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The Prospect of Global Environmental Relativities After an Anthropocene Tipping Point

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Abstract

While there is vigorous debate on whether the Anthropocene epoch began in 1800, as originally proposed, less attention has been paid to the transition from Stage 2 of the existing three stage chronology, in which carbon dioxide emissions accelerated after 1945, to Stage 3, in which after 2015 acceleration is expected to reach criticality, and the Earth System is predicted to pass through an irreversible "tipping point" to a warmer state, unless this is averted by a new planetary stewardship. This paper critically evaluates this chronology and finds (a) that there is insufficient evidence for an imminent irreversible tipping point, and (b) that the international community established a new planetary stewardship in 1992 when it agreed on new conventions on climate change and biodiversity in response to three decades of warnings about global environmental problems. The paper proposes an alternative framework for conceptualizing the transition between Stages 2 and 3 of the Anthropocene. This generates the hypothesis that after the actual carbon dioxide concentration of the atmosphere has exceeded a critical threshold level, some biophysical processes will change at rates proportional to the difference between the carbon dioxide concentration of the atmosphere and the threshold level, and to the rate of climate change. Evidence is presented which suggests that this new reversible tipping point could have been passed before 1980, when enhanced forest growth was first observed in mature forests in Amazonia. Modelling simulations suggest that this temporal relativity effect could soon be joined by a spatio-temporal relativity effect, as species become committed to extinction and/or form new species assemblages in the 21st Century when climate zones shift. Since this new tipping point is reversible there is still time for planetary stewardship to become more effective and minimize the harmful effects of climate change.

Keywords: climate change, tipping point, environmental transitions, temporal ecology, global change science, global environmental governance

1. Introduction

Increasing human modification of the global environment led Crutzen and Stoermer (2000) to propose that we should "emphasize the central role of mankind in geology and ecology" by recognizing that since the end of the 18th Century we have lived in a new geological epoch, called the "Anthropocene". They chose to start the epoch at the beginning of the Industrial Revolution, whose dependence on fossil fuel combustion initiated the rise in carbon dioxide emissions that is now changing global climate, by enhancing the natural warming mechanism of the 'greenhouse effect' (Arrhenius, 1896).

This paper aims to assess, and enhance, the relevance of the Anthropocene to forest research. While welcoming the fact that geology is now incorporating phenomena which they have studied for decades, forest researchers would also be quite justified in thinking that the Anthropocene concept is unlikely to benefit them. Indeed, only a few forest studies have been framed by it so far (e.g. Paquette and Messier, 2010; Malhi et al., 2014; Allen et al., 2015; Lugo, 2015). One crucial difficulty is that *time* means different things to different scientific disciplines, and the periods of time over which geologists detect significant changes far exceed those to which scientists in other disciplines are accustomed. Forest science is proud of taking a long-term view, supporting the sustainable management of forests on rotations of typically 50 years or more in temperate countries. Yet it is dwarfed by geology, which measures time in units of millions of years. The 216 years since the Anthropocene epoch began may seem to have passed like the blink of an eye to geologists, but they encompass the entire history of forest science: the founding of the first schools of forestry in Europe around 1800 coincided with the start of the Anthropocene, and much knowledge has been gained since then. So if the new term is to be used properly, "Forestry in the Anthropocene" should not refer to a new type of forestry that responds to *current* conditions in "the last several decades" (Lugo, 2015), but to the whole history of forestry over the last 216 years! Other studies with 'Anthropocene' in their titles fall into this trap too.

Those promoting recognition of the Anthropocene as a new epoch in the taxonomy of geological time are engaged in two main lines of research. First, determining when the *start* of the epoch will be best measured in rocks by future geologists (e.g. Zalasiewicz et al., 2011, 2015). Second, viewing the Anthropocene as a *process* which is evolving in distinct stages. In one chronology, the first stage began in 1800. A second, "Great Acceleration", stage followed in 1945, after which there was a dramatic rise in the human imprint on the planet, as measured by such indicators as carbon dioxide emissions from fossil fuel consumption and tropical deforestation. A third stage would begin after 2015, as the human imprint accelerated towards "criticality". If business proceeds as usual, and the human imprint is not controlled by a "new planetary stewardship", the planet could pass through a "tipping point" to a permanently warmer state, with serious consequences for all life on Earth (Steffen et al., 2007, 2011a).

After reviewing the Anthropocene literature, this paper draws three conclusions. First, the process approach is of most relevance to forest researchers, since it can provide a tangible focus for *contemporary* studies. Second, forest research will derive most benefit if the process at the core of Anthropocene research is the enhanced greenhouse effect, as originally proposed by Crutzen and Stoermer (2000), complemented by biodiversity change, which is also highlighted by Steffen et al. (2007, 2011a) and is studied by both contemporary ecologists and palaeoecologists (Barnosky et al., 2011). Third, greater clarity is needed about the transition between Stages 2 and 3 of the three stage chronology, and about the timing of the concepts of "criticality", "new planetary stewardship" and "tipping point" and the mechanisms that link them.

To fill this gap, and respond to an invitation to all scientists to collaborate in "re-conceptualizing the Anthropocene" (Brondizio et al., 2016), this paper proposes a new conceptual framework for explaining the transition between Stages 2 and 3. This framework generates the hypothesis that above a threshold level of carbon dioxide in the atmosphere the planet will pass through a *reversible tipping point* and move from the special condition of relative "*stationarity*" in climate, which has prevailed since at least the start of the Anthropocene (Wolkovich et al., 2014), to a *non-stationarity* condition common in pre-human times, when climate zones and ecosystem types were more mobile on the Earth's surface. Under non-stationarity, we further hypothesize that new *global environmental relativities* will emerge in which key biophysical processes start to change at rates that are directly proportional - though not necessarily in a linear way - to the difference between the carbon dioxide concentration of the atmosphere and this threshold level, and to the rate at which climate changes. In this more uncertain non-stationary world, ecosystem properties can no longer be predicted by using past environmental measurements, but will change in ways that are related to changes in environmental variables linked to the enhanced greenhouse effect. Empirical data are vital for timing the transition to Stage 3, and the paper presents evidence that the new tipping point could have been passed before 1980. Since conventions on biodiversity and climate change were agreed at the United Nations Conference on Environment and Development in 1992, the shift to a "new planetary stewardship" may have already taken place too. There is still time to avoid passing through the later irreversible tipping point predicted by Steffen et al. (2007, 2011a).

The rest of the paper is in four parts. Part one critically evaluates the Anthropocene literature and the three stage chronology and suggests how to refine the latter. Part two outlines a new conceptual framework for explaining the transition between Stages 2 and 3, and generates from this hypotheses linked to a reversible tipping point. Part three examines the currently available evidence for testing these hypotheses. Part four discusses the research, economic and policy implications of this new approach.

2. Literature review

2.1 The core Anthropocene literature

One conceptual advance made by the originators of the Anthropocene concept (Crutzen and Stoermer, 2000) was to identify humanity as a "major geological force" on a *global scale* (Crutzen, 2002). Another was to connect anthropogenic global environmental change and geological time. Geologists divide the 4,550 million (M) years of the Earth's existence into ten eras, most of which are divided in turn into periods and then epochs (Table 1). We are now in the Cenozoic era, which began 66 M years ago (Mya), and in its Quaternary period, which began 2.6 Mya. The first epoch of the Quaternary, the Pleistocene, was characterized by various glaciations and non-glacial intervals. Almost 12,000 years ago it was followed by the Holocene epoch, which is the latest to be officially recognized by the International Commission on Stratigraphy (ICS) of the International Union of Geological Sciences (Cohen et al., 2013). In the "accommodating" and "resilient" environment of the Holocene (Steffen et al., 2011a), human beings have played an increasingly important role (Roberts, 1989). This taxonomy of geological time will be modified to insert an Anthropocene epoch after the Holocene epoch if representations by advocates of the Anthropocene succeed.

Since the year 2000 the Anthropocene concept, and its justification, have been refined by a collaboration between one of its originators, an environmental scientist (Crutzen), and scientists from other disciplines, especially geology, who are also members of the ICS Anthropocene Working Group (http://quaternary.stratigraphy.org/workinggroups/ anthropocene/). These *core Anthropocene scholars,* as they will be referred to here, have made two further fundamental contributions.

First, they have examined various options for reaching international agreement on timing the start of the new epoch in the *geological record* (see below) and have provided four justifications for the epoch (Zalasiewicz et al., 2010):

1. It is necessary to distinguish a new interval of time which is "dominated by human activity" that has had environmental impacts at *global* scale, from the Holocene in which humans had more limited (and localized) impacts.

2. Human impacts have led to "an order of magnitude increase in the long-term rate of erosion and sedimentation" which is geologically important.

3. Humanity has also had a global impact by greatly increasing the atmospheric concentrations of trace gases, such as *carbon dioxide* and *methane*. This is expected to raise the mean average temperature of the planet by 2-5 ºC during the 21st Century.

