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A REVIEW OF THE POTENTIAL ROLE OF GREENHOUSE GAS ABATEMENT IN NATIVE VEGETATION MANAGEMENT IN QUEENSLAND'S RANGELANDS

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Abstract

Concern about the risk of harmful human-induced climate change has resulted in international efforts to reduce greenhouse gas emissions to the atmosphere. We review the international and national context for consideration of greenhouse abatement in native vegetation management and discuss potential options in Queensland. Queensland has large areas of productive or potentially productive land with native woody vegetation cover with approximately 76 million ha with woody cover remaining in 1991. High rates of tree clearing, predominantly to increase pasture productivity, continued throughout the 1990s with an average 345,000 ha/a estimated to have been cleared, including non-remnant (woody regrowth) as well as remnant vegetation. Estimates of greenhouse gas emissions associated with land clearing currently have a high uncertainty but clearing was reported to contribute a significant proportion of Australia's total greenhouse gas emissions from 1990 (21%) to 1999 (13%). In Queensland, greenhouse emissions from land clearing were estimated to have been 54.5 Mt CO_2-e in 1999. Management of native vegetation for timber harvesting and the proliferation of woody vegetation (vegetation thickening) in the grazed woodlands also represent large carbon fluxes. Forestry (plantations and native forests) in Queensland was reported to be a 4.4 Mt CO_2-e sink in 1999 but there are a lack of comprehensive data on timber harvesting in private hardwood forests. Vegetation thickening is reported for large areas of the *c.* 60 million ha grazed woodlands in Queensland. The magnitude of the carbon sink in 27 million ha grazed eucalypt woodlands has been estimated to be 66 Mt CO_2-e/a but this sink is not currently included in Australia's inventory of anthropogenic greenhouse emissions.

Improved understanding of the function and dynamics of natural and managed ecosystems is required to support management of native vegetation to preserve and enhance carbon stocks for greenhouse benefits while meeting objectives of sustainable and productive management and biodiversity protection.

Key words: Climate change, Kyoto Protocol, land use change, carbon stocks, emissions, sequestration

Introduction

Clearing of native vegetation in Australia commonly involves replacement of ecosystems dominated by woody vegetation of high biomass with agriculturally more productive systems of low biomass and higher rates of turnover. Plant dry matter is approximately 50% carbon (IPCC 1997, Gifford 2000) and oxidation of the carbon in cleared biomass by burning or decay results in its emission to the atmosphere mostly as carbon dioxide (CO_2), the major anthropogenic greenhouse gas. Burning also results in emissions of other greenhouse gases in trace amounts, primarily methane, carbon monoxide, nitrous oxide and other oxides of nitrogen. Carbon dioxide emissions result not only from the burning or decay of the visible aboveground component of vegetation but also decay of roots and net loss of soil organic carbon following disturbance with reduction in inputs of organic matter and impacts on the rate

[1,2] The views expressed herein are those of the authors and do not represent a policy position of the Queensland Government or the Departments of Natural Resources and Mines or Primary Industries.

of heterotrophic respiration. Some carbon loss following clearing is offset by growth of replacement vegetation.

From 1850 to 1998 it has been estimated that 136±55 Gt[a] C have been emitted worldwide as a result of land use change, primarily deforestation. This is approximately one third of the total estimated carbon emissions from human activities in this period, with fossil fuel burning and cement production contributing 270±30 Gt C as CO_2 (Watson *et al.* 2000). Destruction of forests continued at approximately 14.6 million ha/a on average during the decade of 1990 - 2000 (FAO 2001), mostly in tropical developing countries in South America, Africa and Asia, but also in Australia with an average of more than 0.4 million ha/a cleared from 1990 to 1999 (AGO 2001a). Australia is unique amongst industrialised countries in still having large areas with native woody vegetation cover potentially available for agricultural development, predominantly grazing. Clearing of native vegetation is seen as a major environmental issue in all States but attention focuses on Queensland with approximately 90% of the total national tree clearing (469,000 ha/a) in 1999 (AGO 2001a). In Queensland, vegetation clearing includes significant areas of woody regrowth from previous clearing. One of the major reasons that is cited for reducing land clearing is concern about greenhouse gas emissions as well as loss of biodiversity and risk of land degradation. This concern is highlighted by the international commitment to address global climate change through emission targets that will become binding if the Kyoto Protocol enters into force (Article 3.1, Kyoto Protocol) (UNFCCC 1997).

In this paper we discuss the potential role of greenhouse abatement in native vegetation management in Queensland in the context of the uncertainty in current estimates of greenhouse gas emissions and sinks for the terrestrial biosphere and of the uncertainty in future international and domestic agreements to limit net emissions of greenhouse gases to the atmosphere. We review: 1) the scientific basis for concern about the enhanced greenhouse effect and climate change; 2) resulting international agreements on climate change and greenhouse gas abatement; 3) the significance of greenhouse considerations for native vegetation management in Queensland; 4) greenhouse gas accounting for land use, land use change and forestry; and 5) the potential for management of vegetation in Queensland to contribute to reducing Australia's greenhouse gas emissions.

