

Climate Change Impacts and Research Priorities for the Forestry Sector

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1) Impacts of climate change on the NSW forest sector

The increase in atmospheric concentration of greenhouse gases due to human activity, particularly combustion of fossil fuels and land clearing, is increasing global temperatures and affecting global and regional climate systems. In NSW, temperature has increased by 0.9°C between 1910 and 2005, and the average rainfall since 2000 is 20% lower than the average rainfall received in the second half of last century. Irrespective of success in curbing future emissions, further warming is expected, due to the lagged effects of past greenhouse gas emissions.

Climate change is predicted to increase average temperatures in NSW by 0.7° to 6.4°C by 2070, with the greatest increase in the west of the state. Rainfall is likely to be reduced across the state, apart from in the north-east. Projections suggest an increased incidence of bushfire and intense storms. Drought frequency may increase, especially in winter and spring. These predicted impacts of climate change are likely to have serious negative impacts on all NSW primary industries, including the forest industry.

The potential impacts on forests from these changes are not clearly understood, especially for Australian tree species under typical Australian conditions. Besides the impacts of changes in the climatic variables, plants will be directly influenced by the increasing concentration of CO₂ in the atmosphere.

Physiological impacts

International research carried out over the past 20 years has generated general understanding of the direct effects of increasing CO₂ concentration on plant growth and function. Doubling of CO₂ concentration generally increases plant growth by 10%–25% (Nowak et al. 2004; Luo et al. 2005b; Norby et al. 2005), through the so-called “CO₂ fertilisation effect”. Most of the research has been conducted on Northern Hemisphere species under environmental conditions different to those typical of Australia. Furthermore, most research does not consider the feedbacks at the ecosystem level that need to be factored in when predicting effects on whole forests from results measured on individual trees/saplings. Importantly, plant physiologists and modellers alike now recognise that the effects of elevated carbon dioxide measured in experimental settings and implemented in models may overestimate actual field responses, due to many limiting factors, such as pests, weeds, competition for resources, soil water and air quality, which are neither well understood on large scales, nor well implemented in leading models (Korner et al. 2005; Ainsworth & Long 2005; Tubiello & Ewert 2002; Karonsky 2003; Fuhrer 2003). A handful of experiments are now in progress to directly measure forest ecosystem-level responses to increased carbon dioxide; however, these FACE (free air carbon dioxide enrichment) experiments are all being conducted on temperate species in the Northern Hemisphere.

The lack of field-based forest experimentation in Australia makes it difficult to predict the effect of climate change on Australian native forests and plantations. The Hawkesbury Forest Experiment, in which NSW DPI is a collaborator, is beginning to redress this deficiency.

Where trees are not water-limited, climate warming is likely to expand the growing season in southern Australia; however, increased fire incidence and pest damage may negate some productivity gains. Productivity of exotic softwood and native hardwood plantations is likely to be increased by carbon dioxide fertilisation effects, although the amount of increase will be dependent on nutrient availability (Kirschbaum 1999). Growth response to CO₂ may not be strongly limited by nitrogen status of soil: the meta-analysis of Luo et al. (2005b) found a concomitant accumulation of nitrogen as ecosystem carbon stock increased under elevated CO₂, probably through increased biological nitrogen fixation, enhanced N cycling, reduced N loss and increased root growth.

Under elevated CO₂, plants open their stomata less, thus transpiring less water. Therefore, the water use efficiency of plants (i.e. the growth per unit of water transpired) is predicted to increase at higher CO₂ concentration, which may offset negative impacts on growth in those areas in which rainfall is predicted to decline.

Extreme heat may limit forest growth in summer, as observed in European forests by Angert et al. (2005) and Ciais et al. (2005). Carbon stock in soil organic matter and surface litter may decline due to faster decay in a warmer environment, though this could be offset by higher belowground C input under elevated CO₂ conditions and/or reduced biological activity if soil moisture declines. Thus, the interacting effects of temperature and CO₂ on plant growth and soil heterotrophic respiration will determine the impact of climate change on the net carbon balance of forest systems. Better understanding of these interacting factors is required, so that forest managers can plan species selection, silvicultural management and breeding programs to cope with predicted changes in climate.

The actual climate tolerance of many Australian tree species is wider than the climatic envelope that they currently occupy; furthermore, natural distributions rarely extend to fill the current climate envelope (Jovanovic & Booth 2002). Increasing CO₂ concentrations, which change photosynthetic rates and water use efficiency, and which may affect the temperature response (Curtis 1996), will modify species climatic envelopes; so, although climate change will move climate envelopes geographically, it is not at all clear what effect this will have on species distributions. The relative effectiveness of the various seed dispersal mechanisms employed by different species will influence their ability to migrate as climate changes.

Fire

Australia's south-east is recognised as one of the most fire-prone areas in the world, and fire management agencies have identified climate change as one of the most important strategic issues confronting fire managers in Australia (Bushfire CRC 2006). The danger posed by wildfire is dependent on the probability of a fire starting, its subsequent rate of spread, intensity and ease of suppression. Suppression is affected by the air temperature, relative humidity, wind speed, the properties and arrangement of the available fuel, and prior rainfall.

Climate change is likely to increase wildfire risk, largely through its impact on climate extremes rather than gradual changes in average temperature and rainfall occurring over decades. Internationally, there is great uncertainty associated with studies on the impact of climate change on forest fires (Lemmen & Warren 2004; Shugart et al. 2003). Current projections suggest that, in south-eastern Australia, the frequency of very high and extreme fire danger may increase by 4%–25% by 2020, and by 15%–70% by 2050, with greater changes predicted for the inland than for the coast (Hennessy et al. 2005). Lightning strikes are predicted to increase in tropical northern Australia, but the impact of climate change on their incidence in the south is currently uncertain.

In the longer term, changes in the distribution of flora as a result of climate change will also impact fire risk in native forests; for example, replacement of cool temperate rainforest with sclerophyllous forest would increase flammability (Bushfire CRC, 2006). Fire danger is predicted to increase in spring, summer and autumn, so periods suitable for prescribed burning are likely to be restricted (Hennessy et al. 2005).

Forest health

Climate change is likely to affect the incidence and severity of pest and disease outbreaks in native forests and plantations. Firstly, changes in average or extreme values of climate variables can affect the life cycles of pest populations and the severity of disease. Increased summer temperatures are likely to accelerate the development rate and reproductive potential of insect pests, while warmer winters will increase over-winter survival (Old & Stone 2005). For example, the devastating mountain pine beetle (*Dendroctonus ponderosae*) infestation in the Canadian province of British Columbia, which currently affects 8.7 million ha of forest and is predicted to kill over 800 million cubic metres of pine by 2013, is attributed in part to recent mild winters, which contribute to the high survival of beetle populations over winter (Eng et al. 2006).

