The Anthropocene: A new epoch of geological time? *Philosophical Transactions of the Royal Society, Series A* 369: 835–841.

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Narratives of the past for Future Earth: The historiography of global environmental change research

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Abstract

This paper analyses the auto-historiography of global environmental change research. It traces how participating researchers make sense of and rationalise research strategies through narratives of the history of global change and Earth System science. Our study draws on personal and programme accounts of Earth System science's background related to the international global environmental change research programmes International Geosphere-Biosphere Programme (IGBP), the International Human Dimensions Programme on Global Environmental Change (IHDP), the World Climate Research Programme (WCRP), and Future Earth, from 1983 to 2013. The study finds three core narratives: the science history narrative motivates the future development of the programme by building on the successes of earlier international projects. The Earth System departs from an enhanced understanding of environmental change over time. Finally, the Anthropocene narrative underpins arguments for a science-based management of human–environment systems. We argue that including reflexive analytical perspectives in the history writing of Future Earth contributes to making environmental change research relevant and useful for democratic decision-making.

Keywords

auto-history, Future Earth, historiography, research programmes, science history

Science on the shoulders of giants

History is frequently used to legitimise new endeavours in societies (Jardine, 2000), and this undeniably holds true for environmental science and policy. For example, declarations from large environmental summits, such as the UN Conference on Sustainable Development of 2012 (Rio 2012+), underscore their political significance by situating themselves in a historical context of other important events (Linnér and Selin, 2013).

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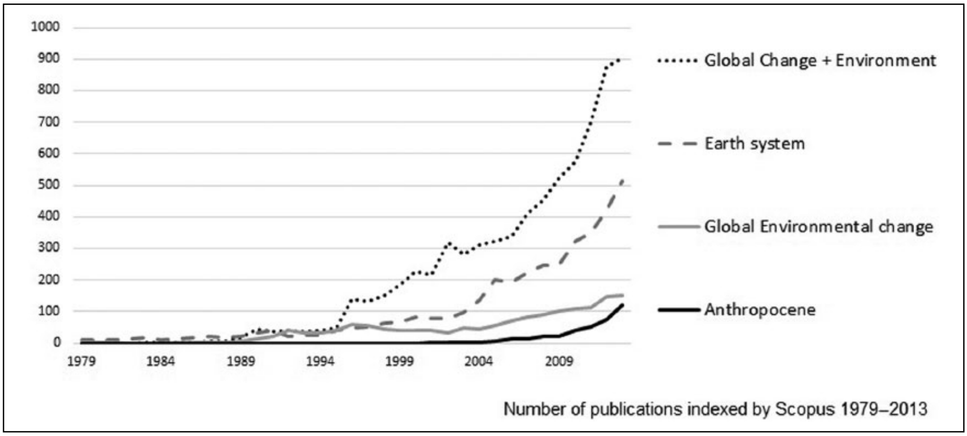

Figure 1. A growing literature related to global environmental change based on publications in Scopus, 1979–2013.

History is also used to promote and defend scientific organisations and practices by appealing to norms, interests, practicalities, epistemologies or success stories. Future Earth (2013: 5), the new international research platform on global environmental change, was launched at Rio 2012+ and highlights its background in 'decades of research and collaboration' and 'important contribution[s]' made by the World Climate Research Programme, the International Geosphere-Biosphere Programme, Diversitas and the International Human Dimension Programme on Global Environmental Change. The historiography of these scientific programmes has received scant attention; yet, when we examine them more closely, they describe the ways in which the legitimisation of environmental change research has shifted over time, how it has influenced the organisation of research, and what implications this may have for environmental governance.

Scientific studies of global environmental change have grown immensely in scope and volume during recent decades (Figure 1), and more than 35% of the literature published in *Scopus* dates from 2010 or later. Historical analysis has covered much of the long-term trends in environmental science (Bowler, 1992), ecology (Worster, 1994), climate research (Weart, 2003) and Earth sciences (Oldroyd, 2006).

Parallel to this historiography constructed by environmental science historians, there is a history written by participating global environmental change researchers. This paper adds to previous analyses by looking at the historical narratives of participating scientists' personal accounts and the official programme documents. Narratives are here understood to be the written or spoken accounts that connect events, actors and objects to meaningful trajectories though time (Jameson, 1986). These histories resonate the identities of the broad network of researchers, and motivate reorganisations of research for its members as well as funders and policy-makers.

The aim of this paper is to study the auto-historiography of global environmental change research; i.e. how researchers rationalise their research strategies through historical accounts of the background and development of their field. In this paper, the study of auto-historiography is a methodological approach with which to analyse meta-historical reflections and how processes, events and actors are made sense of in the internal context (Passerini and Geppert, 2001). Hence, we analyse these historical narratives through three research questions: (1) What processes and events are highlighted in the historical accounts of programmes and participating researchers?

(2) What problems or opportunities were these processes and events in response to, according to this history writing? (3) What conclusions for research practice and organisation are drawn?

Biographies of scientists have been an important component in social studies of science as a means of discerning how the past is rationalised to legitimise current states of affairs and courses of action (Lindskov Hansen, 2007). They have primarily focused on the 'strategic dimension' of history writing. Interest in auto-historiography has grown in recent decades to also encapsulate the sense-making function of writing one's own history. It recognises the contribution to understanding historical developments by also looking at the historical recollections of people who were a part of its processes. We argue that the study of auto-historiographies is a means of contextualising historical accounts and understanding their sense-making function. In the words of the famous historian Edward H Carr (2001: 40): 'Before you study the history, study the historian'. Studying history writing of societal or institutional changes is an important part of analysing historical processes.

Consequently, we distinguish between two interacting objectives of studying auto-historiography: (1) their strategic function; (2) their sense-making function. Together they provide context from within, in contrast to secondary literature and other sources used to externally contextualise the history of science. Our paper acknowledges but doesn't aspire to separate the sense-making and strategy functions but instead focuses on the context from within as an important component in understanding decisions in the design of research. We examine the *change model* of the texts; what *problems* are identified and what *goals* are sought, what is brought in, and whom by? What *key events* are brought into the history? Further, we study the *action model*, i.e. how the past is operationalised. What *leverages* set processes in motion, what key *interventions* have been made in the scientific processes; i.e. what was needed in terms of understanding, decisions, organisation and actions to influence the leverage? (Chen, 2005; Linnér et al., 2012).

The core empirical material in this study consists of accounts of the history of global change research related to the International Council of Scientific Unions (ICSU), the International Geosphere-Biosphere Programme (IGBP), the International Human Dimensions Programme on Global Environmental Change (IHDP), the World Climate Research Programme (WCRP) and Future Earth between 1983 and 2013. The analysed auto-historiographies are delimited to the historical self-reflections found in programme publications, primarily project presentations and individual accounts published in scientific journals. The personal accounts are primarily used to further substantiate or nuance the narratives in programmatic publications.

Three publications have been particularly important for our study: the symposium report *Global Change*, edited by Thomas Malone and Juan Roederer (1985); *Global Change and the Earth System – A Planet Under Pressure*, edited by the IGBP's executive director Will Steffen and ten other leading scientists of the IGBP, IHDP and WCRP (2004); the flagship report *Future Earth Initial Design* (Future Earth, 2013), which synthesises the first decade of internationally coordinated Earth System research.

Global environmental change research as history of science

To provide a relief to the auto-historiographies, this section presents major narratives in the development global environmental change research as outlined by historians of environmental science. The broader literature serves not as a benchmark for evaluating, but rather as a point of comparison to the participants' narratives. Four strands in the literature on post-war science are presented as particularly important for the development of the Earth System concept: global natural resource management, technological innovation, big science and multidisciplinarity. All of these are interconnected and were influenced by strategies to support research for geopolitical strategies.

Global natural resource management

The early post-war period saw two strands of global system-oriented research; one which focused on narrowly defined security concerns such as oceanography, limnology and glaciology, all of which were related to marine warfare, and another which tied into broader security concepts, directed towards safeguarding resources, human security and nuclear fall-out survival. One important part of the ancestry of today's Earth System science is the physical Earth Science research which was directly connected to the conception of the global environment as a potential battleground (Doel, 2003). Extending from this heritage is the notion that it is possible to monitor the entire planet and predict its future behaviour (Edwards, 2000). Ecological research also received a boost due to its links to defence-related research, as it was felt that the behaviour of landscape ecosystems and the marine environment needed to be explored in preparation for nuclear war and marine warfare, as well as to facilitate an understanding of the oceans as a source of food (Golley, 1993; Linnér, 2003).

Drawing on ecology, a new ideology of conservationism emerged in the mid-20th century, emphasising the need for ecological management of the world's natural resources. Global interconnectedness was a recurring theme in international resource science and policy events, such as the seminal international United Nations Scientific Conference on Utilization and Conservation of Resources of 1949, the first major UN science-policy conference, and the near-simultaneous International Technical Conference on the Protection of Nature. The managerial ethos regarding the Earth's resources was often motivated by a growing insight into global environmental interdependence, coinciding with the political objective of achieving greater rational control over the world's natural resources and understanding processes in nature for strategic purposes (Linnér, 2003). It was hoped that ensuring the availability of natural resources, not least in terms of food in socially unstable regions so as to reduce the risk of revolts, would shift the Cold War balance of power and secure resources for the economy and military.

Technological innovation

The period following the Second World War saw the birth of satellites, the fax machine, networks of computers and civil aviation. These new means of recording, storing, communicating, transporting and organising the flow of objects, information and persons did not only open up the world as a new arena for political and civic activity, they also allowed the scientific community to extend the scope of research. Remote sensing techniques allowed for studying global processes, and computers enabled the analysis of large data sets (Bowler, 1992). The technological innovations also provide an example of the interconnectedness of the four strands; funding of the development of these technologies was closely connected to geopolitics (Edwards, 2000), required big science to function (Galison and Hevly, 1992) and compelled the cooperation of researchers in Earth System science (Kwa and Rector, 2010).

Big science

The emergence of the big scientific programmes, such as those focusing on nuclear, microwave or solid-state physics research, coincided with an upsurge in global conservation issues in the media and halls of decision-making.

The mid-20th century saw a remarkable increase in expenditures in research and development. In the USA, expenditure rose from 0.2% of the gross domestic product in 1921, to 3% by the mid-1960s (Maddison, 1982). Big science emerged in the 1920s, and was not simply the result of military needs, but also of energy requirements for growing industrial development (Galison and Hevly, 1992). After the Second World War big science expanded rapidly, as scientific research resources were organised and directed to contribute to the war efforts, such as the development of radar and sonar, penicillin and insecticides (most notably DDT) and, eventually, the atomic bomb. These large-scale organised research activities continued, and were further intensified, after the end of the war.

Continuing with the metaphor of ancestry, today's Earth System science is closely related to the large-scale international cooperation of the International Geophysical Year (1957–1958), which set out to gather data related to understanding the behaviour of the atmosphere above the Arctic and Antarctic. This project, coordinated by the International Council of Scientific Unions, has inspired and become a model for how to organise international research cooperation. A few years later, the International Biological Programme (1964–1974) sought to quantify the 'the biological basis of productivity and human welfare' (Aronova et al., 2010: 199). These programmes were followed by a range of others, which constituted a veritable marathon of acronyms, fostering global perspectives that focused on different pieces of the global puzzle, such as the atmosphere or agriculture.

Multidisciplinarity

These two scientific programmes exemplify how big science meant an increase in resources for scientific research, but also a concentration of resources to specific hubs and goals. Hence the goals pursued in 'big science' endeavours were typically influenced by social, economic and political needs. The shift towards solving problems, as defined by military or political interests, typically required a large set of academic competences, generating multidisciplinary teams (Seidel, 1986). The early post-war years saw a strong push towards multi- or even interdisciplinarity in tackling the natural resource depletion of the world. At conferences such as the International Technical Conference on the Protection of Nature of 1949, strong arguments were made for breaking up the specialisation in science as well as in politics, following the assertion that ecology shows that all is interconnected. Enhanced public education was seen as crucial to changing the mindset of policy-makers and economists around the world (Linnér, 2003).

In the 1950s, the interdisciplinary field of *human ecology*, which brought together the natural and social sciences in analysing human's interrelations with nature, grew in popularity. The fundamental message was that human civilisation had to abide by both physical and moral constraints (Worster, 1993). In a 1954 *Science* outlining challenges for human ecology, Paul Sears (1954) foreboded the Anthropocene argument 'We are an explosion. For the first time in Earth history, a single species has become dominant, and we are it' (p. 959). The concept of *ecosystem* was defined as the whole system, including not only the organism-complex but also physical factors. In the early 1980s the National Aeronautics and Space Administration (NASA) proposed the first programme that would bring together the physical, biological and social components to study 'global habitability'. In 1986, the ICSU decided to launch its International Geosphere-Biosphere Programme (IGBP), tasked with producing a predictive understanding of the Earth as a system. In contrast to NASA's more thoroughly interdisciplinary proposal, the ICSU's geocentric design excluded the social sciences (Uhrqvist, 2015).

