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Identifying Carbon Storage Potential in the Greater Blue Mountains World Heritage Area

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Introduction

This report aims to review methodologies for measuring carbon storage in forested ecosystems, to explore the role that ecosystems play in carbon sequestration, and to propose how valuation for these storage services can be supported through legislative, economic, and policy frameworks. The importance of carbon as a greenhouse gas (GHG) has led to increasing interest in using terrestrial ecosystems to sequester anthropogenic emissions. The ability of these systems to do so is limited, especially when degradation or destruction threatens ecosystem integrity. Measuring the carbon stock of ecosystems helps to determine which areas are better at storing carbon, with estimates obtained through modelling of vegetation data acquired from the field. Protecting carbon stores often aligns with strategies to conserve biodiversity, as complex, resilient habitats are less likely to succumb to natural or anthropogenic disturbance.

This information is then applied to the Greater Blue Mountains World Heritage Area (GBMWHA), located west of Sydney in south-eastern New South Wales, Australia. Recommendations for the estimation and use of carbon values in the GBMWHA are made, based on attributes and limitations of the Area's ecological, geographical, economic, and political settings. These recommendations include conserving biodiversity, enhancing knowledge in climate change and fire management, and encouraging legal and financial frameworks to enable carbon storage to fulfil its potential as a management tool. Finally, keeping in mind the importance of emissions reduction in addition to mitigation is highlighted by ecosystems' limited capacity to absorb carbon.

Methods

This report results from a review of the literature surrounding climate change, carbon storage in forests, the role of protected areas and their management in fulfilling carbon storage potential, and the GBMWHA.

Section 1: Why is carbon important?

Why measure carbon?

Carbon dioxide (CO_2) is a greenhouse gas (GHG) that traps infrared radiation and causes the Earth's atmosphere to heat up. CO_2 concentrations have been increasing since industrialisation due to the combustion of fossil fuels and deforestation (Locke & Mackey 2009). This increase was first noticed in Mauna Loa in the 1950's and led to the creation of the Intergovernmental Panel on Climate Change (IPCC) to report and assess trends in climate change (Keenan 2002). These reports have shown an increase in the certainty and severity of climate change and its consequences (IPCC 2007). The concentration of CO_2 in the atmosphere is now higher than it has been for 420,000 years, and will impact Earth's biogeochemical cycles for hundreds of years (Falkowski et al. 2000).

The effects of this rapid change in Earth's biogeochemical system are still poorly understood. Changes include rising sea levels and shifting weather patterns, which will impact ecosystems, biodiversity, human settlements, agricultural systems and water supplies (Keenan 2002; Locke & Mackey 2009). To avoid these consequences, most scientists agree that reducing CO_2 concentrations through emissions reduction and mitigation is an essential and urgent step (IPCC 2007). Even so, we have added enough CO_2 to the atmosphere to cause climate change, so adaptation is also important (Figure 1, IPCC 2007).

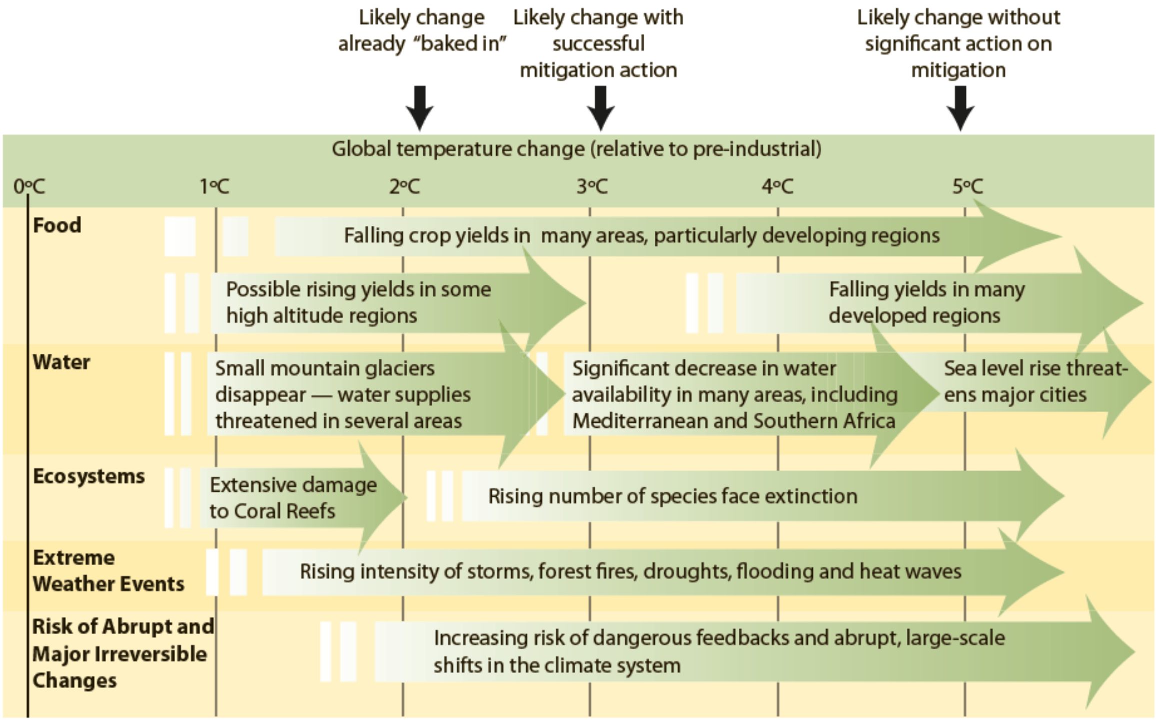

Figure 1: The effects of climate change at different concentrations of CO_2 resulting from various levels of action to mitigate and reduce GHG emissions. *Source: MacKinnon et al. 2008, originally adapted from IPCC 2007.*

These facts and the global nature of both the causes and consequences of climate change have led to the creation of international frameworks to address the problem, such as the United Nations Framework Convention on Climate Change (UNFCCC), formed after the 1992 Earth Summit in Rio de Janiero (Locke & Mackey 2009). Signatories to the Kyoto Protocol, created in 1997 under the UNFCCC, are expected to inventory their GHG sinks and sources (Collaborative Partnership on Forests [CPF] 2008; Keenan 2002). International frameworks for carbon management create pressure for signatories to fulfil their obligations to other countries.

Some regional and national governments have also taken steps to reduce emissions and spur adaptation. The Chicago Carbon Exchange and Voluntary Carbon Standard are two initiatives that give carbon sequestration a value and create incentives to reduce or mitigate emissions (Fahey et al. 2010). Australia's National Carbon Accounting System and National Greenhouse Gas Inventory fulfil the reporting obligation to the UNFCCC (Commonwealth of Australia 2011). However, the assumptions of these inventories are often simplified, out of context for protected areas, or need further calibration with on-the-ground measurements (Keenan 2002). Field studies such as Roxburgh et al. (2006) and Mackey et al. (2008) demonstrate that carbon storage in landscapes can vary significantly to those predicted by stock models with course resolution.

