Carbon Cycle Uncertainty Increases Climate Change Risks and Mitigation Challenges

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ABSTRACT

Projections of greenhouse gas concentrations over the twenty-first century generally rely on two optimistic, but questionable, assumptions about the carbon cycle: 1) that elevated atmospheric CO_2 concentrations will enhance terrestrial carbon storage and 2) that plant migration will be fast relative to climate changes. This paper demonstrates that carbon cycle uncertainty is considerably larger than currently recognized and that plausible carbon cycle responses could strongly amplify climate warming. This has important implications for societal decisions that relate to climate change risk management because it implies that a given level of human emissions could result in much larger climate changes than we now realize or that stabilizing atmospheric greenhouse gas concentrations at a ''safe'' level could require lower human emissions than currently understood. These results also suggest that terrestrial carbon cycle responses could be sufficiently strong to account for the changes in atmospheric carbon dioxide that occurred during transitions between ice age and interglacial periods.

1. Introduction

The consequences of climate change to society hinge on factors both largely under and largely beyond human control. Factors largely under human control include how much greenhouse gas (GHG) we choose to emit and how effectively we prepare for unavoidable climate impacts. Factors largely outside our control include the strength (and sign) of climate feedbacks, the sensitivity of physical, biological, and social systems to climate changes, and the level of human dependence on those systems.

The effectiveness of past efforts to characterize uncertainty in climate feedbacks is somewhat uneven. Although large uncertainties remain in the strength and sign of critical physical feedbacks, particularly from clouds, much of that uncertainty is reasonably well characterized such that the upper and lower bounds are well constrained (Randall et al. 2007). In contrast, upper and lower bounds for potential carbon cycle responses are largely unknown.

Coupled climate–carbon cycle models (Cramer et al. 2001; Friedlingstein et al. 2006) and projections of atmospheric GHG concentrations over the twenty-first century (Clarke et al. 2007) generally incorporate two potentially optimistic assumptions about the natural carbon cycle that are not well supported by empirical evidence (Higgins 2009; Norby et al. 2010). If carbon cycle responses prove less favorable, then 1) more warming could result from a given level of anthropogenic GHG emissions or 2) deeper cuts in GHG emission will be necessary in order to achieve a ''safe'' emissions trajectory.

The first potentially optimistic carbon cycle assumption is that elevated atmospheric CO_2 levels will increase global carbon storage in plants and soil (Higgins 2009). Short duration leaf and plot-level experiments generally support this assumption (Norby et al. 2005; Nowak et al. 2004) but not for all ecosystems (Körner et al. 2005) or when additional factors (e.g., changes in temperature, precipitation, nitrogen availability, and tropospheric ozone pollution) are accounted for (Dukes et al. 2005; Norby et al. 2010; Shaw et al. 2002). Results from long-term experiments also remain somewhat

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equivocal with some experiments demonstrating persistent responses to CO_2 fertilzation (Zak et al. 2011), and others suggesting such effects diminish (Denman et al. 2007; Norby et al. 2010). Furthermore, scaling results from leaf- and plot-level manipulative experiments to the landscape and continental scales that are most relevant for determining global carbon cycle responses is extremely challenging (Higgins 2009).

Therefore, the potential for higher CO_2 concentrations to increase terrestrial carbon uptake and storage appears highly uncertain.

The second potentially optimistic carbon cycle assumption is that plant species will migrate quickly to locations where climate becomes favorable for them (Higgins 2009). This is a potential problem because the effectiveness of plant migration can strongly influence the strength, and even the sign, of key land surface feedbacks to the climate system including carbon storage, evapotranspiration, and the absorption of solar radiation by the land surface (Higgins and Harte 2006).

Furthermore, evidence demonstrating how quickly vegetation responded to past climate changes is ambiguous and contradictory (Higgins and Harte 2006) based on both fossil pollen data (Higgins and Richardson 1999; McLachlan and Clark 2004; Tinner and Lotter 2001) and results from diffusion models (Clark 1998; Clark et al. 2003). At the same time, climate projections for the next century suggest that much faster rates of migration will be necessary for plants to collocate with favorable climate conditions (Malcolm et al. 2002; Solomon and Kirilenko 1997).

Therefore, the capacity for plants to migrate to those locations where climate becomes most favorable for them appears highly uncertain. The consequences of adopting optimistic assumptions about terrestrial carbon cycle responses are potentially severe because we overlook potentially large carbon losses from the land surface that could exacerbate warming.

