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The role of forest management in greenhouse-gas mitigation: a contextual framework for Australia.

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The role of forest management in greenhouse-gas mitigation: a contextual framework for Australia.

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Executive Summary

This paper proposes an holistic basis for incorporating carbon (C) values into Australian forest management for the forest manager and decision maker. Its rationale is links between climate change, the concentration of atmospheric carbon dioxide (CO_2), and the exchange of CO_2 between forests and the atmosphere. The paper is written in five sections, encompassing key conceptual or operational topics, followed by a concluding section.

A prevalent mental model in the Australian public discourse on forest C management and storage considers forests as static or unidirectional systems that only sequester C. In this model, C is viewed as being stored in forests as if it was being deposited into a locked safe or bank. This is referred to as the forest "Safe" model. This model is used to maximise C storage in the landscape, and out of the atmosphere where it would otherwise exist as CO_2, a greenhouse gas that is associated with global warming potential. But this model lacks recognition of, or appropriate emphasis on, processes of forest C loss to the atmosphere. Forests are clearly not static systems and the "Safe" model fails to account for the dynamic nature of forests, and the effects on forests both of climate change and of natural disturbances such as wildfire. The "Safe" model also ignores the contribution of forest industries to C storage in wood products and emissions reductions realised when wood substitutes (the "substitution effect") for alternative materials associated with higher lifecycle greenhouse gas emissions, such as fossil fuel for energy production and metals and concrete in construction. Rather than focusing on maximising forest C stocks, a greater effect on atmospheric CO_2 concentration [CO_2] may be achieved if all potential roles for forests were included in the model, including forest products and the substitution effect.

In this report a dynamic mental model, the "Dam" model", is proposed for managing C storage in forested landscapes. In this model, landscape C storage is represented as the level of water held behind the dam wall. Inflow of C to the dam comes from net forest growth (photosynthesis minus respiration) and outflow from combustion or decomposition. The height of the dam defines the biological maximum amount of C in vegetation that the landscape can contain, often referred to as Carbon Carrying Capacity. Natural disturbances, such as wildfire, that convert stored C to CO_2 will prevent the complete filling of the dam, and its level will vary depending on the frequency and intensity of disturbance regimes. The probability of disturbance generating C outflows increases as C accumulates behind the dam wall. With sustainable forest management, C absorbed by forest regrowth offsets losses during harvesting and forests can be maintained as an atmospheric C sink while providing a resource to society. The "Dam" model allows forest management to be incorporated in ways not possible with the "Safe" model. Sustainable forest management is widely recognised to be the best strategy to mitigate greenhouse gas emissions. The "Dam" model can also readily incorporate the use of wood products, and the substitution effect.

Wood products store C in a dynamic pool that can also be thought of in terms of a dam, the Wood Product C "Dam". In this model, wood-product C storage is represented as the level of water held behind the dam wall. Inflow comes from the production of new products and outflow comes primarily from decomposition of old wood products. The height of the dam wall is not constant but set by economic activities and practices that drive inflow and outflow. Further, avoided emissions from the burning of fossil fuel accumulate in a "Substitution Safe". When forest products substitute for more greenhouse-gas-intensive materials, avoided emissions are permanent and accumulate over time. Avoided emissions cannot be reversed, since no process is able to withdraw avoided emissions. From a forest biomass perspective, the best outcome for the atmosphere is to completely substitute the burning of fossil fuels with renewable resources such as wood products.

The judicious use of forests in the greenhouse gas mitigation debate requires all uses of forests be considered. For this we need tools to measure and optimise landscape C storage, wood-product C storage and the substitution effect. Many such tools already exist and can be further developed. Proper consideration will require support, integration, synthesis, team work, and partnerships across scientific disciplines, among and between the biological, physical, social and political sciences and among institutions, organisations and governments.

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Section 1. Introduction

Describes political and social forces that drive the focus on carbon (C) as a forest value to be included in forest management planning. The goal of managing a forest for C is related to the wider objective of reducing (or reducing the increase in) atmospheric carbon dioxide, rather than solely to the narrower objective of increasing landscape C stores. Forest dynamics and important terminologies are discussed.

Section 2. Forest carbon in Australia

Places discussion from Section 1 in the context of forestry in Australia. Recent emphasis on managing forests to achieve Carbon Carrying Capacity (CCC) in Australia is described and explored, and the term CCC shown to equate to Theoretical Carbon Saturation in some cases. Landscape-scale forest-C management in Australia is explored in the context of disturbance regimes in Australian forests.

Section 3. The full role of forests to reduce atmospheric CO_2

Considers the full role of forests in the greenhouse gas mitigation debate: forest landscape C storage, wood-products C storage, and the substitution of wood products for materials with larger lifecycle greenhouse gas emissions.

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Contrasts levels of measurement and thus reporting needs for two types of forests in Australia, production forests and other, mainly native forests and woodlands. In contrast to the majority of native forests in Australia, production forests are data-rich and this provides opportunities to develop and test forest-carbon-accounting tools. Available carbon-accounting tools that include forest C as a management objective are explored in the context of the above forest types.

Section 5. Management of forest carbon

Places management goals for forest C in the context of managing forests for multiple values. Optimal forest management requires that forest C be considered as one forest value among many. Managing for any forest value, including C, should involve examining trade-offs against and among all forest values. Management of forests for C and other values requires extensive partnerships and collaboration be developed.

Section 6. Conclusions

Concluding comments and an indication of future research needs.

Key messages:

1. Forests are dynamic living systems. C stored in forests is not preserved in perpetuity and cannot be 'locked up'. Consideration of forest C must move beyond thinking of forests as static systems; we must think of forests as dynamic systems, as has already occurred in thinking on management of forest biodiversity.
2. There are two ways to address rising atmospheric [CO_2]: reducing emissions, and absorbing and storing CO_2. Trees and wood products can do both.
3. Forests exchange large amounts of CO_2 with the atmosphere and are able to sequester large amounts of CO_2 into biomass.
4. Carbon sequestered by forests can be stored either in forest landscapes or in wood products. Most C stored in forests and wood products will eventually be returned to the atmosphere upon decomposition; for certain forest types, C may be returned upon consumption by fire. C storage in wood products diversifies the risk of C being returned to the atmosphere.
5. Where wood products substitute for alternatives (e.g. directly as an energy source or for metal, concrete, and plastic in construction) that return more CO_2 to the atmosphere over their lifecycle, their use results in emission reductions (avoided emissions) that accumulate over time.
6. Focusing solely on increasing forest C storage is unlikely to result in the best outcome for the atmosphere than focusing on reducing atmospheric [CO_2] utilising all roles of forest management (landscape C storage, wood-product C storage and substituting wood for alternative more greenhouse-gas-intensive materials).
7. Attempting to attain landscape-level C saturation ("Theoretical Carbon Saturation" sometimes equated with "Carbon Carrying Capacity") is not a meaningful or useful forest management objective, particularly in wildfire-regenerated eucalypt forests. Furthermore, such attempts may not optimise reductions in atmospheric [CO_2].
8. Management objectives for C at the landscape level require that spatial and temporal scales of application be considered and defined. The best outcomes for the atmosphere from forest management will come when a broad range of spatial and temporal scales are considered that include disturbance regimes over these scales.
9. Managing forests solely for C storage will come at the cost of some other forest values.
10. With a relatively large forested area and small population, Australia is in a privileged position to reduce total and per-capita greenhouse gas emissions through forest management and use of wood products.

Table 1. Abbreviations used in the text

Abbreviation	Description
C	Carbon
CO_2	Carbon dioxide
$[CO_2]$	Carbon dioxide concentration
CO_2e	Carbon dioxide equivalent
CCC	Carbon Carrying Capacity
M	Million ($10^{6)}$
G	Billion (10^9)
T	Tonne (1000 kg)

Section 1. Introduction

Greenhouse gases impede the emission of long-wave radiation from earth to space, trapping this energy in the atmosphere; the result is atmospheric warming. The most abundant greenhouse gas emanating from human activities is carbon dioxide (CO_2) and greenhouse gas emissions are often discussed in terms of CO_2 equivalents[1] (CO2e). The dominant anthropogenic greenhouse gas emissions, including CO_2, are associated with the burning of fossil fuels. Thus in the first instance, addressing climate change requires reducing society's dependence on fossil fuels. However, forests exchange gases, including CO_2, with the atmosphere. The net effect is that forests absorb CO_2 from the atmosphere, incorporating the carbon (C) into biomass. After tree death, this process is reversed, and C is returned to the atmosphere, usually in the form of CO_2, through decomposition of biomass. Combustion also returns C from live and dead biomass to the atmosphere; again it is usually in the form of CO_2. The link between forests and atmospheric greenhouse gases and climate change has led to the listing of C storage as a forest management objective. Thus to understand the forest C debate, it must be placed in context of the larger greenhouse gas and climate change debate.

Climate change and greenhouse gases

In 1985, scientists meeting in Villach, Austria concluded that the earth was warming due to increasing concentrations of atmospheric greenhouse gases resulting from human activities and called for global action to limit these emissions (World Meteorological Organization–WMO– 1986). In 1987, an international conference in Toronto, Canada, endorsed the Villach Statement and called for reductions in greenhouse gas emissions. The WMO and the United Nations Environment Programme established the Intergovernmental Panel on Climate Change (IPCC) in 1988. The function of the IPCC was to authoritatively review climate science and provide guidance to policy makers and governments. The first IPCC assessment report, in 1990, supported the Villach assertions: atmospheric [CO_2] had increased as a result of human activities and was likely to enhance the greenhouse effect. The IPCC findings were endorsed at the Second World Climate Conference held in Geneva in 1990 and the accompanying Ministerial Declaration called for UN action to negotiate a convention that would establish international agreements necessary to avoid dangerous climate change. The UN Framework Convention on Climate Change (UNFCCC), which was given the objective of preventing dangerous climate change, and the subsequent Kyoto Protocol are the results of those negotiations. Since 1990, the IPCC has reviewed the science of climate change and its findings several times. The Second, Third and Fourth Assessment Reports were published in 1995, 2001, and 2007, respectively. These assessments express increasing confidence that anthropogenic greenhouse gas emissions will cause the climate to change and conclude that recent climate warming is at least partly attributable to human activities. In 2007, Australia ratified the Kyoto Protocol.

The role of forests in greenhouse gas treaties

The Kyoto Protocol recognises the exchange of greenhouse gases between forests and the atmosphere and has several forest-related articles. The UNFCCC[2], the Montreal Process Criteria and Indicators[3], and the United Nations Food and Agriculture Organization (FAO)[4] all recognise the importance of forests in the global C cycle. In the Australian Government's 2008 submission to the UNFCCC (Commonwealth of Australia 2008), Australia defined "forest" and elected activities under key forest-related articles 3.3 and 3.4 of the Kyoto protocol. Australia defines forest as areas ≥0.2 ha occupied by trees that are, or are capable of achieving, heights ≥2 m and crown cover ≥20%. These characteristics align with the definitions of forest used by Australia in the compilation of its National Forest Inventories[5] (Montreal Process Implementation Group 2008) and its reporting to the FAO, being extended to include a minimum area criterion required by the Kyoto protocol.

There is variability in how forests are defined –administratively, based on land use, or biologically, based on vegetation structure – including variability among signatory nations of the Kyoto protocol onhe basis of vegetative cover. Signatory countries can define a forest as a minimum area of land of 0.05-1.0 ha occupied by trees with or capable of achieving 10-30% crown cover and minimum height of 2-5 m (UNFCCC 2002). In Australia, landscapes with sparse tree cover, such as woodlands and tropical savanna, and landscapes with short tree cover, such as some alpine or arid environments, may contain trees that are not abundant or large enough to meet Australia's definition of forest. Conversely, Australia's definition potentially includes landscapes with trees that are not dense nor tall enough to meet the definition of forests used by others.

Article 3.3 of the Kyoto Protocol requires signatory countries to account for changes in C-stock resulting from land-use change (afforestation, reforestation and deforestation); Australia has elected to report deforestation and land-use change as well as afforestation and reforestation since 1990. Consequently Australia has focused effort on the expansion of the forest plantation estate which is included as reforestation or afforestation reporting to Kyoto in response to Article 3.3 and is a component of the proposed National Greenhouse Gas Emissions Trading Scheme (Commonwealth of Australia 2008, 2009) and Carbon Farming Initiative (Commonwealth of Australia 2010). Article 3.4 deals with land use, providing signatory nations options to account for contributions from forest management and agriculture , both positive and negative, to national greenhouse gas balance sheets. Australia has not elected to account for any activities under Article 3.4. Australia's role with these and other national and international forest and C cycling/climate change agreements is described in detail elsewhere (Keenan 2002).

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[1] There are many greenhouse gases. These differ in their ability to trap energy (heat) in the atmosphere. The effect of emitting a particular gas is often reported in terms of CO_2-equivalents i.e. the equivalent [CO_2] which has the same warming effect as the particular greenhouse gas under consideration.

[2] http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.html

[3] www.mpci.org/

[4] http://www.fao.org/forestry/climatechange/53459/en/

[5] Criterion 5 for sustainable forest management under the National Forest Inventory is "maintenance of forest contribution to global carbon cycles" where quantification and reporting the effects of forest management and forest land-use change on greenhouse gas emissions and sequestration is mandated.

