THE SIGNIFICANCE OF GREEN CARBON

Decorticating bark: *E. dalrympleana*, Kosciuszko National Park. Photo: Ian Smith.

WHAT IS GREEN CARBON?

It is useful to consider the 'colour' of carbon when considering the role of natural forests in the global carbon cycle.

Grey carbon[3] is the carbon stored in fossil fuel (coal, oil and gas deposits in the lithosphere).

Green carbon is the carbon stored in the biosphere. We call it 'green' because carbon is taken up from the atmosphere by plants through the process of photosynthesis, which is dependent on the green chlorophyll pigment found in plant leaves[4]. Here, we use the term green carbon to refer to the carbon sequestered through photosynthesis and stored in natural forests. Natural forests are defined here as forests that have not been disturbed by intensive human land-use activities, including commercial logging.

Brown carbon is the carbon stored in industrialized forests. These are forests that are logged commercially for their wood, which is used as a source of raw material for industrial manufacturing processes. There are two types of industrialized forests: 1) where tree regrowth is from the naturally occurring tree stock and seed bank; and 2) where the trees are planted by humans and usually comprise a single tree species, much like a monoculture crop. Industrialized forests constitute a stock of organic carbon and are therefore part of the biosphere; however, we consider this carbon to be 'brown' in colour rather than 'green' in order to stress the fact that industrialized forests are a 'mix' of green and grey carbon[5]. Fossil fuel is expended and therefore grey carbon emitted in managing these forestry operations and from the associated industrial processes.

Blue carbon refers to the inorganic carbon stored in the atmosphere (carbon dioxide, CO_2) and oceans (carbonate, CO_3^{2-}). While there are significant stocks of marine green carbon in the ocean[6], here we are concerned with the green carbon stored in terrestrial ecosystems, and natural forests in particular.

The significance of natural forests to mitigating the climate change problem is a hotly debated topic. Some commentators argue that forest protection is a secondary issue and the primary focus of discussion should be on approaches to reducing emissions of grey carbon from burning fossil fuels. We can, however, no longer afford the luxury of ignoring any one of the components of the

3 In greenhouse literature, the term 'black carbon' has been used to refer to charcoal in soil and soot in the atmosphere.

4 Carbon is taken up from the atmosphere by photosynthesising bacteria and algae, in addition to plants.

5 We have of course taken some poetic licence in using these colours to describe the different states of carbon. The colour brown is in reality produced from a mix of the three primary colours and not from simply mixing green and grey.

6 There is also biological uptake in the oceans, but the carbon dioxide first physically dissolves from the atmosphere into the ocean, then the dissolved inorganic carbon can be taken up by photosynthesising phytoplankton.

global carbon cycle that are being disrupted by human activity.

Solving the climate change problem requires that atmospheric concentrations of greenhouse gases be reduced and stabilized to a level that prevents dangerous anthropogenic interference with the climate system (UNFCCC). What constitutes a 'safe level' is a critical question that is being debated actively among scientists and policy advisors. Evidence from glacial ice cores has revealed that atmospheric concentrations of carbon dioxide ranged between 180 and 300 parts per million by volume (ppmv) in the past 650 000 years (with typical maximum values of 290 ppmv) (Petit et al. 1999; IPCC 2007). Assuming this natural variability revealed by the ice-core records persisted(7), we should assume a maximum safe level is 300 ppmv. In the language of thermodynamics: through the interactions of various natural processes, Earth's average planetary temperature has been maintained in a state of dynamic equilibrium in the past 650 000 years where the temperature varies but within a well-defined 'ceiling' and 'floor'.

As a result of humans burning fossil fuels and causing emissions from deforestation and forest degradation (especially in the past 100 years), the current level of atmospheric carbon dioxide is about 380 ppmv (IPCC 2007). We have therefore already exceeded a safe level of atmospheric carbon dioxide as defined by the natural variability of the past 650 000 years. Stabilizing atmospheric carbon dioxide at between 350 and 400 ppmv will require that emissions are reduced to approximately 85 per cent of 2000 levels by 2050, and that the peak year for emissions is not later than 2015 (IPCC 2007). Meeting this target will still result in a projected temperature increase of 2 to 2.4°C and a sea-level rise of 0.4 to 1.4 m. Given the current trajectory of emissions, the scientific community is now discussing the consequences of atmospheric levels of carbon dioxide reaching up to 790 ppmv by 2100 (IPCC 2007), which is predicted to result in a temperature increase of up to 6.1°C and a sea-level rise of 1.0 to 3.7 m.

