

# Terrestrial carbon cycle feedbacks in atmospheric and climatic change

Roger M. Gifford  
*CSIRO Plant Industry, Canberra, ACT 2601, Australia*

## Introduction

The terrestrial carbon cycle is influential in the climate system over a wide range of timescales from sub-daily to æons (Gifford 1991). The influences occur via numerous ecological attributes and processes that are driven by the plant requirement to convert atmospheric carbon dioxide into plant dry matter. These requirements involve interactions of the terrestrial carbon cycle with the energy, water, mineral and geological cycles of the earth with repercussions for local and global temperature and rainfall on the range of timescales. This short paper focuses on some aspects of the terrestrial carbon cycle that interact with climate over the decadal to century timescale pertinent to predictions of human induced global climate change via greenhouse forcing.

## The terrestrial carbon sink – potential causes

There are three primary global effects of the increasing atmospheric CO<sub>2</sub> concentration that impact the terrestrial carbon cycle directly: 1) the CO<sub>2</sub> fertilising effect on vegetation growth, 2) the stomatal conductance effect and 3) the enhanced greenhouse effect. All three effects have the potential to impact the global climate via their influence on the carbon cycle. The CO<sub>2</sub> fertilising effect may be a major contributor to the terrestrial CO<sub>2</sub> sink that is currently absorbing almost one third of the human-induced emissions. The stomatal closure effect must be leading to some combination of reduced terrestrial evaporation and increased terrestrial surface daytime temperature, the balance between which at any one site depends on both vegetation properties and atmospheric conditions.

Estimation of the global terrestrial sink has been problematic. It has been calculated by the difference between calculated emissions from fossil fuel burning plus cement production plus net deforestation and the estimated ocean sink. Given the magnitude of such estimates it is important to understand exactly what is causing it in order to appreciate when it will saturate and cease to provide a free ecosystem service of helping to mop up human emissions. The dominant potential causes discussed are the CO<sub>2</sub> fertilising effect mentioned, enhanced vegetation growth due to greenhouse warming, stimulation of vegetation growth and C storage by fertilisation from enhanced N-deposition, and enhanced uptake of CO<sub>2</sub> by previously deforested land recovering CO<sub>2</sub> in the process of growing back to mature stands of trees. None of them are well quantified with observational evidence. However, whatever the balance of contributions to the terrestrial sink from these sources, the net effect has been a remarkable stability of the fraction of the human-emissions that have been taken up by the land. Over the last 35 years of rapid atmospheric CO<sub>2</sub> and temperature increase the fraction has remained close to 27% as a running average.

## Model estimates of the future of the terrestrial C sink

Digital Global Vegetation Models (DGVMs) include equations intended to represent the impacts of the CO<sub>2</sub> fertilising effect and atmospheric warming from the greenhouse effect. Most do not, however, yet deal with the effects of N-deposition and the accumulation of C during regrowth of cleared forest. While incorporation of results of elevated CO<sub>2</sub> experiments on plant growth over several years into global carbon cycle models can readily account for a terrestrial C sink of 2-3 Gt C yr<sup>-1</sup> from that effect (Gifford 1991), comparison of several DGVMs (Cramer et al 2001;

Friedlingstein et al. 2006) provides a wide range of future CO<sub>2</sub> emissions from the land among models. The models evaluated by the C<sup>4</sup>MIP inter-comparisons had the land-uptake of CO<sub>2</sub> anthropogenic emissions declining between the present and 2100, but one (CSM1) had the cumulative land-borne fraction over 250 years (1850 to 2100) declining from 0.26 without the terrestrial carbon cycle coupled to only 0.25 with the C cycle coupled. In contrast the Hadley model (HadCM3LC) had the land-borne fraction declining from 0.31 without the terrestrial C cycle to only 0.05 with the terrestrial C-cycle. By 2100 the modelled net CO<sub>2</sub> flux for the land ranged from an sink of 11 Gt C yr<sup>-1</sup> to a net source of 6 Gt C yr<sup>-1</sup>.

The primary reason for this huge contrast in the effect of the terrestrial carbon cycle on model outcome is that we do not have the information base for quantifying feedbacks of the response of the carbon cycle to atmospheric CO<sub>2</sub> increase and warming. The gross terrestrial sink for CO<sub>2</sub> has been increasing for over a century and is now estimated at 2-3 Gt C yr<sup>-1</sup> (Houghton 2007). The gross sink represents the balance between a large CO<sub>2</sub> uptake by primary production and a large CO<sub>2</sub> output by respiration of plants and microbes. The accelerating trend for the increase is closely matched by the trend for atmospheric CO<sub>2</sub> concentration. The fraction of global emissions taken up by the land has been stable in terms of running average for the last 30 years. This is qualitatively consistent with a CO<sub>2</sub> fertilising effect on terrestrial carbon stocks being the cause but there are other possibilities that would probably correlate with the increasing atmospheric CO<sub>2</sub> concentration; notably stimulation of terrestrial C stocks by enhanced N-deposition and re-establishment of forest on land that was deforested earlier, and a potential positive effect of global warming on forest vegetation growth.