What is the role of forests and protected areas in storing carbon?

One way to mitigate emissions is through their absorption by marine and terrestrial ecosystems (Falkowski et al. 2000). Protected areas could mitigate 10-20% of projected emissions by 2050 if efforts to protect, restore, and utilise these areas succeed (MacKinnon et al. 2008, p. 26). Carbon absorbed by terrestrial systems is called "green carbon" (Locke & Mackey 2009; Mackey et al. 2008). Among terrestrial ecosystems, forests are the largest carbon sinks (Falkowski et al. 2000). This has been recognised by the UNFCCC since 2007 (Mackey et al. 2008). Keenan (2002) argues that international frameworks create obligations for Australia to measure its carbon flux from forests. For example, the UNFCCC requires quantification using "comparable methods", which must yield real, verifiable results (Brown 2002). This is also important for emissions trading schemes such as the Kyoto Protocol. The IPCC also calls for an analysis of how much forests mitigate GHG emissions (Mackey et al. 2008).

Forests store carbon in three ways: in above-ground biomass, below-ground biomass, and in dead woody debris. Although leaf litter also stores carbon, this amount is typically only a small portion of the whole (Brown 2002). Forests store carbon by absorbing and storing it in biomass, but release carbon when they are degraded or destroyed (Mansourian et al. 2009). Some activities such as land conversion and logging release carbon and are a major contributor to GHG emissions. However, natural variability in forest ecosystems and events such as fire, drought, and pest outbreaks also cause forests to release carbon (Mackey et al. 2008). It must also be acknowledged that natural carbon sinks have limits dictated by environmental and physical conditions (Falkowski et al. 2000).

Globally, forests contain about 280GtC, or about 160 t/ha (CPF 2008). Keith et al. (2009) created a predictive framework to identify areas of high carbon storage based on relationships between of ecosystem characteristics and carbon stores. Tree species, the age of the forest, weather patterns, and the degree to which the forest ecosystem has been disturbed all impact carbon storage capacity (Mackey et al. 2008, Grierson et al. 1992; Brown 2002). The term for the difference between a forest's current level of sequestration and its upper limit is known as the carbon sequestration potential (Mackey et al. 2008).

Existing forests with compromised ecosystem function due to past land use may not currently reach their maximum capacity, but given time may reach that limit as the forest re-grows and becomes more ecologically and structurally complex (Roxburgh et al. 2006). Disturbed forests will only reach 40-60% of the carbon carrying capacity of ecologically and environmentally similar undisturbed areas. In addition, the time it takes for carbon to cycle through a natural forest is greater, keeping carbon in the terrestrial part of the carbon cycle for longer (Mackey et al. 2008).

The movement of carbon between terrestrial ecosystems such as forests and the atmosphere, also called flux, is part of the carbon cycle and not fully understood. In 1992, Grierson et al. attributed uncertainty to a lack of good, extensive data because global carbon models were based on only 100 ha of forest data. Since 1992, increasing efforts to measure carbon have yielded estimates that underline the importance of forests in storing carbon. Globally, terrestrial ecosystems including forests sequester about 3 billion tonnes of anthropogenic carbon each year, which equates to about 30% of CO_2 emissions from burning fossil fuels and deforestation. Forests hold about twice the amount of carbon existing in the atmosphere, even though they cover only about 30% of Earth's land area (Canadell & Raupach 2008).

The ability and potential of terrestrial sinks to store carbon highlights two key points: first, the protection and management of terrestrial systems to maximise carbon storage could be a potentially important way to mitigate unavoidable carbon emissions. Second, the ability of terrestrial ecosystems to absorb carbon has finite limits which flex in ways that are not yet fully understood. Adding to this uncertainty, climate change will bring with it more frequent and severe weather events which may alter terrestrial ecosystems and impact carbon storage potential. This creates a cycle in which people must work to protect forests, and healthy forests can buffer people, ecosystem services, and biodiversity against environmental change (CPF 2008; Thompson et al. 2010).

When forests store carbon

Forests become carbon sinks when net primary productivity (NPP)[1] is greater than total respiration and oxidation of plants, soil, and dead organic matter (Brown 2002). This is to say that when plant growth exceeds plant decay and respiration, carbon is absorbed by the forest. Conversely, if the reverse is true and the amount of carbon absorbed by plant

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[1] Net Primary Productivity is the amount of carbon fixed by plants through photosynthesis (Fahey et al. 2010).

growth is *less* than that released by oxidation or decay, the forest becomes a carbon source (Brown 2002). Carbon is released from terrestrial ecosystems through respiration by plants, decomposition by heterotrophs consuming living or dead plants, or through combustion (Falkowski et al. 2000). Factors that influence NPP include light interception, CO_2 concentration, rates of evapotranspiration, temperature, water stress, and nutrient input into the soil (Thornley & Cannell 2000; Brown 2002). The successional stage of different patches of forest can be highly variable throughout a forest landscape, making accurate estimation of carbon storage over broad areas difficult (Hurtt et al. 2004). In addition, the carbon cycle is tightly interlinked with other biogeochemical factors that influence growth such as water and nutrient availability. To add to the difficulty, these inputs will also shift with climate change (Falkowski et al. 2000).

The ability of a forest to store carbon is affected by harvesting, degradation, large wildfires, fire control or management, pest or disease outbreaks, and conversion to other land uses (Brown 2002; CPF 2008). Forest degradation holds a range of definitions, and can be attributed to both direct and indirect causes (CPF 2008, see Appendix). Direct causes include activities such as land clearing and timber harvesting. Indirect causes are the underlying drivers of these activities and include socio-economic considerations such as weak property rights or low income. Some natural degrading processes such as fire and pest outbreak have interactions with human activities or are linked to poor management practices (CPF 2008).

Issues with carbon storage in forested ecosystems

Issues surrounding the value of carbon stored in forests include the permanency of the stores, how to quantify stores, how to measure and predict change in stores, and finally, the social and economic costs of managing forests for carbon storage (Canadell & Raupach 2008). These issues have stalled international agreements on forest conservation as a climate change mitigation strategy, exemplified by the exclusion of deforestation avoidance as a Clean Development Mechanism (CDM) from the UNFCCC's Marrakesh Accords (CPF 2008).

1. Permanency

Carbon stored in forests can be released upon their destruction or degradation, harming the attractiveness of forest carbon storage projects to investors. Destruction and degradation can result from pest outbreaks, disease, storm damage, flooding, landslide, and so on. As the climate changes, weather patterns and pathogen ranges may shift, possibly exacerbating the risk of destruction or degradation to forests and impacting carbon storage values (Canadell & Raupach 2008, Welch 2005).

