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Committed terrestrial ecosystem changes due to climate change

Chris Jones*, **Jason Lowe, Spencer Liddicoat and Richard Betts**

Targets for stabilizing climate change are often based on considerations of the impacts of different levels of global warming, usually assessing the time of reaching a particular level of warming. However, some aspects of the Earth system, such as global mean temperatures[1] and sea level rise due to thermal expansion[2] or the melting of large ice sheets[3], continue to respond long after the stabilization of radiative forcing. Here we use a coupled climate–vegetation model to show that in turn the terrestrial biosphere shows significant inertia in its response to climate change. We demonstrate that the global terrestrial biosphere can continue to change for decades after climate stabilization. We suggest that ecosystems can be committed to long-term change long before any response is observable: for example, we find that the risk of significant loss of forest cover in Amazonia rises rapidly for a global mean temperature rise above 2 °C. We conclude that such committed ecosystem changes must be considered in the definition of dangerous climate change, and subsequent policy development to avoid it.

Future climate change and the carbon cycle are tightly coupled[4]. Many studies (such as refs 5, 6) have now shown positive feedbacks that amplify climate change, reduce the natural uptake of carbon and influence global emissions pathways to stabilization[7,8]. On the timescale of 1 or 2 centuries, the contribution to this feedback is likely to be greater from the terrestrial biosphere than from the ocean carbon cycle[6]. Rising temperature enhances soil decomposition and together with reductions in rainfall, may also reduce plant productivity in large regions. Changes in climate may also alter the important biomes—especially tropical and boreal forests[9]. Climate impacts are often summarized for policy makers as a table of impact magnitude against global mean warming (for example, the Stern Review[10]). However, a significant limitation is that some of the impacts are taken from model simulations at the instant the temperature is reached, and fail to account for subsequent impacts as slowly responding parts of the system fully respond to the given change.

The increase in global mean temperature due to increasing greenhouse gas concentrations lags behind the radiative forcing that causes it because of the thermal inertia of the system[1]. For present-day climate, this committed rise has been predicted to be between 0.25 and 0.5 °C (ref. 11). Other components of the climate system also show committed change. Sea level rise from thermal expansion seems likely to increase for several centuries to millennia following stabilization of radiative forcing[2,11], and the contribution to sea level rise from melting of the Greenland ice sheet is also likely to continue long after radiative forcing is stabilized[3,12]. Terrestrial ecosystems might also show committed change behaviour following stabilization of forcing because changes in both vegetation cover and carbon storage are likely to lag behind that of temperature and rainfall. Hence, we introduce the new concept of committed ecosystem change and examine the extent to which biomes may be committed to significant changes in response to climate forcing before they can be observed.

The Intergovernmental Panel on Climate Change Second Assessment Report noted that climate change is expected at a rapid rate compared with forest ecosystem timescales[13] but neither subsequent IPCC Assessment reports nor the published literature have discussed the implications of this statement in terms of committed changes to important ecosystems. We present examples from the Amazon and boreal forests to show how important such committed changes may be.

The Met Office Hadley Centre climate carbon cycle model, HadCM3LC, is one of only a few coupled general circulation model (GCM)–dynamic vegetation models. Previous analysis[14,15] has examined the large-scale loss of Amazon forest simulated by this model in response to transient scenarios of climate change. Other studies that examined tropical ecosystem response under climate change simulations from a range of climate models[16,17] and using a range of vegetation models (some with a greater degree of species diversity)[9] also showed reductions in tropical forest cover, especially in Amazonia. Observational studies have also shown the vulnerability of the Amazon forest to drought[18]. Although HadCM3LC produces greater regional climate change and die-back than some offline model studies, other models do project changes that, although less extreme, are qualitatively similar[9] (see Supplementary Information). All of these studies, however, have focused on the period of changing forcing rather than behaviour subsequent to stabilization. We study here the long-term committed changes (see the Methods section and Supplementary Information).

Figure 1 shows a comparison of the realized and committed vegetation cover in a region of the Amazon forest (we consider the region of land within the area defined by 40° W–70° W and 15° S–5° N, as shown in Fig. 2). Figure 1a shows fractional forest cover in this region as it changes in time. Figure 1b shows the same data but shown as degree of die-back plotted against global mean temperature above pre-industrial. It is clear that the forest cover in the equilibrium simulations (dashed line) is significantly lower than the dynamic state. This indicates that at any time the forest is showing only a portion of the level of die-back it will eventually reach. For example, by 2050 when die-back begins to be observed in the transient simulation, the forest is already committed to eventually losing 50% of its area even without further increases in forcing (Fig. 2). This is roughly the same loss as seen in the transient simulations, with increasing forcing, by 2100 (Fig. 1). By 2100, even though only a third of tree cover has gone, the forest is committed to almost complete loss in this region. The solid line can be considered as the impact when a particular level of warming is first reached. The dashed line is the eventual impact after warming is sustained at the stabilization temperature for a long period of time.