Global change had then been studied by social scientists and economists since the 1970s, and their exclusion by the IGBP caused social scientists, particularly geographers and resource managers, to organise a sister programme to the IGBP, the Human Dimensions on Global Environmental Change Programme. Around the year 2000, attempts to bring these communities closer together intensified, with the aim of providing effective decision-making support on sustainability issues, primarily via the Earth System Science Partnership (Uhrqvist and Lövbrand, 2009).

The auto-historiography of science organisation

In the first half of our studied time period (1983–2000), a narrative arranged around earlier successful scientific work dominated discussions regarding how to take the next step in research on global environmental change. The ICSU symposium on global change in 1984 played an important role in bringing diverse scientific disciplines together. In the 500-page report *Global Change*, 52 leading natural scientists discussed the viability of the prospective IGBP. In the preface, Thomas Malone, one of the initiators, condensed the background histories in the report (e.g. Friedman, 1985; Roederer, 1985) into four reasons for launching a major international endeavour for interdisciplinary cooperation; all four explicitly drew on developments in the recent history of science.

First, Malone argued that earlier successful approaches, such as the International Geophysical Year and the International Biological Program, had reached the limits of their effectiveness. Recent results had made it clear that further understanding required more in-depth studies of feedback mechanisms in other disciplines (Malone, 1985). The other three reasons correspond to what had been highlighted by big research programmes since the 1950s: (1) human impacts on the global environment; (2) the lack of food security for a rapidly growing world population and a need for concerted research action; (3) the opportunities provided by new technology to ‘complete the triad of theory, observation and data management’ (Malone, 1985: xv). Two years later, these four reasons guided the programme accepted for the IGBP (1986).

In the science history narrative of Earth System historiography, agency is placed in the hands of visionary and bold scientists, able to organise big scientific cooperation. Clothed in the language of exploration, the IGBP was presented as an opportunity for science and scientists to take the next step. With a rhetorically driven reference to Isaac Newton, Malone (1985: xix) situated his audience ‘on the shoulders of our predecessors – on the threshold of a revolution of historic proportions on human understanding’; in another statement, however, he implied a more fundamental break with previous scientific understanding: ‘We are apparently on the threshold of developing a new paradigm’ (Malone, 1985: xiii).

Similar references to the history of science narratives marked the keynote address at a human dimensions symposium in 1990. Here, Roberta Balstad Miller (1991) envisioned ‘rapid changes’ in the international coordination of social science. Social and scientific problems were described as integrated, and therefore new methods for interdisciplinary cooperation as needed. The narrative suggested the growing capabilities of computers as a leverage to foster global perspectives as well as firmer research cooperation. This forward-looking argument was combined with reflections on the century-old tradition of successfully studying environmental change (Price, 1991; see also, Price, 1990). Social scientists argued that their lack of coordinated inquiry, compared with the natural scientists, was a severe obstacle which could now be overcome using computers (HDP, 1990). Thus, the auto-historiographical narratives of both the IGBP and the HDP positioned potential global change scholars as the continuation of a lineage envisaged by decades of bold, trail-breaking researchers. This tradition was connected to the prospect of a lead role in the shaping of a better future due to improved organisational skills and the mastery of advanced technologies.

In this first period, auto-historical accounts of global change science also trace its origins far further back than recent decades. The history of research on human environmental impact is traced back to the American diplomat George Perkins Marsh and his efforts to quantify environmental degradation in the late-19th century (Price, 1990). The integration of Earth System science was argued to be the culmination of a conceptual way of thinking about the biosphere, initiated by the geologist Suess in 1875 (Malone, 1985: xiii; Steffen et al., 2011a). The longer history of science narrative also display an account of changes and agents, organised around a few far-sighted individuals.

The auto-histories supporting global change research convey an idealistic story of international science collaboration, devoid of political interest, with science bridging the geopolitical divisions of the Cold War (Fleagle, 1992). This can be contrasted with the professional historians of science who find close relations between geopolitical-strategy and Cold War rivalry to be an essential conditions for the development of these programmes (e.g. Doel, 2003; Linnér, 2003), Described as a way to leverage in the scientific success story, the ability to make use of new and advanced technology is presented as a key strength, particularly with regard to artefacts such as computers, satellites and data storage.

The design of the IGBP (1986: 9) outlines how the view from space was to be handled in computer simulation models in a way that would create a common lexicon for Earth System science and thus bring the research community together. The viability of this goal was underpinned by examples of the constant improvements of these technologies and their successful utilisation in global change research. The view from space was thus suggested as a means of facilitating a 'quantum leap' forward in human understanding of the environment (IGBP, 1986; see also HDP, 1990). Examples drawn from the past point to what could be achieved if new research programmes build on the technological pathways opened by the International Geophysical Year and its scientific descendants. In the early attempts to bring together a Human Dimensions Programme, which later added International to its title, this function of technology appears as a source of great but untapped potential. Harold Jacobson (1987) argued that this explained the marginal role of the social science community, as it did not yet know how to utilise successfully the tools used by the natural sciences.

When brought into the narrative, these events establish the importance of 'big science' when organised through international scientific cooperation. As a part of the planning process of the IGBP, Earth System science was posited as the logical continuation of earlier research programmes which, due to technological restrictions, could not provide the integration thought to be essential to an understanding of global change (IGBP, 1986: v). Here, huge international projects such as the International Geophysical Year and the International Biological Program provide important landmarks in the scientific landscape.[1] Many key persons in the early IGBP had taken leading roles in some of these cooperative scientific ventures (Bolin, 2007). The quantity of results from the predecessors to the programmes, as well as their organisational quality, motivated and rationalised the beginning of a new and holistic project. The International Geophysical Year is hailed as a role model for scientific cooperation in many accounts, but is also considered to have required significant experience in order to carry out successfully; this is generally attributed to the ICSU (Friedman, 1985: 52; see also, Bolin, 2007; Greenaway, 1996).

The science history narrative found in the auto-histories at this time moved away from the organisation of science and towards conceptual thinking. The synthesis report *Global Change and the Earth System*, from the large global change conference held in Amsterdam in 2001, argues for current global change research as a critical step in the evolution of systems thinking, ecosystems in the 1930s, global biogeochemistry in the 1940s and general systems thinking in the 1970s (Steffen et al., 2004: 2). As later pointed out by Dahan (2010), Earth System science at this time also embraced systems complexity and non-linearity, which were state of the art in the 1990s. The synthesis strongly argued that 'classical analytical science', valuable as it might be, was not enough to solve contemporary problems in the global environment (Steffen et al., 2004: 2). In addition, this narrative builds on earlier scientific work in a more abstract way, primarily referring to better technology and the view from space. Here, only a few 'founding fathers' remained as a backdrop, while new technology was promoted as a leverage to explaining the shift towards an Earth System perspective.

Many documents studied from this period are joint publications of ecologists, geologists, social scientists (primarily geographers) and physicists (e.g. Steffen et al., 2004). Their problematisation of classical analytical science underpinned arguments that studies of the Earth as a system had to develop new modes of science in order to study an object described empirically as a complex, non-linear system, in which both biology and humanity had to be fully integrated (Moore et al., 2002; Steffen et al., 2004).

The Earth System history fosters integration and solutions

Around the year 2000 a new lead narrative emerged which we call *Earth System history*. At this time, the auto-histories become a narrative organised around the history, characteristics and possible futures of the global environment itself, rather than successful scientific work about it. An Earth System threatened by human activities became increasingly central to the discussions about how to develop global change research (Moore, 2000). The goal of providing knowledge for policy-making, expressed since the early 1980s, became all the more central to the Earth System field. Among other things, the four global environmental change programmes jointly established the Earth System Science Partnership to produce integrated decision support (Ignaciuk et al., 2012).

Discussions about the history of the Earth System and the global environment were not a novel idea in the year 2000, but how this history was talked about changed. The planning of the IGBP and the Human Dimensions Program acknowledged that the planet had to be understood as a system, and gave examples from past environmental events (Friedman, 1985; International Federation of Institutes for Advanced Study (IFIAS), 1987). In addition, long time series showing past global changes were important enough to motivate a core project in the IGBP (1986). However, the environment's history was not at that time evoked as an important reason for moving into new scientific territories.

Human societies and their relation to a benign life-support system sets the scene in the opening of the report *Global Change and the Earth System – A Planet Under Pressure*. Here, Steffen et al. (2004: 1) state that 'The interactions between environmental change and human societies have a long and complex history spanning many millennia'. In this narrative, humans were no longer an external stressor, but instead an internal component of the environment, as a global force equalling natural dynamics. This history starts with the Vostok ice-cores, which show the 'natural' co-variation of concentrations of atmospheric greenhouse gases. The characteristics of a non-linear Earth System, visible in the history of the global human–environment system, then supported arguments for suggested reforms of global change research. 'Science is at the threshold of a potentially profound shift in the perception of the human–environment relationship, operating across humanity as a whole and at the scale of the Earth as a single system' (Steffen et al., 2004: 3). The contrasts with Malone's (1985: xix) statement, that we stand 'on the shoulders of our predecessors – on the threshold of a revolution of historic proportions on human understanding', which here exemplifies a shift; from science history to Earth System history.

The embedding of global environmental change research in this Earth System history is connected to three claims for the future development of global change research. First, our planet behaves as an integrated, complex system. In a popularised presentation, a condensed narrative of the long co-variation of carbon, methane and temperature found in the Vostok ice-cores provides the core logic behind a focus on a complex, integrated, Earth System. The authors state that 'the understanding of the natural dynamics of the Earth System has advanced greatly' due to a 'significant increase in the ability to unravel the past' (Steffen et al., 2001: 22). Even if references are still made to science history, this merely provides a context, and the organisation of this research or how it was performed plays no role. Instead, narratives about the Earth System's history are utilised to motivate new modes of research. The complex behaviour of the human–environment system supports the claim that the simple equilibrium models, where humans impact on a pristine environment, cannot be expected to provide the knowledge needed to govern global change and thereby secure human wellbeing (Steffen et al., 2001). This increasingly historical description of the Earth System also motivated biophysicists in the IGBP and social scientists in the IHDP to initiate a new research project on the Integrated History and Future of People on Earth (Robin and Steffen, 2007).

Second, the Earth System narrative outlined above points to the necessity of studying interacting dynamics. Third, the growing body of knowledge derived from palaeo-sciences and archaeology makes it possible to calibrate and verify the results of simulation models, central to the decision-support systems which are envisaged as an outcome of the research (Steffen et al., 2001). A few years later, the history of a human–environment system plays an important role in motivating the new research design of the IGBP (2006) and the related socio-ecological systems of the IHDP (2007). Historicising and localising the Earth System allowed social scientists to assume a role in Earth System research through analyses of economy, technology and culture, which contributed by furthering understanding of how societal development interacts with global environmental changes (Global Land Project (GLP), 2005; IHDP, 2007).

An Anthropocene history toward co-production

From 2001 onwards, a greater emphasis was placed on utilising an Earth System perspective in the governance of water, food, carbon and health (ICSU and IGFA, 2008; Ingram et al., 2007). Strengthening this interdisciplinary and policy-oriented cooperation, the period 2008–2013 marked a third phase of reorganisation in the global environmental change research community. A purpose of the transition to the Future Earth programme was to go from understanding to producing science-based solutions (ICSU, 2010). The Anthropocene, geology of mankind as a proposed epoch with humans as a dominant geological force, provided the theme for these discussions (Steffen et al., 2011a).

In Future Earth's (2013) *Initial Design* report, the history of the global environmental change programmes are related to a growing need for further integration so as to achieve and implement solutions to the issue of global sustainability. The report presents its three main research themes, 'Dynamic Planet', 'Global Development' and 'Transitions Towards Sustainability', and discusses the need for co-production and co-design in improving our understanding of how the planet works as an integrated system. These are argued to be 'a key innovative aspect of Future Earth' (p. 49) in bridging the gap between research, policy and practice by engaging with competent and representative stakeholders in a new social contract (p. 21). The auto-history of the transition team for Future Earth is arranged around narratives of mismanaged human–environmental systems and the increasing ability of social and natural scientists to cooperate for humanity to become an active steward of the global environment. In broader Anthropocene narratives, so central to Future Earth, Steffen et al. (2011a, 2011b) present conclusions drawn by earlier researchers but scientific events and process behind the results, previously so important, is absent.

The character of the Earth System's history as full of surprises calls for quick responses and 'active adaptive management' as a governance ideal in order to secure and develop human wellbeing (Steffen et al., 2011a: 857). Scientific discussions about the interacting human–environment also show a growing interest in the history of collapsing societies (see, Costanza et al., 2007; Turner and Sabloff, 2012). A key argument which supports closer integration of researchers and policy-makers makes use of historical examples of disastrous results when human–environment systems are not managed based on proper scientific understanding. These scientific discussions of more recent Anthropocene history thus include a component of historical science–policy interaction, characterised by decision-makers being unable to comprehend and act on signals of changes in the human–environment system.