Here we use a simplified modeling approach to quantify terrestrial carbon cycle response uncertainty to greenhouse-gas-induced warming at the end of this century under the A1FI emissions scenario. We identify upper and lower bounds for terrestrial carbon storage using the Integrated Biosphere Simulator (IBiS)—a dynamic global ecosystem model (Foley et al. 1996; Kucharik et al. 2000). This extends the results from Higgins and Harte (2006), which demonstrated the potential importance of plant migration on land surface biophysics and biogeochemistry by estimating carbon cycle feedback uncertainty due to a range of key biogeochemical factors. We then use Monte Carlo analysis to determine the plausible range in human emissions that could be compatible with CO_2 concentrations toward the end of the century (roughly 900 ppm) under the A1FI emissions scenario given this carbon cycle response uncertainty.

2. Methods

As previously described (Higgins and Harte 2006), we developed two climate scenarios to test carbon cycle responses to climate change. Each climate scenario is based on output from the third climate configuration of the Met Office Unified Model (HadCM3). We used HadCM3-derived monthly averages for temperature, precipitation, relative humidity, and wind speed over a 20-yr period corresponding to 2081–2100 under (i) control, or preindustrial, GHG concentrations and (ii) the A1FI emissions scenario (Johns et al. 2003).

Under the A1FI emissions scenario, CO_2 concentrations in HadCM3 reach roughly 925 ppm by 2100. This, plus changes in other greenhouse gases and aerosols leads to a globally averaged increase in radiative forcing of roughly 9.1 W m^{-2}, relative to the control. HadCM3 projects increases in annually averaged temperature throughout the world from 1° to 11°C in 2100 (roughly 5.3°C globally averaged) and several substantial regional shifts in precipitation relative to the control simulation (Johns et al. 2003).

To assess carbon cycle responses to each of the climate scenarios, we used IBiS 2.6, a process-based, dynamic global ecosystem model (Foley et al. 1996; Kucharik et al. 2000). In addition to the modeled climate data available from HadCM3 (described above), IBIS requires several climate inputs that were not available from HadCM3 at the time that we began these simulations. We derive these from historical climatology between 1961 and 1990 (New et al. 1999). These datasets include monthly average temperature range, cloudiness, and number of rainy days. IBiS also requires data for soil texture (Global Soils Data Task Group 2000).

The IBiS simulations described here use a spatial resolution of 2.5° latitude by 3.75° longitude, which matches the spatial resolution of HadCM3. IBiS also requires daily and hourly climate conditions, which are produced by an internal weather generator that converts the monthly climate input.

We assess carbon storage throughout the world in response to climate change, CO_2 fertilization, and limited rates of plant migration. Determining the uncertainty range for carbon responses for each factor requires four IBiS simulations: 1) control climate, 2) A1FI climate without CO_2 fertilization of plant growth, 3) A1FI climate with CO_2 fertilization, and 4) A1FI climate with limited (i.e., constrained) plant migration (without CO_2 fertilization).

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Although IBiS can simulate transient (year by year) carbon cycle responses to changes in climate and CO_2, we use the model to simulate near-equilibrium carbon cycle responses in this analysis, similar to Higgins and Harte (2006). The primary advantage of this approach is to explicitly separate equilibrium and transient carbon cycle responses, which have considerable potential to mask one another and are characterized by different levels of uncertainty. Our approach allows us to quantify the factors that contribute to carbon cycle uncertainty more explicitly and robustly than we could without conducting numerous transient simulations. We then explicitly consider the consequence of time lags (i.e., the transient responses) using Monte Carlo analysis, described below. While this approach is not predictive, it does represent a key step in quantifying the range of uncertainty in carbon cycle responses to climate change.

IBiS uses leaf-level calculations for photosynthesis (Collatz et al. 1992; Collatz et al. 1991; Farquhar et al. 1980), respiration, and stomatal conductance (Foley et al. 1996; Kucharik et al. 2000). CO_2 fertilization is particularly strong in IBiS, compared to other ecosystem models (McGuire et al. 2001). This is possibly because there is no down regulation of rubisco production in response to CO_2 enrichment (Higgins and Schneider 2005).

For the simulations without CO_2 fertilization, we hold CO_2 concentrations at 350 ppm in IBiS. This is physically inconsistent with the CO_2 concentration used in the climate model (roughly 290 ppm) but corresponds to concentrations prevalent in the field experiments and validation studies used to develop and test IBiS. The CO_2 fertilization simulation uses an atmospheric concentration of 900 ppm. This combination of simulations allows us to determine the upper and lower bounds for the effect of CO_2 fertilization.