We can no longer afford to ignore emissions caused by deforestation and forest degradation from every biome (that is, we need to consider boreal, tropical and temperate forests) and in every nation (whether economically developing or developed). We need to take a fresh look at forests through a carbon and climate change lens, and reconsider how they are valued and what we are doing to them.

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7 The ice-core records confirm that the Earth has experienced a long sequence of cool and warm periods associated with oscillations in the planetary orbit around the sun. A very long cooling phase (about 100 000 years) culminates in a glacial maximum followed by a rapid warming to reach a temperature maximum (about 10 000 years) (Berger and Loutre 2002).

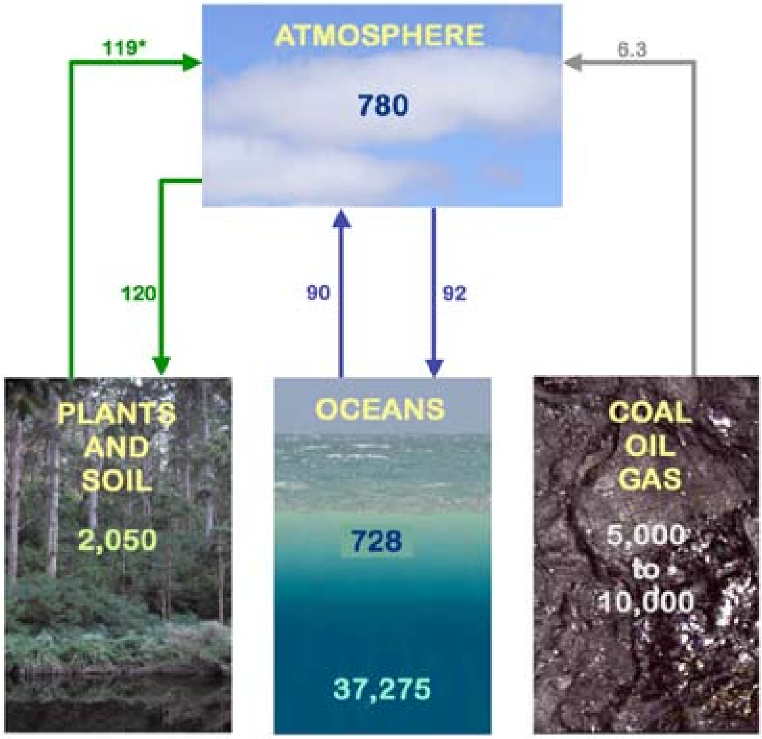

FIGURE 1: GLOBAL CARBON CYCLE

Approximate global carbon cycle stocks (boxes) and fluxes (arrows). (Adapted from Houghton 2007). Units are Gt of carbon, and fluxes are per year. The colours of the arrows correspond to the definition of colour of carbon. * Deforestation contributes ~2 Gt C yr^{-1}.

WHAT IS THE ROLE OF FORESTS IN THE CARBON CYCLE?

Terrestrial ecosystems—especially natural forests—play a critical role in regulating greenhouse gas concentrations in the atmosphere and therefore must be part of a comprehensive response to the climate change problem. An appreciation of the significance of natural forests in the carbon cycle requires understanding of how Earth functions as a system. Because Earth is a closed system in terms of chemical elements, the atomic components of the major greenhouse gases (water vapour, carbon dioxide and methane) are neither created nor destroyed. Rather, they reside in and move between reservoirs (also called 'stocks' or 'pools') within the global carbon and hydrological cycles. As they move between reservoirs, carbon and water change state: water from a liquid, to gas or ice; and carbon from inorganic gases in the atmosphere, to organic compounds in living and dead organisms on land and in the sea, to inorganic substances in the oceans and the Earth's crust.