4. Global climate change is expected to combine with habitat change and other human impacts to greatly increase the current rate of *species extinction*.

Second, by developing a *process-based approach,* and using quantitative indicators of environmental and socio-economic changes, they have proposed that the Anthropocene can be divided into three stages (Table 2) (Steffen et al., 2007, 2011a):

1. Stage 1 began around 1800, at the same time as the Industrial Revolution, which increased fossil fuel combustion and had other major impacts on the planet.

2. Stage 2 began in 1945, and corresponded to the "*Great Acceleration*" after World War II in industrialization, ecosystem changes, fossil fuel use, and associated carbon dioxide emissions. The level of carbon dioxide in the atmosphere only rose by 9% to 310 ppm between 1800 and 1945, but from 1945 to 2005 it rose by 23% to 380 ppm.

3. Stage 3 would begin after 2015, when "the Great Acceleration [would] reach *criticality*", and "recognition that human activities are indeed affecting the structure

and functioning of the Earth System as a whole… [would] filter through to decision-making at many levels". This would challenge humanity to adopt a new form of "planetary stewardship" that could prevent a “business as usual” approach from causing the Earth System to pass through an irreversible "*tipping point*" “to a warmer state."

2.2 Challenges to core Anthropocene claims about Stage 1

The number of Anthropocene studies has risen dramatically in recent years (Fig. 1). According to a search in Google Scholar for publications with the word "Anthropocene" in their titles, between 2000 and 2009 the average number of papers in international peer-reviewed journals was less than 3 per year, but this rate has since risen sharply to 13 in 2010, 59 in 2013, 92 in 2014, 170 in 2015 and 134 in 2016.

Most of the challenges made so far to proposals by core Anthropocene scholars have concerned the first stage of the new epoch and, in particular, when it started. Three elements of this debate are important in the context of this paper, because they affect which process is placed at the centre of the Anthropocene and when it began:

1. Ruddiman (2003, 2013) argues that the Anthropocene started much earlier than 1800, since the atmospheric concentration of carbon dioxide rose after the discovery of agriculture 8,000 years ago (ya) led to extensive forest clearance and wood burning in Europe and elsewhere. The atmospheric concentration of methane also rose after irrigated rice cultivation was developed in Asia 5,000 ya. These two rises in gaseous concentrations could have prevented a subsequent glaciation, thereby suspending the alternation of glaciations and non-glacial intervals that characterized the Pleistocene. Extensive deforestation in pre-industrial times, Ruddiman (2013) argues, makes a case for “a two phase Anthropocene” based on changes in the human imprint and the atmosphere. However, the overall significance of pre-industrial carbon dioxide emissions has been challenged (Broecker and Stocker, 2006; Steffen et al., 2007; Stocker et al., 2011), and starting the Anthropocene 8,000 ya would remove most of the currently recognized 12,000 year Holocene epoch.

2. While Ruddiman’s (2003, 2013) argument is consistent with Crutzen and Stoermer’s (2000) initial focus on the enhanced greenhouse effect process, other critics depart from it to identify a global *marker* that future generations can detect in rocks. Lewis and Maslin (2015) suggest two alternative dates for starting the Anthropocene: 1610, which corresponds to the first recorded transfer of food crops between Latin America and Europe, and a dip in atmospheric carbon dioxide content resulting from a sharp fall in world population; and 1964, when the level of the isotope Carbon-14 (^{14}C) in the atmosphere peaked, since nuclear bomb tests declined after that year.

3. Core Anthropocene scholars are critical of Lewis and Maslin’s (2015) proposal (e.g. Hamilton, 2015), yet they have themselves recently proposed shifting the start of the Anthropocene to the beginning of the "Great Acceleration", since detonation of the first atomic bomb in 1945 disseminated around the world isotopes, such as ^{14}C, which may be measured by future geologists (Zalasiewicz et al., 2015).

This proposal by core Anthropocene scholars to delay the start of the Anthropocene until 1945 would, if accepted, weaken the link between the Anthropocene and the enhanced greenhouse effect process. The inconsistency between it and earlier proposals could also dissuade scientists from disciplines other than geology from incorporating the Anthropocene into their own conceptualizations. The fact that the authors of the three stage chronology reviewed above (Steffen et al., 2007) are co-authors of this new proposal (see also Steffen et al., 2015), and that other geologists are sceptical about it (Walker et al., 2015), could strengthen scepticism in other disciplines.

Another factor that will influence the ease with which the Anthropocene becomes a meaningful interdisciplinary concept is that geologists also use different *clocks* to measure time from those used by scientists from other disciplines. They now employ isotopic dating methods to distinguish between different 'strata' in rocks, and the ^{14}C method proposed by Zalasiewicz et al. (2015) fits into this category. Earlier geologists used fossil content as the basis for their clock: huge numbers of fossils were collected to provide empirical data for stratification, and then grouped by era, period and epoch in geological museums, where later generations can still "read" the fossil record today (Goudie, 1983). Such clocks are internally consistent over millions of years, but differ from clocks used to measure the human calendar (Walker et al., 2015).

Some compromises are therefore inevitable if the Anthropocene is not to remain a niche geological concept, but is to frame research in other disciplines too (Ruddiman et al., 2015). An earlier suggestion by Zalasiewicz et al. (2011), that the start of the epoch in the human calendar (e.g. 1800) could co-exist with a different year for the most attractive “golden spike” in the geological record, seems a sensible compromise. Only future generations of geologists will be able to determine using geological evidence at their disposal when the Anthropocene can be distinguished from the Holocene.

2.3 Challenges to current ideas about the “Great Acceleration”

Later stages of the three stage chronology of the Anthropocene, and the process approach generally, have received less critical evaluation. One aspect of Stage 2 that has been questioned is the claim, e.g. by Steffen et al. (2007, 2011a), that the “Great Acceleration” in the human imprint has eroded natural habitats and led to the loss of many species. Some “non-core” Anthropocene studies support this claim (e.g. Dirzo et al., 2014), and ecologists are debating the prospect of an impending “mass extinction” without referring to the Anthropocene (e.g. Barnosky et al., 2011; Ceballos et al., 2015). However, other non-core studies directly dispute the claim, e.g. Caro et al. (2011) argue that "there are several reasons to doubt that humans have altered everything".

A key weakness in the three stage chronology that has not been noticed so far is that the crisis-based link between (a) “criticality” in the “Great Acceleration” in resource consumption and environmental degradation in Stage 2, and (b) a move to a new "planetary stewardship" in Stage 3 duplicates claims made 40-50 years ago. Core Anthropocene scholars have charted exponential rises in the 20th Century in consumption of products as diverse as water, paper and motor vehicles; and in such environmental impacts as tropical forest loss, species extinctions, and the atmospheric concentrations of carbon dioxide, methane and other pollutants. They link these trends to equally exponential rises in world population and Gross Domestic Product (Steffen et al., 2007, 2011b, 2015), and cite seminal global overviews by Marsh (1864) and its sequel (Turner et al., 1990) to support their conclusions.

However, "Neo-Malthusian" studies of the 1960s and 1970s, such as *The Population Bomb* (Ehrlich, 1968) and *The Limits to Growth* report (Meadows et al., 1972), also recognized these trends and forecast an impending global environmental crisis, and did so on the basis of more systematic analyses of resource depletion and environmental degradation. Yet, apart from Steffen et al. (2011b), core Anthropocene scholars do not cite Neo-Malthusian publications, implying that they are unaware of them and related developments since 1960. A recent study led by non-core scientists did pay more attention to *The Limits to Growth* (Verburg et al., 2016), but as this was part of a technical review of options for modelling the Anthropocene it did not mention that *The Limits to Growth* was the culmination of a huge wave of doom-laden concern that led to the first United Nations (UN) Conference on the Human Environment being held in Stockholm in 1972.

Nor, in spite of some attempts to engage in dialogue (e.g. Steffen and Lambin, 2006), do core Anthropocene scholars refer to:

1. All the research conducted since 1980 into *modelling human-environment phenomena*. This explains why many of the gloomy Neo-Malthusian predictions are still unrealized (e.g. Lambin et al., 2001). For example, it is now recognized that all forested countries can expect to lose forest cover in the course of economic development, but at higher levels of development this may be followed by a "forest transition" in which countries switch from net forest loss to net forest gain (Mather, 1992). A parallel with this U-shaped curve in forest cover can be seen in the inverse U-shaped curve, known as the Environmental Kuznets Curve, that describes how the trend in the atmospheric concentration of gases such as sulphur dioxide first rises in the course of development and then declines as countries become richer (Stern et al., 1996).