For the simulation with constrained plant movement, we allow all plant types to expand locally (i.e., within any grid cell where they exist under control conditions) but prohibit plant movement to grid cells where they are not previously established. This heavy constraint allows us to establish a reasonable lower bound for terrestrial carbon storage under limited plant migration. Our simulations with unconstrained plant movement establish an upper bound for terrestrial carbon storage with respect to plant migration.

We separate responses driven by climate, CO_2 fertilization, and constrained migration to determine their respective impact on terrestrial carbon storage. We treat these as independent factors to estimate uncertainty in the total terrestrial carbon cycle response. Although some of these factors are not entirely independent, the interactions are relatively small (in the model); so this assumption makes sense to a first approximation. For example, IBiS does not include nutrient limitation so rates of decomposition do not strongly affect rates of plant growth. In addition, constrained plant migration reduces the magnitude of CO_2 fertilization effects to a small degree (not shown). Still, the range of carbon cycle response uncertainty is insensitive to this interaction because the lower bound is established without CO_2 fertilization and the upper bound without constraints on migration.

Monte Carlo analysis

We determine plausible net human emissions that could lead to A1FI atmospheric CO_2 concentrations toward the end of the century (i.e., 900 ppm) based on Monte Carlo assessment of carbon sources and sinks outside human control. We assess the implications of four key sources of carbon cycle uncertainty: 1) future ocean uptake, 2) CO_2 fertilization, 3) rates of plant migration, and 4) additional factors that contribute to transient responses, most notably decomposition of carbon from plants and soil.

We determine the potential carbon contribution to the atmosphere from sources and sinks largely outside of human control based on Eq. (1):

$$C_{\mathrm{na}} = C_{\mathrm{pi}} + E_h - U_h - O_f + E_w + M_e - U_{\mathrm{fert}} \qquad (1)$$

in which C_{na} is the atmospheric carbon stock due to factors largely outside human control, C_{pi} is the preindustrial carbon stock in the atmosphere (597 Pg-C), E_h is the historical anthropogenic emissions of carbon (335 Pg-C), U_h is past uptake and storage of human emissions (128 Pg-C), O_f is expected future ocean uptake, E_w is emissions due to warming from plants and soil (0–870 Pg-C), M_e is additional terrestrial emissions due to limited plant migration (0–309 Pg-C), and U_{fert} is additional terrestrial uptake by plants and soil due to CO_2 fertilization (0–1072 Pg-C).

We calculate potential net human emissions under four assumptions about these sources of uncertainty: 1) uncertain CO_2 fertilization, uncertain rates of decomposition, and fast plant migration; 2) uncertain CO_2 fertilization, uncertain rates of decomposition, and slow plant migration; 3) uncertain rates of decomposition, no CO_2 fertilization, and slow plant migration; and 4) no CO_2 fertilization, slow plant migration, and fast decomposition of stored carbon. Future ocean uptake is an additional source of uncertainty under all four assumptions. We assume the oceans will take up 450 ± 150 Pg-C based on model simulations in Friedlingstein et al. (2006). All sources of uncertainty are distributed uniformly in the Monte Carlo analysis.

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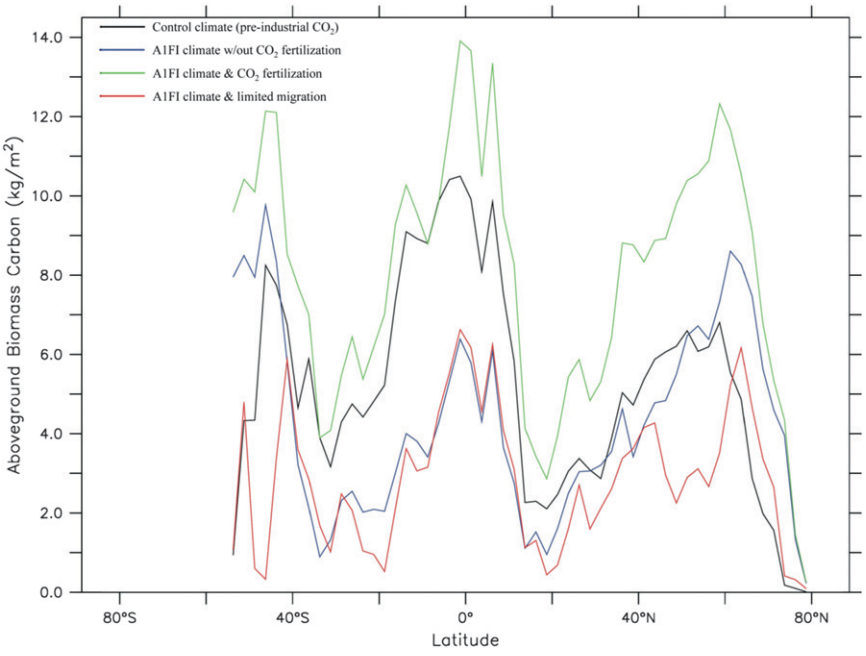