However, even though the carbon stored in forests is capable of shifting, the likelihood of carbon being released from undisturbed forests is less than that of plantations or intensively managed forests. This is due to the complexity, diversity, and resiliency that natural forests possess (Mackey et al. 2008).

Another issue with permanency is the possibility of leakage from protected areas if forest destruction or degradation is simply shifted to another geographical location (CPF 2008). This can occur at local, regional, or global scales.

2. Quantifying stock levels and changes in carbon stock

Again, knowing this information is important to gauge the effectiveness of carbon storage by forested ecosystems and to attract and retain investor interest.

Some models predict high levels of carbon storage occurring in the next century due to the fertilisation effect of higher CO_2 concentrations in the atmosphere. At the same time, the level of uncertainty surrounding the magnitude of the fertilisation effect is high (Canadell & Raupach 2008), with some evidence of limited carbon storage documented in pine forests in the southeast of the US (Schlesinger & Lichter 2001). Historical CO_2 concentrations indicate that terrestrial carbon stores have absolute limits involving the capacity of carbon-fixing enzymes, the availability of other limiting nutrients, and increased respiration rates of microbes due to higher temperatures. As CO_2 concentrations increase, it is likely that forests will become less effective sinks (Falkowski et al. 2000). For example, swamp forests in Southeast Asia are predicted to undergo drier climatic conditions, speeding up respiration rates and increasing combustion risk (Canadell & Raupach 2008).

The degree of uncertainty surrounding how much carbon is stored in and moves through forests is exacerbated by disconnected efforts to determine these factors. Because forests are typically the responsibility of the state, there are no comprehensive carbon measuring procedures that are standardised across Australia. However, joint efforts between federal and state governments have yielded information about vegetation cover across the country (Keenan 2002, Cofinas & Creighton 2001).

The uncertainty inherent in ecosystem processes and surrounding future impacts of climate change demands special consideration by managers. Strategies to overcome uncertainty include adaptive management, diversifying management strategies, and hedging against predicted outcomes. However, these strategies come at the opportunity cost of resources that might have been spent in other important ways (Biggs & Rogers 2004).

3. Social and economic costs of reforestation projects

Increasing the carbon storage potential of forested ecosystems through reducing edge effects, increasing buffer areas and establishing corridors could have social and economic impacts on landholders and industries surrounding the protected area (Canadell & Raupach 2008). These impacts need not be negative if the principles of conservation through sustainable use (CSU) are applied (Secretariat of the Convention on Biological Diversity 2004). Stakeholders could gain benefits such as additional income through forest services, while managers would gain a critical ally in the conservation of important buffer and corridor spaces outside of the protected area (Canadell & Raupach 2008). Developing CSU strategies will require significant amounts of research, outreach, and coordination (Secretariat of the Convention on Biological Diversity 2004).

Beyond carbon

Although carbon is an important component in climate change, other factors weigh in to affect, or force, climate (IPCC 2007). Forests have important effects on local and global climate. Locally, forests increase humidity and cloud cover through evapotranspiration. This cools surrounding areas and increases cloud cover (Bonan 2008). Conversely, in boreal forests, replacing light coloured snow with dark coloured forests decreases the albedo effect and increases warming (Canadell & Raupach 2008). These complex forcing effects cannot be ignored while considering options to sequester carbon.

Protected areas offer services beyond storing carbon and combating climate change. They create refugia for biodiversity, acting as genetic strongholds and giving species additional time to adapt to climate change (CPF 2008, Mackey et al. 2008). Because of this diversity, protected areas are more resilient (Mackey et al. 2008). In addition to biodiversity, forests protect water catchments, cultural values, air quality, and livelihoods (CPF 2008, Dudley & Stolton 2003). Natural areas also buffer human and ecosystems against some of the impacts of climate change such as floods and droughts, and indirectly support economies by dampening the impacts of natural disasters (Mansourian et al. 2009; Dudley et al. 2010).

These values have been recognised internationally, with multiple initiatives and organisations calling for investigation into and protection of these forest services. The UN Forum on Forests discusses and supports these values through its Non-Legally Binding Instrument on All Types of Forest, encouraging parties to consider all potential values that sustainably managed forests can yield. Another international organisation, the Convention on Biological Diversity (CBD), encourages CSU to advance both biodiversity and climate change mitigation goals (CPF 2008). The UN Convention to Combat Desertification highlights the role that forests play in stabilising local climate and topsoil (CPF 2008).

Collaborative organisations such as the CPF draw different bodies of knowledge together, attempting to create an integrated, international policy framework for sustainable forest use. These cooperative efforts yield programmes such as Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD) (CPF 2008). These extra-carbon values are not deeply explored in this paper, but must be considered in any management strategies.

Finally, it is important to consider that the relationship between forests and carbon storage is two-way: forests can affect climate change, but they are also affected by it. Species distribution and movement will create challenges for managers through the loss of ecosystem attributes and movement by key or invasive species. In addition, pests and diseases may become more prevalent (Mansourian et al. 2009).

Section 2: How do we measure carbon?

Mackey et al. (2008) call for measurements of both the existing carbon stock and the maximum amount of carbon that a forest can naturally hold. Calculating carbon carrying capacity is a difficult task that is often accomplished by comparing undisturbed areas with similar ecosystem processes. Because of this difficulty, most research focuses on determining existing carbon stocks.

It is possible to calculate the amount of carbon stored in a forest by measuring biomass and estimating carbon content. Calculated carbon content can be verified by testing biomass, although this may require the destruction of living trees (Brown 2002). The IPCC published the *Guidelines for National Greenhouse Inventories* to help countries catalogue their carbon stores, although significant uncertainty exists around tracking changes in carbon stocks over time (IPCC 2006, CPF 2008). The United Nations Food and Agriculture Organiztion (FAO), International Tropical Timber Organization, and UNEP's World Conservation Monitoring Centre maintain databases to track carbon stocks and biomass, while international resource institutes strive to improve these estimates. At the same time, the veracity and accuracy of this data cannot truly be known (CPF 2008).

Standardised methods of data collection have not yet been established, although there is a need to do so due to the international importance of quantifying forest carbon stocks (CPF 2008). Despite a lack of standardisation, there has been a large body of work in quantifying carbon content of forests at global, regional, and even localised ecosystem scales (LifeWeb 2010; CPF 2008; Wang & Barrett 2003; Mackey et al. 2008; Burrows et al. 2008). An online, interactive map exists that combines IPCC methodologies, GIS technology, and FAO ecotone definitions to yield rough carbon estimations across the globe (LifeWeb 2010, Ruesch & Gibbs 2008). In Australia, efforts have been made to quantify carbon stored in undisturbed forests in the southeast (see Mackey et al. 2008). Burrows et al. (2008) also estimate carbon content of Eucalypt species in Queensland, noting that the results are site-specific and that measuring changes in carbon stock requires more attention to detail in models.