Article 3.7 of the Kyoto Protocol allows industrialised countries such as Australia to use rates of forest clearing, and associated emissions, at 1990 levels to form the base rate to which emissions in future years are compared. Australian land clearing activities resulted in a large net emission in 1990. Reducing land clearing activities from what they were in 1990 therefore counts as an emission reduction, without actually reducing direct emissions. Article 3.7 is taken into consideration during the initial calculation of national emissions, and in the national approach to Kyoto Protocol Article 3 only, and has attracted criticism (Macintosh 2010). Australia's emissions from deforestation dropped from 131.5 Mt CO_2 equivalents in 1990 to 49.7 Mt CO_2 equivalents in 2008 (AGEIS 2010).

Role of forests in the greenhouse gas cycle

Anthropogenic emissions of greenhouse gases are dominated by the burning of fossil fuels. However approximately one- quarter of the increases in greenhouse gases in the atmosphere since pre-industrial times originates from anthropogenic perturbation of the biosphere. This fraction is largely from the conversion of forests to non-forests (agricultural, urban, or other development; Houghton et al. 1995; Schimel 1995). Forests contain large amounts of C in living biomass and dead organic matter (dead wood, litter, soil) and contribute to significant annual C exchanges with the atmosphere (Denman et al. 2007). Forests remove C from the atmosphere via photosynthesis to form organic matter, and return C to the atmosphere via vegetation respiration, and decomposition or combustion of organic matter. Thus exchanges of C between forests and the atmosphere are important in the context of climate change.

The global C cycle is complicated, with various sources, pathways and fates for atmospheric CO_2 and numerous positive and negative feedback loops (Dalal and Allen 2008, Hansen et al. 2007, Smith et al. 1993). With this in mind, the following simplification is made to facilitate a description of the role of forest management in the greenhouse gas mitigation debate. Anthropogenically-sourced greenhouse gases can be simply divided into two pools, greenhouse gases originating from fossil fuel and greenhouse gases originating from the biosphere. Carbon in the biosphere is readily and constantly exchanged between biomass and the atmosphere – C flows two way, in and out of the biosphere. Anthropogenic perturbations of the biosphere transfer biosphere C to the atmosphere, which can be re-absorbed by the biosphere. Thus, in the absence of other significant unidirectional greenhouse gas fluxes, such as the burning of fossil fuels, the pool of C exchanging between the atmosphere and vegetation can be simply thought of as remaining relatively constant[6]. Carbon in fossil fuel is geologically isolated from the atmosphere, but enters the atmosphere upon extraction and subsequent burning, a process very difficult to reverse - a one-way flow to the atmosphere. After fossil fuels are burned, the released C joins the pool of C that exchanges between the atmosphere and the biosphere, increasing the size of this pool. The main way to reduce global warming is thus to reduce emissions related to the burning of fossil fuel (IPCC 2010).

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[6] Other fluxes with the atmosphere can be large, for example atmosphere-ocean fluxes, but these can go both ways.

Emissions of greenhouse gases from the burning of fossil fuels in 2004 were equivalent to emitting ~7.5 Gt C to the atmosphere (IPCC 2007). If these annual emissions were to be absorbed by trees to form wood of density 500 kg m^{-3} where half of this mass is C, sufficient wood to produce a solid cube of 30 billion m^3, or 30 km^3 would be needed in annual tree growth in perpetuity. If plantation trees were established on non-forest land to offset these emissions, and grew their woody biomass at a rate of 10 m^3 ha^{-1} $year^{-1}$, then 30 M km^2 of plantations would be needed, or 3.9 times the area of Australia to grow at this rate in perpetuity. Furthermore, the biosphere must reabsorb amounts of C previously released to the atmosphere from human perturbations before the effect can unequivocally be seen to remove emissions from the burning of fossil fuels. Thus, while forests may have a role mitigating greenhouse gas emissions, they do not provide a total solution to the emissions released from the burning of fossil fuels.

Since the biosphere, and in particular forests, exchange large amounts of CO_2 with the atmosphere, forests could be managed to slow the accumulation of CO_2 in the atmosphere and offset fossil-fuel emissions while we transition out of fossil fuel use. This may involve reduced emissions from forests (where forests are a source of CO_2) or enhanced absorption (where forests are a sink for atmospheric CO_2, or sequester CO_2) and storage of atmospheric CO_2 in forested landscapes.

Forests as carbon sources or sinks

Forested landscapes can both emit and sequester C (Field and Kaduk 2004). As trees grow they remove C from the atmosphere to form biomass, and dead vegetation decomposes returning biomass C to the atmosphere. Thus the C mitigation potential of forests includes reducing deforestation i.e. the conversion of forests to non-forests, and increasing afforestation i.e. the conversion of non-forested land to forest.

Wildfire volatilises organic C, returning it to the atmosphere at the time of the fire. Furthermore, disturbances that kill trees transfer live biomass to dead biomass that will decompose over the following decades to centuries, and by disrupting the photosynthetic apparatus, C sequestration into biomass is periodically reduced (Dore et al 2008). Thus for a period of time following disturbance, forests tend to be a source of C. As vegetation gradually re-establishes post-disturbance and photosynthetic capacity increases, forests transition from a source to a sink for C. Forests then continue to be a strong sink until the forests are old, when C sequestration from photosynthesis approaches C emissions from decomposition and respiration (Field and Kaduk 2004, Luyssaert et al. 2008). Thus for a forested landscape, if the average age of individual stands is increasing, the landscape will likely be a sink for C. Conversely, if the average age of a forested landscape is decreasing, it will likely be a source of C.

The average forest age is dependent on disturbance “return intervals”. Disturbances transfer older forest stands to regenerating young forest stands. If the return interval increases, forests tend to be a sink of CO_2; if the return interval decreases, forests tend to be a source of CO_2. Disturbances can be either natural, such as fire or insect outbreak, or anthropogenic, such as harvesting. Thus when considering forest C stocks, both spatial and temporal scales are important. What may be attainable at one scale may not be possible at a different scale. For example, it may be possible to manage certain forest sites to become very old, but it is unlikely that an entire landscape can contain old forests in environments regularly affected by natural disturbances.

The leaky bucket analogy

Forested landscapes can only be strong C sinks for the period of time required for forests to mature, whereupon tree growth and associated C accumulation slows. Some old forests can remain sinks for C, though rates of sequestration will be significantly less than in actively growing forests; however some old forests transition to become C sources (Field and Kaduk 2004, Luyssaert et al. 2008). Field and Kaduk (2004) describes the ability of forests to store C using a leaky bucket analogy as follows, and expands on the concept significantly in the cited article:

> “Net Primary Productivity (Forest growth) is adding water to the bucket, and decomposition is removing the water. With a leak at the bottom of the bucket, the rate of water loss is proportional to pressure, or the amount of water in the bucket, just as decomposition is typically proportional to the amount of organic matter in the decomposing pools. The carbon storage in the forest is the resultant water level of the bucket. As long as forest growth and the size of the leak do not change through time, the water level (or total carbon storage) will eventually stabilize at the rate where forest growth and the leak are equal. This point of equilibrium essentially defines an old-growth forest and underlies the concept that an old-growth forest should not be a major carbon sink.”

Cycles affecting forest C

Today’s forest C stocks are a legacy of past patterns of disturbance, while future forest C stocks will be driven by future patterns of disturbance, both natural and anthropogenic. Disturbances vary in their intensity, the area affected, and return intervals. In some systems, such as many dry eucalypt and rainforest forest types, disturbances are generally not stand-replacing and such forests are often gap-driven. Gap-driven forests are characterised by individual or small patches of trees dying, creating a canopy gap and light well that allows young trees to grow and eventually fill the gap in the canopy. However, in some systems, such as many wet eucalypt forest types, disturbances such as wildfire kill large proportions of the entire overstorey, replacing older trees with younger regeneration andcreating a landscape mosaic of multi-aged forests.Thus, in these systems forest age-class structure is a product of past disturbance regimes. Changes in the intensity, scale and nature of disturbances will alter forest age-class structure and thus forest C-stocks and fluxes with the atmosphere. It follows that countries with abundant young forests, such as much of Europe and the USA, will tend to have forests that are sinks for C. Countries with abundant older forests, such as Canada, will tend to have forests that are C neutral or a source of C (Flannigan et al 1998, Goodale and Aber 2001, Goodale et al. 2002, Kurz and Apps 1999). These general trends will be very difficult to affect at a national level through forest management.

While the extent of the pre-1750 forest-vegetation community types (without assuming their age-class structure) has been estimated for some regions (e.g. Australia Government and Tasmania Government 2007), the natural age-class distribution of pre-1750 forests and the abundance of old growth or tall forests is likely to have been variable over the millennia time scale (Wimberly et al. 2000).

Anthropogenic effects

Many experts consider that almost all forests are disturbed from their natural state, and should be classified as managed. Possible exceptions are boreal forests in remote parts of Canada and Russia (IPCC 1997). The definitions of native or pristine forests will vary, depending on what anthropogenic influences are included under any definition.

Forest management activities affect forests directly through silvicultural interventions and indirectly through broader forest management practices. Forest management commonly involves interventions beyond the boundaries of production forests, i.e. harvested and scheduled-to-be harvested forests. For example, forest management commonly involves suppression of natural disturbances beyond the production forest boundary to prevent damage to production forest assets from natural disturbances originating elsewhere. This anthropogenic natural disturbance suppression alters forest dynamics and structures. These activities can increase forest C-stocks to some degree when applied appropriately by diminishing C losses from natural disturbances (Hurteau et al. 2009). Thus the area impacted by “production forestry” is dependent on what actions are included in the definition of production forestry.

Human activities not directly related to forest management can affect forests within and beyond the production forest boundary. For example, the burning of fossil fuels releases nitrogen and sulphur compounds, resulting in acid rain and the deposition of these elements onto forests, as well as resulting in greenhouse gases that alter the climate. Increases in nitrogen deposition can positively affect tree growth and C sequestration (Thomas et al. 2010), since forests are often nitrogen limited. However significant acid deposition has negatively and extensively affected forest growth (Likens and Bormann 1974, Likens et al. 1996). Other pollutants also affect forest growth. For example, the burning of fossil fuels releases ozone, which is an important pollutant of forest ecosystems in many parts of the world (Karnosky 2005). In addition, climate change resulting from anthropogenic greenhouse gas emissions is expected to affect the dynamics of forest growth and disturbances, which may increase forest C-storage in some regions but in others tree growth may decline and natural disturbance regimes, such as wildfire, may become more intense, returning landscape-stored C to the atmosphere (Auclair and Carter 1993, Bowman et al. 2009, Bunn et al. 2007, Canadell and Raupach 2008, Galik and Jacobson 2009, Kashian et al. 2006, Kurz et al. 2008, Schiermeier 2005, Schimel and Baker 2002, Smith and Shugart 1993, van der Werf et al. 2006). For example, warmer winters were one factor in the mountain pine beetle outbreak in western North America that is turning affected forest from a C sink into a C source, and releasing a predicted 270 Mt C between 2000-2020 (Kurz et al 2008). While some forest ecosystems may benefit from changing climates, others will become maladapted, leading to forest decline and reduced growth and the release of landscape-stored C, which may already be occurring (Boisvenue and Running 2006, Bunn et al. 2007). Human impacts on forest ecosystems are pervasive and no system will be completely unaffected, especially as the climate changes. Thus forests placed in unmanaged reserves are in modified environments which are not early-history, pre-aboriginal or even pre-European conditions. Non-management, or benign neglect, will often lead to negative outcomes for forests (Brown 1996).

Coloured carbon

A recent report has differentiated forest C stocks based on whether forests are, or are not, production forests (Mackey et al. 2008). The report identifies biosphere C as green and fossil-fuel C as grey, then further separates C in production forests as brown i.e. a combination of green and grey C. Brown C is devalued due to fossil-fuel emissions related to management of production forests, and reductions in landscape C-stocks and changes in C dynamics that commonly occur when a forest is converted from an unmanaged to a production forest. Such a C colour model is not found elsewhere in the literature. Conceptually, everything, including native forests that have grown since the industrial revolution, is brown, being derived from atmospheric C partly comprised of C from the burning of fossil fuels.

Landscape carbon storage

If a forest landscape is managed for maximum C storage, the probability of a large C emission and threats to human life and infrastructure from natural disturbances increase as the forest accumulates C (Kurz and Apps 1995, Kurz et al. 1998, Houghton et al. 1999). Large emissions of C are more likely from landscapes occupied by older forests with large amounts of biomass, which is fuel for natural disturbances such as wildfire or insect outbreak, than in landscapes occupied by younger trees with small amounts of biomass (Kay 2000). It will be very difficult or impossible to maintain elevated C stocks in older forests in landscapes affected by periodic large-scale natural disturbance events. In fire-prone forests, tree-based C-storage may lead to large releases of C if trees are killed and partially consumed by high-severity fire (Breshears and Allen 2002, Hurt et al. 2002, Hurteau et al. 2008, Kashian et al. 2006). In fact, fire suppression has increased forest density and stand replacing fire risk in forests that were historically characterised by frequent, low-intensity fire regimes (McKelvey and Busse 1996). Thus, it may be possible to manage a small area of forest to become old by preventing all disturbances for long periods. However, growing a forest to become old becomes progressively more difficult as the area under consideration increases, due to natural disturbances which make this impossible at the landscape level. Thus, saturating forested landscapes with C is unlikely to be an attainable management goal to reduce atmospheric [CO_2].