FIG. 1. Simulated near-equilibrium carbon stored by latitude in plant biomass. Carbon storage in plants depends heavily on climate, CO_2 fertilization, and plant movement. Warming leads to large losses in carbon storage. Constraints on plant movement exacerbate carbon losses. Simulated CO_2 fertilization largely compensates for carbon losses due to warming.

We calculate potential net anthropogenic emissions (E_{hum}) compatable with A1FI atmospheric CO_2 concentrations using Eq. (2):

$$E_{\text{hum}} = 900\,\text{ppm} \times 2\,\text{Pg-C}\,\text{ppm}^{-1} - C_{\text{na}}. \qquad (2)$$

3. Simulated carbon storage

In the absence of CO_2 fertilization, climate warming leads to carbon losses from plant biomass at most latitudes even when plants migrate freely (Fig. 1). The largest losses of carbon occur between 40°S and 50°N, while some increases in biomass carbon occur in the high latitudes of both hemispheres. This pattern makes intuitive sense in light of previously reported forest losses that occur due to drying in the tropics and forest expansion that occurs in the higher latitudes due to warming (Higgins and Harte 2006).

The combination of climate warming and CO_2 fertilization of plants leads to increases in carbon storage in plant biomass at almost all latitudes, relative to the control (Fig. 1). Thus, simulated responses to CO_2 enrichment compensate for the carbon losses simulated in response to climate warming. This implies that we must consider warming and CO_2 fertilization effects (each of which is uncertain) separately because they can mask one another.

Constraints on plant migration exacerbate carbon losses due to climate warming. Carbon losses due to constrained plant movement are particularly large in the mid to high latitudes where climate becomes favorable for forests.

Broadly similar patterns of carbon storage emerge for soils (Fig. 2). Losses of soil carbon due to warming are particularly large in the tropics, where warming and drying occurs under the A1FI climate scenario and in the mid to high northern latitudes. The mid-to-high-latitude losses reflect increased rates of decomposition as soil moisture and temperature increase. Including CO_2 fertilization largely counteracts the soil carbon losses due to the A1FI warming at most latitudes. In contrast, constrained plant migration increases carbon losses within particular latitude bands, most notably between 40°–50°S, 10°–30°S, and 40°–60°N.

These latitudinal responses translate into large disruptions in global carbon storage. As previously reported in (Higgins and Harte 2006), the near-equilibrium losses under late century A1FI warming, relative to the control, are large even when plant migration is unconstrained: 154 Pg-C from plant biomass and 716 Pg-C from soils (Fig. 3). This 870 Pg-C of combined terrestrial carbon losses to the atmosphere is larger than the amount of carbon currently contained in the atmosphere, suggesting

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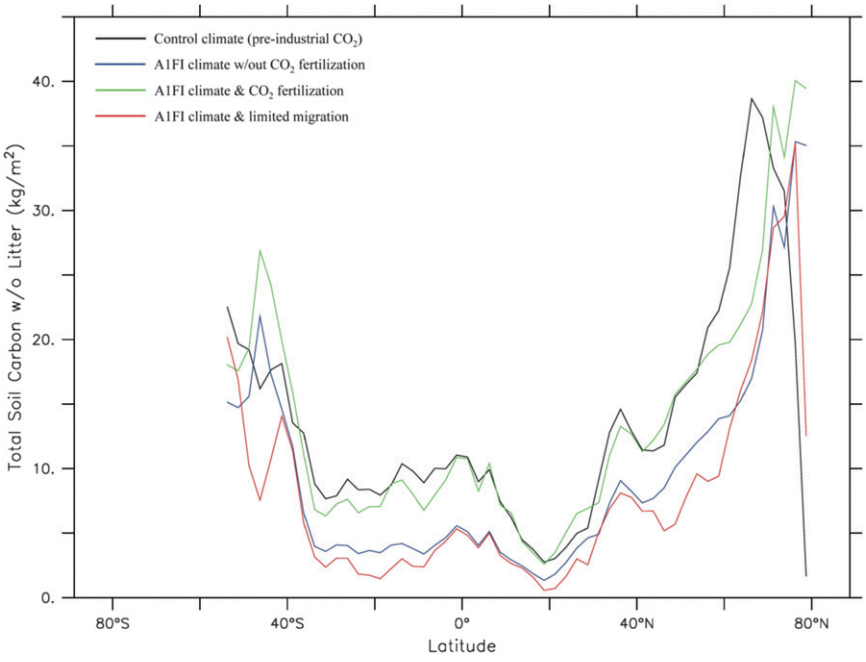