### **Feedbacks moderating the tendency for the global terrestrial sink to become a global source**

Unfortunately, there is considerable uncertainty about the magnitude of the baseline NPP, the impact of concurrent warming, and whether vegetation responses to elevated CO<sub>2</sub> concentration become down-regulated over time in the field. For example, an intercomparison of 18 models of Australian baseline NPP, produced an almost order-of-magnitude range of estimates from 0.38 Gt C yr<sup>-1</sup> to 3.3 Gt C yr<sup>-1</sup> (Roxburgh et al. 2005). Additionally the modelled distribution of NPP around the continent was not consistent even among models that produced similar mid-range values. An evaluation of the above-ground NPP of major world biomes found that it was independent of growing season temperature where growing season was defined as the months having an average temperature above 0°C (Kerkhof et al. 2005). Thus NPP is likely to increase with global warming – all else equal - as the growing seasons get longer. Concerns about the real-world applicability of findings about vegetation growth responses to elevated CO<sub>2</sub> from enclosed experiments (growth cabinets etc) have been diminished by analyses of many-year-long free air CO<sub>2</sub> enrichment experiments in forests that have been summarised to find an average stimulation of growth of 23% by 200ppmv CO<sub>2</sub> across a wide range of productivities (Norby et al. 2005). The proposed “progressive nitrogen limitation - PNL” to the CO<sub>2</sub> fertilising effect (Luo et al. 2004) did not apply (Finzi et al. 2007). Rather the hypothesis that in the long run the nitrogen cycle would follow the CO<sub>2</sub>-stimulated C-cycle (Gifford 1992), applied.

On the respiratory output side of the terrestrial C-balance, which can lead the biosphere to be either a source or a sink of CO<sub>2</sub>, a simple view has been extant in the modelling community that respiration is highly temperature sensitive and hence global warming will lead to reduction in stocks of plant and soil organic matter and hence conversion of the terrestrial sink into a source leading to accelerated global warming (eg Cox et al. 2000). Is this consistent with ecological understanding? First, with respect to plant respiration, its high positive sensitivity to experimental warming is very short lived, down-regulation taking only a few days (Gifford

1995). For fully acclimated whole-plant respiration the respiration:photosynthesis ratio is quite stable over a wide range of growth temperature because respiration and photosynthesis are, in the long term, coupled (Gifford 2003). For heterotrophic (ie microbial) respiration during litter decomposition, there is also a coupling between litter input from plants and its decomposition. That coupling occurs for several reasons. But even without consideration of that coupling there are two aspects of soil organic matter (SOM) decomposition that compensate in the longer term for the initial short term sensitivity of SOM respiration to higher temperatures in lab incubations. The first relates to the huge range of turnover times of fractions within the total SOM pool. When a fast turnover fraction is oxidised by microbes, about half of the C it is converted into a longer turnover time component as the other half emits as CO<sub>2</sub>. Thus as warming accelerates decomposition, there is an acceleration of the conversion of the fast turnover pools into slow turnover pools thereby leading to a redistribution of the fractions – more slow turnover and less fast turnover. This shift in distribution acts as a negative feedback reducing the overall sensitivity of SOM oxidation to warming (Ågren and Bosatta 2002). A second soil aspect is less well understood. It is that the presence of labile organic matter (fast pools) can act as a “primer” for accelerated microbial oxidation of the slower decomposing pools (Subke 2004). Thus, when warming leads to a decrease in the ratio of labile to non-labile SOM, the priming effect will decline with the slower oxidation of the less labile SOM pools, again acting as a negative feedback.

Possibly the strongest feedback moderating the impact of warming on SOM decline is the coupling of soil and plant processes by the N-cycle. Most natural vegetation grows faster with added soluble N to the soil. That is, N-availability is one of the factors that co-limit productivity. In the soil most of the N is in unavailable organic form that is converted to plant-available nitrate and ammonium ions by microbes during litter & SOM decomposition. Plants take up that N and incorporate it into plant organic matter. SOM has a typical C:N ratio of about 12. Vegetation has a wide range of C:N ratios averaging about 100. Thus when SOM, having 12 carbons associated with each N, releases its N which plants take up and convert to plant organic matter having 100 carbons associated, there is a huge *increase* in the net carbon stored by the ecosystem. Thus any warming that accelerates that process, accelerates C storage essentially by shifting some soil N into plant N. This is a powerful negative feedback in the terrestrial carbon cycle.