2. How the Neo-Malthusian crisis paradigm, and the associated globalist discourse of managing the planet to meet purely biophysical criteria, were superseded in the 1980s by a new *sustainable development* paradigm. This recognizes development realities and attempts to find a middle way that alleviates poverty while minimizing resource depletion and environmental degradation (WCED, 1987). It was accompanied by pathfinding economic research (e.g. by Pearce et al., 1989; Jansson et al., 1994) which went beyond past economic critiques of the limitations of *The Limits to Growth* and similar biophysical projections to propose new conceptualizations (see below).

As a result of this fundamental shift in thinking about humanity's relationship with Planet Earth, sustainable development became the basic philosophy of the UN Conference on Environment and Development (UNCED), held in Rio de Janeiro in 1992. At this conference, the world's governments agreed to conventions on biodiversity and climate change (UN, 1992a, 1992b) which, together with the later convention on desertification and a statement of forest principles, form the basis of the new approach to global environmental governing that is taken today (UN, 1993).

It could be argued that UNCED marked the move to "global sustainable environmental management" (Crutzen and Stoermer, 2000) or a new "planetary stewardship" (Steffen et al., 2011a), for which core Anthropocene scholars are calling. Convening UNCED consolidated the response by the UN Conference on the Human Environment in 1972 to Neo-Malthusian claims about an impending planetary crisis, and incorporated more specific later warnings about the need to tackle global climate change, biodiversity loss, desertification and forest change. Consequently, judged on political criteria alone, it is possible that Stage 3 of the Anthropocene, which we call the *Planetary Stewardship* stage here (Table 2), began in 1992.

Criticality in the Great Acceleration in the human imprint has therefore indeed led to a new planetary stewardship, as hypothesized in the three stage chronology. So far, however, implementation of the Rio conventions has not been very effective, as Steffen et al. (2011b) admit. Yet this reflects the difference between (a) the ideal aspirations of core Anthropocene scholars, and (b) the political reality of balancing multiple goals that is recognized in the sustainable development paradigm, and which can be explained in more detail by scientists from other disciplines.

2.4 Limitations of the criticality concept

Another weakness in the existing three stage chronology is a lack of clarity in how its key concepts of "criticality" and an "irreversible threshold", or "tipping point", are linked together in time and by various mechanisms. Core Anthropocene scholars make alarming predictions about what will happen in Stage 3 if planetary stewardship is ineffective in controlling "criticality". If things continue as they are, warn Steffen et al. (2007), the "collapse of modern, globalized society under uncontrollable environmental change is one possible outcome... It is now conceivable that an *irreversible threshold* could be crossed in the next several decades, eventually (over centuries or a millennium) leading to the loss of the Greenland ice sheet and consequent sea-level rise of about 5 m…The Great Acceleration is *reaching criticality*… Whatever unfolds, the next few decades will surely be a *tipping point* in the evolution of the Anthropocene".

The two concepts of "criticality" and "tipping point" will be examined separately. The notion of "*criticality*" as a trajectory with a steep rise in the acceleration of the human imprint is implied by Steffen et al. (2011a), when they propose two ways to refine their conceptualization of how a new planetary stewardship should steer the critical post-Great Acceleration trajectory to avoid a catastrophic tipping point:

1. Plotting the Global Ecological Footprint index (GEF) (in hectares per person) against the UN Human Development Index (HDI). This identifies a goal for the trajectory in the form of a "sustainability quadrant" zone with a high value of HDI (0.8-1.0) and bounded by an upper value of GEF of under 3 hectares per person.

2. Employing the "nine planetary boundaries" proposed by Rockstrom et al. (2009) to identify a "safe operating space for humanity". The nine boundaries are: climate change; rate of biodiversity loss; nitrogen cycle; phosphorus cycle; stratospheric ozone depletion; ocean acidification; global freshwater use; change in land use; atmospheric aerosol loading; and chemical pollution. Some of these

boundaries are related to upper limits to the biophysical parameters used by core Anthropocene scholars to characterize the Great Acceleration (Steffen et al., 2011b).

The true significance of the “criticality” concept becomes apparent when it is realized that these two approaches to monitoring the critical trajectory are essentially equivalent, since the nine planetary boundaries simply disaggregate the upper boundary of the Global Ecological Footprint index. The latter is rooted in one of two scientific conceptualizations devised after the concept of sustainable development emerged in the political arena (WCED, 1987), namely a proposal by ecological economists that development is sustainable if the human footprint does not exceed an upper *carrying capacity* limit (Daly, 1990; Costanza and Daly, 1992). In the other conceptualization, environmental economists proposed that development is sustainable if the rise in Human and Man-Made Capital exceeds in value the associated decline in Natural Capital from which it is derived, and Natural Capital does not fall below a lower limit represented by *Critical Natural Capital*. The latter is the part of Natural Capital that cannot be substituted by Man-Made Capital. It comprises biodiversity, and key global cycles associated with it, that are vital for sustaining the biosphere (Pearce, 1993). So keeping the human imprint below the *upper* limit of carrying capacity is equivalent to preserving the Natural Capital that remains when the human imprint has reached this *lower* limit of Critical Natural Capital (Fig. 2). If “criticality” refers to a path approaching the carrying capacity limit then biospheric processes would break down if the limit were breached. (The GEF “sustainability quadrant” and the nine planetary boundaries are both safely below the carrying capacity limit (Steffen et al., 2011b)).

2.5 Limitations of the tipping point concept

Critical Natural Capital is therefore a crucial intermediate concept for linking the concepts of “criticality” and “tipping point” in time and by common mechanisms. Yet it is not clear that a breach in Critical Natural Capital is imminent. Concerning threats to the biodiversity component, Steffen et al. (2007) claim that “the Earth is in its sixth great extinction event, with rates of species loss growing rapidly.” The current rate of species extinction due to habitat change (e.g. 477 vertebrate species have become extinct since 1900) does exceed the expected 'background rate' (e.g. 9 vertebrate species over this period) (Ceballos et al., 2015), but it cannot compare with previous mass extinction events. For example, in the last event, 65 Mya in the Cretaceous, 75% of all species were lost. So the current threat to species from habitat change is not consistent with an imminent irreversible tipping point. Humanity also still only appropriates 25% of the net primary productivity of potential vegetation (Krausmann et al., 2013).

Another potential threat to Critical Natural Capital comes from global climate change. Steffen et al. (2011a) assert that an “irreversible threshold could be crossed in the next several decades”, but this will only have consequences in the distant future: “eventually (over centuries or a millennium) leading to the loss of the Greenland ice sheet and consequent sea-level rise” that could help shift the Earth to a warmer state. Any proposal that an early passage through a *tipping point* could unleash self-propagating and irreversible forces with consequences hundreds of years later should be treated as sceptically as Neo-Malthusian forecasts of the 1960s and 1970s that were based on exponential biophysical trajectories uncontrolled by economic and policy mechanisms.

The type of switch specified by Steffen et al., (2011a), e.g. "human perturbation to Earth System dynamics... may be strong and persistent enough to tip the system out of the Holocene stability domain and into an alternative, geologically long-lived, generally warmer state of the Earth System", *is* consistent with definitions of a tipping point. For example, "a non-linear relation between a driver and the eventual state of the ecosystem when it finally equilibrates" (Hughes et al., 2013), and a point where "a minor trigger can invoke a self-propagating shift to a contrasting state" (Scheffer et al., 2012).

However, another weakness in the tipping point concept is in the vagueness of the two underlying mechanisms proposed by core Anthropocene scholars:

1. The Earth in the late Quaternary period is portrayed in geological terms as being capable of switching between two states, a glacial state and an inter-glacial state (i.e. the Holocene, where it is now located). Steffen et al. (2011a) hypothesize that, past a critical level of human modification of the global environment, the Earth will shift into a singular state from where it can no longer return to a glacial state.

2. To show how this could happen, Steffen et al. (2011a) use a study by Lenton et al. (2008), based on Earth System Science (ESS) modelling. This classifies key Earth sub-systems into different kinds of *tipping elements*, which include: (a) those that move the earth from one state to another, e.g. "loss of Greenland ice sheet", and (b) those on which the Earth depends for resilience in its inter-glacial state, e.g. tropical rain forest in Amazonia. Steffen et al. (2011a) claim that both the Greenland ice sheet and tropical rain forest in Amazonia "already show signs of instability… [and] if tipped, would move the Earth System toward a warmer state." The first is vulnerable to global climate change, while the second is assumed to be vulnerable to human clearance.

Since core Anthropocene scholars favour ESS as a framework for studying the Anthropocene, it is difficult to determine if these proposals are realistic scenarios, or merely artefacts of highly aggregated/low resolution ESS models of how Critical Natural Capital will unravel under human impact. ESS is "the study of the Earth as an integrated physical and social system" (Pitman, 2005). It was promoted by the US National Aeronautics and Space Administration (NASA) in the late 1980s as a strategy to use data from its satellites "to obtain a scientific understanding of the entire Earth system on a global scale by describing how its component parts and their interactions have evolved, how they function, and how they may be expected to continue to evolve on all timescales" (Bretherton, 1986). However, three limitations of ESS bring into question its suitability for conceptualizing the Anthropocene:

1. It is mainly concerned with predictive biophysical modelling. A search in Google Scholar found that 64 papers published in international peer-reviewed journals in 2014 had "earth system" in their titles, and 49 of these had "earth system modelling" in their titles.