Where forest management is aimed at reducing atmospheric [CO_2], it is wiser to attempt to reduce concentrations of greenhouse gases using all options available to the forest industry. This is likely to have a better outcome for the atmosphere than focusing on just one option, and that option one step removed from the ultimate goal, such as attempting solely to maximise landscape C stocks.

Section 2. Forest carbon in Australia

Australian forests and forest industries

With a relatively large forested area and small population, Australia is in the unusual position of potentially being able to reduce total and per capita greenhouse gas emissions through forest management. The Australian landmass is 19% forested, based on areas occupied by trees that are or are capable of achieving heights ≥2 m and crown cover ≥20%; the total forested area is 149.4 M ha (Commonwealth of Australia 2009) or ~4% of global forested area. Australia's population (February 2011) of 22.6 million (Commonwealth of Australia 2011) is ~0.3% of global population. Among nations, Australia has one of the largest forest areas per person, ~7 ha. Few other nations have comparable potential roles for forest management to reduce atmospheric [CO_2]. Of Australia's forest area 98.6% is native forests and 1.4% is plantations (Commonwealth of Australia 2009). The forest area in nature conservation areas (IUCN-I-IV) is 23M ha or 15.4% of the total native forest area. However, the public focus on forests in greenhouse gas mitigation is on landscape C storage (Commonwealth of Australia 2008, 2009, 2010, Mackey et al. 2008) rather than the processes thought to have the greatest long-term benefit to greenhouse gas mitigation: C storage in wood products and the substitution effect. The focus on landscape C storage is thus explored in some detail below, with the role of wood products and substitution explored in the next section.

Public native forest where timber harvesting is permitted comprises 9.4 M ha, or 6.4% of Australia's native-forest area, mostly among the nation's most productive forests. The primary areas of native forest that continue to be harvested are located in New South Wales, Tasmania, Victoria, and south-west Western Australia. The tall eucalypt forests of south-eastern and south-western Australia, in particular the very tall C-rich and iconic *E. regnans* forests, have attracted most attention in the debate about forest C (Dean et al. 2003, Dean and Wardell-Johnson 2010, Roxburgh et al. 2006, Keith et al. 2009, Mackey et al. 2008). However, these are atypical of the larger forest landscape: for example, only 0.2% of Tasmania's State forest areas have a canopy above 55m with >40% crown cover (Moroni et al. 2010).

The total annual Australian log harvest is 27.1M m^3 and exports for 2007/08 were valued at $AUD2.47 billion (Commonwealth of Australia 2008). Exports of woodchips, paper and paper products and sawn timber were valued in $AUD at 1.07 billion, 461M, and 120M, respectively. However, in 2007/08 Australia imported $AUD 4.4 billion worth of wood products and in that financial year had a trade deficit in wood products of $AUD 1.9 billion. Forestry, timber harvesting and wood manufacturing employed 76 800 people in Australia in 2007/08 and the value of turnover in forest product industries in 2005/06 was A$21.4 billion, or 0.6% of GDP.

Australia's forest certification and management standards are rated as among the world's best (McDermott et al. 2010). This is partly attributable to the response from government and forest managers to demands that non-timber values must be accounted for in forest- and land-management plans, a process in which conservation groups have played an important role. State-by-state overviews of forest management, regulation, history and ecology can be found in Raison and Squire (2007).

Natural disturbances and climate change

Much of Australia is frequently exposed to natural disturbances, predominantly wildfire (Attiwill and Adams 2008). For example in Victoria during the 2000s, wildfires burned an area equivalent to ~14% of the State, with fires in just two summers burning a total of 2.5 M ha (Government of Victoria 2011). These fires were estimated to release 150 Mt C into the atmosphere (Attiwill and Adams 2008). Earlier wildfire events have also burned tens of thousands of square kilometres of Australia's forests (Attiwill 1994). The devastation from these Victorian wildfires has resulted in advocation of an increase in planned burning, including large-scale mosaic burns to reduce fuel loads and the intensity of wildfire, and to promote healthy forest ecosystems (Victorian Government 2008, Victorian Government 2010).

Fire regimes in Australia have long been modified by humans. With the arrival of aboriginal peoples to Australia, up to 120 thousand years ago, fire frequency is believed to have increased dramatically (Pyne 1991). Aboriginal use of fire is thought to have helped promote eucalypt dominance through its frequent application across the landscape. The intensity and frequency of fire in Australian forests and woodlands then changed again as Europeans replaced indigenous peoples as the primary land managers (Bowman et al. 2007, Gifford et al. 1992, Pyne 1991), which is speculated to be associated with alterations in vegetation structure (e.g. Rolls 1981, 1999, Gifford et al. 1992, Noble 1986.). Fire regimes are further expected to change with climate change, with a general increase in wildfire danger expected. The number of extreme fire-danger days in Australia is expected to increase by up to 300% by 2050 compared with 1990 levels (Lucas et al. 2007). With the Australian flora being adapted to fire, and the long history of anthropogenic influence on its frequency (Gill 1975) and emerging climate change effects, separating the effects of natural and anthropogenic fire events is problematic (Keenan 2002). Natural disturbances in Australia are expected to dominate landscape C fluxes compared to the impact of harvesting (Attiwill and Adams 2008), as has been suggested for other countries (Kurz et al. 2008).

Humans have affected and continue to affect forests and their ability to grow and store C. With European arrival to Australia, factors such as forest dieback, degradation of vegetation from increased salinity, grazing pressure from feral animals, land clearing, forest harvesting and silvicultural management have affected the structure and productivity of the forested landscape (Keenan 2002, Raison and Squire 2007). Anthropogenic climate change is also thought to affect both forest growth and disturbance regimes. Changes in temperature, precipitation and atmospheric [CO_2] are expected to alter tree growth, impact tree physiology (including water use) and phenology. In combination with changes in fire, insect, pathogen and invasive weed dynamics, Australia's forests are expected to change with some benefits to growth and hence C accumulation and some negative consequences. There is concern that as climate changes forests will become increasingly maladapted to their climate, but the outcome of the complex interaction of the above factors is difficult to predict (Medlyn et al. 2011).

Harvesting has been reported to increase fire hazard in wet forests (Lindenmayer et al. 2009) but the hazard is diminished by harvesting in other forest types (Hurteau et al. 2008). The Lindenmayer et al. (2009) study is based on wet forests with diverse ecologies, environments and locations where the effects of harvesting gap-driven[7] tropical rainforest systems dominate many of their observations. Lindenmayer et al. (2009) recognise their study was not comprehensive and indicate their data suggest the effect of harvesting on fire hazard in wet forests will differ substantially among forest type. However, eucalypt and rainforest ecologies are not separated in this work, inferring a similar effect of harvesting on fire hazard in these systems, which has been emphasised in the public discourse. However, in contrast to gap-driven tropical rainforest systems, where harvested forests should be compared with mature closed canopy forests, in fire-driven eucalypt forests the impact of harvesting must be compared across all natural seral stages, from old growth to recently burned forests. Regeneration post-wildfire is likely to have similar fire-hazard characteristics to postharvest regeneration in eucalypt forests. Comparisons of fire hazard between clearfell, burn and sow silviculture of fire-driven wet eucalypt forests and harvesting of gap-driven tropical rainforest are unlikely to be meaningful. Mueck and Peacock (1992), the only references cited by Lindenmayer et al. (2009) that include experimental measurements from Australia found ‘logging in some moist forests in south-eastern Australia has shifted the vegetation composition toward one more characteristic of drier forests that tend to be more fire prone’. However a subsequent examination of the Mueck and Peacock (1992) field sites indicated that with time their harvested sites moved along a gradient of increasing elevation and precipitation, which more likely explains their observation, rather than any effect of harvesting (Williams 1995). Thus, the Lindenmayer et al. (2009) assertions of the impact of forest management on fire frequency in wet forests are unlikely to be broadly applicable to Australian wet eucalypt forest systems where these assertions appear premature.

Landscape carbon stocks and Carbon Carrying Capacity

Landscape C storage is commonly emphasised as a means of reducing atmospheric [CO2] with forested landscapes in Australia (Dean et al. 2003, Dean and Wardell-Johnson 2010, Roxburgh et al. 2006, Keith et al. 2009, Keith et al. 2010, Mackey et al. 2008, Cosier et al. 2008) and in some instances internationally (Carlson et al. 2009, Forest Ethics 2007). These publications highlight the gap between current and estimated potential maximum terrestrial C-stocks, often referring to maximum terrestrial C-stocks as Carbon Carrying Capacity (CCC). The difference between actual and potential maximum C-stocks is presented as landscape C sequestration potential. This sequestration potential is in turn presented as the potential of forests to reduce atmospheric [CO2]. Similarly maintaining landscape C-stores by preventing forest harvesting is emphasised as a method to reduce national greenhouse gas emissions. These studies well describe the importance of landscape C-stores but do

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[7] Gap-driven forests are characterised by individual or small patches of trees dying and creating a canopy gap and light well, allowing young trees to grow and eventually fill the gap in the canopy.

not explore the difficulties or impossibilities of attaining and maintaining landscape-scale C saturation in landscapes significantly affected by natural disturbances.

Discussions of forest C-storage in the public arena typically invoke forest types with very large C-stocks (e.g. Keith et al. 2009), even though such forest types are atypical of forested landscapes where most forest types store substantially less C than observed maximums (e.g. Moroni et al. 2010, Norris et al. 2010). Public references to forest C-stocks commonly fail to account for the broad range of forest types, ecologies and C-storage capacities (Mackey et al. 2008, The Wilderness Society 2011) and often imply that all forested landscapes can attain the C-stocks associated with very productive sites. Forests with high C-density such as tall *E. regnans* are found in relatively small areas of south-eastern Australia and have attracted a lot of attention in this context. Few reports are available in Australia that describe forest C-stocks at the landscape scale that do not focus on atypically C-rich forests nor fully include the effect of wildfire on forest C-stocks. The few such landscape-scale studies indicate a wide range in forest C-stocks in south-eastern Australia (e.g. Moroni et al. 2010). Thus the public discourse seems to assume that forests with very large trees can occur over a wider range than is actually possible, resulting in overestimation of landscape C-storage potential. Hence landscape level analyses must include data from all forest and productivity types and age classes, including those with recent canopy death from wildfire.

Roxburgh et al. (2006), Mackey et al. (2008), and Keith et al. (2010) define CCC as “the mass of C able to be stored in a forest ecosystem under prevailing environmental conditions and natural disturbance regimes, but excluding anthropogenic disturbance”. Estimates of CCC in the above are presented as the difference between current forest C-stocks and those anticipated if the landscape was occupied by mature C-rich forests only. Where disturbance dynamics are generally not stand replacing, such as in gap-driven dry eucalypt forests not subject to stand or cohort replacing wildfire that would naturally support a large proportion of older trees, this approach can work. Landscape-level CCC estimation also requires data from a range of forest and productivity types that occur on the landscape. However, where stand or cohort replacing natural disturbances occur, and in particular when they are common or required to regenerate forests, the impact of disturbance history on age-class structure across the forest landscape must be captured, as indicated by Roxburgh (2009).

Eucalypt regeneration strategies vary considerably (Florence 1996), including various requirements for disturbance and disturbance severity for regeneration to occur. Some wet sclerophyll eucalypt forests require severe site disturbance to regenerate, but as we move toward dry sclerophyll forest there is a decreasing reliance on site disturbance for regeneration where adequate regeneration accumulates naturally with minimal disturbance, as in some dry sclerophyll systems. Wet eucalypt forest systems are among the most productive high quality forests in south-eastern Australia, with many requiring severe disturbance to regenerate (Florence 1996, Attiwill 1994).

Roxburgh et al. (2006), Mackey et al. (2008) and Keith et al. (2010) do not capture or adequately address and explore potential effects of natural disturbances on forest age-class structure in the landscapes they examine and do not include this factor in calculations supporting the CCC definition. Tall wet fire-driven eucalypt forests extend in a discontinuous arc from southern Queensland to Tasmania (Ashton 1981). Hence stand or cohort replacing fires are expected across the examined area of the above studies, though likely in greater abundance in Victoria and Tasmania. Without accounting for the effect of wildfire on age-class structure, especially among wet sclerophyll forests, the above studies will overestimate achievable landscape scale C-stocks. It is inevitable that not all forests will be simultaneously mature and able to store the large amounts of C associated with older forests. For example, in Tasmanian State forest, the area of unharvested eucalypt forest that had standing tree C contents below that of equivalent mature forests, due to the presence of young regrowth following wildfire, was 1.2 times the area of mature eucalypt forest (Moroni et al. 2010).

Natural disturbances keep a portion of the forested landscape in younger age classes and below maximum potential C-storage at any one time. Carbon Carrying Capacity as estimated by the above studies is thus a parameter applicable at site but not landscape level, except in gap-driven forests without stand or cohort replacing wildfire. By failing to account for the impact of natural disturbances on forest age-class structure in landscapes, CCC-derived estimates of the potential for forests to absorb C are overestimated. The demonstrated estimation of CCC in the above studies is better defined by the Nabuurs et al. (2007) concept of Theoretical C Saturation (Moroni et al. 2010) where stand or cohort replacing wildfires occur. Theoretical C Saturation is the theoretical physiological maximum vegetation C-stocks that can accumulate on a landscape in the absence of disturbance or other mechanisms of forest C loss, such as those related to forest succession or retrogression. In fact, if natural disturbances are limited anthropogenically – which may be considered a disturbance – it is possible that some forested systems will accumulate, at least temporarily, more C than forests grown under prevailing environmental conditions and natural disturbance regimes. Landscape C-storage is an important component of the role of forests in the greenhouse gas mitigation debate, but unfortunately CCC as estimated by Roxburgh et al (2006), Mackey et al. (2008) and Keith et al. (2010) is not a useful concept for application at the landscape level.