Mooney et al. (2013; see also, Ignaciuk et al., 2012) contextualise the cooperation between social and natural science communities which is required on the part of Future Earth. They describe the troubled start where IGBP was forced to exclude the social sciences so as to secure the integration of physics and biology. Increasingly, with IPCC assessments as leverage, the effects on human wellbeing forced cooperation to bridge this divide. Over time, social and natural scientists developed modes of cooperation and co-design. The Millennium Ecosystem Assessment is proposed as a showcase of this learning process, with its analytical framework developed as a joint effort by natural and social scientists (p. 8). However, as pointed out by the well-known participating ecological economist Richard Norgaard (2008), this analytical framework is far from a neat fit across ecology and social sciences. Social processes are discussed, but social science analysis is barely visible. The history of science narrative found in Future Earth documents tells a story of challenging but well-intended cooperation, seeking, if not always succeeding, to include new participants on equal terms. Here, then, the emphasis has been on cooperation between global change scientists and policy-makers. The auto-history of Future Earth points to the engagement since 1996 with new forms of co-production and co-design. The augmented attention on addressing policy-relevant questions requires integration of the natural and social sciences as well as policy-makers (Future Earth, 2013: 23).

Discussion and conclusions for a reflexive auto-history

As can be expected of narratives on research programmes, the overarching goal was to produce ever-improved knowledge to support the management of global environmental change. The narrative's conclusion of what was necessary to advance knowledge production signifies the raison d'être of the programmes: integration of scientific disciplines and practices. The main problem description has been essentially stable, positing humans as a destructive agent changing the Earth's fundamental functions. However, the narratives have changed in terms of problems, leverage to overcome them and what interventions have been necessary. Initially the primary leverage was sought in the prospects of technological development and possibilities for augmented natural science multidisciplinary collaboration through for example big science. Focus shifted toward the potential benefits of a system dynamics understanding of human impact, and, later, to a human development perspective enhancing the combined analysis and management of global environmental change. As such, it reflects the move towards human development in the UN's sustainable development agenda, reflected in the Millennium Development Goals as an inspiration for the sustainable development goals, which is a result of the Rio+20 summit process (Linnér and Selin, 2013).

In the early period of global environmental change research, discussions on how to organise the research programmes were underpinned by history of science. The IGBP and HDP emerged as interventions to support the logical next step in a narrative where large and successful research projects had reached the limits of understanding within respective disciplines. Here, 'big science' utilising advanced technology was forwarded as the leverage for enhancing both the analysis of huge amounts of data and the integration of disciplines into predictive Earth System models. The strength of natural scientific disciplines made the IGBP the logical next step. In turn, this view reinforced disciplinary research as the basis on which the Earth System could emerge as a synthesis. Thus the history of science narrative supported an increased integration within, but not between, the natural and social science communities.

Around the turn of the millennium, discussions began on how to organise global environmental change research for the decade to come. The earlier history of science was downplayed in favour of an Earth System history approach, providing the primary motivation for further integration of social and natural science. This historical account enforced a new research design, where the strongly interacting biophysical and socio-economic components placed the 'coupled human–environment system [as] the fundamental unit of study' (IGBP, 2006: 14). Historical support for the new approach drew on concrete examples of past global change, displaying the characteristics of a non-linear system with abrupt changes and unexpected results. Hence, while the historical narrative of the 1980s underpinned research programmes based on existing scientific disciplines, the Earth System historical narrative opened for a reorganisation based on a systems perspective.

In the work towards a new, more integrated, research programme – Future Earth – a new Anthropocene history narrative emerges with two key enunciations. The first honed in on the evolution of cooperation between social and natural scientists. Thanks to scientific assessments such as the Millennium Ecosystem Assessment, the previously tense relationship gradually turned into a productive cooperation on more equal terms (Mooney et al., 2013). The second emphasised historical examples of mismanaged human–environmental systems to motivate research outlining and facilitating implementation of transformations toward sustainable societies. Drawing on these examples, it is not enough to understand the Earth System dynamics and planetary boundaries, the safeguarding of human wellbeing requires scientific knowledge about how to steer and implement paths to a sustainable future. The histories of mismanagement also show that the implementation of locally practicable and legitimate solutions requires a fostering of transparent co-designed and co-produced transdisciplinary research.

Science history written by Earth System and global environmental change researchers is rarely used as an object for critical reflection, but rather as a means of contextualising or legitimising a research endeavour. This limitation is visible in two missing elements in the narratives. First, the auto-attribution of agency; which groups in society are afforded the capacity to act, and in what ways? The historical narrative has placed scientists as having the ability to initiate and direct the work leading to sustainable development. This has changed with the co-production twist of the Anthropocene narrative where scientists, policy-makers and other stakeholders are seen as important actors in the pursuit of sustainable transitions.

In agreement with the present lack of progress in current environmental politics, most notably climate change, some researchers propose overhauling the current democratic world system based on sovereign countries (e.g. Biermann et al., 2012; Schellnhuber, 2013), even a moratorium on democracy in favour of an expert crisis management, guided by integrated scientific knowledge (e.g. Hickman, 2010). A historical account aiming to support an analysis of Earth System governance might also have looked at the earlier attempts of science-based governing of large-scale systems, such as the well-intended but failed scientific/bureaucratic management of fishing around Newfoundland up until the collapse in 1992 (Bavington, 2010).

Second, science policies, practices and funding are embedded in cultural values and power struggles. The close connections between scientific knowledge production and other social and political processes is a central topic in historical analysis, but seldom appears in the auto-histories. For instance, scientific practices have been involved in and fostered by colonialism (Agrawal, 2005), the Cold War (Doel, 2003), and the construction of global institutions (Linnér, 2003).

As Future Earth now opens to also include critical analysis from social science, reflexive analytical perspectives may be included in future auto-historical narratives of environmental change research. We believe that this would be a welcome contribution to the ambition of making environmental change research relevant and useful for democratic decision-making.

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Note

1. Also built up by the scientific programmes behind the acronym marathon; TOGA, GARP, WCRP, SCOPE, ISTP, IQSY, ILP, IHP, IGCP, MAB, etc.

References

Agrawal A (2005) *Environmentality: Technologies of Government and the Making of Subjects*. Durham, NC: Duke University Press.

Aronova E, Baker KS and Oreskes N (2010) Big science and big data in biology: From the International Geophysical Year through the International Biological Program to the Long Term Ecological Research (LTER) Network, 1957–present. *Historical Studies in the Natural Sciences* 40: 183–224.

Balstad Miller R (1991) The Human dimensions of global environmental change: A challenge for the social sciences (summary by Price). In: Price MF (ed.) *Report of the ISSC Scientific Symposium on the Human Dimensions of Global Environmental Change: Palma de Mallorca, Spain, 26–27 November 1990*. Palma de Mallorca, Spain ed. Paris: Unesco, pp. 7–8.

Bavington D (2010) *Managed Annihilation: An Unnatural History of the Newfoundland Cod Collapse*. Vancouver: UBC Press.

Biermann F, Gupta A, Gupta J et al. (2012) Navigating the anthropocene: Improving earth system governance. *Science* 335: 1306–1307.

Bolin B (2007) *A History of the Science and Politics of Climate Change: The Role of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

Bowler PJ (1992) *The Earth Encompassed a History of the Environmental Sciences*. New York: W. W. Norton.

Carr EH (2001) *What is History? (With a new introduction by Richard J. Evans)*. Basingstoke: Palgrave.

Chen H-T (2005) *Practical Program Evaluation: Assessing and Improving Planning, Implementation, and Effectiveness*. Thousand Oaks, CA: Sage.

Costanza R, Graumlich L and Steffen WL (2007) *Sustainability or Collapse? An Integrated History and Future of People on Earth*. Cambridge, MA: MIT Press in cooperation with Dahlem University Press, xxii 495 pp.

Dahan A (2010) Putting the Earth System in a numerical box? The evolution from climate modeling toward global change. *Studies In History and Philosophy of Science Part B: Studies In History and Philosophy of Modern Physics* 41: 282–292.

Doel RE (2003) Constituting the postwar Earth Sciences: The military's influence on the environmental sciences in the USA after 1945. *Social Studies of Science* 33: 635–666.

Edwards PN (2000) The world in a machine: Origins and impacts of early computerized global systems models. In: Hughes AC and Hughes TP (eds) *Systems, Experts, and Computers. The Systems Approach in Management and Engineering, World War II and After*. Cambridge, MA: MIT Press, pp. 221–254.

Fleagle RG (1992) From the international geophysical year to global change. *Reviews of Geophysics* 30: 305–313.

Friedman H (1985) The science of global change – An overview. In: Malone TF and Roederer JG (eds) *Global Change*. The Proceedings of a Symposium Sponsored by the International Council of Scientific Unions (ICSU) During its 20th General Assembly, Ottawa, 25 September 1984. Cambridge: Cambridge University Press (on behalf of ICSU Press), pp. 20–52.

Future Earth (2013) *Future Earth Initial Design: Report of the Transition Team*. Paris: International Council for Science (ICSU).

Galison P and Hevly BW (1992) *Big Science: The Growth of Large-scale Research*. Stanford, CA: Stanford University Press.

Global Land Project (2005) *Science Plan and Implementation Strategy*. IGBP Report No. 53/IHDP Report No. 19. Stockholm: IGBP Secretariat, 1.

Golley FB (1993) *A History of the Ecosystem Concept in Ecology: More Than a Sum of the Parts*. New Haven, CT: Yale University Press.

Greenaway F (1996) *Science International – A History of the International Council of Scientific Unions*. Cambridge: Cambridge University Press.

Hickman L (2010) James Lovelock on the value of sceptics and why Copenhagen was doomed. *The Guardian*, 29 March. Available at: http://www.theguardian.com/environment/blog/2010/mar/29/james-lovelock (accessed 26 December 2014).

Human Dimensions of Global Environmental Change Programme (HDP) (1990) *HDP Report 1 – A Framework for Research on the Human Dimensions of Global Environmental Change*. Barcelona: Human Dimensions of Global Environmental Change Programme.

Ignaciuk A, Rice M, Bogardi J et al. (2012) Responding to complex societal challenges: A decade of Earth System Science Partnership (ESSP) interdisciplinary research. *Current Opinion in Environmental Sustainability* 4: 147–158.

Ingram J, Steffen WL and Canadell J (2007) *Envisioning Earth System Science for Societal Needs – The development of Joint Projects and the Earth System Science Partnership (ESSP)*. Earth System Science Parternship. Available at: www.essp.org.

International Council for Science (ICSU) (2010) *Earth System Science for Global Sustainability: The Grand Challenges*. Paris: International Council for Science.

International Council of Scientific Unions (ICSU) and International Group of Funding Agencies for Global Change Research (IGFA) (2008) *Review of the Earth System Science Partnership (ESSP)*. Paris: ICSU.

International Federation of Institutes for Advanced Study (IFIAS) (1987) *The Human Response to Global Change: Prospectus for an International Programme*. IFIAS.

International Geosphere-Biosphere Programme (IGBP) (1986) *Global Change Report 1 - The International Geosphere-Biosphere Programme: A Study of Global Change: Final Report of the Ad Hoc Planning Group*. Prepared for the ICSU 21st General Assembly, Berne, 14–19 September 1986. Stockholm: International Geosphere-Biosphere Programme.

International Geosphere-Biosphere Programme (IGBP) (2006) *Global Change Report 55 – Science Plan and Implementation Strategy*. Stockholm: IGBP Secretariat.

International Human Dimensions Programme (IHDP) (2007) *IHDP Strategic Plan 2007–2015 – Framing Worldwide Research on the Human Dimensions of Global Environmental Change*. International Human Dimensions Programme on Global Environmental Change.

Jacobson HK (1987) *Report of the 9 and 10 September 1987 Ann Arbor Workshop on a Social Science Research Program to Complement the International Geosphere-Biosphere Programme*. UNESCO.

Jameson F (1986) *The Political Unconscious: Narrative as a Socially Symbolic Act*. Ithaca, NY: Cornell University Press.

Jardine N (2000) Uses and abuses of anachronism in the history of the sciences. *History of Science* 38: X–270.

Kwa C and Rector R (2010) A data bias in interdisciplinary cooperation in the sciences: Ecology in climate change research. In: Parker J, Vermeulen N and Penders B (eds) *Collaboration in the New Life Sciences*. London: Ashgate, p. 161.

Lindskov Hansen S (2007) The programmatic function of biography: Readings of nineteenth- and twentieth-century biographies of Niels Stensen (Steno). In: Söderqvist T (ed.) *The History and Poetics of Scientific Biography*. Aldershot; Burlington, VT: Ashgate, p. 135.