Mackey et al. (2008) calculate three kinds of forest carbon for Australian forests. First, carbon stock in the whole of the forest including soils, amounts to 640 tC/ha. Biomass carbon stock, a measure of carbon caught up in living or dead plant matter, amounted to 360tC/ha. Finally, Net Primary Productivity (NPP), a measure of how much carbon is absorbed from the atmosphere through plant growth, reached 12 tC/ha per annum.

Fieldwork to determine biomass and thus carbon content of terrestrial ecosystems can be a resource-hungry endeavour: the US undertakes such measurements across 200 million hectares of land using 3 million sample points. This sampling program runs in five-year cycles and costs approximately US$46.5 million dollars per year (Keenan 2002).

Using models to determine biomass and carbon

Modelling is the primary way in which carbon storage is determined. Carbon stored in biomass, either living or dead, can be estimated by sampling an area in a statistically sound manner. Measurements on the ground are important to support models, especially because different growth rates, environmental factors, or shifts in species composition can change carbon storage (Fahey et al 2010).

First, estimates of biomass are obtained by applying allometric equations to measurements of the vegetation. These measurements typically consist of tree height and trunk diameter at breast height. These measurements are then applied to a biomass equation, which can be obtained through regression of biomass, height, and diameter measurements from felled trees of the same species (Burrows et al. 2008). Carbon content can then be estimated using further equations, which typically assume some proportion of biomass to be carbon (Roxburgh et al. 2006). Remote sensing also has a role to play in determining biomass, although it must be calibrated and verified with spot checks using traditional methods.

Measuring biomass to inform models

Measuring biomass in a forest is no trivial task and requires significant data collection. Such inventories are common in developed countries. Grierson et al. (1992) used assessment reports such as the Forest Resource Inventory and Hardwood Resource Information System (HARIS) for measurement of biomass in Victoria.

Where inventories on forest biomass are missing, sampling plots must be designed. To determine the biomass of trees, destructive sampling must occur on different species of different ages across a range of sites. Sampling plots must be permanent so that changes in biomass may be established through tagging trees. In this way, biomass accumulation, tree death, and ingrowth[2] can be tracked and lead to better estimates of changes in carbon stock. Within sampling plots, it is important to include large diameter trees because they contain a high proportion (30-40%) of aboveground biomass in mature forests (Brown 2002).

The number, size, and distribution of these permanent sampling plots will impact the statistical soundness of the information gathered, so careful attention must be paid to the design of sample plots (Brown 2002). Factors that can influence carbon content must be considered when designing sampling plots so that minimal distortion in data is introduced at this critical stage of data collection.

Calculating biomass from field measurements

Aboveground biomass

After data on tree distribution and size is collected, it can be used in two ways to estimate carbon stock. The first utilises Biomass Expansion Factors (BEFs) but requires that the merchantable volume[3] of all species present in the sample plot are known (Brown 2002). It is important to note that BEFs change depending on the type of tree being considered and cannot be interchanged between forest types without the introduction of error. In other words, the relationship between tree volume and carbon content varies between tree types, and assuming that all trees are the same will yield inaccurate estimates of carbon content. For example, pine tree BEFs are low at low merchantable volumes and steady at high volumes, while tropical hardwoods have higher BEFs than temperate hardwoods (Brown 2002).

The second method for estimating biomass from field measurements of trees is the use of allometric[4] regression equations. This method is more useful when data give only individual tree diameters but no estimation of merchantable volume. Most forests across the globe have had allometric regression equations designed for their specific tree types, although some are quite generalised (Brown 2002). Again, climate type and tree species influence the accuracy of results, so higher quality field data will yield higher quality biomass estimates. Allometric regression equations gain accuracy when additional data describing tree height are included, although these measurements are often difficult to obtain due to terrain and interference from other trees in measuring tree height (Brown 2002). Another interesting issue with allometric regression equations is that many of these equations were developed between 1960-1980 (Brown 2002). Since then, carbon

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[2] Ingrowth means the growth of new trees growing into the size or diameter range considered for sampling.

[3] Merchantable volume means the volume of a tree that can be sold as product and excludes any irregularities in trunk shape (Fenner School 1999).

[4] Allometry, also called dimensional analysis, is applied by Burrows et al. (2000) to quantify biomass in Queensland Eucalypt forests. This paper details the establishment of sample plots, sampling methods, and equations used, which could be useful for setting up studies in the GBMWHA.

concentration and other factors may have changed allometric relationships in trees, possibly impacting the accuracy of regression equations based on these relationships. Verification of allometric regression equations should be conducted to ensure accurate biomass estimation or to update the old equations.

Belowground biomass

Ways to estimate below-ground biomass include obtaining soil core samples for fine and medium-scale roots, excavation for large roots, or allometric studies. There is currently no standardised way to measure below-ground biomass, and the process is difficult, time consuming, expensive, and possibly damaging to trees. Coarse roots are particularly important to measure because they contain up to 70% of a tree's underground biomass (Brown 2002).

Estimating belowground biomass with what is known from aboveground biomass can be accomplished through Root/Shoot ratios (R/S ratios) (Brown 2002). R/S ratios do not change significantly across climate zone or tree type (Brown 2002). Another way to utilise this relationship is with equations developed by Cairns et al. (1997). However, just like estimation for aboveground biomass, different forest types will have different characteristics, impacting the accuracy of the equation's results (Brown 2002).

Dead biomass

Measuring dead wood is important, but currently limited by lack of coherent methodology. Coarse dead wood accounts for 10 to 20% of aboveground biomass in mature forests, and can be estimated by tree mortality tracked through tagged specimens in sample plots as described above. Dead biomass includes the additional complexity of its state of decomposition. Decomposition roughly correlates to density, although this is not always the case. Better ways of determining biomass in decomposing wood must be determined (Brown 2002).

Error is introduced into results from real-world variability, the lack of standardised methodology for data collection, and a lack of statistically rigorous sampling design (Brown 2002).

Estimating carbon from biomass

Once aboveground biomass is determined, estimating carbon can be done by assuming a certain percentage of biomass is carbon. Grierson et al. (1992) assumed this percentage to be 50%. From this relationship, it becomes clear that forests with higher biomass will store more carbon.

A few problems arise in quantifying carbon via biomass through methodologies commonly used for plantation or other disturbed forests. First, large diameter trees that may be found in undisturbed areas often contain more carbon than implied by generic models, and so verification of carbon content should be undertaken. Unfortunately, this requires the destruction of the tree under current methods (Brown 2002). Second, the dwell time of carbon in natural ecosystems is longer than in plantation forests, impacting how sequestration rates and totals could be perceived (Mackey et al. 2008). Models that predict shorter dwell times than those actually occurring might undervalue the carbon stores in protected areas.

