LETTER TO THE EDITOR

Temporary storage of carbon in the biosphere does have value for climate change mitigation: a response to the paper by Miko Kirschbaum

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Abstract Kirschbaum (Mitig Adapt Strat Glob Change 11:1151–1164, 2006) explores the climatic impact over time of temporarily sequestering carbon from the atmosphere. He concludes that temporary storage of carbon in the terrestrial biosphere ''achieves effectively no climate-change mitigation''. His strongly worded statement begs for a response. This paper argues that Kirschbaum's conclusion is an artifact of the specific perspective of his analysis and his choice of a definition for climate-change impact. Even temporary sinks put us on a lower path for climate change, a path that will not otherwise be accessible. For carbon sinks in the terrestrial biosphere, we argue that sooner is better and longer is better, but even known temporary sinks have value.

Keywords Carbon sequestration · Carbon sinks

1 The context

Kirschbaum (2006) (see also Kirschbaum 2003) explores the climatic impact over time of temporarily sequestering carbon from the atmosphere. His focus is on carbon dioxide that is removed from the atmosphere at one time and released again at a later time (up to tens of years later), particularly when carbon is captured and stored temporarily in the terrestrial

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biosphere. He concludes that temporary storage of carbon in the terrestrial biosphere ''achieves effectively no climate-change mitigation'' (Kirschbaum 2006, p. 1161) and hence should not generate carbon credits under national or international agreements to mitigate the impacts of greenhouse gas emissions. His strongly worded statement begs for a response.

We believe that Kirschbaum's conclusion is erroneous and misleading. This paper argues that Kirschbaum's conclusion is an artifact of the specific perspective of his analysis and his choice of a definition for climate-change impact. Application of Kirschbaum's conclusion relies on an ex post facto perspective in which the future is known and is limited to a 100-year time frame. We argue that temporary carbon storage can have significant benefit for a variety of reasons (some of which are listed below and in Marland et al. 2001) and that it is entirely appropriate that carbon credits are recognized for carbon storage in the terrestrial biosphere, even if it is not guaranteed that sequestration is permanent. We agree with Kirschbaum that the ''tonne-year'' approach is not appropriate for awarding these credits but we believe that the concept of temporary or rented credits as described by several authors (see, for example, Government of Colombia 2000; Marland et al. 2001) and embodied in the decisions of the Conference of Parties to the UN Framework Convention on Climate Change (UNFCCC 2004) provides a suitable framework for awarding and trading carbon credits.

Kirschbaum writes that, ''... it is not the rate of emission that constitutes a concern in terms of climate change, but the resultant atmospheric CO_2 concentration, its associated radiative forcing and the climatic changes that result from a change in radiative forcing. Hence, while biosphere sinks can reduce net CO_2 emissions and atmospheric concentrations in the short term, the critical question is how they affect atmospheric concentrations and resultant climate-change impacts in the longer term'' (Kirschbaum 2006, p. 1152). We do not disagree with this framing of the ''critical question''.

2 The model

For his discussion of mitigating climate change impact, Kirschbaum suggests three measures to quantify climate-change impacts (1) the direct and instantaneous effect of elevated temperature, (2) the rate of temperature increase, and (3) the cumulative impact of increased temperatures. For each measure of climate change impact, Kirschbaum suggests that maximum mitigation benefit is achieved if we can reduce the worst impacts, that is, if we can design a strategy to minimize the maximum values. With that objective, Kirschbaum ''adopts a 100-year horizon for the analysis and aims to assess when the worst climatic impacts occur up to the year 2100, and by what land-use strategy the expected worst impacts could be most effectively ameliorated'' (Kirschbaum 2003, p. 54). In this vein, Kirschbaum (2006) picks two CO_2 emissions scenarios from among the set of SRES scenarios (IPCC 2000); determines the path over the next century of temperature change, rate of temperature change, and cumulative temperature change; and asks at what point these three measures reach their maximum values.