Linnér B-O (2003) *The Return of Malthus. Environmentalism and Post-war Population-resource Crisis*. Isle of Harries: White Horse Press.

Linnér B-O and Selin H (2013) The United Nations Conference on Sustainable Development: Forty years in the making. *Environment and Planning C: Government and Policy* 31: 971–987.

Linnér B-O, Mickwitz P and Román M (2012) Reducing greenhouse gas emissions through development policies: A framework for analysing policy interventions. *Climate and Development* 4: 175–186.

Maddison A (1982) *Phases of Capitalist Development*. Oxford; New York: Oxford University Press.

Malone TF (1985) Preface. In: Malone TF and Roederer JG (eds) *Global Change: The Proceedings of a Symposium Sponsored by the International Council of Scientific Unions (ICSU) During its 20th General Assembly in Ottawa, Canada on September 25, 1984*. Cambridge: ICSU Press, pp. xi–xxi.

Malone TF and Roederer JG (1985) *Global Change: The Proceedings of a Symposium Sponsored by the International Council of Scientific Unions (ICSU) During its 20th General Assembly in Ottawa, Canada on September 25, 1984*. Cambridge: ICSU Press.

Mooney HA, Duraiappah A and Larigauderie A (2013) Evolution of natural and social science interactions in global change research programs. *Proceedings of the National Academy of Sciences* 110: 3665–3672.

Moore B III (2000) Sustaining Earth's life support systems – The challenge for the next decade and beyond. *Global Change Newsletter* 41: 1–2.

Moore B III, Underdal A, Lemke P et al. (2002) The Amsterdam Declaration on Global Change. In: Steffen WL, Jäger J, Carson DJ et al. (eds) *Challenges of a Changing Earth: Proceedings of the Global Change Open Science Conference, Amsterdam, the Netherlands, 10–13 July 2001*. Amsterdam, ed. New York: Springer-Verlag, pp. 207–208.

Norgaard RB (2008) Finding hope in the Millennium Assessment. *Conservation Biology* 22: 862–869.

Oldroyd DR (2006) *Earth Cycles: A Historical Perspective*. Westport, CT: Greenwood Press.

Passerini L and Geppert A (2001) Historians in flux: The concept, task and challenge of ego-histoire. *Historein* 3: 7.

Price MF (1990) Humankind in the biosphere: The evolution of international interdisciplinary research. *Global Environmental Change* 1: 3–13.

Price MF (1991) *Report of the ISSC Scientific Symposium on the Human Dimensions of Global Environmental Change: Palma de Mallorca, Spain, 26–27 November 1990*. Palma de Mallorca, Spain ed. Paris: Unesco, 1.

Robin L and Steffen W (2007) History for the Anthropocene. *History Compass* 5: 1694–1719.

Roederer JG (1985) The proposed International Geosphere-Biosphere Program: Some special requirements for disciplinary coverage and program design. In: Malone TF and Roederer JG (eds) *Global Change: The Proceedings of a Symposium Sponsored by the International Council of Scientific Unions (ICSU) During its 20th General Assembly in Ottawa, Canada on September 25, 1984*. Cambridge: ICSU Press, pp. 1–19.

Schellnhuber H-J (2013) *Expanding the Democracy Universe*. Available at: http://www.humansandnature.org/democracy—hans-joachim-schellnhuber-response-61.php (accessed 26 December 2014).

Sears PB (1954) Human ecology: A problem in synthesis. *Science* 120: 959–963.

Seidel RW (1986) A home for big science: The Atomic Energy Commission's laboratory system. *Historical Studies in the Physical and Biological Sciences* 16(1): 135–175.

Steffen W, Grinevald J, Crutzen P et al. (2011a) The Anthropocene: Conceptual and historical perspectives. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 369: 842–867.

Steffen W, Persson Å, Deutsch L et al. (2011b) The Anthropocene: From global change to planetary stewardship. *Ambio* 40: 739–761.

Steffen W, Sanderson A, Jäger J et al. (2004) *Global Change and the Earth System – A Planet Under Pressure*. 1st edition. Heidelberg: Springer Verlag.

Steffen W, Tyson P, Jager J et al. (2001) Earth system science: An integrated approach. *Environment* 43: 21.

Turner BL and Sabloff JA (2012) Classic period collapse of the Central Maya Lowlands: Insights about human–environment relationships for sustainability. *Proceedings of the National Academy of Sciences* 109: 13,908.

Uhrqvist O (2015) One model to fit all? The pursuit of integrated Earth System models in GAIM and AIMES. *Historical Social Research* in press.

Uhrqvist O and Lövbrand E (2009) *Seeing and knowing the Earth as a system – Tracing the history of Earth System Science Partnership*. Available at: http://www.earthsystemgovernance.org/ac2009/papers/AC2009–0107.pdf.

Weart SR (2003) *The Discovery of Global Warming*. Cambridge, MA: Harvard University Press.

Worster D (1993) *The Wealth of Nature: Environmental History and the Ecological Imagination*. New York: Oxford University Press.

Worster D (1994) *Nature's Economy: A History of Ecological Ideas*. Cambridge; New York: Cambridge University Press.

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A critical examination of the climate engineering moral hazard and risk compensation concern

Jesse Reynolds

Abstract

The widespread concern that research into and potential implementation of climate engineering would reduce mitigation and adaptation is critically examined. First, empirical evidence of such moral hazard or risk compensation in general is inconclusive, and the empirical evidence to date in the case of climate engineering indicates that the reverse may occur. Second, basic economics of substitutes shows that reducing mitigation in response to climate engineering implementation could provide net benefits to humans and the environment, and that climate engineering might theoretically increase mitigation through strong income effects. Third, existing policies strive to promote other technologies and measures, including climate adaptation, which induce analogous risk-compensating behaviours. If the goal of climate policy is to minimize climate risks, this concern should not be grounds for restricting or prohibiting climate engineering research. Three potential means for this concern to manifest in genuinely deleterious ways, as well as policy options to reduce these effects, are identified.

Keywords

climate change, climate economics, climate engineering, geoengineering, global warming, mitigation, moral hazard, risk compensation

Introduction

Anthropogenic climate change poses major threats to humans and the environment. The dominant approach thus far to reducing climate risks has been efforts toward reducing annual greenhouse gas emissions (‘mitigation’). However, given the slow rate of the natural removal of additional carbon dioxide (CO_2), this can be only a long-term strategy. There is also a significant chance that this mitigation will be suboptimal. In the meantime, emissions continue to accumulate in the atmosphere and the climatic effects of today’s emissions will not be felt for decades. As a consequence, we are already committed to an uncertain amount of climate change (Allen et al., 2009) which may

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already surpass the internationally agreed-upon 2°C threshold for 'dangerous climate change' (Peters et al., 2013). Therefore, even though mitigation remains vital, society faces an unpleasant future of managing climate change. Adaptation of society and ecosystems to a changed climate has become the second set of responses to climate risks. Significant steps toward adaption may now be evident, as countries are pledging billions of dollars for it. The promised cash is not yet fully in hand, though, and like mitigation, adaptation also easily gets mired in the morass of international politics and divergent perceptions of justice.

In the context of the seriousness of climate risks and the limits of likely mitigation and adaptation, some observers are increasingly considering intentional, large-scale interventions in natural systems in order to reduce climate change risks. These 'climate engineering' or 'geoengineering' proposals are diverse, and fall into two general categories. 'Carbon dioxide removal' (CDR) or 'negative emission technologies' would capture the leading greenhouse gas from the atmosphere and sequester it. Proposals include CO_2 capture from ambient air and ocean fertilization. 'Solar radiation management' (SRM) would slightly increase the reflective albedo of the Earth in order to compensate for the warming effect of climate change. These techniques could include stratospheric aerosol injection and marine cloud brightening.

Climate engineering proposals have been controversial for a variety of reasons. Perhaps the most widespread concern is that they would undermine mitigation efforts. Indeed, nearly any discussion of climate engineering outside of a few scientific journals devotes significant attention to this. Taken to an extreme, this concern – typically called 'moral hazard' but more accurately 'risk compensation' – justifies a taboo, which was essentially the case (Lawrence, 2006) prior to an essay by a Nobel laureate atmospheric scientist (Crutzen, 2006), whose bona fides were beyond doubt and whose career and legacy were secure. Yet this concern has gone mostly unscrutinized (for an exceptional examination, see Hale, 2012). Although attention to climate engineering has increased in recent years, relative to mitigation and adaptation it remains on a distant tier of consideration.

This article challenges the concern that the consideration, research, development, potential for implementation and actual implementation of climate engineering would lessen mitigation and – to a lesser extent – adaptation, leading to undesirable outcomes such as greater climate change damage.[1] This will be called the climate engineering moral hazard-risk compensation (CE MH-RC) concern and, if it manifests, the CE MH-RC effect. Note that, although the CE MH-RC concern could apply to all forms of climate engineering, it is much more pronounced in those forms – particularly within SRM – which may be effective, rapid and inexpensive. It is these proposals which are the primary, but not sole, subject of this paper. The intention in this paper is to be somewhat provocative in order to encourage critical examination of widespread assumptions and assertions. It uses three approaches – empirical evidence, basic microeconomics of substitutes and existing and potential policies – to demonstrate that this concern may be overstated and hindering the development of effective climate policy. Specifically, from these approaches, I assert that

(a) there may be either no CE MH-RC effect or a reverse one;
(b) independent of (a), some substitution of climate engineering implementation for mitigation could provide net reduction of climate risks; and
(c) independent of (a) and (b), if policy-makers wished to reduce any potential CE MH-RC effect, there would be little that they could effectively, realistically and ethically do.

In the process, I highlight three potential mechanisms of a genuinely deleterious CE MH-RC effect. However, these mechanisms are often present in the formation of a wide range of public policies, and their problematic consequences for climate change are much broader than potentially lessening mitigation. Importantly, examination of the CE MH-RC concern raises the question of what precisely are the goal and the means of climate policy. Assuming that the goal is the reduction of climate risks and subsequent damage, and that the means to this include but are not limited to mitigation and adaptation, the CE MH-RC concern should not be grounds for restricting or prohibiting climate engineering research, and responsible climate engineering research should be encouraged. However, there are some policy options to address and reduce the potential deleterious CE MH-RC effects.

Moral hazard, risk compensation and their empirical evidence

The first approach is to examine existing empirical data in order to see whether they imply a probable CE MH-RC effect. Moral hazard and risk compensation, which are the two existing categories of analogous human behaviour, will be examined in general. The former is the term that has most often been used to describe the CE MH-RC concern, although the latter is a closer fit. In each case, existing empirical evidence will be briefly reviewed. This is drawn from the disciplines which developed the terms: for moral hazard, behavioural economics of insurance; for risk compensation, behavioural psychology of risk and safety. Then the existing but limited empirical evidence for the potential CE MH-RC effect will be summarized. Note that this section describes responses of individuals whereas climate engineering is a matter of collective decision-making. Consequently, its actual consideration, research and development could yield distinct results. Collective decision-making will be explored to some extent in the subsequent section.

Moral hazard

Moral hazard is a socially inefficient increase in risk-taking by one party once another party absorbs some of the potential negative consequences of the first party's actions, typically through an insurance-like agreement between the parties and typically without the latter party's full knowledge of this increase. The term's negative connotation is a vestige of its original meaning, which was limited to intentional actions by 'unscrupulous' insurees (Black, 1910: 563). With the rise of more theoretically rigorous economic studies in the mid-20th century, the concept was broadened to include any increase in risk-taking by insurees (Pauly, 1968). This was then seen as a rational but possibly subconscious response to altered incentives. Now, moral hazard has been further generalized to the principal–agent problem in which the agent who creates risk has greater information regarding her actions than the principal who bears the risk (Stiglitz, 1983).

Although moral hazard seems logical and has been supported by modelling, there is no agreement as to its actual magnitude because of several challenges in empirical work (for a review, see Cohen and Siegelman, 2010). Most importantly, the problem is one of information asymmetry, which makes research inherently difficult: if the principal cannot obtain certain information regarding the agent's behaviour, then often researchers cannot as well. Another challenge is how to distinguish among three different behaviours by insurees which each lead those with greater insurance to file more claims, which is typically the actual observable event. The first of these behaviours is the increase in risk-taking after obtaining or increasing insurance. This is more specifically called ex ante moral hazard and is the one most relevant to the CE MH-RC concern. Second, ex post moral hazard is when an insuree, after increasing his coverage, files more or greater insurance claims while his risk-taking remains constant. Third, adverse selection is when those who know beforehand that they present more risk will choose to obtain more insurance. A further challenge to obtaining empirical evidence of ex ante moral hazard is that insurers undertake steps to reduce it, such as monitoring insurees and sharing risk with them through deductibles, co-payments and coverage limits. Finally, there are other behaviours, some of which may remain unknown, which further confound evidence of ex ante moral hazard. For example, obtaining medical insurance may expose insurees to information regarding the benefits of eating healthy, resulting in them *reducing* their risky behaviour.