Recent observations in NSW pine plantations have found that drought-stressed trees are now suffering increased incidence of attack from insect stem borers, bark beetles and fungi. Indeed, mortality in one section of Green Hills State Forest, assessed recently with new remote sensing technology, has been estimated at almost 30% (Christine Stone, pers. comm.). Mortality is due to attack by the exotic bark beetle *Ips grandicollis*, which has been present in Australia for over 30 years, but has previously not been considered a primary mortality agent of mature *P. radiata*. These observations suggest that increased drought stress under climate change could have severe impacts on the pine industry.

In southern Australia, increased frequency of extreme wet and dry periods may increase incidence of the root rot pathogen *Phytophthora cinnamomi*. Trees weakened by *P. cinnamomi* have a reduced capacity to survive periods of drought.

Secondly, climate change may extend the geographic distribution of pests and pathogens, affecting forest communities not previously at risk (Cannon 1998).

Thirdly, effects of climate change on the host plant may increase its susceptibility to insect pests and diseases, or its ability to tolerate and recover from herbivory. For example, elevated CO₂ concentration affects the nutritional quality of foliage, largely due to a decline in leaf N concentration (Ainsworth & Long 2005). The resultant change in C:N ratio may result in increased foliage consumption by some species tolerant of low N availability, while others will be inhibited (Old & Stone 2005). It is, therefore, difficult to predict the impact of climate change on defoliation.

In their review of the likely impacts of climate change on pests and pathogens of Australian forests, Old & Stone (2005) concluded that the diversity of Australia's native forests gives them a strong resistance to pests and pathogens, but that climatic variability due to climate change – particularly an increase in drought frequency – could increase the impact of pest and pathogen attack, thereby compromising the health, and hence the carbon stocks, of Australia's forests.

The interaction between climate change and the impact of insect pests or fungal pathogens is strongly mediated by the condition of the host tree. Potential increases in crown growth rates, due to increased carbon dioxide or length of growing season, may offset the impact of defoliation; however, slow-growing, stressed trees are less able to recover from defoliation events, and are more vulnerable to secondary damaging agents, such as stem borers. The potential impact of climate change on plantations depends, therefore, on the direct effects of climate change on the population dynamics of the damaging agents, as well as the resultant condition and vigour of the trees. Overall, an increase in extreme weather events is likely to exacerbate the impact of insect pests and fungal pathogens on plantations.

2) Mitigation of Climate Change through Forest Management

The forest industry can play a valuable role in mitigating climate change through three major avenues: carbon sequestration in new forests; use of wood products to displace more greenhouse-intensive products; and use of forest biomass for bioenergy, displacing fossil fuels. Forest management should aim to increase carbon sequestration and decrease greenhouse gas emissions, especially non-CO₂ GH gases (such as CH₄, N₂O) that possess much higher warming potential than the equivalent mass of CO₂.

Emissions trading can be an effective market mechanism to promote mitigation activities in the forest sector. Reforestation is recognised as an eligible offset activity that can earn “carbon credits” through the NSW Greenhouse Gas Abatement Scheme (GGAS). Plantation growers including Forests NSW are accredited providers under this scheme. There is potential for smaller landholders to participate, providing an incentive for revegetation of agricultural landscapes that could deliver multiple environmental and economic benefits. However, the onerous and complex regulations restrict the access of small forest growers. There is potential to streamline processes and develop simple cost-effective carbon accounting methods to facilitate their involvement.

A national emissions trading scheme is anticipated by 2011, though the exact timing and scheme details will be determined by the outcome of the federal election. There are two schemes currently proposed: the scheme developed by the States and Territories’ National Emissions Trading Taskforce, to commence in 2010, and the scheme being developed by the Department of Prime Minister and Cabinet, to commence in 2011. Both proposals are for broadly similar cap and trade schemes, covering all sectors other than agriculture and forestry. Both have recommended that forestry offsets be included, but there are significant differences between the two plans.

The Department of Prime Minister and Cabinet’s Climate Change group has proposed that the eligibility date for reforestation projects will be the date of scheme announcement ie 3 June 2007, and that the Greenhouse Friendly initiative will be the basis for development of the forestry protocol. Major differences between the NSW GGAS and Greenhouse Friendly are that GF requires the sequestration to be maintained for 70 rather than 100 years; the project proponent must demonstrate “financial additionality” (ie that the project would not be financially viable without the income from carbon trading); liability rests with the buyer rather than seller; there is no discounting for uncertainty (under GGAS’s “70% rule”, credits can only be created for that quantum of sequestration for which there is 70% probability that actual sequestration exceeds this amount – therefore there is an incentive under GGAS to improve accuracy of predictions, to minimise the discount applied). There will be a period of public consultation after which the scheme rules will be confirmed. The PM&C scheme has indicated the intention to expand the types of forest projects eligible as offsets, to include management of existing forests, avoided deforestation, and carbon storage in wood products.

The alternative national emissions trading scheme, proposed by the States and Territories is broadly similar to the PM&C plan, but differs in several details with respect to forestry offsets: it proposes to base the forestry rule on the GGAS scheme, using 1990 as the date for eligibility, and retaining the 100-year permanence provision. It is not clear at this stage whether discounting for uncertainty (the 70% rule) will be retained. A report detailing the scheme design is expected to be released by November 2007.

Reforestation

Reforestation can contribute to the mitigation of greenhouse gas emissions through sequestration of carbon from the atmosphere. A forest sequesters carbon until it reaches maturity, after which carbon stock remains essentially constant, unless the forest is disturbed (e.g. by harvest or fire). The

sequestration rate of planted forests depends on climate, soil factors and forest management (i.e. planting configuration, species, stocking rate, establishment methods, fertiliser and weed control).

Forests NSW has developed accurate models of sequestration for its major plantation species, which are used in carbon accounting under the NSW Greenhouse Gas Abatement Scheme. The Carbon Sequestration Predictor – a simple software tool produced by the former State Forests, NSW Agriculture and Department of Land and Water Conservation, with the CRC for Greenhouse Accounting – gives estimates of potential sequestration for a range of reforestation types for different rainfall regimes and soil types (Montagu et al. 2003). This tool is specifically developed for lower rainfall regions of NSW (< 800 mm) where few data are available.

The AGO's greenhouse accounting model, FullCAM (Richards 2001) – distributed as NCAT, the National Carbon Accounting Toolbox¹ – is a sophisticated modelling tool, used to quantify Australia's emissions profile for the agriculture, forestry and land use change sector. NCAT can be used to estimate carbon sequestration potential at specific sites.