FIG. 2. Simulated near-equilibrium carbon stored by latitude in soil. Carbon storage in soil depends heavily on climate, CO_2 fertilization, and plant movement. Warming leads to large losses in carbon storage, particularly from high latitudes. Constraints on plant movement exacerbate soil carbon losses. CO_2 fertilization largely compensates for carbon losses due to warming.

this is a potentially powerful additional contribution to climate warming.

Constrained plant migration contributes an addition loss of 309 Pg-C (Fig. 3): this is roughly equivalent to the cumulative anthropogenic emissions of carbon from fossil fuel burning and cement production since the start of the industrial revolution (Higgins and Harte 2006; Marland et al. 2003). Suggesting that constrained plant migration could cause a strong additional contribution to climate warming.

In contrast, CO_2 fertilization increases simulated global carbon storage under A1FI warming to 2605 Pg-C, which is 1072 Pg-C more than stored under the warming only simulation and 202 Pg-C more than under the climate control (Fig. 3). This illustrates the potential for CO_2 fertilization to reduce atmospheric CO_2 concentrations and the climate warming that results. However, it also further illustrates how simulated CO_2 fertilization may obscure large terrestrial carbon losses in response to warming.

Assuming full CO_2 fertilization, constrained plant migration, and rapid rates of decomposition, the central estimate for terrestrial carbon losses to the atmosphere under A1FI-induced warming at the end of the century would be 107 Pg-C (Fig. 3). However, the full uncertainty range is massive, spanning a possible carbon sink of up to 1072 Pg-C (assuming full CO_2 fertilization, rapid plant migration, and slow decomposition) to a possible carbon source of 1179 Pg-C (assuming no CO_2 fertilization, constrained plant migration, and rapid decomposition).

Assuming that the range in potential carbon cycle responses to CO_2 fertilization, plant migration, and decomposition are each evenly distributed, then the

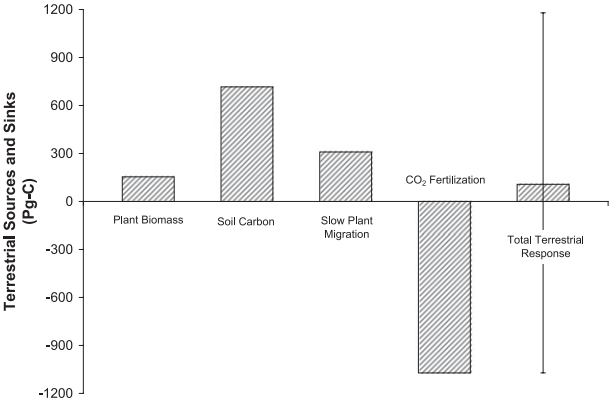

FIG. 3. Global terrestrial carbon sources and sinks under A1FI warming. Uncertainty in the total terrestrial response accounts for uncertainty in the strength of CO_2 fertilization, the rate of plant movement, and rates of decomposition. The maximum terrestrial sink arises if CO_2 fertilization is strong, plant migration is unconstrained, and rates of decomposition are slow. The maximum terrestrial source arises if there is no CO_2 fertilization, heavily constrained plant migration, and fast decomposition.