2. Many of its practitioners lack the confidence to treat ESS as a science in its own right, and so promote it as an umbrella for other disciplines. A Google Scholar

search found that no more than five papers with "Earth System Science" in their titles have been published every year in international peer-reviewed journals since the year 2000. Clifford and Richards (2005) argue that "in its present form, ESS embodies basic contradictions", and any hypotheses that might be proposed by ESS are "untestable because the sampling required to recognize a signal from background noise will be impracticable". They also state that "the knowledge that is embedded in ESS is not necessarily acquired by 'doing ESS', and if this is true, ESS is neither a science, nor indeed an epistemology” (Richards and Clifford, 2008).

3. The original interdisciplinary vision of ESS is consistent with studying human impacts on Planet Earth in the Anthropocene, but it has proved difficult to realize. Schnellnhuber (1999) argued that the two main components of ESS should be *environmental systems* and *human systems*, and that they should have equal status, However, according to Liverman and Cuesta (2008), "Earth system science has always found the incorporation of humans into the Earth system a challenging task". Since human beings should, by definition, be at the heart of the Anthropocene (Palsson et al., 2013), this is a major constraint.

2.6 Discussion

The process approach to the Anthropocene seems from this review to be of most relevance to forest researchers. The three stage chronology proposed by Steffen at al. (2007, 2011a) is a useful starting point for analysis, because a key focus is the enhanced greenhouse effect process, and the latter is integrated with human impacts on biodiversity resulting from changes in habitats and climate. Current forest research by most contemporary ecologists and social scientists is also more closely related to Stage 3, and to the interface between it and Stage 2, than to the whole of the Anthropocene.

However, as this review has shown, the existing chronology has two main weaknesses:

1. Its crisis-based link between “criticality” in the “Great Acceleration” and a move to a new "planetary stewardship" in Stage 3 duplicates claims made 40-50 years ago that led to the first UN Conference on the Human Environment in 1972. This crisis paradigm later gave way to a new sustainable development paradigm that was the basic philosophy of the UN Conference on Environment and Development in 1992, which is a logical point for marking the emergence of a new "planetary stewardship” (Table 2).

2. It does not clearly explain the transition from Stage 2 to Stage 3, and how the “criticality” and “tipping point” concepts are linked together in time and by various mechanisms.

The rest of this paper proposes another way to explain the transition from Stage 2 to Stage 3 that responds to these weaknesses, and to the invitation by Brondizio et al. (2016) to the wider scientific community to collaborate in “re-conceptualizing the Anthropocene”.

3. Methodology

Since the rise in carbon dioxide emissions after the start of the Industrial Revolution, and their acceleration after World War II, have already been recognized and explained by scientists from various disciplines, what makes the three stage chronology of the Anthropocene most distinctive – and useful to other disciplines - is the transition from Stage 2 to Stage 3. Unfortunately, this is the weakest part of the existing chronology. This section therefore proposes an alternative framework for conceptualizing this transition. To achieve greater clarity than the existing chronology it opts for a simpler approach, and deduces from first principles what could happen when the enhanced greenhouse effect process reaches criticality.

3.1 Frames of reference

Frames of reference are needed to measure changes in time and space in variables representing key properties of global ecosystems, such as productivity, biomass, species composition etc., and in the underlying environmental variables, such as temperature, which influence them.

The values of these underlying variables, and more generally the persistence of organisms, can be explained conceptually in terms of the "n-dimensional hypervolume" of their *niches* (Hutchinson, 1957). The environmental variables that constitute these n dimensions comprise the *conditions*, such as temperature, humidity etc., to which organisms are best suited, and the *resources*, such as light, water, carbon dioxide, nutrients etc., which they need for growth.

Over the short period (in geological time) in which ecological measurements have been made only limited variation has occurred in the mean global values of at least three of these underlying *global niche variables*: temperature, precipitation, and the carbon dioxide concentration of the atmosphere. This is described by the concept of *stationarity*, which is "the idea that natural systems fluctuate within an unchanging envelope of variability" (Milly et al., 2012). Stationarity allows the common assumption that climate is stable when environmental data are used to explain ecological processes. In their re-evaluation of "temporal ecology in the Anthropocene", Wolkovich et al. (2014) imply that a shift from stationarity to non-stationarity could occur in the Anthropocene. They argue that "stationarity" is basic to ecology, since "models of the most basic shifts... are generally built on simple static correlations between ecological and environmental data... [Yet] climate change introduces into most systems a level of non-stationarity that is largely unprecedented over the last 200 years."

If 'stationarity' in these global niche variables were to give way to non-stationarity, so that atmospheric carbon dioxide content, temperature and precipitation are no longer invariant (within well-defined limits of variation), these variables could become new *drivers* that move the optimal 'envelopes' of niches outside previous observational experience. We now explore some possible consequences of this.

3.2 A temporal relativity hypothesis

Let us first assume that only one global niche variable - carbon dioxide concentration - can change, and that a temporal frame of reference can be used to examine the impact which this change has on the trend over time in the productivity and biomass of an ecosystem in any location. Temperature and precipitation are assumed to stay constant.

It is not possible to define an optimal temporal envelope for ecosystems in Stages 1 and 2 of the Anthropocene, in terms of a normative trend for post-disturbance changes in ecosystem productivity, biomass and composition etc. Clements' (1916) holistic theory of succession portrayed the deterministic endogenously driven succession of ecosystems up to the final climax equilibrium ecosystem linked to the climate in any location. There has been a century of debate about the competing merits of (a) this and other holistic theories, and (b) the reductionist and non-deterministic theories of Gleason (1926) and others, which state that abiotic factors are influential and allow for no ultimate equilibrium ecosystem. However, the outcome of this debate is that no general theory has been found that can withstand tests against empirical data (Finegan, 1984). West et al. (1981) summarized the problem thus: "It is relatively easy to form a local theory of succession but… development of a general theory with equivalent detail may be a futile objective." State and transition models offer a pragmatic compromise (Phillips, 2011), by allowing for the linear successions proposed by Clements (1916) and for other sequences too (Pulsford et al., 2014).

Forest scientists have long relied on assumptions of temporal stationarity and predictable logistic growth to calculate timber volume yield tables for single tree species based on site classifications (e.g. Johnston et al., 1967). A shift to non-stationarity will challenge the continued validity of these maximum volumes. As Wolkovich et al. (2014) argue, "While succession is fundamentally about temporal non-stationarity in an ecological process, theory is not, however, fully developed to handle temporal non-stationarity in underlying drivers", such as those linked to climate change.

A switch from stationarity to non-stationarity could provide a biophysical marker of the transition between Stages 2 and 3 of the Anthropocene to complement a political marker of the launch of a new planetary stewardship, e.g. the holding of the UN Conference on Environment and Development in 1992. In the absence of general theories of temporal change in ecosystems under conditions of stationarity or non-stationarity, it is only possible to propose possible *drivers* of ecological changes. These new drivers, including carbon dioxide, will act *globally* because the cumulative impact of human activities all over the world is mediated by the atmosphere. Other gases, e.g. sulphur oxides and nitrogen oxides, have previously been *regional* drivers of forest degradation in Europe and North America through acid deposition (Galloway, 1995).

This suggests a *temporal relativity hypothesis,* in which once a certain threshold atmospheric concentration of carbon dioxide has been exceeded the gas can become a global atmospheric driver for changing ecosystem behaviour over time, causing an ecosystem's productivity and biomass profile to expand outside its previously assumed optimal temporal envelope, by an amount that will depend on the relationship between the actual concentration of carbon dioxide and its critical threshold concentration. In other words, once the carbon dioxide concentration of the atmosphere exceeds this threshold, the productivity of ecosystems (and even mature ecosystems) will change as a function of the excess carbon dioxide concentration. This function need not be linear, and will be influenced by synergies with other ecological processes, as discussed below.

This hypothesis could be tested empirically by measuring changes in forest growth rates over time, using reliable historic measurements as baselines.

3.3 A spatio-temporal relativity hypothesis

We now examine what could happen over the entire land surface of Planet Earth when temperature and precipitation are allowed to vary as well as carbon dioxide concentration.

In the stationarity conditions of the 20th Century a number of inter-related systems were devised to classify the distributions of: (a) climate into different climatic zones, and (b) ecosystems into major types of ecosystems, or *biomes,* based on their structures and the climatic envelopes within which they flourish (Table 3). Whittaker's (1976) biome classification system divides ecosystems within a frame of reference defined by axes of temperature and precipitation. When this is matched to a latitude/longitude frame of reference for mapping the distribution of climate zones on the Earth's surface it predicts the spatial distribution of global "biome types" (Fig. 3), which are then divided into distinctive regional "biomes".