Met Office Hadley Centre, Exeter EX1 3PB, UK. *e-mail: chris.d.jones@metoffice.gov.uk.

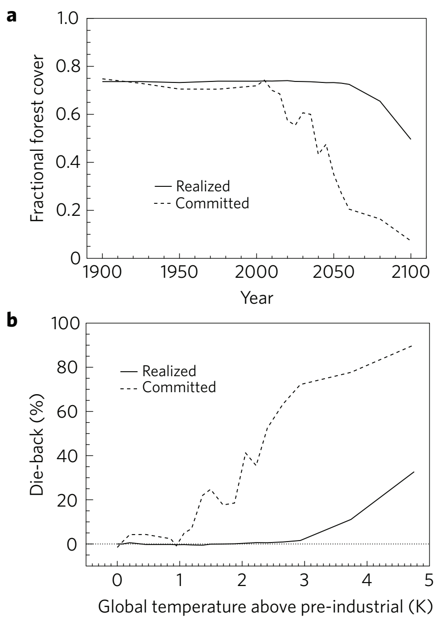

Figure 1 | Dynamic and equilibrium Amazon forest extent throughout the simulations. a, Fractional tree cover (represented as fractional coverage of broadleaf trees in the region 40°–70° W, 15° S–5° N) as it evolves dynamically through the SRES A2 simulation and the committed state corresponding to each year. **b**, The same information plotted as the percentage of complete die-back as a function of global mean temperature rise above pre-industrial (defined as 0 for the original, pre-industrial forest cover, and 100 for complete loss of tree cover in this region).

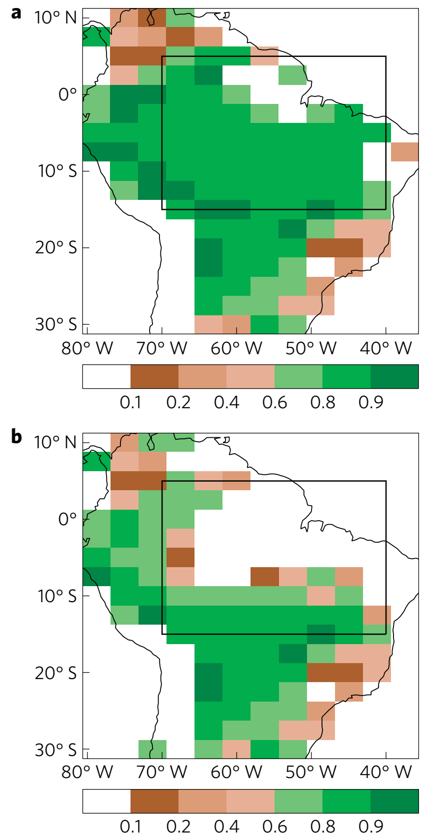

Figure 2 | Geographical distribution of Amazon forest tree cover at 2050. a,**b**, Realized (**a**) and committed (**b**) states represented as fractional coverage of broadleaf trees simulated by the model. The black rectangle shows the region used for calculating mean forest cover.

There seems to be a temperature below which the equilibrium state of the forest is approximately constant, but above which the equilibrium forest cover declines steadily with changing climate. This point could be seen as a threshold beyond which some degree of loss of Amazon forest is inevitable. Beyond this point there is no sudden transition from 'forest' to 'no forest', rather a gradual increase in the level of future committed die-back: the impacts are more progressive than sudden.

Our results also show that the forest may be committed to some degree of die-back before any is observed. For example, if climate forcing was stabilized at 2050, when tree cover fraction is virtually unchanged from the present day, a significant die-back would still occur subsequently over the next 100–200 years (see Supplementary Fig. S3). This has serious implications for any definition of dangerous climate change, as it means that stabilization of climate does not necessarily mean stabilization of climate impacts. It may not become apparent for some time when a threshold of committed change has been passed.

A further aspect of such committed changes is to consider the potential of the system to recover. Experiments to assess recovery of ecosystems under a return to pre-industrial global climate showed that forests did indeed have the potential for recovery but only on very long (multi-century) timescales (see Supplementary Information). This has implications for temperature-overshoot scenarios. First, from an impacts perspective, once the full change in forest cover has been achieved, the length of time that society has to exist without the forest may be so long that the change is, for practical purposes, irreversible. Second, as the amount of forest cover feeds back on to global atmospheric CO_2 concentration, the long recovery implies that the slow regrowth will make it more difficult to lower CO_2 concentrations and make it more difficult to approach a safe level of CO_2 and warming from above[19].

The concept of committed ecosystem changes applies equally to other biomes and to forest expansion as well as die-back although the response/lag times and impact on carbon storage might be different[20,21]. Figure 3 shows equivalent results for the boreal forest. Using tree cover between 45° and 80° N as a simple measure of northern latitude forest expanse, the dynamic solution shows a steady, but slow, increase in coverage up to the year 2100. Much of this is an intensification of tree cover in existing areas of forest, which occurs more rapidly than an expansion of the treeline. By 2100 we also see a northward expansion of forest cover. The committed state shows much greater expansion, by more than a factor of 3, by 2100. The large difference between realized and committed expansion is due to the slow timescales of areal changes.