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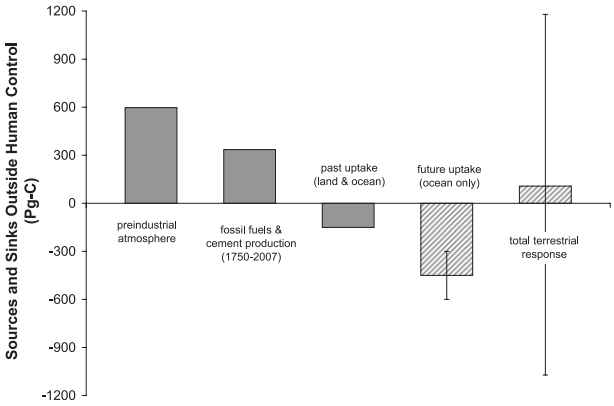

FIG. 4. Factors contributing to atmospheric CO_2 concentrations (900 ppm) largely outside human control. Factors largely outside human control include the current atmospheric stock due to historical concentrations, past anthropogenic emissions, and past removal by the ocean and biosphere (solid), along with future uptake and release by the ocean and the terrestrial biosphere (hatched). We use uncertainty in future ocean uptake based on model results (Friedlingstein et al. 2006).

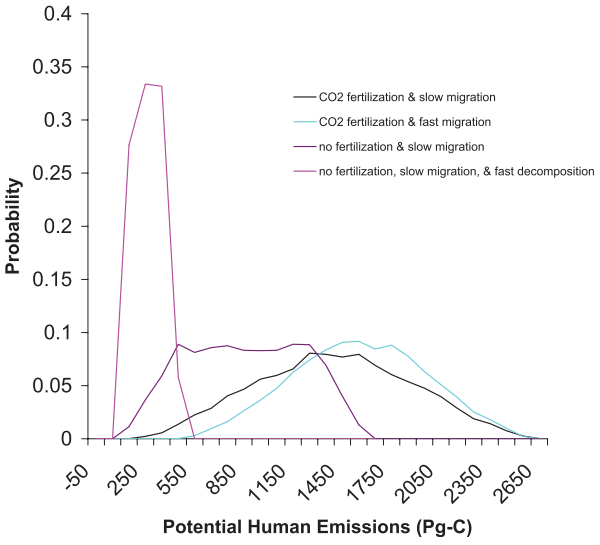

FIG. 5. Potential human contribution to 900 ppm CO_2. These probability density functions (PDFs) show the potential range of human emissions based on different assumptions about the terrestrial carbon cycle response and given remaining uncertainties in the factors that contribute to the carbon cycle response. PDFs are based on Monte Carlo analysis in which remaining uncertainties are uniformly distributed.

probability of total carbon storage being at either end of the uncertainty range shown in Fig. 3 is lower than of it being more toward the middle. This is because each variable must be at its maximum (or minimum) value simultaneously for total carbon storage to be at either end of the range. Nevertheless, this approach allows us to quantify the potential range of carbon cycle response uncertainty and makes sense given that the actual distributions for the variables are unknown.

4. Compatible human emissions

This terrestrial carbon response is largely outside human control as are the contributions to the atmosphere from past terrestrial responses, past human emissions, ocean uptake (past and future), and the preindustrial stock of carbon in the atmosphere (Fig. 4). It is these factors largely outside human control that determine the net emissions that humans can contribute to any particular stabilization target. Of course, carbon removal and storage technologies, though currently unproven at scale, could also offset some human-caused emissions. Therefore, we focus here on net human-caused emissions (i.e., human-caused emissions less human-caused uptake and storage).

The plausible range in net human emissions that could lead to the A1FI atmospheric CO_2 concentration by the end of this century (roughly 900 ppm in the 2080–2100 timeframe) is huge. The probability density functions of conceivable net human emissions (Fig. 5) depend heavily on the assumptions about CO_2 fertilization, plant migration, and decomposition of stored carbon.

If we incorporate the full model range of uncertainty for each of the factors contributing to the overall carbon cycle response (i.e., uncertain values for CO_2 fertilization, plant migration, decomposition, and ocean uptake), then we estimate that humans could emit 1397 $\pm$ 747 Pg-C to reach a CO_2 concentration of 900 ppm (Fig. 6). This is a huge range, with plausible human emissions equivalent