The annual sequestration rate over the growth phase usually ranges from 8–25 t CO₂-e.ha⁻¹. A commercial hardwood plantation on the NSW North Coast is likely to sequester 600–1000 t CO₂-e.ha⁻¹ by the time it reaches rotation age. The average carbon stock over several rotations, representing the long term net mitigation benefit of the plantation, is about 300–500 t CO₂-e.ha⁻¹.

Besides the carbon stock in forest biomass, the dynamics of the soil carbon pool influence the mitigation impact of reforestation. Conversion of cropland to forest is likely to increase soil carbon; from their meta-analysis of published literature, Guo and Gifford (2002) concluded that, on average, reforestation of cropland increases soil C stock by 18%–20%. Conversion from pasture to forest is likely to initially decrease soil C stock, as a result of a decline in pasture root litter inputs in the early phase of plantation establishment; this is especially true of fertile pastures with a high proportion of labile soil carbon. As the plantation grows, soil carbon is replenished from litter fall and root turnover. In broadleaf forest species, soil C is generally restored to the original stock within 30 years. In contrast, evidence suggests that reforestation with pine species generally leads to around a 15% decline in soil carbon stock; however, this conclusion is based on limited data, and so needs to be verified (Guo & Gifford 2002; Paul et al. 2002).

There is considerable uncertainty regarding modelled predictions of carbon sequestration, particularly with respect to the soil carbon pool, for mixed species plantings, and in low rainfall environments. This uncertainty will be reduced by research that measures the actual rates of sequestration and soil C dynamics, and produces data that can be used to improve prediction models. Due to impacts of temporal and spatial climate variability, spatial heterogeneity in edaphic factors, and variable incidence of pests, disease and fire, there will always be uncertainty in estimating the sequestration potential of forests.

Role of forest products

Management of forests for timber production can significantly extend the carbon sequestration benefits provided by forests (Skog & Nicholson 1998; UNFCCC 2003). In addition to the physical storage of carbon in wood products (both in service and in landfills), further greenhouse benefits can be obtained through the use of processing residues to generate energy in lieu of fossil fuels, and through the use of wood products instead of more energy-intensive materials (Ximenes 2006). Wood products play an important role in Australia's carbon balance. The accumulated carbon stock in wood products in Australia (in service and in landfills) is approximately 230 million tonnes of carbon (AGO 2007c), which is equivalent to approximately 1.5 times Australia's annual greenhouse gas emissions.

New South Wales is the main producer of both sawn softwood (790 000 m³) and sawn hardwood (316 000 m³) in Australia (ABARE 2005). Approximately 75% of the sawn timber is used for

¹ Available from the Australian Greenhouse Office <http://www.greenhouse.gov.au/ncas/ncat/index.html>

residential purposes (BIS-Shrapnel 2000), with about 80% of the sawn pine used for framing applications in houses, and approximately 50% of the sawn hardwood used as sub-flooring and fencing (Ximenes 2005). Depending on the type of product manufactured and of the disposal method used at the end of its service life, the carbon will remain 'locked up' in the product for many decades (eg Gardner et al 2002 Figure 1).

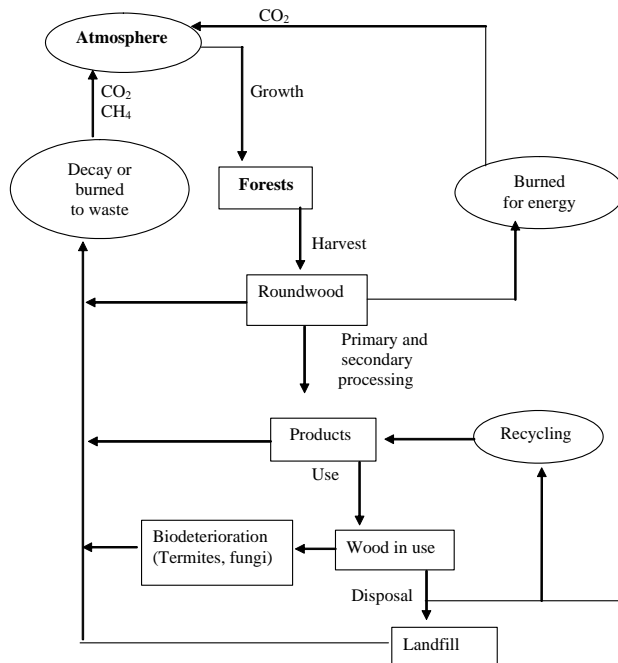


Figure 1. Life cycle of carbon in wood products.

Research by the CRC for Greenhouse Accounting suggested that up to 70% of the carbon in harvested logs can be considered to be permanently stored – either directly in the wood products (including storage in landfill after disposal of redundant products) or through use for bioenergy (displacing emissions from fossil fuels). Thus, for a plantation with carbon stock at harvest of 375 t CO₂-e.ha⁻¹, 300 t CO₂-e.ha⁻¹ would be in the above-ground components, including 250 t CO₂-e.ha⁻¹ in the stem. Of this latter amount, 175 t CO₂-e.ha⁻¹ would be permanently stored at each harvest. After three rotations, the value of carbon stored in wood products or through avoided fossil fuel use would be 525 t CO₂-e.ha⁻¹, compared with the carbon storage in the forest of 375 CO₂-e.ha⁻¹.

Bioenergy options

Energy production and consumption releases large quantities of carbon dioxide. Per capita, Australia is one of the largest consumers of primary energy, ranked 9th in the world (ABARE 2005), with current growth in energy consumption around 1.9% per annum (ABARE 2006).

Renewable energy accounted for around 5% of Australia's total stationary energy production in 2004–05 (265 PJ) (ABARE 2006). Biomass is the major source of renewable stationary energy, most of which is utilised in sugar mills and saw mills to provide heat.

Within NSW, approximately 90% of electricity is currently generated from coal, but a mandatory target of 15% renewable electricity by 2020 has recently been adopted (DEUS 2006). Electricity generation from biomass could contribute to this target, but significant market and technological development is required to meet this opportunity. NSW experience in biomass energy applications

includes installation of high-efficiency boilers in sugar mills to generate electricity from bagasse, and demonstration of co-firing coal with wood waste at several large coal-fired power stations.

Biomass feedstocks can be supplied from harvest and processing residues from forest and agricultural industries, as well as from purpose-grown crops. Forestry residues (thinning and harvest residues that usually remain in the forest, and mill residues) are well-suited to combustion applications, for heat and electricity (small bioenergy plants, co-firing in coal-fired plants, potentially gasification).