Therefore, while numerous studies find that individuals with more insurance file more and larger claims, the majority of these studies do not (and generally cannot) distinguish ex ante moral hazard from adverse selection and especially from ex post moral hazard.[2] One review of several forms of insurance concluded that 'This literature identifies a moral hazard effect in some contexts but not in others' (Cohen and Siegelman, 2010: 72). In the best-examined field, that of medical insurance, 'there are theoretical reasons to believe that health insurance coverage may cause a reduction in prevention activities, but empirical studies have yet to provide sufficient evidence to support this prediction' (Dave and Kaestner, 2009: 369). Research into automobile insurance is just now beginning to try to tease apart ex ante moral hazard; initial data indeed supports at least its existence (Abbring et al., 2008). As a final example, the case of workers' compensation is muddled, in part because three parties are involved: the insurer, the employer and the employee. A recent study found some support of ex ante moral hazard among workers, but this seemed to be more than compensated by greater safety measures taken by the employer in order to reduce their costs (Guo and Burton, 2010). Outside of insurance, other manifestations of ex ante moral hazard – such as mutual defence treaties (Benson, 2012), foreign aid (Bräutigam and Knack, 2004), humanitarian intervention (Kuperman, 2008) and financial investments (Stiglitz, 1983) – can be theorized and perhaps modelled but are even more difficult to confirm empirically.

Risk compensation

Risk compensation is an increase or decrease in risk-taking once an individual perceives that risk to be lower or higher, respectively. The actual risk may or may not have changed in a manner consistent with the change in perception. It relies on a model of human behaviour in which people balance the advantages and disadvantages of risk-taking. If some exogenous change such as a new regulation or technology alters the perceived risk of an activity, then individuals will compensate. It differs from ex ante moral hazard in that the increase in risky behaviour is not due to its negative consequences being transferred onto another party, and there is consequently no information asymmetry. However, like ex ante moral hazard, it can be considered to be a rational, although perhaps subconscious, response to changed incentives.

Empirical evidence of risk compensation is mixed, with studies producing a wide range of rates of offsetting behaviours. The best-studied field is automobile safety, such as seat belts, road lighting and vehicle safety inspection. Early work found that although seat belt laws reduced driver and occupant fatalities, they led to more dangerous driving as evidenced by increases in accidents with pedestrians and bicyclists (Peltzman, 1975). More recent research has shown much smaller effects, with one study concluding that 'If anything, these laws and the accompanying increase in belt use result in safer driving behaviour … Overall, seatbelt laws and the higher belt use these laws induce do not increase nonoccupant risk exposure' (Houston and Richardson, 2007: 933). Similarly divergent results have been observed in the cases of children's and sports protective equipment (McIntosh, 2005; Pless et al., 2006; Scott et al., 2007), bicycle helmets (Fyhri et al., 2012), vaccines and condoms to prevent AIDS/HIV and other sexually transmitted diseases (Brewer et al., 2007; Eaton and Kalichman, 2007) and hypertension drugs (Steptoe and McMunn, 2009). Another notable area of debate is harm reduction efforts in use of alcohol, tobacco and illicit drugs (Ritter and Cameron, 2006). Importantly, the risk compensation literature does not indicate a net increase in harm resulting from the offsetting behaviour, but instead only a smaller net reduction of harm than would be expected from the initial change alone.

In another similarity with moral hazard, these data are uncertain because reliable empirical studies of risk compensation are difficult. In an experimental setting, manipulating research subjects' risk perceptions is challenging, and may raise ethical constraints (Underhill, 2013). Outside of the laboratory or clinic, the offsetting behaviour can be difficult to measure and/or may be confounded by other variables. For example, bicycle helmet laws may lead to a selection effect wherein those who bike more slowly yet helmetless are deterred from biking, leaving behind those who bike for speed while helmeted (Fyhri et al., 2012). There could also be counteracting information effects, in which the perception of safety equipment serves as a reminder of a risk's seriousness, leading to *more* cautious behaviour.

Debates over certain policies which may have risk compensation effects are sometimes muddled by commentators' normative commitments. This is particularly the case with behaviours which are condemned by some as immoral, such as non-marital sex and illicit drugs. Some observers assert that even though policies such as human papillomavirus (HPV) vaccinations, prostitution decriminalization and clean intravenous needle exchanges may reduce harm, such steps would 'send a wrong message' and lead to an increase in the condemned behaviour. These situations are typically disagreements as to the policy goal. To some, the goal is to reduce certain tangible harms, while to others it is to reduce the occurrence of the morally condemned behaviour. This disagreement will be revisited below.

Empirical evidence for climate engineering moral hazard and risk compensation

The case of a potential CE MH-RC effect is even more uncertain than the investigated examples of moral hazard and risk compensation, because climate engineering is not actually being used yet and because the 'actor' in question is global society, behaving collectively with intergenerational impacts. Although the term 'moral hazard' is used more often for climate engineering, risk compensation fits better, although is still imperfect (Keith, 2013; Lin, 2013). In order for climate engineering and its research to present a moral hazard, then risks would need to be consensually transferred to another party who has inferior information as to the behaviour of the risk-taking party.[3] If climate engineering research and development were to reduce mitigation, then this may transfer some risks to future generations, but future generations would also be the ones to benefit by having greater knowledge about climate engineering and perhaps the additional option to implement it. It remains unclear whether these together would result in a net increase in their climate risks. Furthermore, future generations have not (and cannot) consent, and the crux of the CE MH-RC concern is not that the present generation has greater information about its behaviour than future ones do. In contrast, with risk compensation, risks to the actor are exogenously reduced, often through a technological intervention, which in turn impacts risk perception and behaviour. Models thus far do indicate that climate engineering could provide a reduction of risks from climate change,[4] although some risks may be transformed in type (for example, from changes primarily in temperature to changes primarily in precipitation) and to different populations.

There are only a handful of opinion studies of climate engineering, and just five of these have implications for the CE MH-RC concern.[5] Although each has limitations, all point toward a nonexistent or even reverse CE MH-RC effect, perhaps resulting from an information effect analogous to seeing a seat belt. First, the Royal Society of London convened focus groups, which indicated that

> rather than presenting a 'moral hazard' issue, the prospect of geoengineering could galvanise people to act, and demand action, on greenhouse gas emission reductions. Although participants were generally cautious,

> or even hostile, towards geoengineering proposals, several agreed that they would actually be more motivated to undertake mitigation actions themselves (such as reducing energy consumption) if they saw government and industry investing in geoengineering research or deployment. (Shepherd et al., 2009: 43)

Second, a public dialogue organized by the UK's Natural Environment Research Council found evidence 'contrary to the "moral hazard" argument that geoengineering would undermine popular support for mitigation or adaptation' (IPSOS Mori, 2010: 2). Third, an opinion survey of residents of Canada, the UK and the USA produced a moderate degree of opposition (a mean of 2.07 on a scale of 1 to 4, where 2 is 'somewhat disagree') to the statement 'Solar Radiation Management should be used so we can continue to use oil, coal and natural gas' (Mercer et al., 2011: 5). Fourth, in an experimental survey, some respondents were exposed to information about climate engineering, while others were not. 'Contrary to the "moral hazard" effect … subjects in the geoengineering condition did not become sanguine about climate change risks. Indeed, on the whole, they displayed *more* concern over climate change than ones in the control condition' (Kahan et al., 2014: 15). Finally, a public discussion group in the UK found that 'No-one saw the benefit of geoengineering without mitigation' (Integrated Assessment of Geoengineering Proposals, 2014: 3).

Basic economics of substitutes

The second approach to examine the CE MH-RC concern is through the basic economics of substitutes. Suppose that global society is simultaneously a consumer and a producer of various responses to climate change risks. These will have costs which increase for each additional unit 'purchased' (or, better stated, 'invested in') because society would try to begin with the least expensive actions before moving to the more expensive ones. This gives an upward-sloping marginal cost curve. In comparison, the shape of the marginal benefit (or utility) curve is less certain: it is often assumed to be upward-sloping, but it may be horizontal on average, in that the damage averted by reducing warming from 5°C to 4°C may be equivalent to that averted from 1°C to 0°C. Future costs and benefits are included and discounted, in that they are reduced by a compounding rate in order to reflect opportunity costs and the preferences to have benefits sooner and to incur costs later.[6] This yields single marginal cost and marginal benefit curves using present values, even though the costs and benefits will actually occur at various times. Furthermore, in each case, the curves can incorporate other positive or negative effects. For example, mitigation will also reduce other forms of environmental damage, and adaptation will also make society more resilient to natural disasters. A world with elevated atmospheric CO_2 and SRM climate engineering may have higher crop yields (Xia et al., 2014), but precipitation patterns would change (Kravitz et al., 2014b), possibly in harmful ways. These benefits and costs could even include social and political effects, such as the potential misuse of SRM climate engineering and its need to be sustained for a long time, as well as aggregate normative preferences, such as the beliefs that we should minimize human interference in the natural world and that it is better to address a problem closer to its cause.[7] It is important to note that these curves remain uncertain; they could have greater or lesser slopes and could be highly nonlinear. For now, let us maintain five simplifying assumptions: (1) that mitigation is the only possible response to climate risks; (2) that decisions are made by a single, omnipotent benevolent decision-maker; (3) that the decision-maker is omniscient; (4) that the preferences of people coincide; and (5) that decision-makers are rational. With this single response option, society invests in mitigation until an optimal, efficient quantity, where the additional cost of one more unit equals the additional benefit of that unit.

Now the first four assumptions can be removed stepwise, the first of which is to now consider multiple responses to climate risks. (The assumption of rationality will be maintained.) After the introduction of a second response, the imperfect substitute of climate engineering implementation, the marginal benefit of mitigation will decrease because some desire to reduce climate risks will have been met through climate engineering. As a result, the optimal quantity of mitigation will also decrease. However, the net benefit (which includes and is most likely dominated by the reduction of climate risks) will increase. After all, if the net benefit *did not* increase – which could be the case if all the incorporated secondary costs caused the optimal amount of climate engineering to be zero or less – then there would have been no investment in climate engineering implementation, given the current assumptions. This is essentially a case of simple substitution following neoclassical economics. Because the benefit curves for both mitigation and climate engineering include all effects and normative preferences, one cannot simply state that mitigation is the preferred option. Under this, any reduction in the quantity of mitigation after the introduction of climate engineering implementation is both rational and net beneficial to humans and the environment.[8]

In reality, there are at least four top-level response categories: mitigation, climate engineering, adaptation and suffering climate change damages.[9] The last of these is not purchased but instead manifests as human suffering, environmental damage and reduced economic activity. Climate engineering implementation would decrease investments in mitigation and adaptation through substitution, and would decrease climate damages through its primary intended effect. At the same time, because climate engineering implementation is expected to have very low financial costs[10] while those of mitigation, adaptation and climate change damages will be great, this will liberate some of society's financial resources, a portion of which could be used for mitigation.[11] Thus, there would be counteracting effects of climate engineering implementation on the amount of mitigation: a substitution effect, described in the previous paragraph, which would decrease it, and several income effects, described here, which would increase it. It is theoretically possible that climate engineering implementation could increase mitigation through dominant income effects.[12] These income effects would be stronger as the costs of mitigation, adaptation and climate change damages approach a greater portion of total economic activity. However, these are each currently estimated to be only a percent or two of economic activity. On the other hand, they might turn out to be higher, and one can also imagine a scenario in which voters endorse setting aside only a certain percentage of society's income for climate purposes, which would increase the relative importance of the income effect. Nevertheless, the possibility of these multiple income effects actually dominating the substitution effect is interesting but seems unlikely.

Lifting the second assumption transfers decision-making from a single decision-maker to numerous states which pursue their self-interests and can negotiate with each other in various forums. Let us examine in some depth the resulting effects on each of the three primary responses to climate change risks. First, mitigation presents a global, transgenerational collective action problem. In a hypothetical world of homogenous states, the benefits of each country's costly mitigation are diluted across the globe, causing them to each mitigate suboptimally. This is the classic underproduction of a public good. In the real world, those countries that are better positioned to mitigate (i.e. the industrialized countries) are generally less vulnerable to climate change, exacerbating this underproduction. Moreover, the costs are borne now and the benefits reaped later, whereas political decision-makers lack the necessary incentives for this transgenerational investment. Barring unprecedented levels of international trust, self-sacrifice and enforcement in international cooperation, mitigation will be very suboptimal. Second, although adaptation is, for the most part, not a collective action problem, it too will likely be under-provided because the more vulnerable developing countries have less capacity to adapt. Optimal adaptation will require enormous and politically unpopular international wealth transfers from the industrialized ones to the developing ones. Thus, independent of climate engineering, adaptation and especially mitigation will be significantly suboptimal in a world of many countries.