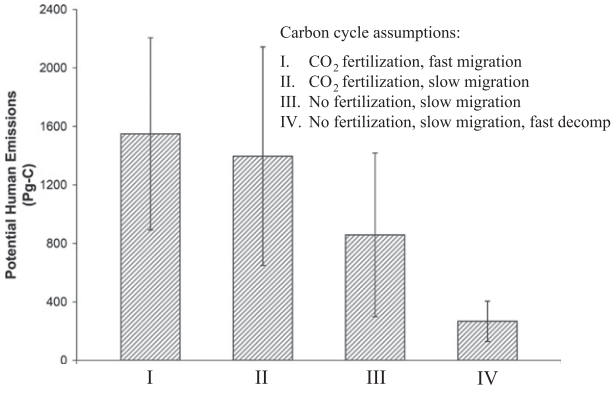

FIG. 6. Potential human emissions needed to reach 900 ppm CO_2 in the atmosphere. How much humans can emit depends heavily on the carbon cycle assumption. Uncertainty estimates represent 95% confidence limits based on Monte Carlo simulations. Ocean uptake is a source of uncertainty for all four assumptions. Additional uncertainty arises for assumptions I–III based on rates of decomposition. Uncertainty over CO_2 fertilization contributes additional uncertainty for assumptions I and II.

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to anywhere from roughly one to three times the current atmospheric stock of carbon.

However, this range shifts dramatically with different assumptions about the natural carbon cycle (Fig. 6). For example, Monte Carlo analysis that assumes plant migration is rapid increases the plausible range in net human emissions to 1549 ± 657 Pg-C. In contrast, if physiological responses to CO_2 have no impact on net carbon storage, then the plausible range in net human emissions falls to 859 ± 560 Pg-C (Fig. 6). If decomposition is also rapid, then the plausible range in net human emissions plummets to 268 ± 138 Pg-C.

These latter estimates suggest that human emissions needed to reach atmospheric concentrations of 900 ppm could be much lower than we now realize. For example, the range in human emissions between 1990–2100 considered by the Special Report on Emission Scenarios (SRES) (Nakicenovic et al. 2000) spans 770 Pg-C (the lower bound of the B1 scenario) to 2538 Pg-C (the upper bound of the A1FI scenario). The analysis above shows that emitting roughly half of the B1 expected emissions (the most optimistic SRES scenario) could lead to atmospheric concentrations currently expected under the much higher A1FI emissions scenario if terrestrial responses prove unfavorable.

Of course, these results are from a simplified approach to uncertainty quantification based on one climate change scenario and one ecosystem model. As such, our results are neither predictive or completely comprehensive. However, this approach represents a key component to quantifying the full range of uncertainty in carbon cycle sources and sinks and a useful compliment to state-of-the-art modeling approaches that use coupled climate–carbon cycle simulations and model intercomparison (Cramer et al. 2001; Friedlingstein et al. 2006).

Notably, coupled climate–carbon cycle simulations enable a mechanistic examination and validation of transient responses based on the best understanding of the relevant processes. Model intercomparison projects enable the quantification of uncertainty that arises owing to different model formulations. Therefore, combining coupled simulations and model intercomparison is most effective for incorporating transient responses and establishing future projections based on our best current understanding.

However, such approaches have the potential to overlook the full range of possible responses because they do not capture the range of plausible responses for all factors that can contribute to carbon uptake or release. Most notably uncertainty in transient dynamics can mask the full magnitude of potential responses. In contrast, simplified approaches, like the one used here, can identify upper and lower bounds of plausible responses for a range of factors beyond those typically considered in coupled climate–carbon cycle simulations and model intercomparison projects.

For example, most coupled climate–carbon cycle simulations anticipate CO_2 fertilization and rapid plant migration (Cramer et al. 2001; Friedlingstein et al. 2006). As a result, they incorporate assumptions that lead to the optimistic end of range that we find here. Similarly, projections of atmospheric CO_2 concentrations this century (Clarke et al. 2007) assume potential responses of the natural carbon cycle that range from a substantial net terrestrial sink to carbon neutrality (i.e., no net terrestrial source or sink). In contrast, our results illustrate the potential for a considerable net terrestrial carbon source.

Note, however, that we do not explicitly address potential changes in the frequency or magnitude of ecosystem disturbance as a consequence of climate change. Such changes appear to be underway and could significantly alter carbon storage in plants and soil (Running 2008) by either speeding (or slowing) the dynamics of the carbon cycle response or by altering potential carbon storage in plants and soil at equilibrium. Therefore, incorporation of disturbance and potential changes in disturbance will be critical to fully quantifying terrestrial carbon cycle response uncertainty to changes in climate and CO_2 concentration.

5. Inferred constraints from ice age/interglacial cycles

Analyses of $\delta^{13}C$ records are widely interpreted as demonstrating that terrestrial carbon storage was considerably higher during interglacial periods than during glacial times (Bird et al. 1994; Leuenberger et al. 1992; Prentice et al. 2001). If correct, these $\delta^{13}C$ records 1) imply that glacial/interglacial changes in atmospheric CO_2 are not driven by the land surface (indeed that the response of the land surface runs counter to the atmospheric changes) and 2) may help further constrain the uncertainty shown here under future warming.