The enhanced greenhouse effect

There is a large naturally occurring exchange of CO_2 between the land, the oceans and the atmosphere. This exchange is believed to have been roughly in equilibrium in the absence of significant human interference as evidenced by past relatively stable atmospheric concentrations of CO_2, varying by only 10 ppmv (parts per million by volume) between 275 and 285 ppmv during the thousand years prior to the industrial revolution (IPCC 2001). However, the atmospheric concentration of CO_2 has increased from 280 ppmv pre-industrial to 368 ppmv in 2000 primarily due to burning of fossil fuels and deforestation. In the same period, the atmospheric concentrations of methane and nitrous oxide have increased by more than 100%, and approximately 16%, respectively (IPCC 2001). Greenhouse gases in the atmosphere, including carbon dioxide, water vapour, methane and nitrous oxide, absorb energy radiated from the Earth's surface and hence influence temperature of the atmosphere at the surface. Over the 20th century, the global average surface temperature has increased by 0.6±0.2°C. The consensus of those scientists contributing to the Intergovernmental Panel on Climate Change Third Assessment Report (TAR) was that "there is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities."

Climate models suggest that over the next century global average surface temperature could rise by 1.4 to 5.8°C with the upper range likely to cause substantial problems for human,

[a] Gt = giga tonne = 10^9 tonnes

physical and biological systems (IPCC 2001). Climate change observations and projections for Australia are similar to the global average values, with projections of an increase in temperature of 1.0 to 6.0°C by 2070 (CSIRO 2001). Of importance to the viability of agriculture are projections for changes in rainfall. These currently have a low confidence because of limited representation in models of global phenomena such as El Niño. This is reflected in the range in projected change in annual average rainfall in Queensland by 2070 of from –35 to +10% for most regions. Despite uncertainty in rainfall, however, most models predict increases in potential evapotranspiration and hence generally drier conditions in Queensland.

International response to climate change

Intergovernmental Panel on Climate Change

International concern about global climate change, and recognition of the need for policy to be based on sound scientific information, resulted in the establishment in 1988 of the Intergovernmental Panel on Climate Change (IPCC) by the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP). The focus of the IPCC is on improved scientific understanding of global climate change through assessing and reporting the latest climate change research.

United Nations Framework Convention on Climate Change

The IPCC paved the way for the United Nations General Assembly to form the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 to provide the policy framework for international response to address climate change. The UNFCCC has as its ultimate objective limiting greenhouse gas emissions to a level that will avoid "dangerous anthropogenic interference with the climate system".

Under the Convention, Annex I parties (OECD countries and the Eastern European countries with economies in transition to a market economy) are required to take a lead in reducing the growth of anthropogenic greenhouse gas emissions. Obligations of Annex 1 countries include a periodic report on climate change policies and mitigation programs, and submission of an annual national inventory of anthropogenic greenhouse gas emissions and removals. The UNFCCC recognised the role of vegetation and soils (sinks) in the global carbon budget by including emissions and removals from Land Use Change and Forestry (LUCF) activities in greenhouse gas accounting.

The Kyoto Protocol

The Kyoto Protocol to the UNFCCC was adopted in 1997 to strengthen the Convention by introducing quantified emissions reduction or limitation targets for countries in Annex 1. The objective is to achieve an overall reduction in annual greenhouse gas emissions of at least 5% below 1990 levels in the first commitment period of 2008-2012. Australia's target is to limit average annual emissions in 2008 to 2012 to 108% of 1990 emissions.

Key features of the Kyoto Protocol relating to land use and land use change are:

1. The six main anthropogenic greenhouse gases (carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride) for all six sectors reported to the UNFCCC except LUCF (Article 3.1) are included in estimates of the assigned amount of emissions for Kyoto Protocol compliance;

2. Parties for whom LUCF was a net source of greenhouse gas emissions in 1990 also include emissions from land use change (LUC) in their 1990 baseline for the purposes of estimating the assigned amount (Article 3.7, the 'Australia Clause');

3. Specified land use, and land use change and forestry (LULUCF) activities – direct human induced afforestation, reforestation and deforestation since 1990 (Article 3.3) and some additional sink activities relating to management of vegetation and agricultural soils (Article 3.4) – can be credited towards meeting targets; and

4. Three mechanisms increase the options for Annex I Parties to meet their national targets cost-effectively:
   - Joint Implementation (JI) (Article 6) allows for emissions-reduction projects jointly between Annex I Parties;
   - Clean Development Mechanism (CDM) (Article 12) encourages emissions- reduction projects by Annex I parties to be carried out in non-Annex I parties; and
   - International Emissions Trading (Article 17).

The overarching principles of the Kyoto Protocol were agreed at COP 3 in 1997, but the technical details were left to be resolved later. One of the most contentious issues in the negotiations on operational details over the following four years was the role of sinks in meeting emissions targets. Agreement was finally reached in July 2001 at Bonn on rules operationalising the Kyoto Protocol despite a decision by the United States Bush Administration to withdraw from the treaty in March 2001. The US with 36.1% of Annex 1 emissions in 1990, announced an alternative to the Kyoto Protocol, the "Climate Action Plan", in February 2002. The Climate Action Plan has the objective of reducing the greenhouse gas intensity of the US economy by 18% over the next 10 years. Australia subsequently signed a climate action partnership with the US with the intention of sharing research and scientific understanding of climate change.