Remote sensing

Remote sensing holds great potential for increasing data collection in forests due to the difficulty of reaching large areas of remote or difficult terrain with traditional methods. Hurtt et al. (2004) argue that on-the-ground approaches often lead to great uncertainty for some regions, and that remote sensing in combination with appropriate modelling can provide more accurate estimations of carbon storage. Tree height can be measured using aerial photography and Lidar[5]. This technology has given high correlation to data collected manually in the forests of the US's Pacific Northwest, yielding accurate estimates of crown, height, and density measurements (Brown 2002). However, Keenan (2002) cautions that spot-checking and calibration of remote-sensing data with on-the-ground measurements still needs to occur to ensure the accuracy of results.

Section 3: The GBMWHA and carbon storage

Background

The GBMWHA totals 1,075,452 ha in area and measures about 250 km from north to south (NSW DECCW 2008, Figure 2). The area became World Heritage listed in 2000, creating international obligations to protect its values (Merson 2006; NSW DECCW 2008). The landscape within the GBMWHA varies considerably and includes forested gullies, sandstone cliffs, hanging swamps, rainforests and heathlands (see p. 26 of Hammil & Tasker 2010). This variability is due to geology and leads to distinct vegetation communities that capitalise on different tolerances and requirements in fire frequency, soil fertility, and moisture (Hammil & Tasker 2010).

The GBMWHA was inscribed onto the World Heritage List because of its natural values of "outstanding universal significance":

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[5] Lidar, or light detection and ranging, uses a pulsed laser at different resolutions in conjunction with GPS to measure tree canopies, undergrowth, and topography (see Lefsky et al. 2002)

1. It contains “outstanding examples” of “significant on-going ecological and biological processes”; and
2. it “contains significant natural habitats for in-situ conservation of biological diversity” (NSW DECCW 2008, p. 7).

For example, the diversity of eucalypt species coexisting within the GBMWHA with ancient species such as the Wollemi Pine (*Wollemia nobilis*) demonstrates the traits that granted the area WHA status (Hammil & Tasker 2010).

The WHA’s large size, coupled with about 5,000 kilometres of border between adjacent land, creates multiple levels of management. Land tenure of the WHA spreads across 7 national parks and the Jenolan Caves Reserve, a karst conservation reserve (Figure 2). Additionally, there are the considerations of co-management and native title (NSW DECCW 2008). Management of the GBMWHA falls under the Director-General of the National Parks and Wildlife Service under the NSW DECCW, as established by the NSW National Parks and Wildlife Act (1974). The Jenolan Caves Reserve also is responsible for management in the GBMWHA (Merson 2006, NSW DECCW 2008). Management responsibilities are subdivided by area (NSW DECCW 2008), and are guided by a Steering Committee consisting of representatives from DECCW, the Jenolan Caves Reserve Trust, and the Federal Department of Environment and Conservation (Merson 2006).

Carbon potential

The region’s carbon potential has not been estimated to date. However, from studies performed on other areas of South-eastern Australia, some estimates may tentatively be put forward. Mackey et al. (2008) suggest that “cool temperate evergreen forest with a tall eucalypt overstorey and a dense *Acacia* spp. and temperate-rainforest tree understorey” have the highest carbon storage values, while short-lived species in warmer, drier conditions result in lower carbon stores. The carbon storage values obtained by Mackey et al. (2008) are approximately thrice the value assigned to the region by the IPCC’s standard values for these forest types, which Mackey et al. (2008) explain with the additional resiliency and storage capacity of natural forests over disturbed or plantation forests.

It is important to note, however, that environmental factors, species composition and fire regimes play important roles in forest growth and oxidation cycles, so local carbon stocks may vary considerably. Applying the carbon estimation techniques outlined above to the GBMWHA would yield the best estimate for the potential carbon stores available. At the same time, higher specificity costs more to measure on the ground (Fahey et al. 2009).

Figure 2: Map demonstrating the expanse and multiple areas of land tenure that make up the GBMWHA. *Source: NSW DECCW 2008.*

Threats to carbon storage

As discussed earlier, a forest's ability to store carbon depends on the rates of its growth and oxidation. Additionally, complex ecosystems typically hold more carbon than simple ones. This means that activities or events that harm ecosystem complexity and resiliency will also damage the ability of the ecosystem to store carbon.

Climate change and fire have shaped the GBMWHA's ecological communities, but new pressures from land-use change and accelerated climate change may outstrip the ecological communities' abilities to adapt (Hammil & Tasker 2010, p. 7). Merson (2006) outlines some of the key threats facing the GBMWHA as temperatures rise and droughts become more frequent. These include more intense, higher frequency bushfires that limit recruitment of even fire-tolerant species, the spread of plant diseases such as *Phytopthora,* and the loss of biodiversity. These effects may lead to forest destruction, degradation, and shifts in species composition (Figure 3, Merson 2006, Hammil & Tasker 2010).

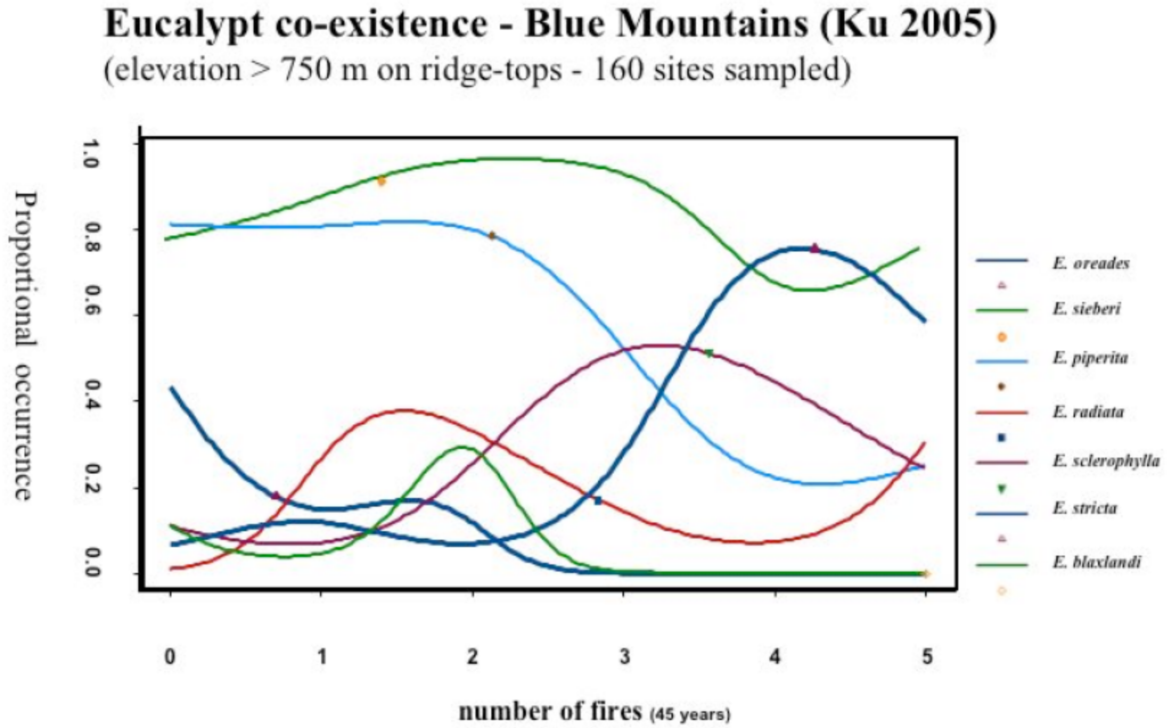

Figure 3: Graph depicting the proportional occurrence of different eucalypt species depending on the frequency of fire. *Source: Merson 2006, originally adapted from Ku 2005.*

These threats are a formidable challenge to management due to their magnitude and scope, and because of the uncertainty surrounding them. In addition, some conflicts arise between different management goals, as is the case with fire management in the GBMWHA that must protect human life and property, biodiversity, and heritage values with limited resources (Hammil & Tasker 2010). Together with the larger problem of global climate change, regional shifts in precipitation and temperature regimes, and localised responses to these changes, the picture becomes quite complex.