A range of potential biomass feedstocks could be utilised to produce liquid biofuels. The most common biofuels are ethanol (produced by fermentation from sugar and starch crops) and biodiesel (produced from waste cooking oil, tallow and oilseed crops). Production of ethanol from ligno-cellulosic feedstocks has not been economically viable to date, but recent developments have greatly improved prospects for this technology. The increased cost of fossil fuels for transport, as well as environmental concerns (including health and climate change) and concerns for the security of energy supply, have increased interest in biofuels. In NSW, a 2% ethanol blend has now been mandated, and this may be increased to 10% by 2011. Some basic considerations in meeting the demand generated by this mandate include:

- capacity to produce feedstock
- sustainability and resilience of production systems
- energy balance of production systems
- impact of new markets on existing industries (e.g. grain use by intensive industries)
- development of technology for 'second generation' biofuel systems that will deliver greater energy efficiency and greenhouse gas mitigation, and will not compete directly with food supplies.

Pyrolysis is an alternative energy conversion process that can utilise a wide range of biomass feedstocks. Pyrolysis is thermal degradation achieved through heating biomass to temperatures generally between 300 and 900°C in the absence of oxygen. Volatile components are released as syngas (H₂, CO, CO₂, CH₄), which can be used as fuel to generate heat or electricity, or condensed to a liquid fuel product. The non-volatile components are left as char (also known as biochar or agrichar).

There is growing interest worldwide in the use of char as a soil amendment. Evidence from the "terra preta" soils in the Amazon, to which char has been applied for centuries, indicates that char is highly effective in increasing plant productivity. Due to its highly recalcitrant nature, char amendment is anticipated to provide long-term increases in soil carbon stocks. Besides this direct sequestration benefit, there is evidence that char provides further mitigation of greenhouse gas emissions through reduction in nitrous oxide emissions from soil (Rondon et al, 2006; Yanai, et al 2007; Van Zwieten, unpublished). Furthermore, char is claimed to reduce fertiliser requirements, thus reducing indirect greenhouse gas emissions from fertilizer manufacture (Wood and Cowie, 2004). The syngas produced is a renewable energy source that can provide additional greenhouse mitigation benefits through displacement of fossil energy sources.

Significant research and policy work is required to ensure that bioenergy systems deliver substantial greenhouse gas mitigation impacts. Confirmation of beneficial greenhouse outcomes will increase consumer acceptance, thereby increasing market potential.

The benefit of a bioenergy system is sometimes expressed in terms of energy output relative to energy input, or greenhouse gas emissions per unit energy output; however, the most appropriate measure of greenhouse mitigation benefit is the emissions reduction of the bioenergy system with respect to the fossil fuel system that is displaced (Schlamadinger et al. 1997). The benefit depends on the feedstock (e.g. use of wood residues or wastes from processing yield more positive greenhouse and energy balance outcomes than use of purpose-grown crops), and the energy

conversion process (e.g. fermentation, pyrolysis, gasification). Various studies have calculated a wide range of values, ranging from low (and even negative) mitigation benefit, through to strong, positive values. For example, Pimentel (2001) argues that there is more energy consumed than produced in production of ethanol from maize in the USA. This is rebutted by Graboski & McClelland (2002) and Hill et al. (2006). Much of the variation is due to inconsistent application of Life Cycle Assessment (LCA) methodology; the analysis is strongly influenced by determination of the system boundaries. LCA should be conducted in accordance with the International Standards Organisation series 14040 (Life Cycle Analysis). Specific guidance on the application of the life cycle approach to calculating greenhouse gas balance for bioenergy systems is available from Schlamadinger et al. (1997). To allow for comparison of the respective fossil and biofuel systems, it is important that 'upstream' emissions are included.

Upstream (or pre-combustion) emissions are produced during:

- extraction of fuel (e.g. removal from oil fields)
- production of fuel (e.g. cultivation and harvest of biomass)
- transport of crude oil/biomass to respective conversion facility (e.g. by ship, rail, road or pipeline)
- processing and conversion of oil/biomass to a finished fuel (e.g. with energy from coal, gas or co-generation)
- distribution of fuel to retail stations or bulk wholesale uses.

There are few detailed LCA reports available for Australian bioenergy systems. The most comprehensive work on biofuels in Australia has been undertaken by CSIRO (Beer et al. 2002, 2004). There is a clear need for Australian research to assess the performance of bioenergy systems under local conditions and agronomic systems.

Generally, the production of biofuels from annual crops (e.g. corn, wheat, sugarcane), with associated high intensity of production, will have a marginal environmental benefit compared with biofuel production from woody and grass (ligno-cellulosic) production systems, which have higher efficiency and energy yields. Reported net energy balance for corn to ethanol usually shows that around 10%–25% more energy is produced than is invested (IEA 2007); for biodiesel from oilseeds this figure is 70%–90% (Hill et al. 2006) while for ligno-cellulosics, a range from 200% to over 600% has been suggested (Farrell et al. 2006). An additional advantage of bioenergy systems based on woody crops is that they are less susceptible to yield fluctuations due to climate variability.

Significant research is still required to develop an understanding of the optimal biomass production systems (e.g. which product from which crops), as well as how the systems compare in terms of greenhouse gas mitigation. The LCA process helps to systematically identify areas in which research is required to meet the objectives of sustainable production systems; however, there is significant work required to develop the science and policies to support this process, and assure consumers that the biofuel they use is benefiting the environment in relation to air quality, energy balance, greenhouse gas emissions and production system sustainability.

Mitigation of Non CO₂ greenhouse gas emissions

Nitrous oxide is a significant contributor to greenhouse gas emissions from agriculture and forestry. On the other hand, forests can be a significant sink for methane.

Nitrogen fertilisers, biological nitrogen fixation by legumes species, and the urine and dung of grazing animals are all potential sources of nitrous oxide emissions. Nitrous oxide is produced in soil through three major biological processes: (i) during nitrification (i.e. conversion of $\text{NH}_4^+\text{-N}$ to $\text{NO}_3^-\text{-N}$), N_2O is produced as a by-product at the first stage, the conversion of NH_4 to NO_2 ; (ii) in the second stage of nitrification nitrite is converted to nitrate, however under low oxygen conditions denitrifying nitrifiers use nitrite as an alternative electron acceptor, thereby producing N_2O ; and (iii)

through denitrification, where heterotrophic denitrifying aerobic bacteria cause respiratory reduction of nitrate or nitrite to N_2O and N_2 under anoxic conditions (Wrage et al 2005). These processes are thought to occur simultaneously in soil, with the first taking place in aerobic microsites and the latter two processes confined to suboxic and anoxic sites. Thus, soils can be a significant source of nitrous oxide, under both anaerobic and aerobic conditions.