Falloon et al. (1998), Gupta and Rao (1994), Laclau (2003), and Zhang and Justice (2001) are cited as the source of the CCC concept. These studies examine landscape C sequestration potential in the context of afforestation and reforestation, tend to focus on soil C, and do not use the above CCC definition. In their context these sources cannot be used to guide C management in already forested landscapes, especially those managed sustainably. A more reasonable calculation of landscape level CCC was provided by Roxburgh (2009). This included the effect of natural disturbances on forest age-class structure in estimating landscape C storage potential as well as the effect of forest management on landscape C storage. However, the difference in demonstration between Roxburgh (2009) and the above CCC studies remains unresolved, and indeed the CCC parameter appears at times to have been applied differently to how it is defined.

Comparisons of the effect of forest management at the landscape level will typically encompass a range of individual forest stands encompassing all natural seral stages and natural disturbance dynamics (Kurz et al. 1997). Mackey et al. (2008) state that forest management reduces total C-stocks compared to mature unlogged forests by 40% and cite Roxburgh et al. (2006) as the source of the reduction factor. However, Roxburgh et al. (2006) derive this figure by examining the impact of harvesting only on the above-ground biomass of older C-rich forest stands. At the landscape level wildfire will prevent all forests from becoming old and C rich. Thus, impacts of forest management on C pools are overestimated if comparisons are only made between managed landscapes and individual stands at their maximum C contents (Kurz et al. 1997).

The work of Mackey et al. (2008) also includes a further overestimate of the effects of harvesting on forest C-stocks by applying the Roxburgh et al. (2006) 40% reduction factor to both above- and below-ground biomass. Below-ground forest C-stocks are commonly in the range 0.5-1.0 times above-ground forest C-stocks, and soil C-stocks are unlikely to be significantly reduced by forest management (Johnson and Curtis 2001, O'Brien et al. 2003). Thus by reducing soil C by 40%, Mackey et al. (2008) also strongly overestimates any effect of forest management on C stocks.

The transition from a natural to a managed disturbance regime in forested landscapes does generally result in a reduction in landscape C. In most ecosystems the harvest disturbance cycle is shorter than the natural disturbance cycle, with harvesting specifically targeting older, mature stands. Harvesting also removes stemwood, the C in which would otherwise be added to soil and detritus pools by natural disturbances (Kurz et al. 1997). However, landscape C-stocks then stabilise if forests are managed sustainably (FAO 2010).

The lack of accounting for forests recently mortally affected by fire in much recent work has potentially resulted in overestimates of landscape C-stocks in the eucalypt forests of south-eastern Australia. Mackey et al. (2008) and Keith et al. (2010) estimate natural forests of south-east Australia contain an average of 360 t C ha^{-1} of live and dead biomass and 289 t C ha^{-1} live biomass. While many report individual forest C densities to be equivalent to or larger than these estimates (Keith et al. 2010), these figures are based on datasets biased toward mature or older C-rich forests and lack data from poor and/or recently burned forest sites supporting forests that will have low C-masses (Moroni et al. 2010).

Landscape forest C-stock estimates in Mackey et al. (2008), and Keith et al. (2010) are larger than other estimates for south-eastern Australia. In Tasmanian State forest for standing live and dead trees, forested areas had a C density of 133 t C ha^{-1} and areas never commercially harvested supported 155 t C ha^{-1} (Moroni et al. 2010). Tasmanian State forest able to achieve the Keith et al. (2010) average for south-eastern Australian forest live tree biomass of 289 t C ha^{-1} is restricted to forest types and age classes that currently occupy ~2.5% Tasmanian State forest, with only ~10-15% of State forest being estimated to be able to support forest with this biomass at some stage of the disturbance cycle (Moroni et al. 2010). Similarly, average forest C density for all Victorian State forest was only 96 t C ha^{-1} (Norris et al. 2010) in standing trees with production forests containing 136 t C ha^{-1} (Norris, J. pers.comm.) and forests of the NSW south coast thought to be at CCC and representing native forests of high, medium and low site quality were at 199, 144, and 110 t C ha^{-1}, respectively (Ximenes et al. (2004); assuming biomass is half C).

Mackey et al. (2008) and Keith et al. (2010) incorrectly suggest IPCC global biome-level forest C-stock estimates are below their landscape level estimates of forest CCC in south-eastern Australian forests due to the effect of anthropogenic disturbance across the IPCC dataset. However, if south-eastern Australian landscape C-stocks are equivalent to, or even significantly higher than, the Moroni et al. (2011), Norris et al. (2010) or Ximenes et al. (2004) estimates, south-eastern Australian forest C stocks are well within the range of temperate forest C-stocks collated by the IPCC.

The IPCC does not provide a global biome-level estimate of forest C density. For temperate forests the IPCC provides estimates of average forest biomass densities in the range 120-660 t ha^{-1} biomass (60-330 t C ha^{-1} assuming half biomass is C) by region for oceanic, continental, and mountain forests (Table 4.7, pp 4.53; IPCC 2006). Keith et al. (2010) have estimated global biome-level C-stocks based on data in Table 4.7 of the above IPCC reference. The source data describing average biome-level C-stocks in Table 2 of Mackey et al. (2008) are unavailable, being incorrectly credited to Watson et al. (2001). The above estimate of 360 t C ha^{-1} for south-eastern Australian forests is just above the IPCC range of temperate forest C-densities described above, which includes estimates from the C-dense large-treed forests of oceanic western North America. The Keith et al. (2010) estimate is likely to be too high, due to the avoidance of recently burned and low quality forests in their estimates of CCC, as discussed above, rather than due to the effect of anthropogenic disturbance across the IPCC dataset.

Some south-eastern Australian temperate forest sites accumulated unusually large amounts of C, up to 1867 t C ha^{-1} in living and dead biomass (Keith et al. 2009). Temperate hardwood forests outside south-eastern Australia are generally comprised of smaller trees that have lower potential dimensions than tall wet eucalypt forests, except for some larger-treed forests of oceanic western North America (e.g. Burns et al. 1990). The very large C-stocks of Keith et al. (2009) were located in Victoria's O'Shannassy catchment, of which 93% was burned by wildfires in February 2009 (Melbourne Water 2010). As indicated in Section 1, wildfires will likely cause this forest to periodically become a source for C before once again transitioning to a C sink, repeating the process at the next wildfire. Forest C losses from fire and from subsequent decomposition, as well as the time required for the forest to once again become a sink for C, are not well documented in Australia and require further study. The reduction in fuel loads following wildfire and anthropogenic burns is also expected to be variable. Although both fire types consumed roughly half the pre-fire fuel (Raison and Squire 2007), these findings require validation over a wide range of fire intensity, fuel load, forest type and climatic conditions. The Bushfire CRC aims to improve our understanding of how wild and prescribed fires affect the C cycle (Bushfire CRC 2010).

A potential source of forest measurements to develop a more holistic landscape-level view of forest C-stocks is the inventories of forest managers. While these datasets are often skewed toward productive (faster growing, large-tree) and production (regrowth following harvesting) forests, data on production forests are needed to enable evaluation of the impact of disturbance, and changes in disturbance regimes, on forest C-stocks. Biomass in forests regenerating following harvesting will have much in common with regeneration following wildfire. There are sufficient data in forest inventories to estimate native forest C-stocks in mature and unharvested younger forests of natural disturbance origin in some locations (e.g. Tasmania; Moroni et al. 2010). Forest inventories provide an unrealised data source that may help complete landscape-scale estimates of forest C. However, further data collection will be required in over-mature, non-commercial, and less productive forests.

Deforestation (converting a forest to a non-forest; e.g. agriculture, urban development) and forest degradation (following destructive or unsustainable forest practises) are recognised as a significant source of forest C, particularly among developing nations. The United Nations REDD programme supports developing countries to reduce emissions from deforestation and forest degradation (UN-REDD 2010). Deforestation in developed countries is also discouraged and captured by international reporting under UNFCCC Land Use, Land Use Change and Forestry reporting (UNFCCC 2010). Sustainable forest management maintains forest cover and is not recognised by the UNFCCC, FAO or IPCC as deforestation or forest degradation. At the same UNFCCC 2007 meeting in Bali that gave rise to REDD (UNFCCC 2010a), the role of sustainable forest management to reduce greenhouse gas emissions was further emphasised and is widely seen as a method to reduce greenhouse gas emissions (FAO 2010, Nabuurs et al. 2007), including within the REDD+ program of the United Nations (UN-REDD+ 2011). While rates of deforestation in Australia are concerning and require further action (Macintosh 2010, AGEIS 2010), Australia's forest management standards are highly respected (McDermott et al. 2010) and include consideration of forest C (Commonwealth of Australia 2008b, Keenan 2002, Montreal Process Implementation Group 2008).

Making links between domestic sustainable forest management in Australia and destructive international forest practices is problematic. For example Mackey et al. (2008) cite Fargione et al. (2008) to support assertions that forest management in Australia is equivalent to forest degradation and destruction. In fact, Fargione et al. (2008) examined C costs of converting native forests to food crop-based biofuel production systems. Confusing forest harvesting with a change in land use should be avoided when assessing the effect of forest management on landscape C-stocks.

The "Safe" model for forest carbon

In public discourse, a prevalent mental model often applied to forests and forest management in Australia, including in relation to forest C cycles and CCC, is akin to forests forming a safe for atmospheric C. Such a model considers forests as static or unidirectional (C sequestering only) systems. In this model, C is stored in forests as if it was being deposited into a locked safe or bank. This model lacks recognition of processes of forest C loss to the atmosphere (Mackey et al. 2008, Still Wild Still Threatened 2011, The Greens 2011, Wilderness Society 20011; Figure 1A).

Figure 1A.

The forest C “Safe” model demonstrates a prevalent way of thinking about forests in the greenhouse gas mitigation debate. Simply keep adding forests to the safe and lock them up - a static system.

In this model, forests grow and draw down atmospheric C forming biomass and ‘depositing’ this C into the forest safe. This process continues until each part of the landscape is populated by forests comprising the largest trees possible and storing the largest amounts of C. At this point forests are ‘locked up’, the safe door is closed ‘locking up forests’ and making stored C ‘safe’ from the atmosphere where it would otherwise contribute to global warming. For this to occur, not only must harvesting be halted, but natural disturbances, C losses during succession (Moroni et al. 2010), and forest decline due to changes in nutrient cycling commonly associated with the removal of fire (Turner et al. 2008) must be prevented.

It is, of course, impossible to maintain all forests at or near theoretical C saturation. Thus the potential of the safe to store C is over-estimated (Figure 1b) as natural disturbances and cycles return C to the atmosphere.

Figure 1B.

Natural disturbances and the dynamic nature of forests challenge the forest “Safe” concept. Natural disturbances cannot be stopped and will return forest-stored C to the atmosphere.

Theoretical C saturation may be attainable in all stands individually, but not all stands simultaneously. Natural disturbances are often required to trigger succession and must occur to ensure the continued presence of large-dimensioned C-dense eucalypt forests in the landscape (Attiwill 1994). Some of Australia’s most C-dense wet eucalypt forests (Keith et al. 2009) are often mid-successional and will change to rainforest with trees that are less C-dense and of smaller dimensions (Gilbert 1959; Jackson 1968). Hence, the removal of fire will often eventually result in landscape C-losses.

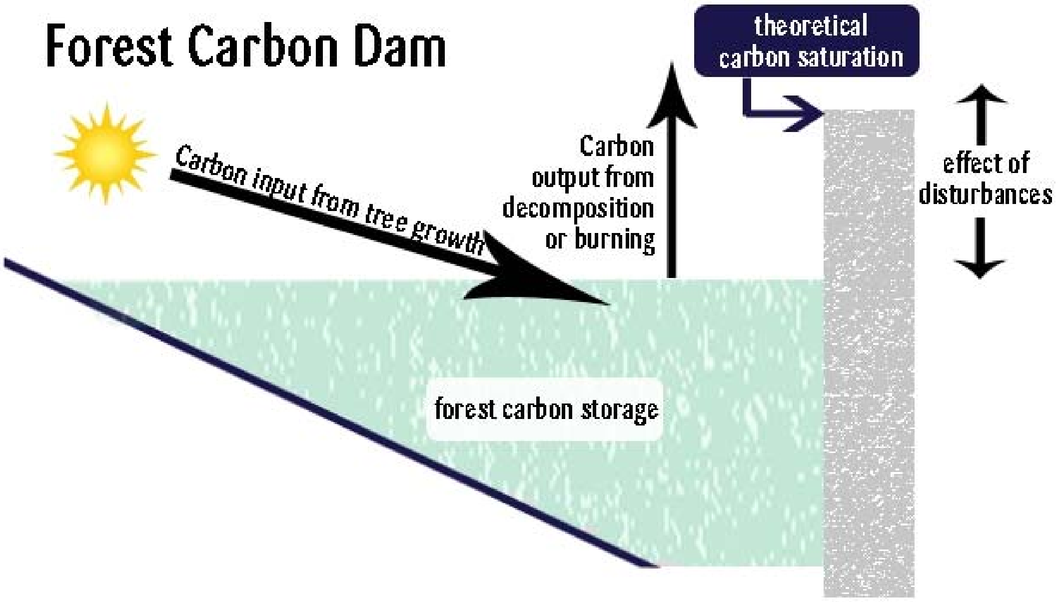
The “safe” model of forest management encourages the preservation of old trees. However, emissions of forest stored C following natural disturbances, and more generally the dynamic nature of forests, challenge the notion that C can be locked up in “safe” forests. While preventing forest disturbances may result in a short-term benefit to the atmosphere, one cost is the same forest C cannot be stored in forest products or substitute for products with larger lifecycle greenhouse gas emissions (substitution effect; see Section 3: Lippke et al. 2004, Marland et al 1997, Marland and Marland 1992, Mathews and Robinson undated, Nabuurs et al. 2007, Perez-Garcia et al. 2005, Schlamadinger 1996, Seidl et al. 2007). Thus a new model for forest management is needed.