If the stationarity of the envelopes of climatic zones, biomes and species no longer applies in Stage 3 of the Anthropocene, but the division of biome envelopes in the temperature/precipitation frame of reference (e.g. Fig. 3) stays the same, then shifts in climate zones - or what Ohlemüller (2011) calls shifts in "climate space" - will cause the *potential* envelopes in a latitude/longitude frame of reference to move relative to their *historic* Holocene equilibrium positions. The same will occur with the envelopes of individual plant species. Although the ideal maps of global ecosystem types that are represented by maps of biomes have long since been altered by clearance for agriculture and modification of ecosystems to harness their productive services, these maps can still serve a useful purpose by predicting the possible effects of climate change.

The movement of *potential* biome (and plant species) envelopes will be driven by atmospheric processes, mediated by physical features, such as altitude. The movement of *actual* biome (and plant species) envelopes in search of the new locations to which their potential envelopes have shifted will be influenced by ecological processes, and by physical barriers, such as mountains. The disparity between these shifts in potential and actual envelopes will result in some species becoming extinct, because they cannot keep pace with the movement of their ideal habitats, and the size of the disparity will influence the actual rate of extinction. (It is not assumed that biomes and species will move independently - their movements are merely described collectively here because they are two of the key dimensions of biodiversity (UN, 1992a)).

Since ecosystems and individual plant species are likely to migrate more slowly than climate zones, this leads to a *spatio-temporal relativity hypothesis*, in which the global rate of plant species extinction will be directly proportional to the rate of climate change. The hypothesis refers to the *global* rate of extinction because the impacts of climate change on the biosphere will be spatially variable over the surface of the planet, just as the velocity of climate space - and climate generally - is spatially variable (Burrows et al., 2011; Sandel et al., 2011). It does not preclude various forms of adaptation of species to climate change, or even the formation of new species (e.g. Thomas, 2015). Only the area of the Earth's land surface is assumed to be constant here. Future research may identify other constant factors.

This hypothesis can be tested empirically for biomes by measuring the shift in the envelopes of biomes away from their ideal locations. For species, shifts in the envelope encompassing the locations of all individuals of a given species could be monitored by using as a baseline a global map of the current *actual* distributions of individuals of all species in *existing* ecosystems. No such map is yet available but there is support for its construction (e.g. Newton et al., 2015).

3.4 Synergies and anthropogenic influences

Temporal and spatio-temporal relativities have been described separately here because they have different drivers, and the former will, by definition, precede the latter. However, both will operate simultaneously once spatio-temporal relativities appear, and this permits the proposal of a *joint relativity hypothesis*, in which after a tipping point some biophysical processes will change at rates (R) which are directly proportional - though not necessarily in a linear way - to the difference between the carbon dioxide concentration of the atmosphere at any time t (c_t) and a critical threshold concentration (c_0), and to the rate at which climate changes (DC/dt). In algebraic form:

$$R = f\ [c_t - c_0, DC/dt] \qquad (1)$$

The combination of the two forms of relativity will not be additive but will involve synergies too. The exact nature of this function, and the role of such synergies, could be specified in more detail by future research. However, it is likely that the positive effects of carbon fertilization on growth will be offset by other effects, e.g. on mortality, which result when biomes and species are 'left behind' in non-optimal conditions when their potential envelopes shift. Synergies are also likely with anthropogenic drivers of ecosystem change for, as Taylor (1984) pointed out, the interaction between "society-derived and environment-derived processes... generates new processes that may be peculiar to that interaction." Sustained human impacts and manipulation have already led to the appearance novel types of human-modified ecosystems (Eyre, 1963; Ellis et al., 2010) whose analysis requires a cultural as well as a natural biogeography (Simmons, 1979). Fortunately, state and transition models of ecosystem succession can encompass a range of possibilities of this kind (Phillips, 2011).

While our discussion of global environmental relativities here has focused on forest biomes, these relativities will affect all biomes, including those in dry areas whose degradation is at the heart of desertification (UN, 1994).

3.5 Discussion

The shift from stationarity to non-stationarity which is proposed here has five advantages as a biophysical marker for clarifying the transition between Stages 2 and 3 of the Anthropocene proposed by Steffen et al. (2007, 2011a):

1. It is a tipping point in its own right, but not an irreversible one.

2. It is clearly linked to “criticality” in a specific process, namely the enhanced greenhouse effect.

3. It has been deduced from a bottom-up understanding of ecological processes, not inferred from simulations with a top-down model of the planet and therefore subject to the latter’s limitations.

4. It can be measured by empirical research.

5. It is a major global environmental transition, comparable with environmental transitions already recognized (Van den Bergh et al., 2011).

This tipping point could complement the use of a political marker for the transition between Stages 2 and 3, e.g. using the UN Conference on Environment and Development in 1992 to signify the launch of a new planetary stewardship at the start of Stage 3. It does not preclude an irreversible tipping point (as proposed by Steffen et al., 2007) occurring in future if failures in Earth sub-systems lead to a permanent shift to a warmer planet. Representing the irreversible tipping point as a transition to a new fourth stage of the Anthropocene, called here the Super-Warm Stage (Table 2), corrects another deficiency in the existing three stage chronology, namely, that it includes in the same stage both a new planetary stewardship and the tipping point which could occur if this is ineffective.

Since the shift to non-stationarity will change the direction in which the planet is evolving under human impacts, scientists working in this and related fields will need to question how they use *time* in their research. In particular, they should:

1. *Question uniformitarianism*, a term which is understood to mean that "basic physical laws apply to all of geologic time as well as the present" (Garner, 1974). Paul (2015) claimed that uniformitarianism is "a salient pillar of geology", as even in its "weak form" it implies that "suggestions based on present-day observations [can be] applied to past or future" and that, for example, processes in the Middle Pliocene will be replicated by those in the 21st Century with similar levels of carbon dioxide (Salzmann et al., 2008). Uniformitarianism is assumed in many natural sciences, e.g. "the assumption of spatial and temporal invariance of natural laws is the basic mode of reasoning in empirical science" (Gould, 1965), and Einstein’s Special Theory of Relativity assumes that the laws of physics apply to all frames of reference in uniform motion relative to each another (Einstein, 1905). Yet Knight and Harrison (2014)

have questioned its continued relevance in ecology, arguing that "under ongoing climate change... Earth systems are now operating in ways that are substantially different to how they are believed to have operated in previous geologic time periods." One justification they give for this claim is "the explicit involvement of human activity in Earth system processes and feedbacks in ways that have not been experienced throughout Earth's previous history."

2. *Expect developmental transitions*. Previous research into human-environment relationships in land change science has shown that climate change and other major global environmental 'problems' are not abnormalities, but phenomena linked to economic development in ways that can be identified through empirical and theoretical research. As mentioned above, all forested countries can expect to lose forest cover as they develop, but at higher levels of development they may pass through a "forest transition" by switching from net forest loss to net forest gain (Mather, 1992). In the same way, national "carbon transitions", in which countries switch to low-carbon economies at high levels of development, are also expected (Grainger, 1997; Van Kooten et al., 1997). However, every country has a different type of forest transition curve, e.g. while some developed countries, such as the USA, exhibit fairly discrete forest transitions (Mather, 1992), transitions now under way in developing countries are more fuzzy (Grainger, 2010a). The hundreds of U-shaped national forest transition curves are unsynchronized, since every country is at a different stage on its development path, so it is understandable that how these curves combine to give the long-term *global* forest area trend is still imperfectly understood (Barbier et al., 2010). A similar lack of synchronicity is likely between the huge number of national carbon transitions and will affect the trend in the carbon dioxide concentration of the atmosphere.

3. *Expect global environmental uncertainties*. Modelling the terrestrial component of global environmental change is hindered by uncertainty about estimates of the distributions of land use and land cover, and of how these change over time because of human impacts. For example, there is still great uncertainty about trends in the global distribution of closed canopy forest, found in moist areas of the world, even though such ecosystems are the most visible to optical satellite sensors and therefore easily measured from space. One reason for this lies in the previous reluctance of scientists to engage in planetary measurement: satellites have collected global environmental data since 1972 at the medium (30 m) resolution that can identify even the small 1 hectare clearances in tropical forests made by shifting cultivators, but these medium resolution data have not been operationally processed into usable global forest information until recently (Grainger, 2010b; Townshend et al., 2012; Hansen et al., 2013).

The diversity of ecosystem classification systems (Table 3) exacerbates these uncertainties, since the potential extent of a biome depends on the system used to calculate it. In FAO's Tropical Forest Resources Assessment 1990 (FRA 1990), for example, the potential area of the "tropical rain forest" biome was mapped by combining the Yangambi and UNESCO classification systems (FAO, 1993; CSA, 1956; UNESCO, 1973). In the next report, FRA 2000, the Köppen-Trewartha system (Köppen, 1931; Trewartha 1968) was used instead (FAO, 2001), and this increased the potential size of the tropical rain forest biome by 36% (Grainger, 2007).