Studies of nitrous oxide emissions or methane uptake have not been published for Australian forest systems. Accurate data on fluxes of these two non- CO_2 gases from forest soils are required to devise appropriate mitigation and adaptation strategies.

Reforestation of pasture lands and associated silvicultural practices, such as site preparation, N-fertilisation and burning of slash, have the potential to significantly alter the rates of mineralisation and nitrification of soil organic matter, as well as carbon dioxide, nitrous oxide and methane fluxes from soil (Dalal et al. 2003; Tang et al. 2006). However, there is limited knowledge of the potential for modification of forest management to contribute to mitigation of greenhouse emissions.

Until recently, the estimates of nitrous oxide emissions included in Australia's inventory were calculated using general default emissions factors published by the IPCC. Recent studies in Australian agricultural systems have determined that for dryland cropping the nitrous oxide emissions from applied fertiliser were an order of magnitude lower than the IPCC default value, though emissions from irrigated crops and pastures were several times greater than the default. New research suggests that the default emissions factors may underestimate nitrous oxide emissions three- to five-fold (Crutzen et al, 2007).

Globally, soils are an important sink for methane, and can consume about 50% of the annual load of methane to the atmosphere (IPCC 2001). Aerobic, well-drained soils are usually a sink for methane, due to the high rate of methane diffusion into such soils and its subsequent oxidation by methanotrophic microorganisms (Simpson 2005). In contrast, large emissions of methane are common where anaerobic conditions are favoured (e.g. wetlands, rice paddies and landfills), due to high activity of methanogenic microorganisms in these environments (Conrad 1989). Very few studies have measured rates of methane exchange from soils in Australia (Simpson 2005). Recent observations (B. Singh pers. comm.) have shown that plantation soils are a stronger sink for methane than adjacent pastures.

Recent evidence (Rondon et al, 2006; Yanai, et al 2007; Van Zwieten, unpublished) suggests that soil amendment with biochar dramatically reduces nitrous oxide emissions. Further detailed studies are required to determine the longevity and prevalence of this effect.

Forest fires emit large quantities of carbon dioxide, as well as small but significant quantities of the greenhouse gases methane and nitrous oxide, and the greenhouse gas precursors CO and NO_x and NMVOC (IPCC 2005). Excluding carbon dioxide², forest fires (controlled fire and wildfire) contributed 4.4 Mt CO_2 -e in 2004, and 1.2 Mt in 2005 (AGO 2007c). Thus, management to reduce the incidence of fire could assist in the mitigation of greenhouse gas emissions. Indeed, some have advocated the inclusion of fire management as an eligible offset activity in the proposed National Emissions Trading Scheme (NETT 2006); however, accounting for the impacts of fire management on greenhouse gas emissions will be complex, in that:

- if prescribed burning is used to reduce the risk of high-intensity wildfire, the emissions from prescribed burns must be balanced against predicted emissions from avoided wildfire
- carbon dioxide emissions during fire are assumed to be balanced by sequestration during regrowth, so carbon dioxide emissions are excluded from reporting. However, if fire incidence

² CO_2 loss during fire is considered to be balanced by CO_2 removal during forest regrowth, so CO_2 flux due to fire is not included in the national inventory.

increases in extent or intensity due to management or climate change, average carbon stocks will be affected, and this impact must be included

- the formation of charcoal should be included in the estimation of greenhouse impacts of fire: approximately 4%–5% of the carbon consumed by forest fires remains on site as black carbon, which has a turnover time of thousands of years (Forbes et al. 2006).

3) Current DPI projects on climate change in the forest sector

1. Mitigation

- **Emissions trading**

NSW DPI (through Forests NSW) has undertaken the world's first carbon dioxide emissions trade for carbon sequestration by planted forests, under the NSW Greenhouse Gas Abatement Scheme, and developed sophisticated carbon accounting procedures to support its emissions trading business. Forests NSW is playing a leadership role in forest carbon accounting for emissions trading.

- NSW DPI is continuing research into **carbon storage of wood products** in landfill, and working on forest carbon accounting procedures that better reflect the fate of timber products after harvest. (The current NSW GGAS excludes the contribution to mitigation of carbon stored in wood products.)

- *Greenhouse footprint of wood products*

This research will guide policy and management decisions that will optimise the use of building materials and management of end-of-life options, particularly in light of the threat posed by climate change. The objectives of the project are:

- Development of an energy budget for the main types of wood products used in the NSW building sector;
- Quantification of the greenhouse gas impacts of the various waste disposal options for wood and paper products in NSW;
- Development of an economic analysis of alternative disposal options of wood and paper (landfill, recycling, bioenergy);
- Quantification of the rate and extent of decay of wood and paper products in landfills in NSW and their associated greenhouse gas emissions; and
- Development of data that will inform further development of carbon trading rules in NSW.

While this current project will deliver useful research outcomes, further research on the carbon cycle in paper products, as well as the development of methodologies and mechanisms for inclusion of wood products in an emissions trading scheme is required.

- NSW DPI is undertaking several projects researching potential for **low rainfall forestry** to deliver carbon sequestration benefits. These include:

- *a pilot project with catchment management authorities (CMAs)*, funded through the NSW Greenhouse Plan, to develop a system whereby CMAs can act as carbon pool managers on behalf of landholders, to facilitate participation in the GGAS carbon trading market, and thereby provide an incentive for revegetation.
- *Developing Elite Trees for Economically Viable Forest Plantations in Low Rainfall Sites*
The project aims to develop elite germplasm (seed and clones) of alternative species of Eucalyptus that have the potential to produce economically viable forest plantations in low rainfall areas (such as the Hunter Valley, South West Slopes and North West Slope and Plains). Selection of the elite germplasm will be based on growth, wood density and their ability to sequester carbon.
- *Improving methods to reliably estimate C sequestration by environmental plantings.*
NSW DPI is collaborating with Lachlan CMA and CSIRO in a Climate Action Grant project to develop a reliable tool for estimating C sequestration by environmental plantings in NSW. Lack of reliable models and inventory methodologies is a major impediment to incorporation of such plantings in C trading schemes. As a consequence, landholders are denied income that would increase planting rates with consequent benefits for greenhouse abatement, and meeting of statewide NRM targets. Activities funded will address technical and management issues, and facilitate landowner participation in the NSW GGAS and potentially in other C trading schemes. Findings will be shared with other CMAs.
- **Fluxes of N₂O and CH₄ from forest soils**
NSW DPI is collaborating with Ensis, CSIRO L&W and Queensland DNR&M to study N₂O and CH₄ fluxes during pasture–plantation transitions. The project, funded by AGO, will quantify in situ N₂O emission rates and CH₄ fluxes for hardwood and softwood plantations of different ages in climatically different regions of Australia (NSW, Qld, WA). Soil moisture and temperature data measured concurrently with gas fluxes, investigation of diurnal flux patterns, and laboratory incubations studies will all be used to develop understanding of the processes driving N₂O and methane emissions. The objective of the project is to utilise this knowledge to improve the predictive ability of the FullCAM model for estimating nitrous oxide and methane emissions during the transition from pasture to plantation.
Further funding to continue this project, which ends December 2007, will be sought.
- NSW DPI is continuing research into use of **recycled organics** in forestry as a soil amendment to supply nutrients and sequester carbon, including application in mine site rehabilitation.