The “Dam” model for forest carbon

A more appropriate mental model of forest C management at the landscape level is a dynamic model akin to that of a dam (Figure 2).

Figure 2.

Forests are dynamic systems with C inputs from forest growth and losses from decomposition or burning. This dynamic system is better thought of in terms of a dam than a safe. As C accumulates in forests the amount returned to the atmosphere increases. Theoretical C saturation (often called Carbon Carrying Capacity) cannot be achieved due to the activity of disturbances.



In this model, landscape C storage is represented as the level of water held behind the dam wall. As trees grow, C is added to the dam and accumulates behind the dam wall, being drawn from the atmosphere. Tree death from natural or anthropogenic disturbances results in C returning to the atmosphere, akin to evaporation of water behind the dam wall. As trees age and grow larger, the amount of dead material accumulates, increasing rates of decomposition and return of C to the atmosphere, akin to the lake behind the dam wall growing and increasing in surface area, which increases rates of evaporation. Eventually, in the absence of disturbance, rates of C accumulation behind the dam wall from tree growth and return of C to the atmosphere will become roughly equivalent, setting the maximum C level of the dam for any given combination of inflow from growth and outflow by decomposition. This is similar to the "leaky bucket" analogy of Field and Kaduk (2004).

The height of the dam wall can be seen as representing Theoretical C Saturation, or the theoretical biological maximum amount of C in vegetation a landscape can contain, often referred to as CCC. However, natural disturbance will periodically kill trees, reducing C inflows from photosynthesis and increasing outflows from combustion or decomposition. Such disturbances will prevent the complete filling of the dam, and the dam level will vary depending on the frequency and intensity of the disturbance regimes. The probability of disturbance generating C outflows increases as C accumulates behind the dam wall (Kay 2000).

There is another significant advantage to a "Dam" model over a "Safe" model. Sustainable forest management can maintain or increase forest C-stocks, while also producing an annual sustained yield of timber, fibre, or energy from the forest. This strategy will generate the largest sustained atmospheric [CO_2] mitigation benefit (Lippke et al. 2004, Marland et al 1997, Marland and Marland 1992, Mathews and Robinson undated, Nabuurs et al. 2007, Perez-Garcia et al. 2005, Schlamadinger 1996, Seidl et al. 2007). The "Dam" model can readily incorporate the use of wood products, and further, the substitution effect as described in Section 3.

There are two ways of reducing atmospheric [CO_2], one by reducing emissions, the other by absorbing atmospheric CO_2 and storing it. Trees and wood products do both. Consequently, forest management as a greenhouse gas mitigation strategy is widely recognised, is commonly a key component of Nation and State greenhouse gas mitigation policy, and is commonly supported by environmental organisations internationally[8]. The benefits of forest management in reducing atmospheric [CO_2] are also recognised by the Australian Government[9] and others in Australia (e.g. Kapambwe et al. 2008).

Rather than focus on maximising terrestrial C stocks, were this even possible, a better outcome would be to focus on reducing atmospheric [CO_2], taking a perspective that considers all potential roles for forests, including a role for forest products (Canadell and Raupach 2008, Chen et al. 2008, Conti 2008, FAO 2010, FAO 2010a, Karjalainen et al. 1994, Price et al. 1997, Ter-Mikaelian et al. 2008).

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[8] For example; USA http://www.fs.fed.us/ccrc/topics/carbon.shtml; Canada http://cfs.nrcan.gc.ca/news/473; Quebec http://www.coalitionbois.org/). British Columbia http://www.bcclimatechange.ca/; Oregon http://www.oregon.gov/ODF/privateforests/carbon.shtml; Great Britain http://www.forestry.gov.uk/forestry/infd-7m8fa6; "One of the best ways to address climate change is to use more wood, not less. Every wood substitute, including steel, plastic and cement, requires far more energy to produce than lumber." — Patrick Moore, Ph.D., Greenpeace co-founder; "Forest Management: Part of the Climate Change Solution," California Forests Winter 2006: 8-9;

[9] http://www.daff.gov.au/__data/assets/pdf_file/0008/1386431/climate-change-061109.pdf

Section 3. The full role of forests to reduce atmospheric CO_2

Extracting products from forests provides options for forest management to reduce atmospheric [CO_2] beyond those provided solely by C-storage in forest landscapes. When incorporated into products, extracted wood diversifies C-storage of sequestered atmospheric CO_2 and thus diversifies the risk of CO_2 return to the atmosphere. Furthermore, sustainable forest management not only stores C in forest products, it also allows silvicultural improvements to increase forest productivity (Kurz et al. 1997, Price et al. 1997). Most forest products have a lifespan and their C will eventually be returned to the atmosphere. However, when wood fibre displaces fossil fuels via the substitution effect, prevented emissions are permanent and accumulate over time. It is widely recognised that with time, the best use of forests in greenhouse gas mitigation is to sustainably manage them for products that produce a substitution effect (Lippke et al. 2004, Marland et al 1997, Marland and Marland 1992, Mathews and Robinson undated, Nabuurs et al. 2007, Perez-Garcia et al. 2005, Schlamadinger 1996, Seidl et al. 2007).

Wood products

After extraction from forests, wood fibre is stored in products for the duration of their useful life, and then in places of disposal such as landfill. Annually in Australia ~25 M m^3 logs are extracted from forests, equivalent to 8 Mt C or 30 Mt CO_2 (Ximenes 2006). In 2005, in-service wood products were estimated to contain ~96 Mt C, equivalent to 354 Mt CO_2 (George 2008). Carbon stored in wood products increased by 1.6% per year from 2001 to 2005. In 2004, wood products containing 5.3 Mt C were produced, which increased the Australian wood-products C-pool by 1.4 Mt C once emissions from decomposition of wood products produced from 1944 onwards were deducted (Richards et al. 2007).

In service, structural wood products are stable C-stores with limited losses from decomposition for many decades, with further storage achieved (with limited losses) if disposed of in landfills (Ximenes et al. 2008b). Residential dwellings incorporated 70% of the sawn wood volume consumed in Australia (BIS-Shrapnel 2008). The average lifespan of Australian residential dwellings was estimated to range from 44 to 90 years (Ximenes et al. 2008b). Most dwelling demolitions are not due to the state of the structural system, or the structural failure of wood products. Of the wood in demolished buildings, 40% is salvaged and 60% placed in landfills (Ximenes et al. 2008b). Of salvaged wood products, 77% is installed in new buildings. Decomposition of wood products, both sawn timber and paper, in landfills is minimal (Micales and Skog 1997). Of original wood-product C placed into landfill, 86-97% remained in wood products 46 years after burial (Ximenes et al. 2008b, Gardner et al. 2002). Thus, wood products easily store C in the centuries time-scale when both in-service and disposal lifespans are considered.

Australian landfills were estimated to receive ~2.5 Mt wood products per year (AGO 2004) and to store 137-142 Mt C in 2003, 2.4-2.7 times the estimated in-service wood product C-store (Richards et al. 2007). In 2004-2005, Australians used 4.2 Mt paper products (ABARE 2005) with ~0.3 Mt of papermaking waste disposed of in landfills annually (A3P 2006). Jaakko Pöyry Consulting (1999 and 2000) estimated the lifespan of some wood products, not including storage in landfill, as short. For example, paper products, softwood pallets and cases and plywood were assumed to decay over three years. With relatively little decay of wood products in landfill (Micales and Skog 1997, Ximenes et al. 2008b), the lifespan of these and other wood products will in fact be significantly longer.

Tree to wood product

The proportion of above-ground biomass entering the product stream and the types of products produced are dependent on the quality of harvested trees. Of the above-ground biomass, 15 to 63% is extracted in high-quality commercial logs (Ximenes 2008c). This varies with source i.e. plantation, managed regrowth, or unmanaged native forest. For example, regrowth forests can be managed to increase the proportion of stems that form high-quality logs capable of producing structural-grade long-lived materials.

Forest harvesting for wood products produces residues, as does processing to produce in-service products. For a range of plantation and regrowth forest species in Australia: 30-55% of total above-ground biomass is left in the forest as harvest residues (Ximenes 2008c). These include non-merchantable portions of stems and dead trees, content that is not well described for Australian forests (Mackensen et al. 2003). Other harvesting residue includes the nutrient-rich branch, foliage and bark components of the above-ground biomass that, when left on site, help maintain forest productivity and promote regrowth.

Of original log masses, 40-60% is recoverable as green rough-sawn boards with the remainder forming sawmill residues. A large proportion of these residues is recovered to produce paper and panel-boards, the balance largely used to generate steam, and thus substitute for fossil-fuel usage, leaving little initial log C as waste (Ximenes et al. 2006b). Timber produced from plantations stores 33 times the amount of C emitted during its harvesting and manufacturing (May et al. 2009); timber from native forests stores 15-16 times the amount of C emitted during its harvesting and manufacturing (Lawson, W.R. 1996, May et al. 2009). These data include C emissions from site preparation and slash burning for plantation establishment (May et al. 2009). The above studies do not examine emissions from the full wood product lifecycle, thus not all emissions from production forestry were accounted for. A full account of emissions related to the forest industry requires accounting for emissions from production, installation, deconstruction, and post-useful life handling and losses, for both longer-lived solid wood products and shorter-lived paper products. Paper products, due to their short lifespan and thus limited C storage potential, usually result in net greenhouse gas emissions over their full lifecycle (FAO 2010).

Industrial roundwood removed from global forests annually contains 420 Mt C (FAO 2010) and the global forest product C-pool is estimated to be growing by 150 Mt (± 50%) annually (Miner and Perez-Garcia 2007), equivalent to removing 540 Mt CO_2 from the atmosphere annually. FAO (2010) estimates annual global C-storage of in-use wood products produced in 2007 at 20 and 243 Mt CO_2-equivalent for paper and wood products, respectively, amounting to 263 Mt of total CO_2-equivalent stored. This accumulation is attributed to long in-service lifespan for many wood products, growth in demand for wood products, and long survival after useful life for that fraction placed in landfills. Globally in 2007, landfills accumulated 67 Mt CO_2-equivalent in paper, and 94 Mt CO_2-equivalent in solid wood products, resulting in the increase in annual storage of 161 Mt CO_2-equivalents in all forest products (FAO 2010). Thus globally FAO (2010) estimates in-use and landfill-located forest products to be accumulating C equivalent to removing 424 Mt CO_2 from the atmosphere annually.

Forestry-related activities involve greenhouse gas emissions related to transportation, silviculture, the production of fertilisers and pesticides, and the release of greenhouse gases when fire is used as a management tool. In addition, emissions from forest products occur during the transport of products to the consumer and transport of used products to end-of-life locations where emissions from burning wood products or decomposition in landfills occur. When these emissions are considered, globally the solid wood product value chain sequesters ~100 Mt CO_2 equivalent per year (FAO 2010).

However, the global paper-products chain, which produces products with a shorter lifespan and thus accumulates far less C compared to lifecycle emissions than solid wood products, emits between 500-600 Mt CO_2-equivalent annually (FAO, 2010). Thus, when solid wood and paper products are combined, there is a net emission of 400-500 Mt CO_2-equivalent annually from supplying society with both solid and paper forest-based resources. Increased production of longer-lived wood products can potentially mitigate this loss, but replacing forest-based resources with alternative resources such as metal and concrete would release far more greenhouse gases.

Substitution

The most effective way to limit greenhouse gas emissions through forest management is to displace the burning of fossil fuels through the utilisation of wood products over alternative, more greenhouse-gas-intensive materials (Lippke et al. 2004, Marland et al 1997, Marland and Marland 1992, Mathews and Robinson undated, Nabuurs et al. 2007, Perez-Garcia et al. 2005, Schlamadinger and Marland 1996, Seidl et al. 2007, Sathre and O'Connor 2010). Harvested wood can displace fossil-fuel burning either directly as an energy source, or by replacing materials that emit more CO_2 during their lifecycle. Avoided emissions are permanent and accumulate over time. FAO (2010) describes the substitution effect well, as follows:

> "In commerce, many different products often fulfil the same function. If the impacts of these different choices on greenhouse gas emissions vary, societal emissions are affected when one product substitutes another. Forest products compete with other types of products in many situations, so there are an enormous number of potential substitution effects involving the forest products industry".

The above report continues to assert that there are so many opportunities for substitution involving wood products that examination of all potential options is not possible. However, there has been some work on substituting wood for fossil fuels to generate electricity and heat, as well as substituting wood for non-wood material during residential construction. For further details and greater depth related to substitution see FAO (2010, 2010a).