Section 4: Valuing carbon in the GBMWHA

The following effects could eventuate if management strategies that took carbon accounting into consideration were implemented. Determining the monetary value of these effects depends on political, economic and legislative frameworks, discussed further in Section 5.

Mitigation and adaptation effects

Managing the GBMWHA to mitigate against climate change should promote resiliency in the area's ecosystems (CPF 2008). As the climate changes, maintaining protected areas creates places where species face reduced pressures from other human interferences such as habitat loss. Networks of protected areas also allow species to move as conditions change (Mansourian et al. 2009). Measures to enhance mitigation potential in the GBMWHA include enhancing fire management, buffer zones, and connectivity. The benefits of these steps are buffers against the effects of climate change to services such as water provision, biodiversity protection, and localised climate stabilisation (CPF 2008; Anderson et al. 2011). One of the biggest challenges associated with the valuation of ecosystem services is overcoming the political and social difficulties of determining who should pay for them (Appanah & Shono 2009).

Economic effects

One can estimate how much the service of storing carbon is worth by calculating the cost of employing other methods to sequester the same amount of carbon. The economic gains of carbon sequestration depend largely on the price per tonne of carbon. This price in turn will depend on complex political, legislative, and social pressures at local, regional, national, and international levels.

The NOUS Group (2010) reports that carbon sequestration costs through natural area protection are lower than through industrial sector emissions reductions. This must not be interpreted as a reason for industries to avoid reducing emissions, but highlights the attractiveness and economic efficiency of forests and other ecosystems in sequestering carbon.

The cost of managing land to sequester carbon is, in most cases, less than the carbon price proposed under the Australian Government's Carbon Pollution Reduction Scheme (The

NOUS Group, as of July 2010). This low cost is due primarily to the low-tech solution that sequestration offers and the immediate effect that existing natural areas will have on carbon accounting (The NOUS Group, 2010). In other words, the carbon is being stored, but no one is counting it.

The costs of climate change are also reduced by protected areas through the ecosystem services they provide. Large forested areas influence local rainfall and temperature patterns, slow runoff and provide water security, and protect against damaging floods (Mansourian et al. 2009). These indirect credits to the economy should also be considered when valuating protected areas.

Section 5: Managing the GBMWHA for carbon storage

The CPF (2008) suggests that sustainable forest management can be effective in mitigating (and adapting to) climate change, provided that governments, private industries and private landholders cooperate and that management is flexible, adaptive, and informed by monitoring. Canadell & Raupach (2008) add that increasing forested areas and decreasing forest degradation are the best ways to increase carbon stores in forested ecosystems. Combined, these requirements mean that managers should aim to keep forests healthy, expand and connect protected areas, and seek avenues for valuation of forest services to support management activities. To support managers in these objectives, legal, policy, and institutional frameworks must be in place (CPF 2008).

However, increasing the amount of carbon stored in the forests of the GBMWHA may not be a viable option because the resources required to intensively manage large, remote areas might prove unrealistic to obtain. Protecting carbon-rich areas over carbon-poor areas might damage other valuable assets such biodiversity or heritage values. Fahey et al. (2010) caution against managing forests to enhance carbon sequestration values because such practices may lead to temptation for mismanagement. In other words, carbon management and the income it may or may not generate could supersede cultural, recreational, biodiversity and other ecosystem service values, even though these additional values are worthy of protection.

These management trade-offs arise from limited resources. Using forests sustainably, or CSU, could create larger incentives and benefits than management for carbon storage alone, whilst expanding the pool of resources available to manage the land (Canadell & Raupach 2008). CSU could be part of a management toolbox that must contend with other threats to forest health. Canadell & Raupach (2008) give the example of thinning undergrowth as part of fire management, creating feedstock for biofuel production, and bolstering support for forest protection by its users.

Protecting the GBMWHA during climate change requires additional consideration. Mansourian et al. (2009) list some approaches to managing protected areas in the face of climate change, including the creation of protected areas with connections and linkages into the surrounding landscape and consideration of the area's size, shape, and altitudinal gradients. Preserving the complexity and resiliency of these systems enables them to continue providing ecosystem services such as carbon storage (TEEB 2010).

Section 6: Discussion & suggested interventions

With these objectives, the background of the GBMWHA, the role of forests in storing carbon, and the importance of reducing atmospheric CO_2 concentrations in mind, it becomes possible to recommend strategies for managers to enable valuation of the carbon stored by the GBMWHA. It becomes increasingly clear that valuation of this service is one tool to highlight and protect one of many interconnected values of the GBMWHA.

Suggested interventions

1. Protect biodiversity: Especially in primary forests where carbon stock is highest, protecting biodiversity enhances the resiliency of the GBMWHA and thus its carbon capacity. Maintaining and enhancing connectivity between the GBMWHA and surrounding potential habitats is also recommended to increase these values (Locke & Mackey 2009).

2. Increase knowledge: Increasing understanding of the Earth's biogeochemical cycles becomes more important as humans experience higher levels of CO_2 in the atmosphere. This is relevant to protection and utilisation of forested areas due to both their potential roles in buffering changes and sensitivity to shifts in these cycles. Knowledge gaps in climate science, changes in fire regimes, and carbon accounting currently limit application of a programme to value carbon storage in the GBMWHA.

The uncertainty in climate science is high, with multiple competing hypotheses involving interactions between geological, chemical, and biological cycles to explain historical events. Predicting future trends in a world outside historical limits is therefore even more challenging. Policy-makers should take this uncertainty for what it is and adopt a precautionary approach that protects stakeholder values instead of waiting for more evidence to "prove" the most prudent course of action (Falkowski et al. 2000). In other words, uncertainty must not be used as an excuse for inaction.

Overcoming known threats such as fire is already a critical part of the WHA's management. Fires present a danger to lives, property, biodiversity, historical and cultural values, and carbon stores. Managing against threats from fire depends on understanding fire regimes. Together with understanding ecosystem responses to shifting fire regimes, this knowledge helps managers identify areas, ecosystems, and species at risk (Hammil & Tasker 2010).