- **Bioenergy**

- NSW DPI is actively involved in bioenergy activities through participation in Bioenergy Australia (peak government-industry forum) and representing Australia at the International Energy Agency Bioenergy forums on ‘Short rotation crops for bioenergy systems’ and ‘Greenhouse gas balances of biomass and bioenergy systems’.
- Through the CRC Future Farm Industries, NSW DPI is working with Victoria, Western Australia and South Australia to investigate the suitability and productive capacity of native woody species for bioenergy production that may be integrated into farming systems for the 300 – 700 mm rainfall zone.
- NSW DPI has formed an alliance with the University of New England, to create the Primary Industries Innovation Centre. Biofuels and biomass energy have been identified as a key future program of this Centre and alliances with industry and researchers are being pursued. Through PIIC, DPI is collaborating with UNE on a project funded under the NSW Government’s Climate Action Technology Grants to examine candidate feedstocks for ligno-cellulosic ethanol production and identify best bet feedstocks from the point of view of their availability, environmental impact, and possible pre-fermentation and fermentation techniques to optimise their use.
- NSW DPI is developing with Crucible Carbon and the University of Newcastle the concept of the “NSW Carbon Pump”, aimed at accelerating and scaling up projects for large scale bioenergy production from novel sources (e.g. algae) and concurrent production of biochar for carbon sequestration in agricultural and mine rehabilitation uses. This project is not currently funded.

2. **Adaptation**

- NSW DPI is continuing to breed and evaluate new tree species and varieties, to cope with changed climatic conditions (eg. drier conditions, shorter seasons and increased rainfall intensity). See “Developing Elite Trees for Economically Viable Forest Plantations in Low Rainfall Sites” listed above.
- ***Impacts of climate change on tree growth and carbon dynamics: Hawkesbury Forest Experiment***
DPI is collaborating with national and international experts to conduct research into the direct effects of increased atmospheric carbon dioxide on tree growth and belowground respiration.

The Hawkesbury Forest Experiment has been established at the Richmond campus of the University of Western Sydney (UWS) to investigate the interaction between elevated atmospheric carbon dioxide and water availability in Australian forests. The experiment brings together an expert team of researchers from the University

of Western Sydney, University of New South Wales, University of Technology, Sydney, NSW Department of Primary Industries and the Swedish University of Agricultural Sciences with \$1.2 million funding from the Australian Greenhouse Office.

The project is a carefully integrated program of experimental and modelling approaches. The centre-piece is a field facility with twelve CO₂ and temperature-controlled whole-tree chambers (WTCs), valued at over \$2million, which have been provided by the Swedish University of Agricultural Sciences. The WTCs can house entire trees up to 10m tall and have for the last eight years been used in a boreal Norway spruce forest in northern Sweden.

The broad focus is on developing a predictive understanding of the growth, carbon storage potential and water use of both managed and unmanaged eucalypt forests growing in typical Australian, water-limited conditions, and their responses to the rising CO₂ that will occur during the next 50 years. Potential increases in water-use efficiency at high CO₂ are of huge potential importance to Australia, the driest inhabited continent. Consequently, the experiment will include contrasting watering treatments, which will allow researchers to test for the first time the effect of elevated CO₂ on productivity of large woody plants under water-limitation.

Long-term predictions of forest responses to climate change cannot be accomplished directly in experiments, and must rely on ecosystem models that incorporate our best understanding of plant eco-physiological responses. The Hawkesbury CO₂ enrichment experiment will guide the development of ecosystem models by testing specific, well-defined hypotheses about the response of water-limited forests to elevated CO₂. The facility should continue to provide valuable information for at least 10 years, though current funding finishes in June 2008.

Belowground carbon allocation and tree root and soil respiration are the least well understood aspects of forest carbon cycle. Researchers from NSW DPI and UNSW have recently been funded an ARC-linkage project (2007-2009) that will quantify belowground tree root and soil respiration and their responses to climate change (elevated CO₂ and water availability), within the larger Hawkesbury Forest Experiment. The information obtained will aid in development of predictive models of ecosystem C storage potential of eucalypt forests growing in water-limited and elevated CO₂ conditions.

4) RD&E priorities, including current and potential linkages with other research providers

Climate change mitigation

Research into mitigation options through **reforestation, forest management and inclusion of trees in the agricultural landscape:**

- full life cycle assessment of current and alternative land management systems (including direct and indirect emissions and removals), in conjunction with quantifying the environmental footprint of major NSW production systems on the soil, water and atmospheric environment.
Small current sub-project within PIIC Climate Action Grant project, in collaboration with UNE, on life cycle greenhouse benefits of ethanol production systems. Potentially linkages could be built with CSIRO project on biofuels (CSIRO FFP and Sustainable Ecosystems), and RMIT life cycle assessment group. It is recommended that DPI utilise its existing LCA expertise and detailed knowledge of NSW agricultural and forestry systems, with additional staff resources, to build capacity to undertake NSW-specific LCA studies.
- development of production systems with enhanced carbon sequestration in biomass and soil, as well as lower life cycle emissions, that are sustainable with regard to all environmental attributes, and have the capacity to adapt to climate change.
Build on current effort in farming systems research, to include consideration of carbon sequestration and all other aspects of sustainability, and a wide range of potential production systems including integration of trees into farming systems. Requires stronger linkages across DPI – between branches and between divisions.
- investigation of the potential for low-rainfall tree species to be integrated into farming systems, to provide environmental benefits in addition to carbon sequestration (e.g. salinity mitigation, biodiversity enhancement)
Substantial effort already undertaken, including establishment of a network of species demonstration trials and current testing of new species through Climate Action Grant, to identify suitable genotypes for low rainfall environments. Require continued support for management of these long term trials, and additional resources to trial additional species and extend research into forest management for low rainfall environments. Potential linkages with CSIRO forestry.
- investigate potential for breeding to increase carbon sequestration in biomass of conventional forest species, eg through faster growth and higher density
Build on current tree improvement program. Requires linkages between researchers in Forests NSW and DPI.
- investigation into the viability of products such as biomass for bioenergy production (for liquid fuels and stationary energy), as well as composite wood products, to enhance greenhouse mitigation benefits of forestry, and capacity to develop a financially viable forest industry in low rainfall environments

Some previous work in assessment of fast pyrolysis – linkage with Dynamotive Canada and Country Energy; previous project trialling camphor laurel and forest residues in sugar mills; recently renewed interest in bioenergy by Forests NSW; planned research in CRC FFI on new products from low rainfall forestry (requires additional funding).