Kirschbaum suggests that ''The question must, therefore, be asked when best to use the sinks option, and what benefit, if any, derives from temporary carbon sinks.'' (Kirschbaum 2003, p. 50). For two of its three measures of climate mitigation, i.e., the temperature change and the rate of temperature change, the Kirschbaum analysis thus focuses on a single event (year) regardless of the path by which it is reached or the duration of the

extreme values, and from the SRES scenarios and his 100-year boundary it is known in advance when that extreme event will occur. Kirschbaum does a simple model analysis that ''quantifies climate-change impacts up to the year 2100 (Kirschbaum 2006, p. 1152).'' He asserts that the analysis does not use any discount factors and thus treats climate change impacts in any year as equally important.

A critical factor in the analysis, as Kirschbaum notes, is that if a pulse of CO_2 is released into the atmosphere at any time, the pulse will immediately begin to decay as the CO_2 is incorporated into the global cycling of carbon. A pulsed removal of CO_2 from the atmosphere will decay similarly, as the concentration gradient between CO_2 in the atmosphere and in other reservoirs of the global carbon cycle is changed. This decay is described by the sum of several exponential terms (as basically described in the Bern model (Meier-Reimer and Hasslemann 1987)), as the CO_2 mixes into the ocean, interacts with the biosphere, etc. (see Kirschbaum 2006, Fig. 1).

Among the three measures of climate-change impact presented, Kirschbaum's analysis leans toward the first two, the first of which he defines as:

$$I_T = T_t - T_{1900}$$

where I_T is the instantaneous temperature impact, T_t is the temperature at time t, T_{1900} is the temperature in 1900, and T_t follows the atmospheric concentration of CO_2 with a delay described with a 10-year time constant. Given this formulation, the change in impact, or percent mitigation, achieved by sequestering 1 Gt of carbon from the atmosphere, would be:

$$\text{Change in maximum impact (in \% per GtC sequestered)} =$$
$$100 * (T_t - T_{t'})/(T_t - T_{1900})$$

where $T_{t'}$ is the temperature at time t (the time of maximum temperature) with the mitigation measure employed and T_t is the temperature at the time of maximum temperature without the mitigation measure employed. In both of the SRES scenarios examined the maximum temperature is reached at the end of the time period examined, that is, in 2100.

We note that with this formulation the climate-change impact does not depend on anything that happens between years 1900 and t, or after time t, but depends only on the instantaneous value at the chosen point t, the time (up to year 2100) of maximum temperature. If the maximum temperature happens to occur in 2100, clearly the worst thing one can do for a parcel of CO_2 that is set to be released to the atmosphere, is to capture it, hold it, and release it shortly before 2090, so that the 10 year time constant results in maximum ''climate-change impact'' precisely in 2100.

The second of the three measures of climate-change impact is given as:

$$I_\Delta = (T_t - T_{1900})/(t - 1900),$$

where I_Δ is the rate of change of temperature since 1900 and t is the year in which I_Δ has its maximum value. Given this formulation, the change in impact, or percent mitigation, for sequestering 1 Gt of carbon would be:

$$\text{Change in maximum impact (in \% per GtC sequestered)} =$$
$$100 * ((T_t - T_{t'})/(t - 1900))/((T_t - T_{1900})/(t - 1900)) = 100 * (T_t - T_{t'})/(T_t - T_{1900})$$

We note that with this formulation this climate-change impact is not path dependent, but depends only on the instantaneous temperature at the point t, and is the average rate of change over the full interval 1900 to t. We note too that the formulas for the two expressions of change in maximum impact can be shown to be mathematically identical and the values will be identical whenever the temperature and average rate of temperature change have their maximum values at the same time t (as is seen in Kirschbaum's (2006), Figs. 2, 3). Because these two measures of climate-change impact are so highly correlated, the additional value of the second is questionable under these circumstances. Still, the worst thing to do by this measure, is to capture an amount of CO_2 and to release it about 10 years before the maximum impact occurs at time t.

Kirschbaum's third measure of climate-change impact is defined as:

$$I_\Sigma = \sum_{i=1900}^{t} (T_i - T_{1900})$$

where I_Σ is the cumulative temperature impact and T_i is the temperature in each year. This is essentially the integral of the temperature change over time from 1900 to t and it does depend on the path and what happens between years 1900 and t. Given this formulation, the change in impact, or percent mitigation, for sequestration of 1 Gt of carbon would be:

$$\text{Change in maximum impact (in \% per GtC sequestered)} =$$
$$100 * \sum_{i=1900}^{t} (T_i - T_{i'}) / \sum_{i=1900}^{t} (T_i - T_{1900})$$

where $T_{i'}$ is the temperature in each year from 1900 to t with the mitigation measure employed and T_i is the temperature in each year without the mitigation measure. With this formulation, the worst thing one can do with a parcel of CO_2 that is set to be released is to release it promptly, so that it has the maximum amount of time to impact the global temperature.