The effect of multiple decision-makers on climate engineering implementation will depend on its form. CDR is much like mitigation, and will follow a similar pattern with the magnitude of its underproduction dependent on the various techniques' costs, risks and capacities. The case of SRM varies by the method's specific scale of impact. At one extreme, it could hypothetically be implemented locally.[13] Each country would provide for its own SRM at its locally optimal level, with some positive and negative side effects for other countries. Negotiations between countries for payments could lead to compensation for victims of negative side effects, to reimbursement for positive effects, or to an agreement to adjust the magnitude of local SRM climate engineering. In this situation, SRM would be provided at a level close to its optimum, but probably somewhat higher because of uncompensated negative externalities. At the other extreme, SRM could be completely global, with no capacity for local optimization. In an ideally cooperative world, countries would agree upon a level of SRM which maximizes total net benefits with side payments to compensate any losers, or – barring that – upon a level which would maximize total net benefits without leading to net harm for any country (see Kravitz et al., 2014b; Moreno-Cruz et al., 2012). In reality, any negotiations would occur among states with diverse levels of power, interests and capabilities. Considering its low expected financial cost, and assuming that countries may increase but not decrease the intensity of SRM, the amount of global SRM might be determined by the country that preferred the highest SRM intensity while possessing sufficient international power and influence to withstand any retaliation or reputational damage from those which preferred a lower intensity.[14] Assuming no correlation between countries' power and SRM preference, SRM climate engineering in this scenario would then be over-implemented, the magnitude of which would depend upon the degree of alignment among countries' SRM preferences. One study modelled the preferred intensity of global SRM for 22 different regions (Ricke et al., 2013).[15] The highest preferred SRM intensity among the regions was approximately 20% greater than that of the lowest. This general alignment among regions implies that, in the world of selfish 'great powers' described above, global SRM climate engineering implementation is likely to be overproduced, but not by a very large amount. In reality, SRM intensity will likely be less extreme through technical measures, such as optimization by latitude (MacCracken, 2009; MacMartin et al., 2013; Modak and Bala, 2014) and by time of year, and through social measures, such as implementation through multinational coalitions (Ricke et al., 2013).

Therefore, the inclusion of multiple decision-makers leads mitigation and adaptation to be suboptimal, independent of climate engineering. In the presence of climate engineering implementation, these two might be somewhat more suboptimal while SRM climate engineering may be slightly over-implemented.

The third assumption to remove is that of omniscience. Thus far, I have assumed that decision-makers knew the shapes of the marginal cost and marginal benefit curves for each response. As noted above, climate science and economics are uncertain. Both mitigation and climate engineering pose uncertainty, some of which can be reduced through research and some of which may remain irreducible. As the reality of climate change and our responses to it unfolds, decision-makers can adjust policies as they learn more about the consequences of earlier actions.

The implications of uncertainty for mitigation and SRM climate engineering are not equal. The latter poses greater uncertainty both because there has been much less research to date, and because it relies upon intentional interventions in a highly complex system which has already been subject to other (unintentional) interventions. In contrast, mitigation has been studied for decades, and its irreducible uncertainty is lesser because it would reduce interventions in complex climate systems (although it would increase interventions in complex economic systems). Thus, assuming that society is risk averse, decision-makers should be willing to increase mitigation and to decrease climate engineering relative to their risk-neutral optimal levels. This would result in greater financial costs and environmental damage, but this does not imply that such risk aversion is irrational.

As research reduces the uncertainty for a given climate change response option, its expected costs, benefits and optimal amount often change. That is, later research may yield results contrary to initial expectations and preliminary research. Again, this has different implications for mitigation and climate engineering. Because researchers have been refining the costs and benefits of mitigation for decades, it seems unlikely that society would now aim for an optimal mitigation level which later mitigation research reveals to be dramatically different from optimal. In contrast, future climate engineering research may point toward an optimal level which is indeed dramatically different from what we now believe. Because the expected optimal level of mitigation is influenced by the expected optimal level of climate engineering via imperfect substitution and possible income effects described above, this creates the first of three potential deleterious CE MH-RC effects which this paper identifies. If (1) the initial expectations of climate engineering implementation were highly positive, (2) this reduced mitigation via expectations of a beneficial substitution effect and (3) later research or experience yielded more negative results, then net climate risks would increase (see Moreno-Cruz and Smulders, 2010). However, the reverse could be true as well, in which an excessively pessimistic view of climate engineering would hinder its research and development, also increasing net climate risks. Regardless, all these scenarios call for further research.

Furthermore, mitigation and SRM climate engineering differ in how decision-makers learn from and respond to the effects of their policies. In both cases, decision-makers may aim for a level which they believe to be optimal but, because of lingering uncertainty, only after implementation learn to be significantly different from than optimal. In the case of mitigation (as well as CDR climate engineering), because climate change and its damages lag for decades behind the greenhouse gas emissions which cause them, the benefits of mitigation will also lag. Furthermore, mitigation itself – new technologies, policies, infrastructure, agricultural practices, ecosystem management practices, etc. – is slow to implement. Once decision-makers learn more about the magnitude of climate change and its damages, as well as about the revised level of optimal mitigation, excessive or insufficient mitigation cannot be rapidly corrected. In contrast, the intended effects of SRM climate engineering implementation would be felt on a relatively short timescale. If society were to implement a level of SRM which it later learned differed significantly from optimal, then this level could be adjusted upward or downward relatively rapidly, at least with the most widely discussed SRM methods which appear to be effective and inexpensive, such as stratospheric aerosol injection and marine cloud brightening (Kravitz et al., 2014a). Of course, in the meantime, the costs of insufficient or excessive SRM would be borne by humans and the environment. Although the SRM intensity could be adjusted relatively quickly to respond to global temperatures, the observation and attribution of some secondary effects of SRM climate engineering implementation, such as precipitation changes, could require many years, and any corrections would be subsequently delayed.

Finally, let us remove the assumption that all people in a given country have similar preferences. This leads to the last two potential deleterious CE MH-RC effects. For one thing, the preferences of decision-makers and the broader population may not coincide. For example, they may have different discount rates, magnitudes of risk aversion, preferences for maintaining a more natural world, and preferences for addressing a problem closer to its source. They could also live in different locations and thus give different weight to particular effects of climate change and responses thereto. That is, the personal costs and benefits for the various climate response options may differ between the two groups. There is therefore a risk of a genuine bias if decision-makers prefer a higher level of climate engineering and a lower level of mitigation relative to the genuine population. Of course, the reverse may be true.[16] The third and final potential deleterious CE MH-RC effect could arise if there were temporal misalignment of preferences. If earlier generations were to prefer a higher level of climate engineering and a lower level of mitigation relative to future generations, then the results could be suboptimal. Again, the reverse may turn out to be the case.

To summarize, this section's simple economics of substitutes indicates that, even if climate engineering were to reduce mitigation, then its implementation could still provide net benefits through substitution. This conclusion continues to hold when considering several responses to climate change risks and many independent decision-makers. Through multiple income effects, it is theoretically possible that climate engineering implementation could even increase mitigation. The relative impact of uncertainty is less clear, in part due to lesser current knowledge regarding climate engineering relative to that of climate change and mitigation. Nevertheless, the response times of mitigation, adaptation and SRM climate engineering implementation indicate an advantage for the latter in response to learning. This section identified three potential deleterious CE MH-RC effects: (1) inaccurate initial expectations for mitigation and especially for climate engineering; (2) misalignment of the preferences of decision-makers and those of the general population; and (3) misalignment of the preferences of earlier generations and those of later generations. Each of these could decrease or increase the level of mitigation with respect to its optimal level.

Policy options

Assuming that policy-makers wished to reduce any potential CE MH-RC effect, independent of whether their concerns were warranted, then what could they do? We can first examine policies in other areas with ex ante moral hazard or risk compensation. The former is caused by information asymmetry between a principal and an agent regarding the risky behaviour of the agent. One response is for the principal to adopt policies which reduce the information asymmetry. For example, insurers offer lower rates if insurees demonstrate that they behave in certain low-risk ways. Another response to ex ante moral hazard is policies wherein the insuree shares some risk, such as through deductibles and co-payments. Although ex ante moral hazard is a weak analogy, the suggestion that the present generation should *increase* its exposure to climate risks is considered further below.

Policies regarding risk compensation are more instructive although, as noted, imperfect. Here, the technology or the regulation which induces the risk compensation is generally promoted or required because it leads to a net decrease in harm, despite the compensating behaviour. In the best-studied case, people drive automobiles more riskily with seat belts, air bags and improved lighting, and thus cause slightly more accidents. However, these safety devices are promoted or required because they lead to net reductions in injuries and fatalities. The mirror-image of this is when people drive more carefully when they are intoxicated or use a mobile telephone, behaviours which are discouraged or prohibited because they increase harm despite the more careful driving. After all, the reduction of injuries and fatalities (balanced with rapid transportation) is the goal of automobile safety policies; encouraging cautious driving is merely one means to that end. Some economists have made a tongue-in-cheek proposal that, if the goal were indeed to be cautious driving, then a spike in the centre of the steering wheel pointed at the driver would be preferable to a seat belt (McKenzie and Tullock, 1981: 40). Other examples of risk compensation are promoted by similar policies or norms in the cases of sports safety equipment, gun storage and public health measures. Furthermore, large public investments are made in developing treatments for medical conditions which are caused by personal choices, such as lung cancer and type 2 (adult onset) diabetes. These approaches are consistent with the simple economics described above, in which the introduction of a substitute might reduce cautious behaviour but results in decreased net harm.

A notable exception to this pattern is when the behaviour is condemned by some as immoral. As noted above, harm reduction policies with regard to non-marital sex and illicit drugs are often opposed not because of their likely effect on tangible harms (although opponents sometimes also try to make that argument) but because they would likely increase the occurrence of the condemned behaviour. Here, the disagreement is over the policy goal. If the goal is to reduce the tangible harms, then these harm reduction policies are beneficial. However, if the goal is to reduce the condemned behaviour, then the measures are opposed because they would lead to an increase in the behaviour's occurrence. Indeed, from this perspective, the risks of the behaviour should intentionally be kept high.

These examples shed light on the CE MH-RC debate. If the goal of climate policy is to minimize climate risks to humans and the environment, then climate engineering should be seriously considered, at the present time through research. However, if its goal is mitigation itself, then climate engineering and its research should be taboo.

In this context, it is relevant to consider the history and current status of adaptation in the climate change discourse. In the 1990s, there was widespread concern that consideration of and research into adaptation to a changed climate would hinder mitigation. It was called 'an unacceptable, even politically incorrect idea' because, among other reasons, it 'could make a speaker or a country sound soft' on mitigation (Burton, 1994: 14). Along similar lines, then-US Vice President Al Gore initially called adaptation 'a kind of laziness, an arrogant faith in our ability to react in time to save our skin' (Gore, 1993: 240). During this time, 'the first obstacle to adaptation is reluctance to contemplate it' (Waggoner, 1992: 146), and it 'was viewed with the same distaste that the religious right reserves for sex education in schools. That is, both constitute ethical compromises that in any case will only encourage dangerous experimentation with the undesired behaviour' (Rayner and Thompson, 1998: 292). However, adaptation is now a second widely accepted category of responses to climate risks. This change was due to the facts that some climate change cannot be avoided and that the burdens of it will fall largely on the world's poor. Gore now admits that he was 'wrong in not immediately grasping the moral imperative of pursuing both policies [mitigation and adaptation] simultaneously, in spite of the difficulty that poses' (Lind, 2013). Although there cannot be a 'control group' in order to compare the climate change discourse with and without the consideration of adaptation, it would be difficult to argue that the mainstreaming of adaptation has significantly reduced mitigation. It is unclear how and why climate engineering is fundamentally different from adaptation in this regard.

Let us concede for a moment that policies should indeed strive to reduce any CE MH-RC effect, regardless of whether the concern is warranted. At this point in time, the issue is whether and how to discuss and research climate engineering.[17] The assertion that the taboo against publicly discussing climate engineering should be reinstated or that climate engineering research should be severely restricted (or at least not be publicly funded) is an argument that climate engineering constitutes a form of 'forbidden knowledge' and is, at its core, a case for sustained wilful ignorance in the face of large risks to humans and the environment (see Rayner, 2014). This is even more so because of the uncertainty of climate change. Climate sensitivity may turn out to be much higher than expected; harm to humans and the environment from climate change may be greater than expected; the capacities of ecosystems and society to adapt may be much lower than expected; and mitigation and adaptation may remain too low. In these events, climate engineering could be more beneficial than it is now understood to be because of the possibilities of rapid and unilateral implementation, as described above.[18] Indeed, prohibiting or restricting climate engineering research could increase the likelihood of a hazardous CE MH-RC effect resulting from lingering but unsubstantiated expectations of climate engineering's potential to reduce climate risks, and would lead to future decision-making to be based upon a thinner knowledge base.