- research into the use of char and other recycled organics as soil amendments to sequester carbon and reduce nitrous oxide emissions
Current research into slow pyrolysis for production of char – linkage with BEST energies. Long history of research into use of recycled organics, potential to expand focus to include greenhouse gas emissions and removals. NSW DPI plan to collaborate with researchers from UNSW, University of Western Sydney and Massey University/Landcare Research New Zealand to understand the role of biochar in mitigating soil nitrous oxide and methane emissions (funding required). Potential additional collaboration with soil scientists and microbiologists in WA Dept Agriculture and Food, Qld DNRM, Universities of Western Sydney, Adelaide, WA, CSIRO Land and Water.
- Assessment of best mechanisms to provide incentives for land managers to change practices to deliver GH benefits. The land use sector has potential to contribute significantly, in the short term, to the urgent requirement to mitigate GHG emissions. Strong policy incentives will need to be devised to encourage widespread implementation of changed practices. GHG policy for this sector has potential for spill-over impacts within and beyond the sector. It is vital that policy measures devised for this sector give incentive for wide participation in effective mitigation measures, for which the life cycle GH benefits have been demonstrated, and sustainability (from all perspectives) has been assessed. This requires collaboration between agricultural and forest science, economics and policy perspectives so we can devise appropriate, workable and effective greenhouse policy.
Requires linkages across DPI. Planned collaboration with UNE through PIIC – requires funding.

Emissions trading

Development of the underpinning science to facilitate mitigation through emissions trading:

- quantification of the impacts of management practices on soil carbon, in the major cropping, grazing and forest systems of NSW, to guide policy development, for input to guidelines for land managers
Current collaboration with DECC will make substantial progress but further work on additional management systems will be required.
- parameterisation of models of soil carbon dynamics for NSW agricultural and forest systems, to be used in greenhouse inventory, project level emissions trading, and to guide investment in sequestration activities
Current collaboration with CSIRO Land and Water; need to develop closer links with AGO.

- examination of soil carbon dynamics in NSW radiata pine forests. Current model, based on literatures and limited experimental evidence, assumes substantial decline in soil C under pines. Testing of the model assumptions, and development of more accurate models for NSW (This could have a major impact on DPI's returns from carbon trading under the NSW Greenhouse Gas Abatement Scheme).
Previous work in CRC Greenhouse Accounting; current project with UNSW; needs further effort to develop rigorous and defensible model for emissions trading.
- development of improved models of sequestration for dryland forest species and mixed-species revegetation, for use in emissions trading, greenhouse inventory, and to guide investment in incentives for land use change.
Previous work and current projects with CSIRO Forestry and Lachlan CMA, and CRC FFI (collaborators in SARDI, WA FPC, U Melbourne), will make a substantial contribution. Further work will be necessary to expand the range of systems modelled.
- Incorporation into sequestration models
- research into the role of forest products in climate change mitigation, including the effect of landfill type, management and environment on the rate and extent of decomposition of wood and paper products, for input to greenhouse policy development, greenhouse inventory, project level emissions trading.
Previous work through the CRC Greenhouse Accounting and current Climate Action Grant Project have made substantial progress in this novel area of research. Further work is required to study the decomposition of paper, and to extend the research to other environments. Collaboration planned with forestry, paper and waste management industries, North Carolina State University (requires funding) Current collaboration with Melbourne University in the refinement of estimates of C stocks in Australian housing.
- development of acceptable methods for inclusion of wood products in emissions trading schemes, acknowledging their important role in continuing carbon sequestered during forest growth. This could result in increased revenues from carbon trading for forest growers (including NSW DPI), and further incentives to establish forests in NSW.
Previous effort during the CRC Greenhouse Accounting generated new approaches to carbon accounting for wood products. Further work is required to assess and demonstrate proposed approach. Collaboration with A3P and forestry offset industry players has been proposed.

Bioenergy:

- development of technologies for the production of bioenergy and other bio-products from agricultural and forest biomass
- examination of a range of feedstocks for suitability for bioenergy production, including novel sources such as mallee eucalypts, woody weeds, giant reed (*Arundo donax*), jatropha, pongamia and algae
- breeding for bioenergy traits (e.g. high-starch wheats, high-biomass grasses)

- socioeconomic assessment of the impacts of a bioenergy industry on other NSW primary industries, and the macro-economic implications for the national economy
- assessment of biochemical options, including the concept of biorefinery, whereby high-value chemicals are produced from biomass in addition to energy products.

This research will provide the basis for development of sustainable bioenergy systems for NSW.

Recent interest in bioenergy in Forests NSW, previous project with camphor laurel; Planned research in CRC FFI especially with WA FPC; Current PIIC project assessing feedstocks for ethanol. Potential for research into new feedstocks, efficient methods of harvest of crop and forest residues, novel energy carriers, novel products. It is critical that LCA studies of proposed systems are undertaken to guide greenhouse policy development.

Climate change adaptation

Development of resilient forest systems through the enhancement of strategies developed to cope with climate variability, in order to increase forests' capacity to cope with the greater variability, trends in climate variables, and indirect impacts (fire, pests) anticipated under climate change, through:

- breeding and testing of new species and varieties with wider tolerance of climate variability, including the ability to tolerate warmer and drier conditions, shorter seasons, increased rainfall and storm intensity.

Current research through Climate Action Grant on suitable genotypes for low rainfall environments. Collaboration through Australian Low Rainfall Tree Improvement Group.

- research into the interactive effects of increased atmospheric carbon dioxide in a water- and nutrient-limited environment on the growth, function and belowground carbon allocation of major forest species. Good understanding of these impacts of climate change will inform adaptation strategies.

Current research through Hawkesbury Forest Experiment but more work is required to investigate species differences. Pulse labelling studies are planned, to better understand below-ground carbon allocation. Potential collaboration with UNSW. Funding required.

- research into the effects of climate change on forest water use, taking into account possible increases in fire frequency and intensity, and concept of catchment thinning.