These uncertainties, and developmental factors, will limit the accuracy of tests of the hypotheses proposed here about a reversible tipping point, and the subsequent emergence of temporal and spatio-temporal relativities. Knight and Harrison (2014) even suggest that a proper analysis of trends at this point in the Anthropocene needs a new kind of science that can incorporate high global environmental uncertainties. This would correspond to what Funtowicz and Ravetz (1990) call a "post-normal science".

4. Evidence

This section presents available evidence to provide *preliminary* tests of the temporal and spatio-temporal relativity hypotheses proposed above.

4.1 Evidence for global temporal relativity

Despite the longstanding debate about the concept of climax ecosystems, mentioned above, it was long assumed that mature 'old growth' forests do not achieve any net growth in biomass over time. So it was entirely unexpected when measurements by Phillips et al. (1998) found an average net *uptake* of 0.62 ± 0.37 $MgC.ha^{-1}.a^{-1}$ between the mid-1970s and mid-1990s in above-ground biomass in 97 plots in intact tropical forests in Amazonia. This uptake was extrapolated to 0.44 ± 0.26 $PgC.a^{-1}$ for all forests in lowland Amazonia. The effect has since been confirmed by other measurements in tropical forests in Amazonia in the 1980s and 1990s (Malhi et al., 2004; Phillips et al., 2008) and in Africa between 1968 and 2007 (Lewis et al., 2008).

The first signs of enhanced growth were noticed in Amazonia, according to Phillips et al. (1998), in "the late 1970s" and were clearly evident by 1980 (Fig. 4). A net carbon sink has also been observed by remote sensing measurements, supported by ground data, in northern temperate and boreal forests as well as tropical forests, and in all forests, and not just mature ones, between 1981 and 1999 (Myneni et al., 2001) and between 1982 and 1999 (Dong et al., 2003), but not with the same temporal resolution.

These findings are consistent with passing through a tipping point predicted by the temporal relativity hypothesis at some time before 1980. The critical threshold beyond which carbon dioxide became a global atmospheric driver was therefore less than 335 ppm, which was the concentration measured in Hawaii in 1980 (Keeling et al., 1995). Owing to the delay before the impact of 'excess' carbon dioxide appears in growth, it is not possible to specify the threshold concentration more accurately.

If earlier data become available, most likely from forests outside the tropics, their analysis could help to identify more clearly the timing of the tipping point. Recent studies have been focusing on how growth has been complicated by new phenomena and support the above qualifications that emerging synergies will make this simple relationship more complex. The rate of net increase in above-ground biomass in Amazonian forests has fallen by 30% since the year 2000 in comparison with 1990s values, after growth rates levelled off and mortality rates rose (Brienen et al., 2015). The authors suggest that this could result from feedback from higher growth rates - i.e. an indirect consequence of the global atmospheric driver - and/or from an increase in climatic variability (e.g. drought), which could be the first indication of the additional impact of global climate change through spatio-temporal relativity.

4.2 Predictions of global spatio-temporal relativity patterns

Various simulations have been undertaken of possible future shifts in the envelopes of biomes in response to climate change (e.g. Malcolm et al., 2006). Testing the relationship between shifts in biome envelopes and climate zones will be helped by the results of a recent modelling study, which used the Koppen-Geiger climate classification system and concluded that the velocity of climate space for each climate zone will be proportional to the rise in mean global temperature (Mahlstein et al., 2013). This suggests that temperature rise could be a useful proxy for overall climate change when testing the spatio-temporal relativity hypothesis.

Questions are already being asked about whether another "mass extinction" is under way, since the current rate of species extinction largely due to *habitat change*, based on empirical measurements, far exceeds the historical background rate (Barnosky et al., 2011) (see Section 2.5). However, according to experiments with simulation models, the extinction rate is likely to rise sharply when extinctions linked to habitat change are supplemented by those linked to *climate change*. In one early study, which modelled future trends in climate zones, and combined the climate envelopes of individual species with a classification of their plant functional types, Miles et al. (2004) showed that in a high scenario 43% of all plant species in Amazonia could become non-viable by 2095 since their potential distributions would become disconnected from their actual distributions. If climate changed less rapidly the loss could be halved to 20%. The high scenario was based on the Hadley HADCM2 IS92a 'business as usual' scenario, which would raise carbon dioxide concentration by 84% to 644 parts per million between 1990 and 2099 and increase mean global temperature by 3.2ºC (Table 4). In a more comprehensive study, which included the findings of Miles et al. (2004) for Amazonia but used climate envelope models for other parts of the world, Thomas et al. (2004) predicted that 35% of all species on the planet could be "committed to extinction" by 2050 in the high scenario in which temperature rises by over 2.0ºC, but only 18% would be lost if climate changes more slowly and temperature rises by up to 1.7ºC.

These early models have been criticized for their simplicity, which was understandable given the lack of reliable global environmental data (McMahon et al., 2011). Later studies have called for models that have better coverage of the dynamics of species populations (Keith et al., 2008); ecological processes (Morin et al., 2008; Van der Putten et al., 2010; Lavergne et al., 2010); migration (Thuiller et al., 2008); resilience (Hof et al., 2011; Moritz and Agudo, 2013); ecosystem composition (Urban et al., 2012); relationships between species distributions and environmental variables (Austin and Van Niel, 2011); and interactions between habitat change and climate change impacts on species viability (Mantyka-Pringle et al., 2012). Nevertheless, while the magnitude of potential species extinctions can be debated, since the movement of the actual envelopes of species is generally expected to lag behind the movement of their potential envelopes it is likely that the rate of extinctions will rise as proposed in the spatio-temporal relativity hypothesis (Bellard et al., 2012).

Various adaptive pathways, both natural and intentionally constructed, will emerge to limit the rise in the rate of extinctions. For example, mountains offer pathways for lowland species to migrate to moist conditions as low altitude environments become more arid, e.g. in Amazonia (Miles et al., 2004). On the other hand, species currently found in tropical montane ecosystems will become vulnerable as climate zones shift to higher elevations (Larsen et al., 2011). Artificial transportation of threatened species to new areas has been proposed by Thomas (2011) to counter constraints on adaptation.

As stated above, enhanced global environmental uncertainties are a key feature of the new global environmental relativities. One source of uncertainty about spatio-temporal relativity is linked to the future of the large proportion of species which are still able to flourish in novel climates, e.g. potentially 65-82% of species worldwide (Thomas et al, 2004) and 57-80% of plant species in Amazonia Miles et al., 2004). It has been suggested that "no-analog communities" (Williams et al., 2007) or "novel species assemblages" (Young, 2014) could form through a combination of remaining species, immigrating species, and declining populations of exiting species. The content of these assemblages/communities will be complicated by how the relative movements of species interacts with novel anthropogenic ecosystems that have emerged as result of sustained human impacts and manipulations (Ellis et al., 2010).

5. Discussion

5.1 Implications for future research

While the previous section provided some evidence to support the temporal and spatio-temporal relativity hypotheses proposed in this paper, formal tests will require the construction of properly organized observations specifically designed to capture the effects suggested here, rather than to answer other questions. For example:

1. Testing for temporal relativity will require the measurements of changes in growth in mature forests with high temporal resolution (as in Phillips et al., 1998), and in other forests the separation of changes in growth due to CO_2 fertilization from changes in growth for other reasons.

2. Testing for spatio-temporal relativity will require a new focus on the global monitoring of shifts in major ecosystem types (Grainger, 2009), and in the distributions of individual species (Newton et al., 2015).

3. As humanity progresses through Stage 3 of the Anthropocene the features of the natural world will change in ever more complex ways, not least in the formation of new communities and species assemblages, and this provides opportunities for scientists to observe these changes and to report them to their fellow citizens and to policy makers.

While the rise in the number of papers in international peer-reviewed journals that refer to the Anthropocene is encouraging (Fig. 1), the Anthropocene literature will not advance in a generic way if papers do not engage with the basic principles and conceptualizations of the Anthropocene. This is hindered if papers merely equate the Anthropocene to “the last several decades” (e.g. Lugo, 2015; Sun and Vose, 2016) or to increasing complexity in the effects of global climate change (e.g. Allen et al., 2015). Hopefully, this paper will encourage fellow scientists to link their contemporary studies to Stage 3 of the Anthropocene, or to the transition between Stages 2 and 3.

Many authors are, understandably, attracted to associate their existing research with the latest paradigm (Visconti, 2014), but it is disappointing when the Anthropocene is merely the latest in a line of paradigms that is chosen because previous paradigms have not been effective. For example, conservation biologists devised the paradigm of biodiversity in the 1980s to promote better species conservation, but at the turn of the Millennium a new paradigm of ecosystem services was adopted to place more emphasis on the economic benefits of conservation (e.g. De Groot et al., 2002). Recently, some forest hydrologists have adopted the Anthropocene paradigm after becoming disenchanted with how well the ecosystem services paradigm had succeeded in integrating catchment management into forest management (e.g. Creed et al., 2016).