However, interpretation of the $\delta^{13}C$ record is complicated by ocean temperature and circulation and the prevalence of C4 plants (thought to increase during glacial periods and characterized by a different $\delta^{13}C$ signature) (Crowley 1995). As a result, the implications of the $\delta^{13}C$ record are at least potentially more ambiguous than often realized. Indeed, inconsistencies within the $\delta^{13}C$ record during the previous ice age raise questions about the use of the $\delta^{13}C$ record as an estimate of terrestrial carbon storage (Crowley 1995). Therefore, the constraints on terrestrial carbon responses to past and future changes in atmospheric CO_2 concentrations are somewhat suspect.

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Nevertheless, it is tempting to explore whether carbon cycle responses during ice age/interglacial transitions can constrain the uncertainty of future terrestrial carbon cycle responses. Temperatures between ice age and interglacial periods changed roughly 4°–7°C (Jansen et al. 2007), which corresponded to changes in atmospheric CO_2 concentration of roughly 80–100 ppm (Petit et al. 1999; Prentice et al. 2001). These temperature changes are roughly on par with model projections of warming in 2100 under the A1FI emissions scenario (Meehl et al. 2007). Assuming future carbon cycle responses are similar to those of the past and that terrestrial carbon responses accounted fully for the ice age/interglacial changes (i.e., a carbon neutral ocean), then the upper limit on the terrestrial contribution of carbon to the atmosphere would be roughly 200 Pg-C (using 2 Pg-C corresponding to 1 ppm)—considerably less than our upper estimates of potential carbon releases from the land surface.

One major problem with this approach is that the responses of other carbon sources and sinks (e.g., the ocean, mineral weathering, and volcanic activity) could increase or decrease the contribution to atmospheric CO_2 changes from the terrestrial response. Therefore, using past changes in atmospheric CO_2 to determine past changes in terrestrial carbon storage is suspect.

Similarly, carbon cycle responses during the previous ice age/interglacial cycles are problematic as a constraint on future carbon cycle responses because the magnitude and rate of expected warming anticipated under the A1FI scenario are outside the range of ice age/interglacial periods. Because the rates of change expected during this century are considerably faster than those during ice age/interglacial transitions, constraints on plant migration are more likely to contribute to additional terrestrial carbon losses than during the ice age/interglacial transitions.

Furthermore, the high concentration of soil carbon in high latitudes results from an imbalance between production and decomposition that is driven by soil moisture and temperature being too low for decomposition but not for production. It is plausible that considerable amounts of soil carbon built up over the past two million years when temperatures have been roughly at or below current levels (i.e., with soil temperatures and moisture too low for decomposition to keep pace fully with production at high latitudes). However, the warming anticipated in high latitudes over the next century could alter this imbalance and allow the release of considerably more carbon than typically occurred during the ice age/interglacial transitions in the past.

The uncertainty in the magnitude (and direction) of carbon cycle responses demonstrated here also suggests a possible need to rethink the role of terrestrial carbon storage in ice age and interglacial transitions. Note, for example, that the potential terrestrial contribution of CO_2 to the atmosphere shown here for future warming is large relative to the ~200 Pg-C changes in atmospheric CO_2 associated with ice age/interglacial transitions. This suggests that terrestrial carbon cycle responses to climate changes could be sufficiently strong to fully account for carbon cycle responses evident during transitions between ice age and interglacial periods even if the ocean was carbon neutral or a modest negative feedback to atmospheric CO_2 changes.

6. Conclusions

Increasingly, results from coupled climate–carbon cycle models suggest natural carbon sinks will weaken over the next century (Denman et al. 2007; Friedlingstein et al. 2006). Nevertheless, our results suggest that these previous studies underestimate the potential for terrestrial carbon losses because they do not fully account for plausible constraints on plant migration and CO_2 fertilization.

A more comprehensive accounting of carbon cycle response uncertainty suggests that the natural carbon cycle could become a major source of (or sink for) carbon emissions over the next century. This has important implications for societal decisions that relate to climate change risk management because it implies that a given level of human emissions could result in much larger climate changes than we now realize or that stabilizing atmospheric greenhouse gas concentrations at a specific level could require lower human emissions than currently understood.

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