Recently, papers by two legal scholars proposed policies which would attempt to reduce any CE MH-RC effect (Lin, 2013; Parson, 2013). Some of these proposals, such as international deliberation regarding the circumstances under which climate engineering would be warranted, public outreach to counter perceptions that climate engineering would 'solve' climate change and accountable oversight (Lin, 2013) would aim to reduce two of the potential deleterious CE MH-RC effects cited in the previous section, those due to high expectations and to different preferences between decision-makers and the general population. Other norms and rules, such as open publication of results and no patents on SRM technologies, could also reduce these potential negative effects (see Bipartisan Policy Center Task Force on Climate Remediation Research, 2011; Leinen, 2011; Rayner et al., 2013; Solar Radiation Management Governance Initiative, 2011).

More ambitiously, the authors propose that climate engineering research or implementation could be contingent upon whether states meet mitigation targets.[19] While this logic from our current vantage point may appear wise, imagine if those targets are not met – which seems not unlikely assuming that the targets are meaningful – and climate engineering were then not permitted. Should – and would – global society or individual nations then forego an option which may reduce climate risks, or would such an agreement lack credibility? Other writers have posited that climate engineering should not be considered whatsoever, and among their reasons is the CE MH-RG concern (for example, see Hamilton, 2013; Winter, 2011). These are often arguments that considering climate engineering would discourage normatively desirable behaviour, but I assert that they may have mistaken the means (i.e. mitigation) for the end (i.e. risk reduction) of climate policy. Whether through linkage agreements, restrictions or prohibitions, a denial of a potential means to reduce climate risks is arguably equivalent to intentionally increasing risk in order to incentivize mitigation.[20] This is analogous to the spike in the automobile's steering wheel, described above, increasing the driver's risk in order to incentivize cautious driving. More accurately, it would be like a spike in front of a passenger, as it is largely the current residents of wealthy countries who are shaping climate policy but future generations and the world's poor who will bear most of the climate change harm. It seems unwise and unethical to increase climate risks which will largely be borne by others as an assertion of mitigation's primacy or as a sort of high-stakes wager that mitigation and adaption will be sufficient, and that climate engineering would never be beneficial.

An exception among these authors' proposals is the most sophisticated of Parson's (2013) proposed means to link mitigation and climate engineering. In this, he suggests that nations agree to a treaty in which those states that fail to meet their mitigation targets would be excluded from decision-making regarding climate engineering implementation. The author acknowledges its shortcomings. For example, if states' preferences for the form and intensity of climate engineering were to be closely aligned, as implied by some studies (Ricke et al., 2013), or if effective and affordable localized SRM methods were developed, then they would have little incentive to participate in the agreement. Furthermore, if the mitigation requirements were quite aggressive – which appear necessary in order to significantly reduce climate change risks – then powerful countries might not participate in the treaty or fail to meet their targets, with the knowledge that they would have enough international power and influence to later implement climate engineering regardless of the agreement. Moreover, climate engineering presently remains too uncertain to serve as an effective inducement to mitigate, although this may change in the future. Nevertheless, Parson's proposal warrants further consideration.

Discussion and conclusion

This paper has attempted to demonstrate three things. First, the empirical evidences of ex ante moral hazard and risk compensation in general and of a CE MH-RC effect specifically are not fully conclusive. Indeed, the limited empirical evidence thus far indicates that climate engineering could present a reverse CE MH-RC effect. Second, and independent of the first conclusion, the simple economics of substitutes suggests that, to the extent that climate engineering implementation might actually reduce mitigation through substitution, this could be rational and beneficial. In fact, it is theoretically possible that implementation could increase mitigation through strong income effects.

Third, technologies and regulations which cause risk compensation – the better analogy of the two – are usually promoted. Even if policy-makers wanted to reduce any CE MH-RC effect, regardless of its actual existence, restricting or prohibiting climate engineering research would likely do net harm, would not be feasible and might be unethical.

In the process, this paper identified three potential mechanisms of deleterious CE MH-RC effects. First, expectations of mitigation and especially of climate engineering may differ significantly from what is later learned. Second, the relevant preferences of decision-makers and those of the general population may not coincide. Third, the relevant preferences of earlier generations and of later generations may not coincide. To the degree feasible, effective and ethical, policies should be adopted which would reduce the likelihood and intensity of these mechanisms, or at least of the first two. As noted above, more and better research into all response options – including that of climate engineering – to climate change risks would more quickly reduce uncertainty and bring expectations closer to reality. Public consultation, international deliberations, accountability, transparency and intellectual property restrictions could reduce the negative impacts of the first two mechanisms. The third possible mechanism is particularly thorny, as preferences are dynamic and are partially dependent upon the actions of previous generations (see Norton et al., 1998). In particular, the development of new technologies can have a strong influence upon future generations' preferences. The present generation makes value-laden decisions, such as trade-offs between incommensurable goods, in certain ways, and does not wish to be constrained to doing this exactly as previous generations would have done. Likewise, future generations presumably will not want to be constrained to doing exactly as we do. It is unclear to what extent we should attempt to influence the preferences and constrain the behaviour of future generations in order to reduce the likelihood that they will make choices contrary to current preferences.

However, these three potentially problematic mechanisms are not limited to climate engineering, climate change or even the environment but instead are present in many – and perhaps all – significant social undertakings, ranging from the relatively mundane (e.g. land use planning) to the extraordinary (e.g. war). Similarly, even when considering only the climate engineering discourse, these three mechanisms point to challenges which are broader than the CE MH-RC concern, such as regulatory capture, technocracy, scientism, hype, technological lock-in and the so-called slippery slope. These challenges are not unique to climate engineering and it is not immediately evident why climate engineering policy should be held to especially high standards in these regards.

In addition, all three mechanisms could operate in manners which would increase mitigation and suppress climate engineering, even to harmful degrees. The presently expected net benefits of mitigation and those of climate engineering could be greater and less, respectively, than actual reality. Decision-makers could be more favourable to mitigation and more averse to climate engineering than the general population. Future generations could also be more averse to mitigation and more favourable to climate engineering than earlier ones. These are, to some degree, empirical matters whose answers are not obvious.

We should not assume that the CE MH-RC concern is warranted and that any substitution of climate engineering for mitigation would be negative. Even in the cases of the potential mechanisms which might cause deleterious mitigation reduction – mechanisms which go beyond the scope of the CE MH-RC concern and which are also present in many other policy choices – we should not assume that optimal mitigation is always the victim. Policy should be rationally designed and based upon the central goal of minimizing net climate risks to humans and the environment in accordance with society's preferences. I assert that those who argue that consideration of and research into climate engineering should be restricted because of the CE MH-RC concern have the burden to demonstrate that such effects are likely and would be harmful, and that humans and the environment would be better protected by foregoing this option. Until then, this concern should not be grounds for restricting or prohibiting climate engineering research.

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Notes

1. This is intended to be a broad definition with an emphasis on efficiency (i.e. welfare) concerns (per Hale, 2012). Below I try to incorporate what Hale calls responsibility and vice considerations.
2. For reviews of insurances such as annuities, automobile, crop, health, housing, life and long-term care, see Chiappori and Salanié (2013) and Cohen and Siegelman (2010). See also the examples of automobile repairs (Hubbard, 1998), deposit insurance (Gropp and Vesala, 2004), international lending (Dreher and Vaubel, 2004), public bailouts of banks (Nier and Baumann, 2006) and unemployment insurance (Chetty, 2008).
3. Actual climate engineering implementation may transfer risks onto others by, for example, changing precipitation patterns, and those who would choose to research and implement it may, in fact, have greater information than those who would bear the increased risk. However, as noted, the transfer of risk would neither be made socially inefficient by this information asymmetry nor be part a consensual insurance-like agreement. At the same time, if anything, climate change itself presents a similar dynamic in that those whose actions create or increase the risk – that is, mostly wealthy countries (or technically, the residents thereof) in the past and present – transfer those risks onto others – mostly poor countries in the future – and thus suboptimally mitigate (Samson et al., 2011). Andrew Parker (personal communication, 2014) speculates that this dynamic could fuel a form of climate engineering moral hazard in which wealthy countries which presently feel insulated from climate change risks will insufficiently research climate engineering, in the process leaving vulnerable countries exposed to greater climate change risks.
4. The Intergovernmental Panel on Climate Change recently reported that 'Models consistently suggest that SRM would generally reduce climate differences compared to a world with elevated greenhouse gas concentrations and no SRM' (Boucher et al., 2013: 575). See also Kravitz et al. (2014b).
5. In some studies, respondents expressed a CE MH-RC concern, but this implies nothing as to whether these concerns are warranted.
6. Although discounting is widely accepted, intergenerational discounting is somewhat controversial, even though its assumed value is perhaps the most important variable in climate economics. See Nordhaus (2007).
7. This paper adopts a consequentialist approach, and does not directly address deontological ethics. However, here I attempt to incorporate individually held normative preferences. This implies that those who hold these preferences would be willing to pay for them in terms of greater damage to humans and the environment as well as greater financial costs.
8. Climate engineering as a partial or imperfect substitute for mitigation has also been discussed by Barrett (2008); Bickel and Lane (2010); Emmerling and Tavoni (2013); Goeschl, Heyen and Moreno-Cruz (2013); Moreno-Cruz and Smulders (2010); Moreno-Cruz (2011) and Rickels and Lontzek (2012).
9. Davies wrote that 'it seems far from impossible that policy packages will ultimately include a mix of reduced emissions, climate intervention, and acceptance of warming. One does not need to believe that geoengineering may be a complete solution, or a best option, to believe that it may be a desirable element of a realistically achievable total policy package' (Davies, 2010: 269–270).
10. Estimates for the direct financial costs of implementation for the most effective yet inexpensive proposed climate engineering method, stratospheric aerosol injection, are on the order of a few to tens of billions US dollars annually (McClellan et al., 2012). In terms of climate economics, this is 'essentially costless'

(Nordhaus, 2013: 153). The costs of mitigation, adaptation and climate change damages are each orders of magnitude greater.

11. An income effect is more prominent if the good in question is necessary and as it accounts for a greater portion of the consumer's budget. It has been empirically observed to dominate the substitute effect in the case of, for example, dietary staples among poor consumers (Jensen and Miller, 2008).
12. As a notable aside, other studies have modelled how climate engineering could lead to an increase in mitigation. Millard-Ball (2012), Moreno-Cruz (2011) and Urpelainen (2012) each considered a case in which countries are asymmetrical. Countries which could be harmed by the negative secondary effects of climate engineering would increase mitigation or be more likely to participate in mitigation agreements in order to reduce or prevent implementation of climate engineering by other countries. Goeschl et al. (2013) found that a present generation which researches and develops climate engineering could simultaneously increase its mitigation level if it believed that future generations would have a strong bias in favour of climate engineering implementation.
13. Localized SRM is offered here primarily as a theoretical exercise. Current assessments of proposed SRM methods show them to be either inexpensive and global (e.g. stratospheric aerosol injection) or expensive and potentially localized (e.g. surface albedo modification). Some researchers are presently discussing limited seasonal and latitudinal variation (MacCracken, 2009; MacMartin et al., 2013; Modak and Bala, 2014). In this paragraph, assume that an inexpensive, effective, local SRM method becomes available in the future.
14. Weitzman (2013) calls this a 'free-driver externality'.
15. This model assumed that the regions desired their 1990 conditions.
16. Although it may be tempting to portray decision-makers as being captured by powerful wealthy interests who favour continued greenhouse gas emissions, note also that aggressive mitigation would hinder economic development in poor countries.
17. This is not to say that *how* climate engineering is considered and researched will have no impacts on how it might be implemented and on mitigation.
18. Of course, the opposites may turn out to be true, and knowledge of climate engineering would have less value. I emphasize its potential value in the event of greater climate damage because people tend to be risk averse and because SRM climate engineering could be rapidly implemented.
19. Note that Parson uses this proposal primarily as a logical stepping stone to others, which he then endorses more strongly.
20. This assertion brings up the distinction, or lack thereof, between doing and allowing (see Morrow, 2014). However, note that a conscious decision to deny the possibility of climate engineering, perhaps through a taboo or a prohibition, could be considered a 'doing' action.

References

Abbring J, Chiappori P-A and Zavadil T (2008) *Better safe than sorry?* Ex ante *and* ex post *moral hazard in dynamic insurance data*. Tinbergen Institute Discussion Paper 2008–075/3.

Allen MR, Frame DJ, Huntingford C et al. (2009) Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature* 458(7242): 1163–1166.

Barrett S (2008) The incredible economics of geoengineering. *Environmental and Resource Economics* 39(1): 45–54.