5.2 Economic implications

The new global environmental relativities will have major economic implications. Longstanding yield tables for timber species will become increasingly inappropriate, and estimating the net economic returns of forestry investments will be made more difficult by increasing uncertainty about site classes, growth rates and economic returns. Sites currently optimal for planting certain tree species will become more marginal as climate zones shift, and currently marginal sites will become more economic. Changes in species composition will also affect estimates of the non-market environmental values of ecosystem services which forests provide.

Forest economists will therefore need regular updates of forest inventories to keep pace with relativistic effects. If this is to happen, national forestry departments must be aware of the new relativities when they schedule inventories and interpret inventory data. This was not the case when an inventory of the volume of timber in coniferous trees in forests and woodlands in Great Britain was made in 2011. It found a greater volume than had been forecast as recently as 2005, and while various explanations were proposed they did not include what is called here temporal relativity (Forestry Commission, 2012).

5.3 Policy implications

The policy implications of the analysis of the Anthropocene in this paper differ from those emerging from the analysis by Steffen et al. (2007, 2011a) because:

1. This paper recognizes that the world's governments have already responded in 1972 to the 'planet in crisis' predictions of Neo-Malthusians in the 1960s, and elaborated this response in 1992 by adopting a new sustainable development paradigm that also responded to later predictions of threats from climate change and biodiversity loss. As a result, it is concluded here that the new planetary stewardship for which core Anthropocene scholars are calling actually began in 1992.

2. This paper does not accept there is sufficient evidence for the predictions of Steffen et al. (2007, 2011a) concerning the imminent passage through an irreversible tipping point within the next few decades, the effects of which will not be empirically testable for hundreds of years and perhaps millennia. The world's governments now properly insist on evidence-based policy advice and, bearing in mind that there is still a significant body of sceptical opinion about climate change, it is important for scientists to avoid speculations for which there is limited empirical support.

These conclusions do not reduce the need for greater urgency in acting to mitigate global climate change. Despite receiving the best scientific advice available, from the Intergovernmental Panel on Climate Change (e.g. Bernthal et al., 1990), actions under the Kyoto Protocol to the UN Framework Convention on Climate Change, agreed in 1997, would, even if fully implemented, only cut carbon emissions by developed countries by 5% relative to 1990 levels by 2012 (UN, 1998; UNFCCC, 2011). Actual global emissions rose by 35% from 1980-89 to 2002-2011 (Le Quéré et al., 2013). After starting in 2007 to negotiate further reductions in developed countries, and a Reducing Emissions from Deforestation and Forest Degradation (REDD+) mechanism to help cut emissions in developing countries (UNFCCC, 2014), developed and developing countries could only agree in Paris in 2015 to follow the binding Kyoto Protocol with a non-binding agreement to keep the rise in mean global temperature under 2°C (UNFCCC, 2015).

In these circumstances, in which there is now an acceptance that some climate change up to 2°C will happen, the message for policymakers that emerges from this paper is that the more that climate changes as a result of human actions, the greater will be the effects on the natural world. Positive effects have already appeared in the form of increased growth in forest ecosystems, but negative effects are likely in the form of increased species extinctions that will significantly exceed in scale what some scientists are already referring to as the "sixth mass extinction crisis" (Barnosky et al., 2011). For example, Thomas et al. (2004) predicted that 18% of all species could be "committed to extinction" by 2050 if temperature rises by up to 1.7°C.

6. Conclusions

This paper has found that an Anthropocene perspective can be useful to forest researchers for framing changes in forest cover over the last 216 years and for evaluating the contributions of these changes to global climate change and biodiversity loss in an integrated way. However, the element of Anthropocene research that seems to be of most value to forest researchers involves taking a process-based approach. An existing three stage chronology of the Anthropocene epoch proposes that recent decades have involved a transition from Stage 2, in which the human imprint on Planet Earth accelerated, to Stage 3, in which after 2015 acceleration in carbon dioxide emissions and other impacts is expected to reach criticality, and the Earth System could pass through an irreversible "tipping point" to a permanently warmer world, unless this is averted by a new planetary stewardship (Steffen et al., 2007, 2011a).

After critically evaluating the existing three stage chronology, this paper finds that there is insufficient evidence for an imminent irreversible catastrophic tipping point, and that the international community has already established a new planetary stewardship when at the UN Conference on Environment and Development in 1992 it agreed on new conventions on climate change and biodiversity. Warnings by Steffen et al. (2007) and other core Anthropocene scholars about an imminent crisis in resource depletion and environmental degradation duplicate claims made by Neo-Malthusian scholars in the 1960s and 1970s, to which the international community responded by convening the UN Conference on the Human Environment in 1972.

This paper has responded to these weaknesses in the existing three stage chronology, by proposing an alternative framework for conceptualizing the transition between Stages 2 and 3 of the Anthropocene. The framework has been derived from first principles rather than simulations with an Earth System Science model. It generates the hypothesis that after the carbon dioxide concentration of the atmosphere has exceeded a critical threshold level, some biophysical processes will change at rates proportional to the difference between the carbon dioxide concentration of the atmosphere and the threshold level, and to the rate of climate change. Empirical evidence has been presented which suggests that this new reversible tipping point could have been passed before 1980, when enhanced forest growth was first observed in mature forests in Amazonia. Modelling simulations suggest that this temporal relativity effect could soon be joined by a spatio-temporal relativity effect, as species become committed to extinction and/or form new species assemblages in the 21st Century as climatic zones shift. Since this new tipping point is reversible there is still time for planetary stewardship to become more effective and minimize the harmful effects of climate change. If this does not happen, passage through an irreversible tipping point linked to failures in Earth sub-systems, as proposed by Steffen et al. (2007, 2011a), could still occur in future.

By placing the 216 years of the enhanced greenhouse effect process within the wider framework of the geological timescale, an Anthropocene perspective also allows current assumptions about the role of time in environmental change to be questioned, just as Einstein (1905) questioned the role of time in physics in his Special Theory of Relativity. Even within disciplines that study the environment, time is approached differently. For example, when forest economists evaluate the net economic returns of forestry investments by discounting to the present the future costs of management and revenues from yields (Faustman, 1849), they favour the short-term over the long-term, and so essentially speed up 'economic time' at a rate which depends on the value of the discount rate which they choose. Contemporary ecologists have accumulated a huge amount of knowledge over the last 200 years about the functioning of ecosystems, all based on an assumption of "*stationarity*" where climatic zones and continents move relatively little and the glacial cycle is interrupted. Geologists assume uniformitarianism when extrapolating from the past to the present, and vice versa; they also embrace two views of time: time as an arrow, which stretches continuously into the future, and time as a cycle, in which purely physical factors can cause huge extinctions, after which the natural world has to "start over again" (Gould, 1988). This paper has stressed the need to question assumptions about stationarity and uniformitarianism. It has suggested that the transition between Stages 2 and 3 of the Anthropocene could be marked by a shift from stationarity to *non-stationarity*, and that passing through this tipping point could change the direction of the path along which the planet is evolving under human impacts.

Future theoretical and empirical research will discover a lot more about global environmental relativities, and about the Anthropocene in general. This paper has shown how the Anthropocene concept can serve as a framework for integrating various forest phenomena to find broader patterns. One constraint is that the tools which scientists currently use to study human impacts on the global environment are still rooted in disciplines which were developed to study sub-global phenomena. Although core Anthropocene scholars favour the use of Earth System Science as a framework for their research, this paper has suggested that this approach has limitations for studying human impacts on the planet. The global environmental relativities proposed here could become important elements of a new global change science, together with global environmental transitions and uncertainties, to which they are linked.

Developing a new global change science could increase public support for better international policies to tackle global climate change, after governments failed to reach agreement in Paris in 2015 on a binding protocol to replace the binding Kyoto Protocol. Massive sales of Stephen Hawking's (1988) book, *A Brief History of Time*, and demand for TV documentaries on the discoveries of 20th Century Physics, show that non-scientists are fascinated by relativity theory, even though it does not affect them personally. Since global environmental relativities *will* affect every person on the planet, growing awareness of them could change public perceptions of the threats posed by climate change, and help to speed up international action to control it.

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Table 1
The geological time scale since the Cambrian period.

Era	Period	Epoch	Millions of Years Ago
Cenozoic	Quaternary	Holocene	0.01
		Pleistocene	2.6
	Tertiary	Pliocene	5.3
		Miocene	23.0
		Oligocene	33.9
		Eocene	56.0
		Palaeocene	66.0
Mesozoic	Cretaceous		145.0
	Jurassic		201.3
	Triassic		252.1
Palaeozoic	Permian		298.9
	Carboniferous		358.9
	Devonian		419.2
	Silurian		443.4
	Ordovician		485.4
	Cambrian		541.0

Source: Cohen et al. (2013).