Biomass supplies ~11% of global energy demands, with developing countries more reliant on biomass energy than developed countries. Developing countries utilise biomass energy to meet 50-90% of their energy demand, largely in the form of cooking and space heating (FAO 2008, IEA 2007). Biomass supplies ~10% of global industrial energy needs, largely in the forest-product industry where biomass supplies 61% and 48% of the energy demands from the wood products and the pulp and paper sectors, respectively (IEA 2006). The IEA (2007) expects bioenergy use to grow, with large potential to substitute the burning of fossil fuels across a range of sectors with new technologies currently under study or being commercially deployed (FAO 2010). Bioenergy has been thoroughly reviewed by FAO (2010a), which suggests that by 2030 the global use of biomass for heat and power will potentially save more than 1 Gt C emissions annually. Recently in Australia, 23% of households burned firewood for domestic purposes, combusting 4.5-5.0 Mt of dry firewood annually (Driscoll et al. 2000). Emissions of CO_2 per unit of heat energy for fossil-fuel energy sources were 0.3-1.0 kg CO_2 kWh^{-1}, while emissions from the burning of dead wood were <0.03-0.11 kg CO_2 kWh^{-1}(Paul et al. 2006). Thus, in Australia substituting wood for fossil fuel as an energy source for heating reduces total CO_2 emissions and displaces significant emissions originating from fossil fuels, and there is a significant opportunity to expand this effect.

The use of wood-based building materials as substitutes for non-wood alternatives has been examined in detail. In buildings with similar energy demands for heating and cooling, wood-based materials have almost always been found to have lower lifecycle greenhouse gas emissions than other materials (refer to reviews by Sathre (2008), Sathre and O’Connor (2010), and Upton (2008)). The literature suggests that this will likely be the case for most temperate, tropical and cold climates, and so broadly across Australia. However, in some arid climates with large differences between day and night temperatures, and where the human comfort zone lies midway between the two, as may occur in arid portions of Australia, this may not be the case. Since energy required to heat and cool residential structures is usually far greater than emissions related to producing, transporting and installing building materials, in some arid environments it may be difficult for wood-based structures to match the thermal performance, and hence lifecycle emissions, of construction materials with high thermal mass, such as concrete (Upton 2008).

Sathre (2008) conducted a meta-analysis of 20 North American and European studies that examined the effects of substituting wood-based building materials for alternatives, to estimate the substitution effect of using wood in construction. This study revealed that:

> “The calculated displacement factors (C of emission reduction per tonne of C in wood product) ranged from a low of -2.3 to a high of 15.0 with most lying in the range 1.0-3.0. The average displacement factor value was 2.0, meaning that for each tonne of C in wood products substituted for non wood products, and average greenhouse gas emission reduction of approximately 2 tonnes of C can be expected. In other units, this value corresponds to roughly 3.7 tonnes of CO_2 equivalent emission reduction per tonne of dry wood used. This average number can be viewed as a reasonable estimate of the greenhouse gas mitigation efficiency of wood product use, over a range of product substitutes and analytical methodologies.”

Applying the above average substitution factor, McKeever (2009) estimated that in 2006 the use of wood in housing construction in the United States avoided the emission of 135 Mt CO_2. Wood-based housing accounts for >90% of total housing in the United States, more than most other countries (Eriksson 2009), indicating significant potential global substitution benefits in housing construction. Based on the above, FAO (2010) estimated the 2007 global substitution effect of using wood in residential house construction alone to be 483 Mt CO_2-equivalent. Sathre and O'Connor (2010) expand on Sathre (2008), increasing the average displacement value to 2.1 which would increase the above estimates of the substitution effect by 5%. In Australia, during house construction, emission reductions of up to 25 t CO_2 per house could be realised if wood substituted other products wherever possible (Ximenes et al. 2006). Furthermore, a lifecycle assessment, excluding operation-related emissions, of alternative constructions of a typical standard Australian house design found the use of wood in Australian houses reduces greenhouse gas emissions, resource use, and energy use (Carre 2011). Specifically, concrete slab floors are associated with 13% more CO_2e emissions than elevated timber floors, steel frame construction types generate 21-43% more CO_2e than timber frames, and brick veneer cladding generates 43% more CO_2e than weatherboard type cladding. With an expanding demand for residential dwellings where non-wood building materials are common (BIS-Shrapnel 2008), the opportunity to use wood to substitute the use of more greenhouse-gas-intensive materials during residential dwelling construction is large in Australia.

Marland and Marland (1992) summarise the substitution effect well:

> "the most effective strategy for using forest land to minimize increases in atmospheric CO_2 will depend on the current status of the land, the productivity that can be expected, the efficiency with which the forest harvest is used to substitute for fossil fuels, and the time perspective of the analysis. For forests with large standing biomass and low productivity the most effective strategy is to protect the existing forest. For land with little standing biomass and low productivity, the most effective strategy is to reforest or otherwise manage the land for forest growth and C storage. Where high productivity can be expected, the most effective strategy is to manage the forest for a harvestable crop and to use the harvest with maximum efficiency either for long-lived products or to substitute for fossil fuels. The longer the time perspective, the more likely that harvesting and replanting will result in net C benefits."

The FAO (2010) also summarises the role of forestry in the greenhouse gas mitigation debate as follows:

> "The processes that govern the cycling of C between the atmosphere and the biosphere operate over time scales ranging from seconds to centuries. Forest-based mitigation activities designed to achieve short-term benefits may, therefore, not be helpful in the medium to long term. One important reason for this is that there are limits to the amount of C that can be stored in the forest; i.e. the benefit saturates. The saturation point and the time it takes to reach it depend on many factors, including the starting conditions, the type of forest and the growing conditions (e.g. Marland 1997).
>
> In the short term, maximum atmospheric [CO_2] reductions may sometimes be accomplished by preservation, allowing C to accumulate in forests. At some point, however, the accumulation of C in the forest saturates and the net removals of CO_2 from the atmosphere cease. In the long term, using

> sustainably produced forest biomass as a substitute for C intensive products and fossil fuels provides greater permanent reductions in atmospheric CO_2 than does preservation. The time required for long-term effects to become more important than short-term ones is highly variable. The optimum approach in a particular situation depends not only on the forest's response to various management strategies, but also on the size of the substitution effect (e.g. Marland et al. 1997, Schlamadinger and Marland 1996)."

Since forests have a finite ability to grow and accumulate C, optimising management of forests for greenhouse gas mitigation over the long term will require forest management to realise the substitution effect. The substitution effect is often maximised with the production of the highest-value wood products, such as structural materials, and judicious use of residues. Under such circumstances pressure will arise to convert all productive forests to managed forests. To maximise the flow of wood products for substitution, pressures on forests will arise that include application of silviculture to maximise forest growth and harvesting before forest growth and C sequestration slows. A better understanding and recognition of the substitution effect is needed in Australia to encourage forests to be managed, and this management to be recognised, for optimal greenhouse gas mitigation by maximising the flow of wood for substitution.

Accounting, reporting, and policy

Accounting, reporting, and policy challenges must be overcome before the full benefit of forest management to reduce greenhouse gases can be captured. Challenges exist both nationally and internationally to determine how to report, credit and structure policy to provide forest management incentives that result in appropriate use of wood product C-storage or the substitution effect as greenhouse gas mitigation/management strategies. The challenges described in detail elsewhere (Nabuurs and Sikkema 2001, UNFCCC 2003 Ximenes 2006a, Ximenes et al. 2008a), are complex, but must be dealt with to allow market forces to properly recognise the value of forests for reducing greenhouse gas emissions.

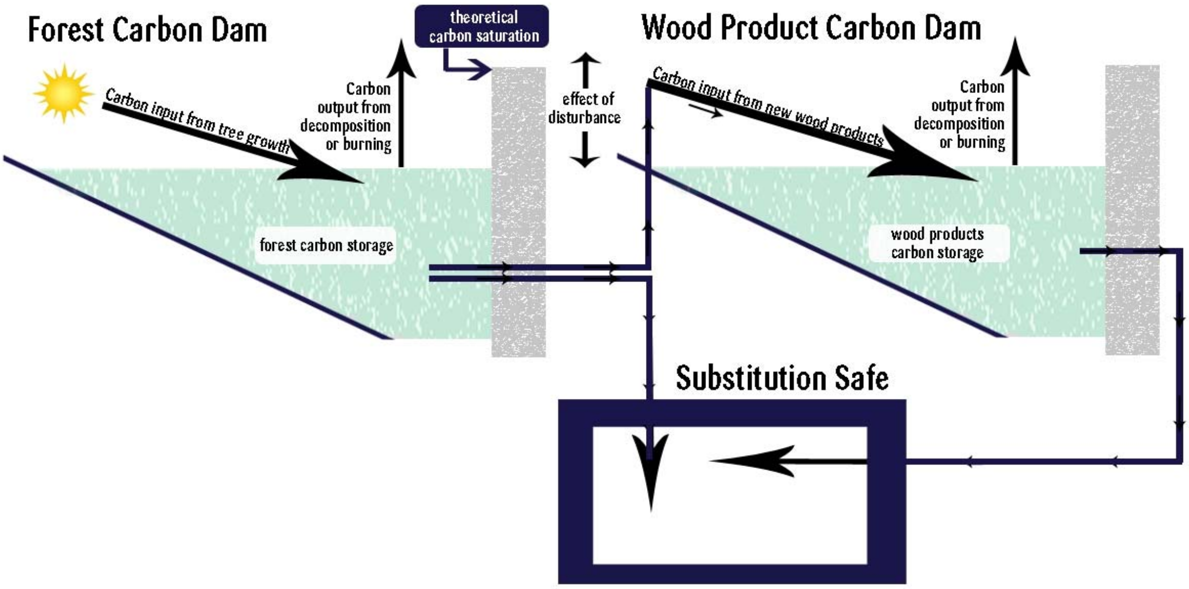
The "Dam" analogy with wood products and a substitution "Safe"

Taking the "Dam" analogy from Section 2 further, forest managers have the ability to influence water levels behind the dam and to direct the fate of some C stored behind the dam wall. Forest managers can influence the amount of landscape-stored C to some degree by influencing the scale and pattern of disturbances (Figure 2). Suppression of disturbances tends to elevate the 'water level', while increases in disturbances tend to lower the 'water level'. Forest management can also transfer some of the 'water' in the dam, or C stored in the forest, to another C-storage "Dam", C stored in wood products (Figure 3). Thus forest C-storage can be diversified through storage in wood products. The forest management community needs to discuss the appropriate level, or range of C, to be held behind the dam wall to meet all of society's needs and values, both non-timber in the forest and timber in use. As C is given a value to limit fossil fuel C emissions, the substitution effect is likely to grow in value and recognition. Increasing the value of C is thus expected to place added pressure on the maintenance of non-C forest values.

In the wood product "Dam", wood-product C storage is equivalent to the level of water held behind the second dam wall. As forest products are produced C is added to the wood-products C dam. Wood products eventually decompose or are burned, resulting in C stored in wood products being returned to the atmosphere, akin to evaporation of water behind the dam wall. As more wood products are produced and accumulate behind the dam wall, the amount of wood products subject to burning or decomposition increases. This is akin to the C lake behind the dam wall growing and increasing in surface area, which increases rates of evaporative return of C to the atmosphere. Eventually rates of C accumulation behind the dam wall from the production of new wood products and return of C to the atmosphere from old wood product decomposition and burning will become roughly equivalent, setting the maximum C level of the dam.

Figure 3.

A conceptual framework for the role of forests in the greenhouse gas mitigation debate. We take the Forest Carbon Dam of Figure 2 and add anthropogenic removal and use of forest-stored C. Carbon can be taken from forests and added to the Wood Product dam, a dynamic pool with inputs and outputs. Carbon can also be taken from the forest dam or wood product dam and substitute for use of more greenhouse-gas-intensive materials, preventing emissions from the burning of fossil fuels.



When forest products substitute the use of more greenhouse-gas-intensive materials, avoided emissions are permanent and accumulate over time. Thus prevented emissions can be thought of as being placed into a "Substitution safe" which accumulates avoided emissions as they accrue (Figure 3). Avoided emissions are possible from the use of new wood products or use or re-use of old wood products after their useful life to generate heat or electricity, or displace more greenhouse-gas-intensive materials. No process is able to empty or withdraw avoided emissions from the safe. The best outcome for the atmosphere is to completely substitute the burning of fossil fuels with renewable resources such as forest products. The greatest benefit from the substitution effect will be to displace products where the largest emissions savings can be realised, such as metals, concrete, plastics and brick in construction.

Section 4. Measurement of forest carbon

Tools are required to describe landscape and wood-products C "Dams", estimate the substitution "Safe" effect, and allow forest managers to explore different management scenarios on forest-C stocks, C-storage in wood products, and the substitution effect. In this way forest C-values can be incorporated into forest management planning processes and used as the basis for reporting on the role of forest management as a greenhouse gas mitigation tool. Here we focus on landscape C estimation, which has received the most attention nationally and internationally, but briefly discuss measurement of C in wood products and the substitution effect.

Australia's native forest landscape can be separated into two parts; production forests and other native forests. Production forests encompass ~6% of Australia's native forests, roughly equivalent to multiple-use forests (Commonwealth of Australia 2009b) and are generally far richer in data describing merchantable yields, growth rates, and the effect of silvicultural interventions than are the much larger areas of other native forests. Production forests tend to be measured (forest class/type, tree diameter and height) and subject to predictable patterns of human intervention as well as stochastic natural disturbances, although the risk of natural disturbances may be managed and natural disturbance events suppressed. In contrast, the majority of Australia's vast native forest area lies outside the production forest estate and encompass enormous variation in forest types, geographical location, climate and productivity but is described by little ground-based data and subject to stochastic patterns of natural disturbance only.