Benson BV (2012) *Constructing International Security: Alliances, Deterrence, and Moral Hazard*. Cambridge: Cambridge University Press.

Bickel JE and Lane L (2010) Climate engineering. In: Lomborg B (ed.) *Smart Solutions to Climate Change: Comparing Costs and Benefits*. Cambridge: Cambridge University Press, pp. 9–51.

Bipartisan Policy Center Task Force on Climate Remediation Research (2011) Geoengineering: A National Strategic Plan for Research on the Potential Effectiveness, Feasibility, and Consequences of Climate Remediation Technologies. Available at: http://bipartisanpolicy.org/library/report/task-force-climate-remediation-research.

Black HC (1910) *A Law Dictionary Containing Definitions of the Terms and Phrases of American and English Jurisprudence, Ancient and Modern*. St. Paul, MN: Lawbook Exchange.

Boucher O, Randall D, Artaxo P et al. (2013) Clouds and aerosols. In: Stocker TF, Qin D, Plattner G-K et al. (eds) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, pp. 571–657.

Bräutigam DA and Knack S (2004) Foreign aid, institutions, and governance in sub-Saharan Africa. *Economic Development and Cultural Change* 52(2): 255–285.

Brewer NT, Cuite CL, Herrington JE et al. (2007) Risk compensation and vaccination: Can getting vaccinated cause people to engage in risky behaviors? *Annals of Behavioral Medicine* 34(1): 95–99.

Burton I (1994) Deconstructing adaptation… and reconstructing. *Delta* 5(1): 14–15.

Chetty R (2008) Moral hazard versus liquidity and optimal unemployment insurance. *Journal of Political Economy* 116(2): 173–234.

Chiappori P-A and Salanié B (2013) Asymmetric information in insurance markets: Predictions and tests. In: Dionne G (ed.) *Handbook of Insurance*. 2nd edition. New York: Springer, pp. 397–422.

Cohen A and Siegelman P (2010) Testing for adverse selection in insurance markets. *Journal of Risk and Insurance* 77(1): 39–84.

Crutzen P (2006) Albedo enhancement by stratospheric sulfur injections: A contribution to resolve a policy dilemma? *Climatic Change* 77(3): 211–220.

Dave D and Kaestner R (2009) Health insurance and *ex ante* moral hazard: Evidence from Medicare. *International Journal of Health Care Finance and Economics* 9(4): 367–390.

Davies G (2010) Framing the social, political, and environmental risks and benefits of geoengineering: Balancing the hard-to-imagine against the hard-to-measure. *Tulsa Law Review* 46(2): 261–282.

Dreher A and Vaubel R (2004) Do IMF and IBRD cause moral hazard and political business cycles? Evidence from panel data. *Open Economies Review* 15(1): 5–22.

Eaton LA and Kalichman SC (2007) Risk compensation in HIV prevention: Implications for vaccines, microbicides, and other biomedical HIV prevention technologies. *Current HIV/AIDS Reports* 4(4): 165–172.

Emmerling J and Tavoni M (2013) *Geoengineering and abatement: A 'flat' relationship under uncertainty*. Fondazione Eni Enrico Mattei Working Paper 782.

Fyhri A, Bjørnskau T and Backer-Grøndahl A (2012) Bicycle helmets: A case of risk compensation? *Transportation Research Part F: Traffic Psychology and Behaviour* 15(5): 612–624.

Goeschl T, Heyen D and Moreno-Cruz J (2013) The intergenerational transfer of solar radiation management capabilities and atmospheric carbon stocks. *Environmental and Resource Economics* 56(1): 85–104.

Gore A (1993) *Earth in the Balance: Ecology and the Human Spirit*. New York: Plume.

Gropp R and Vesala J (2004) Deposit insurance, moral hazard and market monitoring. *Review of Finance* 8(4): 571–602.

Guo X and Burton JFJ (2010) Workers' compensation: Recent developments in moral hazard and benefit payments. *Industrial and Labor Relations Review* 63(2): 340–355.

Hale B (2012) The world that would have been: Moral hazard arguments against geoengineering. In: Preston CJ (ed.) *Engineering the Climate: The Ethics of Solar Radiation Management*. Lanham, MD: Lexington, pp. 113–132.

Hamilton C (2013) *Earthmasters: The Dawn of the Age of Climate Engineering*. New Haven, CT: Yale University Press.

Houston DJ and Richardson LE (2007) Risk compensation or risk reduction? Seatbelts, state laws, and traffic fatalities. *Social Science Quarterly* 88(4): 913–936.

Hubbard TN (1998) An empirical examination of moral hazard in the vehicle inspection market. *RAND Journal of Economics* 29(2): 406–426.

Integrated Assessment of Geoengineering Proposals (2014) *Views about Geoengineering: Key Findings from Public Discussion Groups*. Available at: http://iagp.ac.uk/sites/default/files/Views%20about%20geoengineering%20IAGP.pdf.

IPSOS Mori (2010) *Experiment Earth? Report on a Public Dialogue on Geoengineering*. Report for NERC Public Dialogue on Geoengineering Steering Group, August.

Jensen RT and Miller NH (2008) Giffen behavior and subsistence consumption. *American Economic Review* 98(4): 1553–1577.

Kahan DM, Jenkins-Smith HC, Tarantola T et al. (2014) Geoengineering and the science communication environment: A cross-cultural experiment. *Annals of American Academy of Political and Social Science*. Epub ahead of print 9 January 2012. DOI: 10.2139/ssrn.1981907.

Keith D (2013) *A Case for Climate Engineering*. Boston, MA: Boston Review Books.

Kravitz B, MacMartin DG, Leedal DT et al. (2014a) Explicit feedback and the management of uncertainty in meeting climate objectives with solar geoengineering. *Environmental Research Letters* 9(4): 044006.

Kravitz B, MacMartin DG, Robock A et al. (2014b) A multi-model assessment of regional climate disparities caused by solar geoengineering. *Environmental Research Letters* 9(7): 074013.

Kuperman AJ (2008) The moral hazard of humanitarian intervention: Lessons from the Balkans. *International Studies Quarterly* 52(1): 49–80.

Lawrence M (2006) The geoengineering dilemma: To speak or not to speak. *Climatic Change* 77(3): 245–248.

Leinen MS (2011) The Asilomar International Conference on Climate Intervention Technologies: Background and overview. *Stanford Journal of Law, Science, and Policy* 4(1): 1–5.

Lin A (2013) Does geoengineering present a moral hazard? *Ecology Law Quarterly* 40(3): 673–712.

Lind M (2013) Democracy, hacked. *New York Times*, 8 February, p. 13.

McClellan J, Keith DW and Apt J (2012) Cost analysis of stratospheric albedo modification delivery systems. *Environmental Research Letters* 7(3): 034019.

MacCracken MC (2009) On the possible use of geoengineering to moderate specific climate change impacts. *Environmental Research Letters* 4(4): 045107.

McIntosh AS (2005) Risk compensation, motivation, injuries, and biomechanics in competitive sport. *British Journal of Sports Medicine* 39(1): 2–3.

McKenzie RB and Tullock G (1981) *The New World of Economics: Explorations into the Human Experience*. Homewood, IL: RD Irwin.

MacMartin DG, Keith DW, Kravitz B et al. (2013) Management of trade-offs in geoengineering through optimal choice of non-uniform radiative forcing. *Nature Climate Change* 3(4): 365–368.

Mercer AM, Keith DW and Sharp JD (2011) Public understanding of solar radiation management. *Environmental Research Letters* 6(4): 044006.

Millard-Ball A (2012) The Tuvalu Syndrome: Can geoengineering solve climate's collective action problem? *Climatic Change* 110(3–4): 1047–1066.

Modak A and Bala G (2014) Sensitivity of simulated climate to latitudinal distribution of solar insolation reduction in SRM geoengineering methods. *Atmospheric Chemistry and Physics* 14: 7769–7779.

Moreno-Cruz JB (2011) *Mitigation and the geoengineering threat*. Georgia Institute of Technology School of Economics Working Paper # WP2011–007.

Moreno-Cruz JB and Smulders S (2010) Revisiting the economics of climate change: The role of geoengineering. Unpublished paper available at: http://works.bepress.com/morenocruz/4/.

Moreno-Cruz JB, Ricke KL and Keith DW (2012) A simple model to account for regional inequalities in the effectiveness of solar radiation management. *Climatic Change* 110(3): 649–668.

Morrow DR (2014) Starting a flood to stop a fire? Some moral constraints on solar radiation management. *Ethics, Policy and Environment* 17(2): 123–138.

Nier E and Baumann U (2006) Market discipline, disclosure and moral hazard in banking. *Journal of Financial Intermediation* 15(3): 332–361.

Nordhaus WD (2007) A review of the 'Stern review on the economics of climate change'. *Journal of Economic Literature* 45(3): 686–702.

Nordhaus WD (2013) *The Climate Casino: Risk, Uncertainty, and Economics for a Warming World*. New Haven, CT: Yale University Press.

Norton B, Costanza R and Bishop RC (1998) The evolution of preferences: Why 'sovereign' preferences may not lead to sustainable policies and what to do about it. *Ecological Economics* 24(2–3): 193–211.

Parson EA (2013) Climate engineering in global climate governance: Implications for participation and linkage. *Transnational Environmental Law* 3(1): 89–110.

Pauly MV (1968) The economics of moral hazard: Comment. *The American Economic Review* 58(3): 531–537.

Peltzman S (1975) The effects of automobile safety regulation. *Journal of Political Economy* 83(4): 677–725.

Peters GP, Andrew RM, Boden T et al. (2013) The challenge to keep global warming below 2°C. *Nature Climate Change* 3(1): 4–6.
Pless I, Magdalinos H and Hagel B (2006) Risk-compensation behavior in children: Myth or reality? *Archives of Pediatrics and Adolescent Medicine* 160(6): 610–614.
Rayner S (2014) *To know or not to know: A note on ignorance as a rhetorical resource in geoengineering debates*. Geoengineering Governance Research Working Paper 10.
Rayner S and Thompson M (1998) Cultural discourses. In: Rayner S and Malone EL (eds) *Human Choice and Climate Change*. Columbus, OH: Battelle Press, pp. 265–343.
Rayner S, Heyward C, Kruger T et al. (2013) The Oxford principles. *Climatic Change* 121(3): 499–512.
Ricke KL, Moreno-Cruz JB and Caldeira K (2013) Strategic incentives for climate geoengineering coalitions to exclude broad participation. *Environmental Research Letters* 8(1): 014021.
Rickels W and Lontzek TS (2012) Optimal global carbon management with ocean sequestration. *Oxford Economic Papers* 64(2): 323–349.
Ritter A and Cameron J (2006) A review of the efficacy and effectiveness of harm reduction strategies for alcohol, tobacco and illicit drugs. *Drug and Alcohol Review* 25(6): 611–624.
Samson J, Berteaux D, McGill BJ et al. (2011) Geographic disparities and moral hazards in the predicted impacts of climate change on human populations. *Global Ecology and Biogeography* 20(4): 532–544.
Scott MD, Buller DB, Andersen PA et al. (2007) Testing the risk compensation hypothesis for safety helmets in alpine skiing and snowboarding. *Injury Prevention* 13(3): 173–177.
Shepherd J, Caldeira K, Haigh J et al. (2009) *Geoengineering the Climate: Science, Governance and Uncertainty*. London: The Royal Society.
Solar Radiation Management Governance Initiative (2011) *Solar Radiation Management: The Governance of Research*. Available at: http://www.srmgi.org/report/.
Steptoe A and McMunn A (2009) Health behaviour patterns in relation to hypertension: The English longitudinal study of ageing. *Journal of Hypertension* 27(2): 224–230.
Stiglitz JE (1983) Risk, incentives and insurance: The pure theory of moral hazard. *The Geneva Papers on Risk and Insurance* 8(1): 4–33.
Underhill K (2013) Study designs for identifying risk compensation behavior among users of biomedical HIV prevention technologies: Balancing methodological rigor and research ethics. *Social Science and Medicine* 94: 115–123.
Urpelainen J (2012) Geoengineering and global warming: A strategic perspective. *International Environmental Agreements: Politics, Law and Economics* 12(4): 375–389.
Waggoner PE (1992) Now, think of adaptation. *Arizona Journal of International and Comparative Law* 9(1): 137.
Weitzman ML (2013). *A voting architecture for the governance of free-driver externalities, with application to geoengineering*. The Harvard Project on Climate Agreements Discussion Paper 13–55.
Winter G (2011) Climate engineering and international law: Last resort or the end of humanity? *Review of European Community and International Environmental Law* 20(3): 277–289.
Xia L, Robock A, Cole J et al. (2014) Solar radiation management impacts on agriculture in China: A case study in the Geoengineering Model Intercomparison Project (GeoMIP). *Journal of Geophysical Research: Atmospheres* 119(14): 8695–8711.