A simplified diagram of the global carbon cycle is shown in Figure 1. The estimates of global carbon stocks and fluxes are only approximate due to lack of data. The annual uptake of carbon (as carbon dioxide) by plants (through photosynthesis) from the atmosphere to the plant and soil reservoir (organic carbon) is about 120 Gt yr^{-1}. Through the respiration of living organisms (including humans and their livestock), and oxidative combustion

by fire, a little less than 120 Gt yr^{-1} of ‘plant and soil’ reservoir carbon is emitted to the atmosphere. The biosphere is estimated to be a small carbon sink. Approximately 2 Gt of carbon emissions by the plant and soil reservoir is due to deforestation. This acts to increase the loss of carbon and decrease the uptake of carbon by the plant and soil reservoir. Over time, therefore, the size of the reservoir of carbon in plants and the soil is decreasing. The coal/oil/gas reservoir (which supplies most of the energy requirements of industry) is also decreasing by approximately 6 Gt yr^{-1}. If there is less carbon in the plant and soil pool, and in the coal/oil/gas pool, there must be more in the atmospheric and ocean pools. To date, humans have released about 300 Gt of grey carbon, but there is over 5000 Gt remaining in the lithosphere that potentially can be accessed for human use (Archer 2005). About 2000 Gt of carbon is estimated to reside currently in terrestrial ecosystems (plant and soil reservoirs), with about 75 per cent of this stored in natural forest ecosystems. However, about 50 per cent of the world’s forests have been cleared so that current terrestrial carbon stocks are substantially below their natural carbon carrying capacity (Archer 2005; MEA 2005; Houghton 2007).

Carbon cycles between the lithosphere, hydrosphere, atmosphere and biosphere, but its residence time in each of these reservoirs varies significantly[8]. The concentration of carbon in the atmosphere due to the release of carbon from the lithosphere reservoir will remain at elevated levels for a long time even if grey carbon emissions are stopped immediately (Archer 2005). The two pathways for transfer of carbon out of the atmosphere are: 1) dissolution in river and ocean water and, eventually, incorporation into carbonate rock; and 2) uptake of carbon by plants and storage in the biosphere. The terrestrial biosphere–atmosphere fluxes operate on a faster time scale and are under a greater degree of human control than the fluxes of the hydrosphere. Solving the climate change problem will require both reducing grey-carbon emissions and maximising the uptake of carbon in the biosphere. A healthy biosphere provides a buffering capacity for changes in the carbon cycle.

ARE GREEN CARBON STOCKS RELIABLE?

The argument is commonly heard that forests are an unreliable carbon sink because of their vulnerability to fire, pests, diseases and drought, which can reduce the standing stock of carbon and inhibit forest growth. Another argument is that climate change might cause conditions to be less conducive to forest growth, for example, by reducing water available for photosynthesis or increasing temperatures beyond the thermal tolerance of tree species, thereby causing forests to become a source of rather than a sink for carbon. It is also argued that the stock of green carbon

8 Residence time is the average time a unit of carbon spends in a given reservoir, that is, carbon stock or pool. It is calculated by dividing the reservoir volume by the rate of flow.

is too small to make a significant contribution to greenhouse gas mitigation and is therefore not an important policy consideration.

As noted earlier, green carbon in the biosphere has a significantly different residence time compared with grey carbon in the lithosphere. Therefore, in terms of the global carbon cycle, green and grey carbon should not be treated as equivalent with respect to policy options. In terms of preventing harmful change to the climate system, it is important to avoid emissions of grey carbon from burning fossil fuels, and leave oil, gas and coal stored in the lithosphere. Additionally, the uptake and storage of carbon by natural forests has a powerful and relatively rapid negative feedback on the enhanced greenhouse effects from emissions. Feedbacks are the key to understanding how relatively minor increases in greenhouse gas concentrations can result in massive changes in Earth's climate system (Hansen et al. 2007).