The Australian Government has national and international reporting commitments (e.g. UNFCCC, Kyoto Protocol, Montreal Process) for all forests, both in and out of production forests. As a signatory to the United Nations Framework Convention on Climate Change (UNFCCC 2011), Australia must provide annual reports on emissions and removals of CO_2 and non-CO_2 greenhouse gases in all managed lands, including production forests. For national reporting, and a requirement of Kyoto Protocol Tier 3 models, a consistent national forest-carbon-accounting systems approach is needed that encompasses how different areas and data are integrated and represented. For national level reporting, a method of forest C estimation is needed that does not rely on local inventory. However, in production forests we have a choice to adopt a procedure that does not require or link to inventory and forest-management protocols or procedures, or we can develop a method that utilises forest measurements and links to the measurements and management procedures and protocols that are already in place in production forests.

Forest management dataset and protocols in production forests.

Depending on the size and nature of the resource in production forests, individual forest managers operate with varying levels of sophistication. As management demands increase, forest managers tend to develop: 1) inventory to estimate the standing resource; 2) projections to estimate the standing resource yield when grown into the future; 3) simulation of the effects of management interventions on the standing resource; 4) optimisation of the standing resource through a selected combination of simulations; and 5) calibration of projections, where realised harvest volumes are compared against inventory and yield predications and used to calibrate further predictions. Forest measurement, projection, simulation, and optimisation procedures that forest estate managers use to manage the resource could support estimates of forest C.

Production forests in many regions are well-described by inventories. Typically production forests are mapped into homogeneous stands which are stratified by forest type. Sample plots are allocated among forest types, where forests are measured to develop estimates of current timber volume. Measurement of forests in a forest type at different ages allows growth and yield curves to be developed, which in turn allow timber growth to be projected into the future. Forest inventories can also capture non-timber attributes of interest, for example fuel load for wildfire risk, and habitat availability. The effect on forest growth of silvicultural interventions such as thinning, fertilisation, planting alternative or improved seedlings and weed control can be simulated from data based on field trials. These underlying inventory and growth models (descriptions of forest stands, growth and yield data, transition rules to account for forest successions and responses to disturbances, and model activities in the forest) are then provided to forest estate modelling tools.

Most managers of large forest estates use modelling and linear optimisation tools such as Remsoft's Spatial Planning System (including Woodstock and Stanley (Remsoft 2011)) to develop and compare alternative simulations of silvicultural and harvesting scenarios and select the one that optimises fibre supply while maintaining non-timber values. Management objectives typically include maintenance of merchantable yield and, as constraints, the preservation of non-timber values such as habitat requirements. By varying or modifying objectives and constraints, various future forest management strategies are produced that describe future forest landscapes. Multiple runs can be conducted with relative ease, each producing a variety of outputs (e.g. harvest schedules, maps of activities, potential future forest landscapes) describing the impact of management options, such as changes in harvest prescription, increases in rotation length, fertilisation, change of species, thinning, etc. Many forest managers routinely compare harvested volumes against inventory and yield predictions, using the results to calibrate subsequent predictions.

Land managers need to evaluate the impacts of management on forest C-stocks where interventions occur at the stand or coupe scale. To then understand landscape-level C-dynamics, not only must C stored in above- and below-ground live biomass be accounted for, but also C in dead wood, litter and soil. The C in these pools is commonly assessed across vegetation and forest types over time, accounting for factors that impact C-stocks in these pools such as climate, productivity, successional dynamics and disturbance history. Thus a modelling framework is needed to estimate landscape C-stocks, and the impact of forest management on these stocks.

Ideally, for forest managers to routinely evaluate the impact on forest C of differing harvest schedules or management objectives, output from forest-estate modelling tools and inventory-based growth and yield data should be able to be loaded into forest C-accounting tools. These datasets are at the coupe or management-unit scale. This would allow the forest C-accounting tool to utilise the forest manager's datasets, inventory, growth and yield and timber supply planning routines and thus the considerable effort and resources already in place and deployed in forest measurement and modelling. Additionally, by linking to the planning routines of forest managers, forest-C assessments are likely to require less effort to conduct and would avoid duplication. Linking forest-C estimation to forest planning routines increases the probability that C will be incorporated into normal forest-management processes, with forest managers likely to have greater confidence in C estimates derived from routine forest management procedures based on their collected datasets.

The 2006 IPCC Guidance for National Greenhouse Gas Inventories recommends that models used for reporting on forest C be evaluated against field data collected independent of calibration (IPCC 2006). The IPCC further recommends that the representation of dead organic matter and soil C dynamics in Tier 3 models (the highest standard and often the most accurate, complex or detailed) be linked to the biomass dynamics of the stand. Knowledge of stand growth and yield, time since disturbance and the type of last disturbance, often included in inventory datasets from production forests, will reduce uncertainties in the estimates of stock changes in dead organic matter and soil C pools. Incorporation of forest measurement data collected by forest estate managers provides data sources that could be used to further calibrate and evaluate forest C-accounting tools.

Accounting for landscape carbon

To measure and report on forest C-stocks, the Australian Government has developed FullCAM (Waterworth and Richards 2008), a Tier 3 approach of the Intergovernmental Panel on Climate Change (IPCC) for reporting C-stocks and stock changes (IPCC 2003, IPCC 2006). FullCAM provides an innovative mass-balance approach to estimate forest C-stocks at the national level using Landsat imagery to identify land use and land-use change (Waterworth and Richards 2008). Natural disturbance regimes can be described to FullCAM based on the main effects of percentage of forest affected by the disturbance, post-disturbance growth and yield, and how the disturbance affects biomass pools (e.g. proportions of: loss to the atmosphere, live to dead biomass, and turnover in dead organic matter pools such as transfers to soil). Modelling harvesting includes information describing the intensity of harvest and the destination of residues and products (that can then be further modelled). Development of FullCAM has focused on accounting for deforestation, afforestation, and reforestation due to accounting and reporting requirements relating to Australia’s signing to Kyoto Protocol Article 3.3, where plantations form a component of the proposed National Greenhouse Gas Emission Trading Scheme (Commonwealth of Australia 2008, 2009b) and the Carbon Farming Initiative (Commonwealth of Australia 2010). However, application of FullCAM to production native forest has not received the same attention.

FullCAM estimates initial native-forest C-stocks at the national level based on a forest productivity index derived from climate, site data such as natural and anthropogenic disturbance regimes, and long term Normalised Differential Vegetation Index (remotely sensed vegetation cover index) that provides a spatial estimate or layer for forest cover and productivity across Australia (Waterworth and Richards 2008). This Forest Productivity Index has been calibrated with relatively few ground-based data, which are limited to forest biomass measurements, compared to ground-based data available for inventory purposes in production forests, which tend to be volume estimates based on tree allometry, usually tree diameter and height. The strength of the Tier 3 modelling method applied in FullCAM is that it overcomes the challenges of estimating forest C at the national scale over forest areas for which there are relatively little ground-based data. FullCAM also has the ability to conduct relatively easily consistent, repeatable continental-scale estimates of full forest C-stocks and to estimate these stocks with no or little on-ground measurement data, which allows estimation for much of Australia's forested landscape. FullCAM also supports the use of growth and yield data when insufficient data are available to use the full Tier 3 model-based methods. In addition, FullCAM currently uses a consistent method for all forms of land cover (i.e. forest and agriculture), enabling changes in land use to be easily accounted for. For these strengths, FullCAM or the model concepts and structures have attracted international interest (Rob Waterworth pers. comm.). Equally, these strengths or features of FullCAM, in its current form, makes it challenging for use by managers wanting to make accurate and auditable stand-level or estate-level estimates on a routine basis. FullCAM does not include routines for optimising harvest schedules nor does it provide direct links to other systems, such as Woodstock, that would allow it to most effectively guide production forest C management. Large volumes of forest inventory and growth and yield can be uploaded to FullCAM using a prototype import tool (Norris et al. 2010) for which stronger linkages to production forest management, growth and yield systems is being developed (Rob Waterworth pers. comm.). Such importing processes are important to integrate FullCAM-driven forest C assessment into routine production forest timber supply plans, and for its use to manage forests for C. In the absence of such an import tool it is not easy to upload forest data in detail for large landscapes or entire forest estates on a routine basis. Accordingly, earlier attempts at logistically feasible application of FullCAM to forest estates involved forest cover within an estate being stratified into a manageable number of strata that are then described to FullCAM (e.g. MBAC 2007; MBAC 2008). Simplified growth and yield estimates are thus developed, but these duplicate and are inconsistent with those used during conventional forest planning and reporting. Without direct input of detailed inventory-based growth and yield data and harvest schedules, it will be difficult to use FullCAM to accurately or precisely estimate the C consequences of different management goals or prescriptions. The lack of a direct link therefore confines users to either using growth estimates from FullCAM based on national productivity layers or broad generalisations instead of using actual data. This is not an attractive commercial proposition to influence forest management. The significant extra effort required to estimate forest C with FullCAM and the inconsistencies with inventory-based approaches are significant disincentives for use of FullCAM by forest managers.

However, if forest measurements, procedures and protocols used in production forests are adopted by forest-carbon-accounting tools, challenges will emerge when comparing production forests with differing sophistication and standards in procedures and protocols, making equitable reporting or distribution of C credits or debits between production forests problematic.

Estimates of forest C-stocks produced using inventory methods by estate managers are possible (Conti 2008, Goodale et al. 2002, Li et al. 2002, Nabuurs et al. 2010, Penner et al. 1997), and have been performed in Tasmania (MBAC 2007) and Victoria (MBAC 2008). For example, output from Woodstock, a forest planning tool commonly used in North America and Australasia (including most Australian State agencies), is easily uploaded to the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3; Kurz et al. 2009). This has resulted in adoption of CBM-CFS3 for forest-C reporting and accounting by many Canadian Provinces and forest estate managers, as well as the Canadian Government. This approach has attracted international interest, being applied to forests in Russia, the United States, Italy, China, Korea, and Mexico (Werner Kurz pers. comm.). The CBM-CFS3 is a stand- and landscape-scale forest-carbon-accounting framework utilising a Tier 3 approach of the IPCC for reporting C-stocks and stock changes (IPCC 2003, IPCC 2006). The CBM-CFS3 simulates the impacts of anthropogenic and natural disturbances — including harvesting, insect outbreaks, and fire — on forest C-stocks (Kurz et al. 1992, 2009; Kurz and Apps 1999).

FullCAM-modelled estimates of forest C, based on earth observation images and national-scale data layers, are likely to give inconsistent estimates of forest C when compared to estimates derived from individual inventory-based estate models. Much effort could be wasted in reconciliation of the different approaches, similar to recent differences in the approach between the Australian and Queensland government descriptions of land-use change (Macintosh 2010). Approaches to estimating forest C stocks are available that utilise different methods to address differing objectives and needs.

Each method of forest-carbon-accounting has strengths and weaknesses. However estimates of forest C stocks for the same area using different methods will differ, providing potential avenues of conflict. To mitigate potential conflict, differences in approach and their strengths and weaknesses should be recognised and the most appropriate method used for each reporting circumstance. Forest managers and the Australian Government would benefit from agreeing on a consistent and mutually-beneficial methodology to measure and report on forest C across production forests. There are several potential ways forward: 1) FullCAM could be modified to access production forest datasets and management protocols; 2) FullCAM could be used for national reporting alone and as a default option for unmanaged or un-measured forests, leaving reporting of C contents in production forest estates to an alternative C-accounting model capable of utilising datasets and forest management tools (e.g. CBM-CFS3); 3) alternative methods could be linked to FullCAM utilising select FullCAM datasets and capabilities where they are the best option for application to production forests; and 4) high quality, verified forest management data could be used to further calibrate and validate the Tier 3 model-based approach to improve its stand and estate level accounting for production forests.

Accounting for wood-product carbon and the substitution effect

There are two main methods used to estimate C storage and avoided emissions in wood products: top-down approaches based on national statistics or bottom-up approaches based on transfers of C from individual stands or production forest estates to the wood products pool.

While wood products are not currently accounted for under the Kyoto Protocol, countries can report C emissions and removals from the atmosphere due to use of wood products under the UNFCCC. For the purposes of reporting to the UNFCCC, Australia uses a top-down model to estimate the stock of C flowing to and from the wood products pool (Richards et al 2007) and the transfer of wood products to landfill. The top-down approach is well suited to national-level reporting as it easily allows inclusion in analyses of C in wood products produced in earlier years, currently since 1943, as well as the separation of products produced and consumed domestically and those which are exported or imported. To estimate the current stock of C in wood products the model utilises national wood product statistics, information on service life, recycling rates, decay rates and rates of transfer to landfill. The model allocates wood products to pools depending on type and decay attributes. As wood products age the probability of loss from the wood products C-pool, or of recycling, increases. The model uses Microsoft Excel and is flexible, and theoretically useable at the estate level by forest managers. However, it has no direct links to any forest growth model and does not account for the fate of forest harvesting residues, which are accounted for when using FullCAM.