Creating institutional frameworks that build capacity for adaptive planning and carbon accounting will help managers overcome uncertainty (Nolte et al. 2010; see also Busenberg 2004).

To gain financial benefit from carbon stored in the GBMWHA, carbon accounting must be undertaken. At present, carbon accounting and forest monitoring is not yet adequate to inform management decisions about carbon storage (The NOUS Group 2010). Determining the economic and environmental risks and benefits of management for carbon storage in Australian ecosystems is also required (The NOUS Group 2010). Baker et al. (2010) suggest areas where ecological research will aid decision making in establishing effective payment for environmental services schemes. Potential services in addition to carbon storage include livelihood support, hydrological services, bioenergy production and biodiversity protection, each of which offer potential avenues for valuation and accounting (CPF 2008).

3. Create legislative frameworks: The successful application of natural resource management hinges on the support management receives from local, regional, national, and international frameworks. It is imperative that this framework be established to support the valuation of carbon storage in Australia's ecosystems.

Part of creating this environment includes pushing for comprehensive policies at the international level. The UNFCCC does not yet have policy that fully recognises carbon stores in terrestrial ecosystems (The NOUS Group, 2010). In addition, the primary focus of these international conventions is on reforestation or preventing deforestation in developing countries- not on accounting for the value of existing protected areas (Locke & Mackey 2009). Locke & Mackey (2009) also comment that although many international organisations have similar goals, their actions are separated by political boundaries. For example, both the CBD and the UNFCCC stand to gain from conserving forested habitats, yet neither dual recognition, equal attention, nor coordination between these conventions exists. This ultimately harms the effectiveness and utility of programmes in either area.

Domestically, frameworks that allow stakeholders to secure fair and sustainable benefits from forest protection must be established, reformed, or clarified (The NOUS Group, 2010). These stakeholders must include indigenous and local communities and establish a two-way flow of communication (Ross 2007). One suggestion might be the creation of buffer zones that store carbon, protect the GBMWHA, and offer neighbouring landholders opportunities to be involved in the management of the WHA and gain economic benefit from the carbon stores and biodiversity protected by their land (Dwyer et al. 2009).

4. Establish sources of funding: On the international stage, there is a call for developed countries to support developing countries in valuing and protecting or sustainably using forest resources (CPF 2008). This support is based on the amount of carbon that forests store and the price of carbon emissions, although at this stage payments for carbon sequestration through programmes such as REDD are still contentious due to the issues of leakage, veracity, and baseline determination (CPF 2008). In addition, concerns of how the introduction of REDD-type carbon credits into the international carbon market might affect the value of carbon exist (Dudley et al. 2010). Finally, protecting places based only on their capacity to provide services creates bias in protection of ecosystems, when in reality all types of carbon storage, and the biodiversity on which it depends, are worthy of protection (Locke & Mackey 2009).

Dargusch et al. (2010) offer a review of the different types of funding mechanisms available to support conservation of forests. Most useful in the context of the GBMWHA are the creation of markets for environmental services and participation in carbon trading.

The establishment of voluntary carbon markets offers an opportunity for carbon sequestered by the GBMWHA to be valued. The market for voluntary carbon offsets was about US$91 million in 2006 (CPF 2008). The value that these markets place on carbon creates a source of income for land managers to continue to protect and conserve the ability of forests to store carbon and adapt to environmental changes (Eltham 2010).

Private investment could play a role in conserving the GBMWHA for its carbon values, but this opportunity might be expanded by recognising a broader suite of benefits, or co-benefits, that the ecosystem offers. This option for funding forest management may be important as demands increase on public funding from other issues such as energy, water, infrastructure, education, and so on (CPF 2008).

Another idea is the establishment of an independent body that handles the financing of land management strategies, such as Costa Rica's use of an independent National Forestry Financing Fund (FONAFIFO), to support and sustain CSU (Appanah & Shono 2009). FONAFIFO cooperates with other independent bodies, all of which are firmly supported by legislation and inclusive, iterative, adaptable governance. In Costa Rica's case, carbon storage is one of four values that legislations recognises as held by forests. It may be difficult to extract single benefits such as water or biodiversity values from a forest's portfolio, so the concept of co-benefits should be explored and publicised.

Any option to finance forest management must take care to avoid corruption and misappropriation of funds (CPF 2008).

5. Keep in mind the big picture: Finally, it is critical to emphasise that carbon sequestration services by forests or other ecosystems offers a finite solution to managing anthropogenic CO_2 emissions (Falkowski et al. 2000). Although green carbon storage offers a cost-effective, multiple-benefit option for mitigating GHG emissions, decision-makers must not be tempted to forgo or delay the difficult choices in emissions reduction because of the limited promise of ecosystem absorption and storage (Keenan 2002). In this regard, parks should lead as an example by reducing emissions generated and providing education on GHG issues to visitors (Welch 2005). Reducing emissions is the primary way to manage climate change, while green carbon storage will only ever be capable of playing a supporting role. If carbon storage values take primary importance, temptation for mismanagement of forested areas may come to outweigh management for other values such as biodiversity, hydrological services, cultural, historical, and other values (Fahey et al. 2010).

Conclusion

This report has explored the potential of carbon storage in the GBMWHA through a review of the literature surrounding climate change, carbon storage, the measurement of carbon in terrestrial ecosystems, the factors of the GBMWHA that may impact its carbon storage, and management strategies for maximising carbon storage.

Increasing concentrations CO_2 in the Earth's atmosphere threatens to upset natural, physical, and human systems, and increasing attention is being paid to how existing emissions can be absorbed by ecosystems. Complex, global frameworks such as the UNFCCC and its REDD Programme have arisen to attempt to encourage this strategy. Storing carbon in terrestrial ecosystems raises numerous, complex dilemmas ranging from purely technical hurdles to ethical, social and economic problems. However, promising new technologies and extensive databases could alleviate technical problems, while good governance may address social, political, and economic concerns.

The GBMWHA aims to protect its world heritage values, which revolve around its biodiversity. However, managers must face a complex web of cultural, economic, land tenure, and risk control factors with increasingly tightly stretched pools of resources. Adding carbon values to this mix requires additional training and planning, although it has become clear that carbon values and other values such as biodiversity can mutually benefit from similar management actions. The additional value that carbon storage can add to the GBMWHA will depend largely on the institutions created to support carbon markets. At the same time, other sustainable uses of the GBMWHA, such as recognising the role it plays in water catchment health, could also be considered as part of the benefits package that the GBMWHA provides to the local, regional, and national population.

With these points in mind, this report concludes with several recommendations in pushing forward any attempt to value the carbon stored in the GBMWHA. Protecting biodiversity, increasing knowledge and pushing for legislative and economic support are all critical components of creating carbon accounting for the area. Most importantly, realising the finite ability of terrestrial ecosystems to mitigate GHG emissions should highlight the primary importance of continuing efforts to lower emissions.