Generally, a greenhouse-enhanced world is a warmer and wetter world—albeit with changing regional patterns (Zhang et al. 2007). Water is essential for photosynthesis (the uptake of carbon by plants from the atmosphere) and production of new biomass. When water is plentiful (and the soil is not degraded), atmospheric carbon will continue to be sequestered in new biomass. In addition, as atmospheric levels of carbon dioxide increase, photosynthesis becomes more efficient as plants can fix more carbon dioxide using the same amount of water (Farquhar 1997). Increased cloud cover (associated with increased rainfall) is not necessarily an impediment as photosynthesis utilizes diffuse as well as direct solar energy (Farquhar and Roderick 2003), and it could even enhance photosynthesis in multi-layered vegetation canopies (Hollinger et al. 1998).

The stock of green carbon in an ecosystem is the result of the difference between the rates of biomass production and decomposition. Like the global carbon cycle, green carbon cycles between pools: living biomass, dead biomass and soil. The residence time of a unit of carbon in each pool varies—the longest is for woody biomass and soil (Roxburgh et al. 2006). Rates of decomposition scale with increasing temperature and moisture (Golley 1983). An excess of soil water, however, leads to anaerobic conditions, a decrease in decomposition and a build-up of dead organic matter. This is why tropical peat forests and boreal forests have large pools of soil organic carbon, while tropical and temperate forests have proportionally more living biomass carbon.

Various processes enable forests to persist in the face of changing environmental conditions, including climate change. Natural forests are characterized by a rich biodiversity at all levels: genetic, taxonomic and ecosystem. This is obvious especially when, in addition to the diversity of plants and vertebrate animals, we consider the invertebrates, bacteria and fungi, and the vast webs of ecological and coevolving interactions that together constitute a functioning ecosystem (Odum and Barret 2005; Thompson 2005). The genetic diversity found within species provides the capacity

for, among other things, micro-evolution whereby populations can become rapidly adapted to local conditions (Bradshaw and Holzapfel 2006). High taxonomic diversity provides a pool of species with different life histories and niche tolerances from which natural selection can reveal the plant or animal best suited to new conditions (Hooper et al. 2005). Natural selection, acting on the rich biodiversity found in natural forests, can also result in the optimisation of plants' physiological processes (Cowan and Farquhar 1977) and in the optimization of trophic interactions (Brown et al. 2004) in response to environmental change. Natural forests are therefore more resilient to climate change and disturbances than plantations because of their genetic, taxonomic and functional biodiversity. This resilience includes regeneration after fire, resistance to and recovery from pests and diseases and adaptation to changes in radiation, temperature and water availability.

Oxygenic/photosynthetically based ecosystems have persisted on Earth for at least 2.8 billion years (Des Marais 2000), due in no small measure to the kinds of biological, ecological and evolutionary processes noted above. While the genetic and taxonomic composition of forest ecosystems changes over time, forests will continue to uptake and store carbon as long as there is adequate water and solar radiation for photosynthesis. From this perspective, the carbon in natural forests is stored in a more reliable stock than in industrialized forests, especially over ecological time scales. Carbon stored in industrialized forests has a greater susceptibility to loss than that stored in natural forests. Regrowth forests and plantations have reduced genetic diversity and structural complexity, and therefore reduced resilience to pests, diseases and changing climate conditions (Hooper and Vitousek 1997; Hooper et al. 2005, McCann 2007). The risk of fire in industrialized forests is greater than in natural forests because of the associated increase in human activity in the area, the use of machinery and public access.

Given the resilience of natural ecosystems, the green carbon stocks in forest biomes are more likely in the longer term to expand than to shrink under enhanced greenhouse conditions, and in the absence of perturbations from human land-use activities[9]. Indeed, the negative feedback (with respect to increased atmospheric concentrations of carbon dioxide) provided by enhanced plant

E. obliqua, Mt. Wellington, Tasmania. Photo: Rob Blakers.

9 This statement must, however, be qualified by the high level of uncertainty about regionally scaled climate change predictions of rainfall and evaporation—the main variables controlling water availability.

growth has been argued to be critical to the long-term stability of Earth's environment within the bounds conducive to life (Gorshkov et al. 2000).

WHAT ABOUT INDUSTRIALIZED FORESTS?