Bottom-up approaches are commonly used by forest managers to estimate the flow of wood products from stands and production forest estates, but currently lack suitable data for establishing a legacy wood products pool and do not separate products by their final destination (e.g. domestic consumption or export), required for national level reporting. Two bottom-up wood products models are readily available in Australia for use by forest managers: FullCAM and TimberCAM.

FullCAM includes a wood products model that is linked directly to the forest model and therefore accounts for wood products in a full mass-balance framework. FullCAM adds to the wood products pool through harvesting events. The movement of C from stemwood to wood products is accounted for by either allocating proportions of stand C directly to products at each harvest event, or through identifying a series of log grades produced at a harvest event, which are then used to produce differing wood products. The wood products are then subject to decay over time, are burnt as biofuel or moved to landfill. FullCAM also incorporates the lifecycle components of GORCAM (Schlamadinger et al. 1997), which includes emissions from fossil fuels burnt as part of forest management activities, displacement of fossil fuels due to use of products as bioenegy and displacement of emissions through use of wood products compared to other products. FullCAM also accounts for the movement of dead organic matter to products, for example, firewood collection. Harvest residues are added to the debris pools in FullCAM where their fate is further modelled.

TimberCAM, is also a bottom-up model designed for application by forest managers or wood processors of production forest estates. A users guide and manual are available free of charge at http://www.dpi.nsw.gov.au/forests/info/timbercam. TimberCAM is an empirical C-accounting tool that tracks the fate of wood products and harvest residues, including use and end-of-life storage, including in landfills, the fate of residues produced by the above processes, and the displacement of fossil fuel emissions through the use of wood products for bioenergy (Forest and Wood Products Australia 2008). TimberCAM captures the effect of different forest-harvesting scenarios for a range of different wood products on C stocks and flows in products and residues, and is sensitive to the main effects of recovery rates, fate of residues, service life of products and disposal options after useful life. TimberCAM focuses only on wood products and their use and does not include models of forest growth. Currently neither FullCAM or TimberCAM explicitly account for recycling, although this can be simulated by adjusting the decay and disposal rates.

Little data are available to describe the substitution effect and support further development of existing models such as GORCAM that can describe the effect. The citations provided in Section 3 above provide access to studies that can guide estimates of this effect. Research is needed to further describe the substitution effect and further develop tools and approaches to estimate and evaluate the substitution effect more widely in Australia. The greateset benefit from forest management in greenhouse gas mitigation will be through the production of longer-lived, high-value wood products and those that displace the largest emissions from the burning of fossil fuels. Identification of these products and opportunities so that forest management can be encouraged to move production toward such products is thus required.

Section 5. Management of forest carbon

Forests have multiple values

Forests can be thought of in terms of values that are impacted by agents of change. Among forest values is C, however, forest values are many and varied and include economic values such as merchantable fibre yields, hunting and fishing, ecological values such as biodiversity, habitat, and fresh water supply, and cultural values such as spirituality, views, and wilderness sports. The need to manage forests for multiple values is recognised at the highest levels (Wolfslehner and Seidl 2009, Wong 2008, UN-REDD+ 2011). Biophysical processes in the forest are affected by agents of change, which alter forest age-class structure, growth rates or succession. Natural agents of change include events such as wildfire, insect outbreak, and wind-throw. Anthropogenic agents of change can be direct through silviculture, or indirect through altering patterns of natural disturbance (such as fire suppression), pollution, or anthropogenic climate change.

Agents of change affect forest values as well as the probability of future agents of change. For example, stand-replacing insect outbreaks may transform large areas of mature forest to regenerating forest, altering both forest values and the probability of future agents of change. Such an insect outbreak would alter the availability of early and late-successional habitat, provide a large flux of detritus for decomposer communities, alter views, result in a loss of C, change forest hydrology, and alter the fibre value of standing trees. In relation to agents of change, the probability of future insect outbreaks will be temporarily diminished, the influx of dead trees may temporarily increase wildfire risk and the probability of salvage logging, but the probability of routine forest harvesting will be diminished until regrowth reaches commercial dimensions.

Just as managing forests for C involves trade-offs between C sequestration and timber production (Seidl et al. 2007) to optimise atmospheric CO_2 mitigation over different timeframes (FAO 2010), managing forests or ecosystems involves trade-offs between competing forest values and managing for agents of change. Such management requires an analysis of entire systems rather than individual societal values such as C (Alias et al. 2008, Baskent et al. 2008, Costanza and Jørgensen 2002, Diaz-Balteiro, L. and Romero, Pollard et al. 2008). Thus, ecosystem-based management is needed, which has been defined by Kappel, et. al. (2006) as follows:

> “an integrated, science-based approach to the management of natural resources that aims to sustain the health, resilience and diversity of ecosystems while allowing for sustainable use by humans of the goods and services they provide.”

Ecosystem-based management will involve examining alternative management scenarios and evaluating multiple ecological responses, affecting a range of values that policy- and decision-makers must evaluate and use to inform management decisions (Baskent et al. 2008). Decisions need to be prioritised and risk-informed. Risk can be considered as a combination of consequences of an event occurring multiplied by the likelihood of those consequences. A managed risk that is reduced is one where either the probability of the event, or its consequences, or both, have been reduced (Pollard et al. 2008). Thus, while forest C is an important consideration, management of forests for C will affect other values and agents of change, altering risks associated with these values and agents of change. To prevent perverse outcomes for other forest values and agents of change, whether ecological, economic, or social, forest C must be evaluated against all forest values and effects on agents of change and included in forest or landscape management plans accordingly.

Forests at the global scale

In Australia, with abundant forests, ethically we should attempt to balance our domestic fibre supply and demand to ensure we practice sustainable forestry, and thus manage forest C at the global scale and access the global forest resource equitably. This will involve balancing access to resources with rates of resource consumption, where we are capable of and should be managing both (Shifley 2006).

With an international market for wood products, management of forests to mitigate greenhouse gas emissions requires that we extend our thinking to the international level. Where forest management involves harvesting, sustainable forest management practices that adhere to respected certification standards aim to preserve and accommodate multiple values. Sustainable forest practises are recognised as a key to maintaining forest landscapes and forest C-stocks (McDermott et al. 2010, Nabuurs et al. 2007). As a net importer of wood products, Australia exerts pressure on international forests to meet domestic forest fibre demands. Reductions in domestic forest fibre supply will result in that supply being met from forests elsewhere. Australia has highly respected levels of forest certification and sustainable forest-management practices, with much of the world's forests being managed to a lesser standard (McDermott et al. 2010). Thus, any Australian landscape C gains realised by preventing forest harvesting will increase wood imports, which will result in emissions from forests elsewhere that are potentially larger than the domestically avoided emissions. Difficult ethical questions thus arise about forest management (Shifley 2006).

Application of our best biophysical knowledge to landscapes

Addressing the biophysical basis of optimal forest management is unlikely to be sufficient without accounting for the social, political and economic factors that influence decision makers, people's behaviour and markets (Harris 2002, Baskent et al. 2008). Deployment of our best biophysical knowledge will require a process that will cross and integrate social, political and scientific disciplines, and which will thus be wickedly complex (Costanza and Jørgensen 2002, Harris 2002, Mendoza and Martins 2006, Rammel et al. 2007). We should beware of oversimplification, such as landscape C storage arguments or production forest management alone. Proper consideration will require integration, synthesis, team work, and partnerships across scientific disciplines, among and between the biological, physical, social and political sciences and will require countries, states and organisations to obtain and maintain capacities and mandates for such collaborative endeavours (Baskent et al. 2008, Kay et al. 2008).

Section 6. Conclusions.

Carbon has become a forest management goal due to increases in atmospheric greenhouse gases, largely from the burning of fossil fuels, and from the exchange of such gases between forests and the atmosphere. Of the potential roles for forest management in greenhouse gas mitigation, the public discourse in Australia emphasises landscape C storage, which, while important, will not result in the greatest long-term greenhouse gas mitigation benefit from forest biomass. The greatest long term greenhouse gas mitigation benefit from forest management will arise from substituting wood for other products associated with larger lifecycle greenhouse gas emissions, targeting those associated with the largest emissions first.

A pervasive response in forest management to climate change in Australia has been to focus on storing as much C in forest landscapes as is biologically possible. Such an approach often treats forests as static systems and assumes C can be permanently added to this forest “Safe”. The “Safe” model is flawed, since forests are dynamic rather than static systems. Furthermore, the forest “Safe” does not accommodate C storage in wood products or the substitution effect, where greater benefits lie.

Forest “Safe” thinking must be abandoned and a dynamic mental model for thinking on the interaction of forests and C must be adopted. This is required to fully explore the role of forests in the greenhouse gas mitigation debate and to achieve the best outcome for the atmosphere using forest management. A more appropriate model is the forest “Dam”, with C inflow from tree growth and outflow from decomposition and combustion. Such a model can incorporate the necessary dynamics of forest growth and disturbance regimes, and can be expanded to include thinking on wood products and the substitution effect. Wood products can be added to our thinking on forest C cycles with the inclusion of a wood product C “Dam”, with inflow from the production of new wood products and outflow from the decomposition or combustion of old wood products. The substitution effect can then be added to our thinking with the inclusion of the substitution “Safe”, where wood product use prevents emissions that accumulate over time and are irreversible, thus forming true “safe” thinking.

To estimate landscape C stocks and fluxes, routine measurement and evaluation of forest C by forest managers requires forest-carbon-accounting tools that integrate with forest management tools and routines, and preferably avoids duplication and inconsistencies. Forest C reporting needs vary in detail and scale of application, from the Australian government’s need for a consistent national-level approach, to the forest manager’s coupe-level approach, preferably integrating with management systems, protocols and underlying data. All approaches would best include C as one value among many that require consideration and trade-off evaluations by policy makers and land managers.

With varying forest types, growth rates, ecologies, disturbance regimes, potential products, markets, policies and practices across the country there can be no generic prescription to forest managers of the role of landscape C storage, wood-product C storage and the substitution effect. Rather, forest managers will have to evaluate the potential of each of these components for the forests they manage to determine the best outcome. However, it is widely recognised that the greatest benefit in greenhouse gas mitigation results from the substitution effect. Hence, opportunities to substitute the burning of fossil fuel with wood should be explored, emphasised, and encouraged. Forest managers must view and evaluate, and be encouraged through market and policy instruments to view and evaluate, forests not only in terms of landscape C storage, but also in terms of the potential roles of wood product C storage and the substitution effect. Forest managers should be encouraged to identify long-lived products that displace the greatest amount of fossil fuels and to develop the use of residues for heat or electricity generation (Farr and Atkins 2010).

Mitigation of atmospheric greenhouse gases through forest management requires consideration of broad temporal and spatial scales. These should be sufficient to account for the effect of disturbance regimes, ecological processes, climate change, and trends in population, markets and policies. Since wood products are traded on the global market, the C consequences of changes in forest management locally can potentially affect forest C management interstate or internationally, with emissions savings locally potentially being masked by greater emissions elsewhere. Thus we need a global view of forest management.

Research Needs

This report does not intend to list and evaluate forest C research needs comprehensively. A comprehensive list of national forest C research needs have been produced elsewhere, for example the National Carbon Accounting System Technical Report Series [volumes 1-49] http://pandora.nla.gov.au/tep/23322. However, it is possible to describe a range of ways to improve our ability to judiciously incorporate forest management into greenhouse gas mitigation plans.

Better estimates of landscape-level forest C stocks requires expanded measurement of non-merchantable forests and tree components (branch, foliage, roots, dead wood and soil), specifically including old forests and forests regenerating after wildfire. These may be direct biomass measurements to facilitate the biomass approach of FullCAM or volume estimates to link with the inventory approach in production forests. A link between inventory-based estimates of tree volume and the tree biomass approach of FullCAM should be encouraged and explored. In addition, forest measurements by forest estate managers provide data sources that could be used to further calibrate and evaluate forest-carbon-accounting tools.

Development of approaches to measure forest C that satisfy and are mutually beneficial to both national- and production forest- level reporting and planning needs are required. Ideally, effort already undertaken to develop national C accounting methodologies and measurements and management procedures and protocols already in place in production forests should be linked, and future efforts coordinated to benefit the requirements of both national level reporting and production forest level reporting and decision making. In addition, production forest managers require a forest-carbon-accounting tool that enables various management interventions at the site or coupe level to be evaluated.

The effect of both natural and anthropogenic disturbances on forest C-stocks and fluxes requires further attention. We need to be able to compare the effect on all forest C stocks and fluxes of natural disturbances such as wildfire with anthropogenic disturbances such as harvesting to better evaluate the effect of converting unmanaged forests to production forests and vice versa.

The roles of C storage in wood products, and in particular the role of the substitution effect, require greater recognition, attention and research in Australia. Forest managers will be able to take better advantage of wood product C storage with better information on wood product lifecycle analyses where the production of longer-lived wood products should be encouraged. However, the greatest long-term greenhouse gas mitigation benefit associated with forest management will be through the substitution effect, which should be emphasised and promoted, identifying where the largest emissions reductions are possible through the substitution of other products by wood. Mechanisms to measure and report on wood product C storage and the substitution effect, and policy to encourage their use, require research so that a balanced treatment of landscape C storage, wood product C storage and the substitution effect is possible.

To avoid perverse outcomes for non-C forest values, ecosystem-based management is required that accounts for C as well as other biophysical, social, and economic values and disturbances that can affect them. For this to occur skill-sets will need to be accumulated for application to landscape management requiring integration, synthesis, team work, and partnerships across scientific disciplines, among and between the biological, physical, social and political sciences.

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