3 Discussion

3.1 Mitigating impacts

Kirschbaum's three measures of climate change impact are essentially independent choices for what is the critical element in a changing climate. We suggest that of Kirschbaum's three measures of climate-change impact, the third is, in fact, often the most useful. It is a matter of choice, of course, how one elects to define climate-change impact, but this integrated measure of temperature change (e.g. of climate forcing) provides a measure of both the magnitude and the duration of change and is similar to what the international community has chosen to use in defining the ''global warming potential'' of the different greenhouse gases (Ramaswamy et al. 2001).

Kirschbaum's other two formulations ultimately refer only to the temperature impact in a single year, the year that defines either the maximum in temperature or the maximum average rate of temperature increase (up to 2100). Kirschbaum's first two measures of impact could be important if there are critical temperature or temperature change thresholds that should not be exceeded, in which case one of these measures may provide an

Fig. 1 Examples of temperature development to illustrate the difference between evaluating the path of temperature change and the maximum impacts at a single point in time
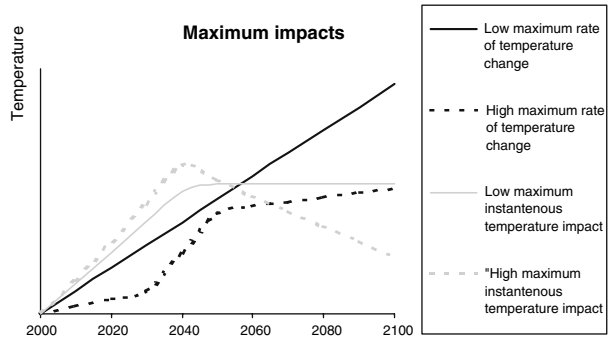
opportunity to avoid that critical threshold. But, this assumes, again, that the threshold is visible and we know when to implement the carbon removal. In the SRES scenarios analyzed by Kirschbaum the maximum single-year impacts of instantaneous temperature occur in 2100, but would be even higher in 2101. In these cases, avoiding the maximum threshold in 2100 is meaningless from the point of view of long-term climate-change impact. None of Kirschbaum's measures refer to the multitude of important climate-change impacts beyond yearly average temperature.

The cumulative temperature impact is the only measure analyzed by Kirschbaum that takes into account the development of impacts over time. The scenarios shown in Fig. 1 illustrate that the development of impacts over time might evolve along many paths and suggest that a measure of impact might be sensitive to the pattern of change. For each pair of curves in Fig. 1, the dashed curve reaches the higher maximum temperature or the higher maximum rate of temperature change, but the solid curve has greater cumulative impact over time. Figure 1 illustrates the difficulty one would have in implementing the best mitigation strategy, according to Kirschbaum's first two measures, if one did not have advance knowledge of the path that would be followed into the future.

Using these three different measures of climate change impact, Kirschbaum explores two scenarios of CO_2 emissions, a high-emissions scenario and a low-emissions scenario. Figure 2 in Kirschbaum illustrates that, as expected, the maximum benefit of permanent carbon removal by the biosphere will be achieved if (for his first two measures of change in maximum impact) the removal from the atmosphere occurs some 10 or so years before the time of maximum temperature (the exact value defined by his lag function between CO_2 increase and temperature increase) or if (for his third measure of change in maximum impact) the permanent removal occurs immediately. Actual implementation of a mitigation strategy based on the first two alternatives depends, of course, on knowing in advance when the maximum impact will occur and in not taking into account everything that will occur after 2100.