There are important distinctions between the carbon dynamics of natural forests and industrialized forests, especially monoculture plantations. The majority of biomass carbon in natural forests resides in the woody biomass of large old trees. Commercial logging changes the age structure of forests so that the average age of trees is much younger. The result is a significant (more than 40 per cent) reduction in the long-term average standing stock of biomass carbon compared with an unlogged forest (Roxburgh et al. 2006; Brown et al. 1997). Plantations are designed to have all of their above-ground biomass removed on a regular basis. The rotation period between harvests varies from 10 to 70 years globally, depending on species and commercial purposes (Varmola and Del Lungo 2003). The carbon stock of forests subject to commercial logging—and of monoculture plantations in particular—will therefore always be significantly less on average than the carbon stock of natural, undisturbed forests.

It is argued by some industry advocates that commercial logging is greenhouse gas neutral because: a) young trees have high rates of growth and carbon fixation; and b) some of the biomass removed from the forest is used for wood-based products with a substantial residence time. Regarding the first point, it is true that the rate of carbon uptake by young trees in plantations and regrowth forests is high. However, this carbon uptake over a rotation would not compensate for the amount of carbon presently stored in natural forests that would be lost if they were harvested (Harmon et al. 1990; Schulze et al. 2000). Responding to the second point, it is critical from a carbon-mitigation perspective to account for all carbon gains and losses associated with logging and associated industrial processes. Comprehensive carbon accounting is needed that includes carbon uptake and emissions from all human activities associated with commercial logging and processing of the associated wood-based products, as well as carbon storage in products.

Emissions that need to be accounted for include grey carbon from burning fossil fuels for energy to do work and green carbon from killing living biomass and accelerating the rate of decomposition of dead biomass. When considering the carbon accounts associated with industrialized forests, it is therefore necessary to include carbon emissions resulting from: a) forest management (for example, the construction and maintenance of roads, post-logging regeneration burns); b) harvesting (including use of machinery, and wastage from collateral damage to living woody biomass and soil carbon); c) transportation of logs, pulpwood and woodchips; and d) manufacturing. All of these emissions must be subtracted

from the carbon stored in wood-based products. Also, it needs to be demonstrated that the carbon in wood-based products will remain in the terrestrial biosphere carbon reservoir for a longer period than it would have if it had remained in an unlogged natural forest.

Ideally, a comprehensive carbon audit should be conducted using the energy audit method of Odum (1981). We cannot find any such comprehensive accounts of the grey carbon emitted from commercial logging and wood-products manufacturing inclusive of all stages in the product life cycle: forest management, harvesting, transportation and manufacturing. Of these, the most critical are likely to be: 1) collateral damage to forest biomass and soil carbon (also called 'wastage'); and 2) the differences between the residence time of carbon in the natural forest pools and the wood-product pools. In natural forests with large carbon stocks, the wastage of biomass due to commercial logging is significant. For example, commercial logging in tropical natural forests has been shown to dramatically reduce carbon stocks. In Papua New Guinea, commercial logging has been found to result in about 27 per cent of stem volume being removed, another 13 per cent being killed and half of the trees with a stem diameter of more than 5 cm destroyed (Abe et al. 1999). The residence time of the wood-based products is also a critical factor given the longevity of woody stems, coarse woody debris and soil carbon pools in natural forest (Roxburgh et al. 2006). An additional critical consideration is the loss of green carbon from natural forest pools when industrialized forests and plantations are first established, and the time it will take for this biomass to be regrown (Fargione et al. 2008).

In summary, forest protection is an essential component of a comprehensive approach to mitigating the climate change problem for a number of key reasons. These include:

- For every hectare of natural forest that is logged or degraded, there is a net loss of carbon from the terrestrial carbon reservoir and a net increase of carbon in the atmospheric carbon reservoir. The resulting increase in atmospheric carbon dioxide exacerbates climate change.
- Given the long time that grey carbon will remain in the atmosphere–biosphere–hydrosphere system, maintaining the natural processes that regulate atmosphere–biosphere fluxes will be critical for moderating carbon levels in the atmosphere in the short to medium term. If natural forests are able to expand then the increased buffering capacity will act as a negative feedback on the accumulation of greenhouse gasses.
- The carbon dynamics of natural forests are significantly different to those of industrialized forests, especially monoculture plantations. The carbon in natural forests has a longer residence time, the system is more resilient to environmental perturbations and natural processes enable ecological systems and their component species to respond to changing conditions.