Current project at UWS funded by Climate Action Grant "Trade-off between carbon sequestration in forests and water yields under rising CO₂" will investigate aspects of this using the Hawkesbury Forest Experiment.

- research into the impacts of climate change on quality of wood and other forest products, in order to inform breeding programs and development of adaptation strategies

- research into the impacts of climate change on pest and disease organisms, and the resulting impacts on forest production systems.
Current project in CRC Forestry quantifying the impacts of climate change on the incidence and severity of key insect pests and pathogens in plantations.
Potential collaboration: ensis (CSIRO Forestry) group modelling the potential changes in insect/fungal distributions as a consequence of climate change in relation to their tree hosts.
- research into the impacts of climate change on forest weeds and weed management
- development of integrated forest and agricultural systems, with greater resilience
Builds on farming systems research included under “Mitigation”
- research to determine the adaptation capacity of different forest species.

5) Critical linkages

Current and potential linkages are indicated in Section 4. Besides these specific interactions it will be vital that DPI maintain close contact with AGO, PM&C Climate Change Group, the CSIRO National Research Flagship on Climate Adaptation and the new Australian Centre for Climate Change Adaptation.

6) Interactions with other Primary Industry sectors

Expansion of bioenergy based on 1st generation biofuels will impact negatively on the intensive livestock industries that rely on grain; increase returns to grain farmers; encourage imports of grain (potential biosecurity issues); create incentive for expansion of cropping into marginal land, which may increase land degradation, reduce biodiversity and water quality.

Development of 2nd generation biofuels based on native tree species may promote adoption of more sustainable farming systems that integrate trees with agricultural production.

Knowledge from Hawkesbury Forest Experiment about the physiological impacts of elevated CO₂ will be valuable to planning adaptation in the tree-based horticultural industry.

Knowledge of management of soil carbon, modeling of soil carbon dynamics, and drivers of nitrous oxide and methane fluxes from soil, will be relevant to agricultural systems.

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Current projects on management of soil carbon – in agriculture and forestry – included here in case not picked up elsewhere

A program of work is being carried out by NSW DPI and DECC soil scientists, in collaboration with colleagues from other agencies including CSIRO. DECC and NSW DPI researchers are collaborating with AGO and CSIRO Land and Water to measure:

- (i). Soil C change under tillage systems, looking specifically at the relative effects of combinations of tillage and stubble retention treatments on soil C sequestration; and
- (ii). Soil C changes following revegetation of previous agricultural areas. NSW DPI researchers, with funding from the NSW Climate Action Grants, are investigating the impacts on soil carbon of alternative crop and pasture management systems.

○ ***Increasing soil carbon sequestration of NSW agricultural soils by better managing pastures***

Pastures are an important component of farming systems in NSW, providing diversity, maintaining soil fertility and with perennial pastures, reducing dryland salinity risks. However, little information is available on the soil carbon sequestration potential of pastures in farming systems in southern New South Wales.

Using soil carbon data from two long-term field experiments (since 1979 and 1992) and regional sites in central and southern NSW, this project aims to quantify such soil carbon sequestration potential. The data will then be used to identify the optimal management practices (pasture types, grazing and nutrient management) to maximise soil carbon sequestration under different farming systems, soil types and climatic conditions using modelling.

○ ***Carbon sequestration under summer/winter response cropping in north western NSW***

Soil samples were collected from six cropping and perennial pasture systems over a period of six years (1994 – 2000) in a replicated field experiment on the Liverpool Plains. The objective is to determine whether the exceptional biomass productivity and hydraulic stability of zero-tillage summer/winter response cropping on the cracking clay soils of north-western NSW translate into net carbon sequestration. Results showed little association between biomass productivity and soil C accumulation; the largest rates were associated with perennial growth (lucerne and grass pastures) and the near perennial growth mimicked by very frequent response cropping. Response cropping at this intensity is very unlikely in practice.

○ ***Impact of recycled organics on soil carbon***

Work by NSW DPI has found that recycled organic amendments such as green waste derived composts, char and biosolids have been shown to

improve plant growth and many soil chemical and physical properties. Whilst soil organic carbon is maintained or increased through the application of recycled organics, the persistence of the SOC in the soil and its longer term nature (determined by the proportion of different organic fractions) has not been investigated. NSW DPI researchers, with funding from the NSW Climate Action Grant are building on previous work by analysing existing soil samples to determine total organic carbon and assess the labile and recalcitrant fractions. Older sites are also being re-sampled (>15yrs). The objectives are to:

- Determine the total, labile and recalcitrant fractions of soil organic matter before and sequentially after amendment with recycled organics;
- Assess the efficacy of different recycled organics in increasing and maintaining soil carbon stocks over time; and
- Maximise the role of recycled organics in the long term enhancement of soil carbon.

○ ***Soil carbon assessment and rehabilitation: Landholders develop and implement new practices***

DPI and Richmond Landcare have gained funding from the NLP Community Support program, for an initial 12 month period to complete a project with the following objectives:

- To understand the nature of carbon fractions in farming soils under various best management practices in the northern rivers;
- To measure and account for greenhouse gas emissions (CO₂, N₂O) from farms using existing management practices; and
- To implement, test, demonstrate and promote a technology (application of biochar) that results in significant carbon gain in soil, while at the same time significantly reducing emissions of N₂O to the atmosphere. This technology holds significant potential for rehabilitation of degraded land through rapid enhancement of stable and high surface area carbon.

This Community Project will identify 7 farms in the Northern Rivers which are representative of significant agricultural pursuits in the area. In addition, up to 3 control sites (eg native bushland, rainforest) will also be identified and sampled. Of these sites, 2 will be established as trial sites for the application of black carbon (biochar) to the soil. On-ground activities will include a detailed benchmark assessment and characterisation of soil carbon at the 7 sites and assessment of greenhouse gas emissions from these soils.

○ ***Land management to increase soil carbon sequestration in NSW***

Changed land use and land management practices have significant potential to sequester carbon in soil.

This project aims to:

- Develop capacity to use a rapid and cost-effective method for measuring soil C based on mid-infra red spectroscopy;

- Assess macro- and micro-scale variability of soil C stocks in diverse landscapes to aid quantification of soil C stock;
- Examine the dynamics of soil C sequestration as a result of land management changes, including revegetation, altered crop rotations and grazing management;
- Examine the ability of organic amendments, particularly bio-char, to increase soil C stocks; and
- Contribute experimental data to calibrate and parameterise the carbon accounting model FullCAM, to improve our capacity to estimate the potential for changed land management to increase soil C stocks, and to provide a calculation tool for emissions trading.