The boreal forest region is expected to experience greater than average warming over the twenty-first century[22] and is a region where tree growth is generally more limited by temperature than precipitation. As most GCMs agree qualitatively on warming across high-latitude land areas, it may be expected that results here are more robust across different models (see further discussion in Supplementary Information). Boreal forest expansion has also been seen in other vegetation models[9] and in response to other climate models[16]. Pollen records and tree mortality observations indicate that previous warm periods in the mid-Holocene and medieval warm period did experience greater northward extent of boreal forest[23].

Considering long-timescale changes in ecosystems also has implications for multi-gas mitigation policies owing to the direct physiological effect of CO_2 on vegetation[24]. As ecosystems are also responding to changes in CO_2 concentration, future ecosystem commitments will probably depend not only on the stabilization of radiative forcing, but also the relative contribution of CO_2 and non-CO_2 greenhouse gas mitigation measures. For a given radiative

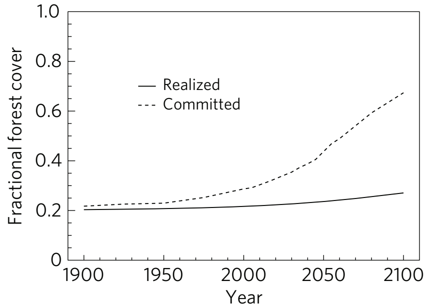

Figure 3 | Dynamic and equilibrium boreal forest extent throughout the simulations. The solid line shows the fractional tree cover (represented as fractional land coverage of both broadleaf and needleleaf trees in the region 45°–80° N) as it evolves dynamically through the SRES A2 simulation and the dashed line shows the committed state corresponding to each year.

forcing, CO_2 and non-CO_2 gases can lead to very different impacts on ecosystems[24]. Elevated CO_2 levels may aid forest resilience (for example, through improved water use efficiency[25]), implying that non-CO_2 reductions may be more effective at reducing committed ecosystem damage. However, quantifying this effect requires much more research. There are also implications for forestry practices, as degraded forest further compounds the risk of committed loss owing to increased vulnerability to fires following disturbance[26].

We have introduced the implications of the hitherto unconsidered application of the concept of committed changes to the terrestrial ecosystem. Although these results are from a single model and hence subject to quantitative uncertainty, we believe the concept of committed changes in the terrestrial biosphere is likely to be robust. The terrestrial biosphere can respond slowly to large, regional-scale forcing, but may not always be in equilibrium with that forcing at any point in time, leading to subsequent commitments to significant future change for decades or centuries following stabilization of forcing. There is a threshold beyond which some die-back is committed and this commitment rises markedly for greater global temperature rise. In our model this threshold is below 2 °C, a threshold often used by policy makers in their definition of dangerous climate change[27], although the quantitative nature of our results carries significant uncertainty. Any subsequent recovery is on such a long timescale as to make the die-back effectively irreversible on human timescales of the next 1–2 centuries.

There has been little or no discussion within the climate or ecosystem research communities on the concept of commitments to ecosystem change due to climate change. Our intention is to draw attention to committed ecosystem changes as an issue requiring serious consideration, and one that requires study with more than a single model. With increasing policy focus on climate mitigation and stabilization of climate change, quantifying such committed changes will make valuable contributions to our understanding of dangerous climate change, and to aiding development of mitigation policies. We argue that committed ecosystem changes, in addition to realized changes, should be considered in any definition of dangerous climate change. Weighing the cost of emissions reductions against the cost of climate damage may lead to very different conclusions for terrestrial ecosystems if committed ecosystem changes are considered in preference to the usual transient response.

Methods

HadCM3LC is a coupled climate/carbon cycle GCM including a dynamic vegetation model. It is able to reproduce many aspects of observed change such as the twentieth-century temperature and CO_2 record[28], observed sensitivity of CO_2 to El Nino and large volcanic eruptions[29]. We base our experiments here on the coupled HadCM3LC transient CO_2-only simulation of C4MIP (ref. 6). This experiment enables us to assess the transient response of ecosystems to the business-as-usual SRES A2 emissions scenario[30]. The changes throughout this experiment give us a projection of the state of the biosphere at any given time during the simulation. We will refer to such a state as the 'dynamic' or 'realized' state—that is, the state that occurs at a point in time as the system evolves but is not necessarily in steady state or in equilibrium with ambient climate or CO_2 levels. Owing to long timescales of response of vegetation, we use an accelerated equilibration technique (see Supplementary Methods) to determine the eventual biosphere state if the forcing was held constant at a given point in time. We will refer to this as the 'equilibrium' or 'committed' state. The difference between the two is therefore a measure of the un-realized but committed change.

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Author contributions

C.J. experiment design, analysis, C.J. and J.L. analysis and text, S.L. carried out model simulations, R.B. advice on design, analysis and text.

Additional information

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