Table 2
Stages in the original three stage chronology (Steffen et al., 2007) and as revised here.

	Original Chronology		Revised Chronology	
Number	Name	Period	Name	Period
1.	Industrial Revolution	1800-1945	Industrial Revolution	1800-1945
2.	Great Acceleration	1945-ca2015	Great Acceleration	1945-1992
3.	Planetary Stewardship	2015-?	Planetary Stewardship	1992-
4.			Super-Warm	2100-?

Table 3
Typical biome classification schemes.

Yangambi (CSA, 1956) (Africa only)	Moist forest, dry deciduous forest, thicket, moist montane forest, dry montane forest, bamboo forest, savanna woodland, tree savanna, shrub savanna, grass savanna, tree/shrub steppe, dwarf-shrub steppe, succulent steppe, herb steppe, aquatic grassland, herb swamp, high montane grassland.
Eyre (1963)	*Tropical*: tropical rainforest, tropical seasonal forest, microphyllous forest and woodland, semi-desert shrub, desert, broadleaved tree savanna, microphyllous tree-tall grass savanna, microphyllous tree desert grass savanna, semi-desert scrub with desert grass, desert alternating with porcupine grass semi-desert, tropical montane forest, tropical montane forest with conifers. *Extra-tropical*: tundra and alpine vegetation, boreal forest dominated by larch, boreal sub-alpine and montane coniferous forest, coast and lake forest, mixed boreal and deciduous forest, mixed boreal and lake forest, mixed lake, boreal and deciduous forest, mixed lake and deciduous forest, deciduous summer forest, blanket bog alternating with deciduous forest, blanket bog alternating with mixed forest, mixed southern pine and deciduous forest, southern pine forest, broadleaved evergreen forest, evergreen mixed forest, forest-steppe, steppe, semi-desert shrub and woodland, sclerophyllous scrub, sclerophyllous scrub with desert grass, Australian sclerophyllous forest, Australian sclerophyllous savanna.
Köppen-Trewartha (1966)*	Tropical, dry, subtropical, temperate, boreal, polar, highland.
UNESCO (1973)	Closed forest, woodland, scrub, dwarf scrub, herbaceous vegetation.
Walter and Box (1976)	Equatorial, tropical, subtropical, mediterranean, warm temperate, nemoral, continental, boreal, polar.
Whittaker (1976)	Arctic tundra, northern coniferous forest, temperate forest, tropical rain forest, tropical seasonal forest, temperate grassland, Tropical savanna grassland and scrub, desert, mediterranean vegetation/chapparal, mountains.

Table 3 (Cont......)

Bailey (1989)	Polar, humid temperate, dry, humid, humid tropical.

*The Köppen-Trewartha system was originally intended to classify climatic zones but has subsequently been used to classify biomes too.

Table 4
The percentages of species committed to extinction by two simulations of low and high climate change scenarios in the 21st Century.

Study	Area	Taxa	Low Scenario	High Scenario	End of Simulation
Miles et al. (2004)	Amazonia	Plant species	20	43	2095
Thomas et al. (2004)	Global	All species	18	35	2050

Fig. 1. The number of papers published in international peer-reviewed journals since the year 2000 which have "Anthropocene" in their titles, as measured by searches in Google Scholar on 3 September 2015 (2000-14), 27 February 2016 (2015) and 20 December 2016 (2016).

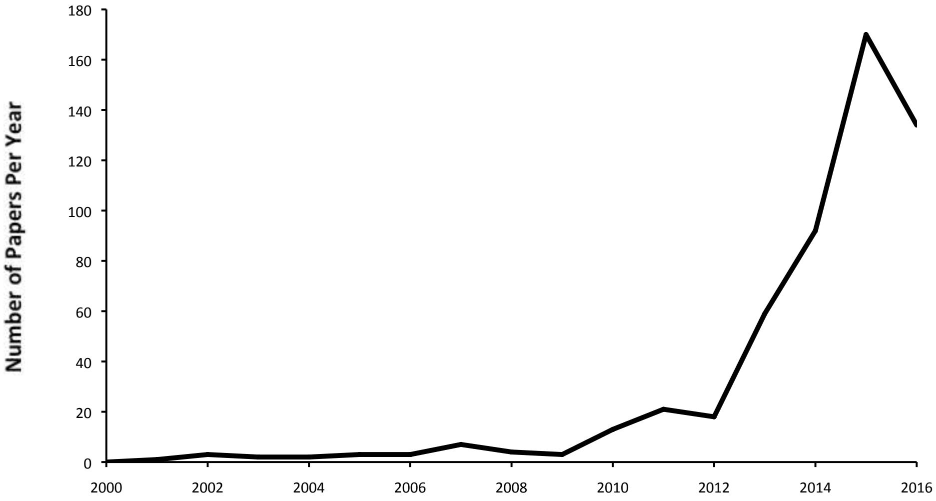

Fig. 2. The equivalence of upper carrying capacity and lower Critical Natural Capital limits for sustaining the biosphere.

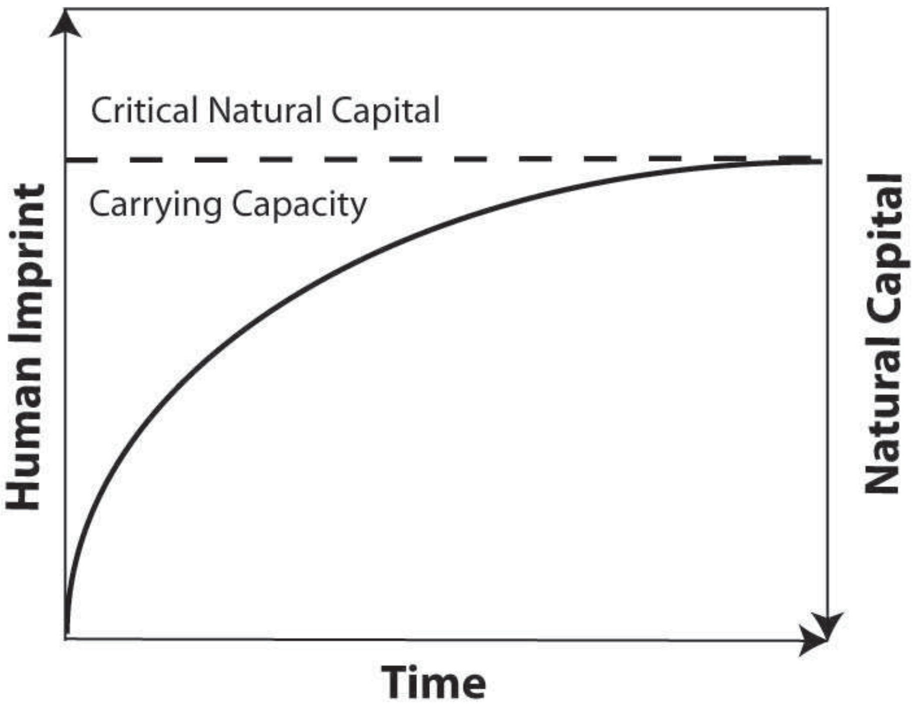

Fig. 3. Whittaker's biome-type classification scheme. Source: Whittaker (1976).

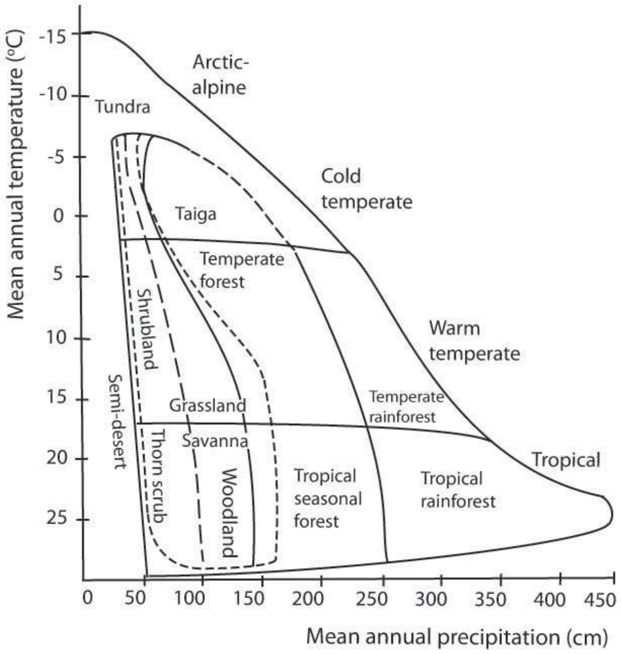

Fig. 4. Cumulative aboveground net biomass change (tons ha^{-1}) in humid forests in Amazonia. Source: Phillips et al. (1998)