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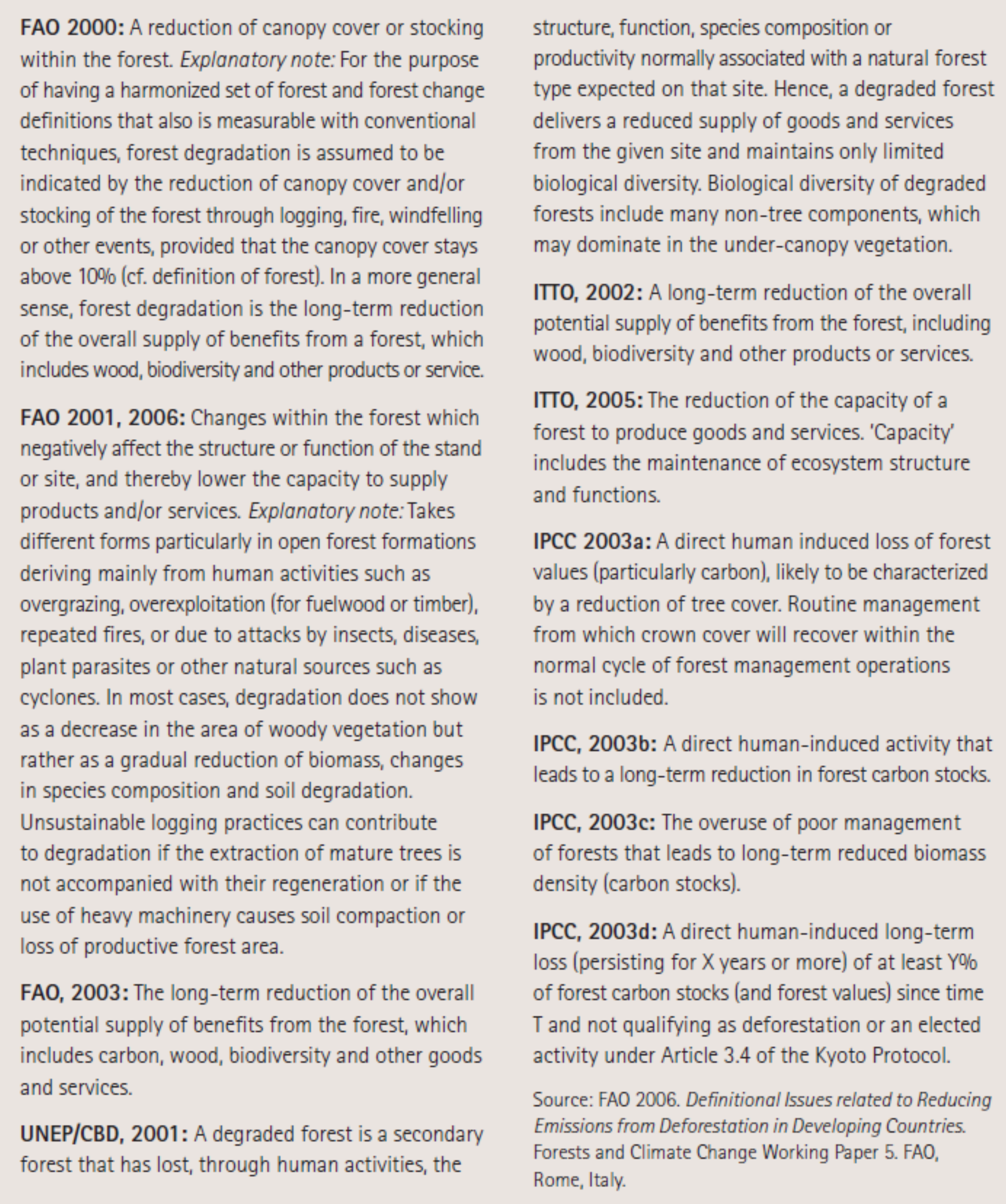
Appendix



FAO 2000: A reduction of canopy cover or stocking within the forest. *Explanatory note:* For the purpose of having a harmonized set of forest and forest change definitions that also is measurable with conventional techniques, forest degradation is assumed to be indicated by the reduction of canopy cover and/or stocking of the forest through logging, fire, windfelling or other events, provided that the canopy cover stays above 10% (cf. definition of forest). In a more general sense, forest degradation is the long-term reduction of the overall supply of benefits from a forest, which includes wood, biodiversity and other products or service.

FAO 2001, 2006: Changes within the forest which negatively affect the structure or function of the stand or site, and thereby lower the capacity to supply products and/or services. *Explanatory note:* Takes different forms particularly in open forest formations deriving mainly from human activities such as overgrazing, overexploitation (for fuelwood or timber), repeated fires, or due to attacks by insects, diseases, plant parasites or other natural sources such as cyclones. In most cases, degradation does not show as a decrease in the area of woody vegetation but rather as a gradual reduction of biomass, changes in species composition and soil degradation. Unsustainable logging practices can contribute to degradation if the extraction of mature trees is not accompanied with their regeneration or if the use of heavy machinery causes soil compaction or loss of productive forest area.

FAO, 2003: The long-term reduction of the overall potential supply of benefits from the forest, which includes carbon, wood, biodiversity and other goods and services.

UNEP/CBD, 2001: A degraded forest is a secondary forest that has lost, through human activities, the structure, function, species composition or productivity normally associated with a natural forest type expected on that site. Hence, a degraded forest delivers a reduced supply of goods and services from the given site and maintains only limited biological diversity. Biological diversity of degraded forests include many non-tree components, which may dominate in the under-canopy vegetation.

ITTO, 2002: A long-term reduction of the overall potential supply of benefits from the forest, including wood, biodiversity and other products or services.

ITTO, 2005: The reduction of the capacity of a forest to produce goods and services. 'Capacity' includes the maintenance of ecosystem structure and functions.

IPCC 2003a: A direct human induced loss of forest values (particularly carbon), likely to be characterized by a reduction of tree cover. Routine management from which crown cover will recover within the normal cycle of forest management operations is not included.

IPCC, 2003b: A direct human-induced activity that leads to a long-term reduction in forest carbon stocks.

IPCC, 2003c: The overuse of poor management of forests that leads to long-term reduced biomass density (carbon stocks).

IPCC, 2003d: A direct human-induced long-term loss (persisting for X years or more) of at least Y% of forest carbon stocks (and forest values) since time T and not qualifying as deforestation or an elected activity under Article 3.4 of the Kyoto Protocol.

Source: FAO 2006. *Definitional Issues related to Reducing Emissions from Deforestation in Developing Countries.* Forests and Climate Change Working Paper 5. FAO, Rome, Italy.

Definitions of forest degradation from several international organisations. Source: CPF 2008.