Kirschbaum proceeds to calculate and plot the average value of the percent change in maximum impact for his three measures of impact, but it is not clear what this average represents either mathematically or conceptually.[1]

Kirschbaum then gets to the core of his thesis and evaluates the value of temporary removal of CO_2 from the atmosphere. Given the circumstance that a pulse of emissions or

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[1] For illustration, to average 10% with 20% may yield an average of 15%, but if it is 10% of 50 and 20% of 150, to what does the 15% refer? Alternatively, if one gains 10% in height and 20% in weight, what does the numerical average 15% imply?

removal will decay with time, it is clear that Kirshbaum's first and second measures of impact will always be worse at all times after the release of captured CO_2 than if the CO_2 had simply been released earlier. His third measure will always show an improvement in the cumulative temperature impact. This is regardless of when the carbon is removed and the length of time it is held. Kirschbaum's Fig. 3 shows, correctly we believe, that the change in maximum impact for temporary sequestration, for his integrated measure, is significant and on the same order of magnitude as for permanent sequestration (comparing Fig. 3 with Fig. 2, it is about 1/5 the benefit for 1/5 the time of sequestration). As Kirschbaum writes ''temporary carbon storage improves some, but worsens other, climate-change impacts'' (Kirschbaum 2006, p. 1151).

The question, we suggest, is which are the critical aspects of climate impact and which are amenable to amelioration. Cumulative impact is surely important and it can be addressed. Instantaneous impact may well be important, but it is likely that we cannot know how to optimize instantaneous mitigation except ex post facto. One could argue that the optimum time for an individual to buy accident insurance is just prior to an accident. So the major issue of temporary sinks becomes one of reducing cumulative impacts, hoping that this addresses instantaneous impacts as well, and ''buying time''.

3.2 Buying time

While permanent sinks are obviously preferable to temporary sinks, we disagree with Kirschbaum's conclusion that ''… there is virtually no climate-change mitigation value in temporary carbon storage'' (Kirschbaum 2006, p. 1158). Before addressing the concept of buying time, we list here two important reasons that temporary sinks have value: (1) they may turn out to be permanent, and (2) even if individual sinks turn out to be temporary, the aggregate of sinks will likely be greater in the presence of incentives than in the absence of incentives (Marland et al. 2001). But even sinks that are known to be temporary have value.

First, temporary sinks decrease the cumulative impact of raised temperature in all of the analyses presented by Kirschbaum. Second, temporary sinks buy time, i.e. they reduce climate changes in the short time while creating or preserving options for the long term. Figure 2 illustrates these two mechanisms. Temporary sinks slow the rise of temperature during their maintenance and, thus, shorten the time of climate change impacts. In an analysis that ''treats climate-change impacts in any year as equally important'' (Kirschbaum 2006, p. 1153), the cumulative temperature impact will always be favorable for

Fig. 2 Principal development of temperature over time with a temporary or permanent carbon sink
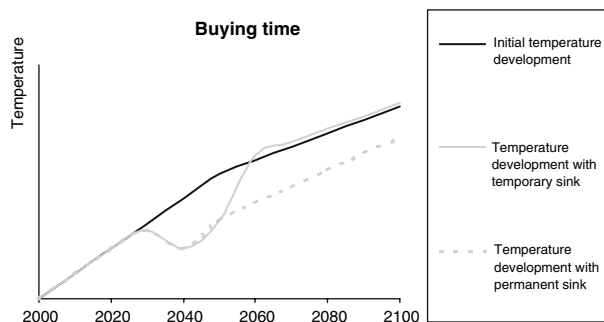
temporary sinks. Denial of temporary sinks eliminates one possibility of preventing short-term climate change. In addition to postponing climate change, Marland et al. (2001) list three reasons that one might buy time with sinks that are known to be temporary: (1) they buy time for learning, (2) they buy time for technological progress, and (3) they buy time for capital turnover.

In short, even temporary sinks put us on a lower path for climate change, a path that will not otherwise be accessible. They minimize impacts while we learn and develop alternatives, they may save money for other purposes, and they preserve a broader variety of options for the future. For carbon sinks in the terrestrial biosphere, we would argue that sooner is better and longer is better (in keeping with mitigating the cumulative temperature impact modeled by Kirschbaum), but even known temporary sinks have value.

And, finally, we recall that if a biospheric sink of carbon is lost, it makes a difference what happens to the carbon. If a forest is planted and subsequently harvested for use as a fuel or to provide products that displace alternate, energy-intensive products; the effective outcome is to make the carbon offset permanent. The primary climate-change benefit of managing the terrestrial biosphere may turn out to be in the protection of existing forests or in production of renewable fuels and materials. We are at a time that all reasonable options ought to be pursued.

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