The final feedback of warming that modulating any tendency to acceleration of SOM decomposition with global warming, is the feedback through species composition change with climate change. This seems to be occurring in numerous parts of the world where woody shrubs are replacing herbaceous species. In Australia we have much woody weed invasion of tropical grasslands (Gifford and Howden 2001) that may in part be caused by climate warming. It is also happening in cold climates including the Arctic. In these cold climates, warming is causing grass and sedge communities, having fast decomposing litters, to be replaced by woody shrubs having slow decomposing litters (Cornelissen et al. 2007). This is a negative feedback that tends to offset the faster decomposition tendency resulting from atmospheric warming.

## References

- Ågren GI, Bosatta E 2002. Reconciling differences in the predictions of temperature responses of soil organic matter. *Soil Biology and Biochemistry* 34: 129-132.
- Cox PN, Betts RA, Jones CD, Spall AS, Totterdell IJ 2000. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature* 408: 184-187.

- Cornelissen JHC, and 50 others. Global negative feedback to climate warming responses of leaf litter decomposition rates in cold biomes. *Ecology Letters* 2007. 10:619-627.
- Cramer W and 16 others 2001. Global response of terrestrial ecosystem structure and function to CO<sub>2</sub> and climate change: results from six dynamic global vegetation models. *Global Change Biology* 7:357-373.
- Finzi AC, Norby RJ, Calfapietra C, Gallet-Budynek A, Gielen B, Holmes WE, Hoosbeek MR, Iversen CM, Jackson RB, Kubiske ME, Ledford J, Liberloo M, Oren R, Polle A, Pritchard S, Zak DR, Schlesinger WH, Ceulemans R 2007. Increases in nitrogen uptake rather than nitrogen-use efficiency support higher rates of temperate forest productivity under elevated CO<sub>2</sub>. *Proceedings National Academy Sciences* 104: 14014-14019.
- Friedlingstein P, and 28 others 2006. Climate-carbon cycle feedback analysis: Results from the C<sup>4</sup>MIP model intercomparison. *J of Climate* 19: 3337-3353.
- Gifford RM 1991. Implications of CO<sub>2</sub> effects on vegetation for the global carbon budget. In: *The Global Carbon Cycle*. NATO ASI Series 1 Vol 15. pp159-199. Ed M. Heimann, Springer-Verlag, Berlin, Heidelberg.
- Gifford RM 2003. Plant respiration in productivity models: conceptualisation, representation and issues for global terrestrial carbon-cycle research. *Functional Plant Biology* 30: 171-186.
- Gifford RM, Howden M 2001. Vegetation thickening in an ecological perspective: Significance to national greenhouse gas inventories and mitigation policies. *Environmental Science and Policy* 4: 59-72.
- Gifford, R.M. 1994. The global carbon cycle: A viewpoint on the missing sink. *Aust J Plant Physiol* 21:1-15.
- Gifford, R.M. 1995. Whole plant respiration and photosynthesis of wheat under increased CO<sub>2</sub> concentration and temperature: long-term and short-term distinctions for modelling. *Global Change Biology* 1:385-396.
- Luo Y, Su B, Currie WS, Dukes JS, Finzi A, Hartwig U, Hungate B, McMurtrie RE, Oren R, Parton WJ, Pataki DE, Shaw MR, Zak DR, Field CB 2004. Progressive nitrogen limitation of ecosystem responses to rising atmospheric carbon dioxide *Bioscience* 54: 731-739.
- Norby RJ, DeLucia EH, Gielen B, Calfapietra C, Giardina CP, King JS, Ledford J, McCarthy HR, Moore DJP, Ceulemans R, De Angelis P, Finzi AC, Karnosky DF, Kubiske ME, Lukac M, Pregitzer KS, Scarascia-Mugnozza GE, Schlesinger WH, Oren R 2005. Forest response to elevated CO<sub>2</sub> is conserved across a broad range of productivity. *Proceedings of the National Academy of Sciences of the United States of America* 102, 18052-18056.
- Roxburgh SH, Barrett DJ, Berry SL, Carter JO, Davies ID, Gifford RM, Kirschbaum MUF, M<sup>c</sup>Beth BP, Noble IR, Parton WG, Raupach MR, Roderick ML. 2004. A critical overview of model estimates of net primary productivity for the Australian continent. *Functional Plant Biology* 31: 1043-1059.
- Subke J-A, Hahn V, Battipaglia G, Linder S, Buchanon N, Cotrufo MF 2004. Feedback interactions between needle litter decomposition and rhizosphere activity. *Oecologia* 139: 551-559.