For entry into force, the legal text agreed at COP 7 in Marrakech in November 2001 must be ratified by the governments of at least 55 countries representing 55% of Annex 1 1990 emissions. The EU (24.4% of Annex 1 1990 emissions), Russia (17.4%), and Japan (8.5%) along with some smaller emitters have indicated their intention to ratify the Protocol. Australia, which accounted for 2.1% of 1990 greenhouse emissions by Annex 1 countries (1.4% of global emissions) has not announced a decision on ratification of the Kyoto Protocol at the time of submission of this paper. Australia's decisions on ratification and reporting of sinks for the Kyoto Protocol or domestic commitments on greenhouse may in future have an impact on land clearing and vegetation management in Queensland.

Greenhouse accounting for land use change and forestry

Land use and land use change affect the amount of carbon stored in vegetation and soils. The resultant anthropogenic flux of CO_2 is at present very difficult to measure directly, so accounting is normally based on the assumption that the net human-induced CO_2 flux to or from the atmosphere is proportional to the change in carbon stocks in biomass and soils in an area influenced by human activity. Change in carbon stocks is most commonly estimated from assumptions on the impact of the land use or land use change on carbon stock density:

$$\text{Carbon flux} = \text{Activity area (ha)} \times \text{Change in carbon stock density (t C/ha)} \qquad (1).$$

For any land use activity, greenhouse gas emissions depend on complex biophysical processes, many of which are supported by limited data or understanding of how natural ecosystems respond to the range of anthropogenic and environmental factors affecting carbon stocks. The carbon in natural ecosystems has traditionally had no direct commercial value as a commodity, and hence statistics relevant to greenhouse accounting have not been collected with the same rigour as for fossil fuels. Accounting for land clearing and land use activities is exacerbated by the contribution of emissions and removals as a result of land use and land use change in earlier years to current anthropogenic greenhouse flux.

The natural spatial and temporal heterogeneity of biological systems and the range of possible management practices further contribute to the uncertainty in estimates of emissions and removals of greenhouse gases for LUCF. This high uncertainty in present estimates of greenhouse gas fluxes associated with tree clearing and woody vegetation management is an important consideration in assessing greenhouse implications of vegetation management.

Two major IPCC categories account for major LUCF fluxes reported in Australia in reporting for the UNFCCC:

1. *Forest and Grassland Conversion* also called Land Use Change (LUC) or land clearing, and

2. *Changes in Forests and Other Woody Biomass Stocks* or forestry, a broad category "intended to account for all significant human interactions with forests and other woody biomass stocks which affect CO_2 fluxes to and from the atmosphere, but which do not result in a land-use change" (IPCC 1997). Plantations and managed native forests are included in this subsector.

A description of inventory methodology for LUCF reporting used by the Australian Greenhouse Office is given in Workbook 4.2, Carbon Dioxide from the Biosphere, and Supplements (NGGIC 1998, 1999). This inventory is compiled in fulfilment of reporting obligations to the UNFCCC and improvements to data and methods have resulted in annual revisions since the first inventory was compiled in 1994. For reporting under the Kyoto Protocol if it enters into force, parties will use different rules as detailed in the Marrakech Accords (UNFCCC 2001).

In 1998, the National Carbon Accounting System (NCAS) was initiated within the Australian Greenhouse Office to improve the estimates of emissions and sinks in land-based sectors (AGO 1999). NCAS has four major programs to address key areas in LULUCF accounting: the Vegetation Cover Program is mapping continental changes in land cover using remote sensing techniques and aims to provide a consistent approach to reporting afforestation, reforestation and deforestation over time; the Soil Change Program is assessing the impact and dynamics of land clearing and management on soil carbon content; the Wood Change Program is improving data for commercially harvested forests (both native and plantation); and the Tree Change Program deals with non-commercial forests, particularly those subject to afforestation, reforestation or deforestation. The NCAS results will be integrated into a spatial modelling application and this system is expected to provide improved estimates of greenhouse fluxes for LUCF in Australia.

Land cover and carbon stocks in native vegetation Queensland

The total land area of Queensland is 173 million ha of which approximately 160 million ha or 85% is grazed (Tothill and Gillies 1992). Baseline land cover mapping for 1991 to 30 m resolution using Landsat Thematic Mapper (TM) imagery by the Statewide Landcover and Trees Study (SLATS) project (Department of Natural Resources 2000) has given an accurate picture of woody vegetation extent (Fig. 1). In the NGGI, forest is defined as in the National Forest Inventory - land dominated by trees with potential or actual height greater than 2 m and potential or actual canopy cover greater than 20% (NFI 1998). A foliage projective cover (FPC) of 12%, approximately equivalent to 20% crown cover, is close to the limits of reliable detection with Landsat TM imagery in high rainfall areas. However, in more arid regions

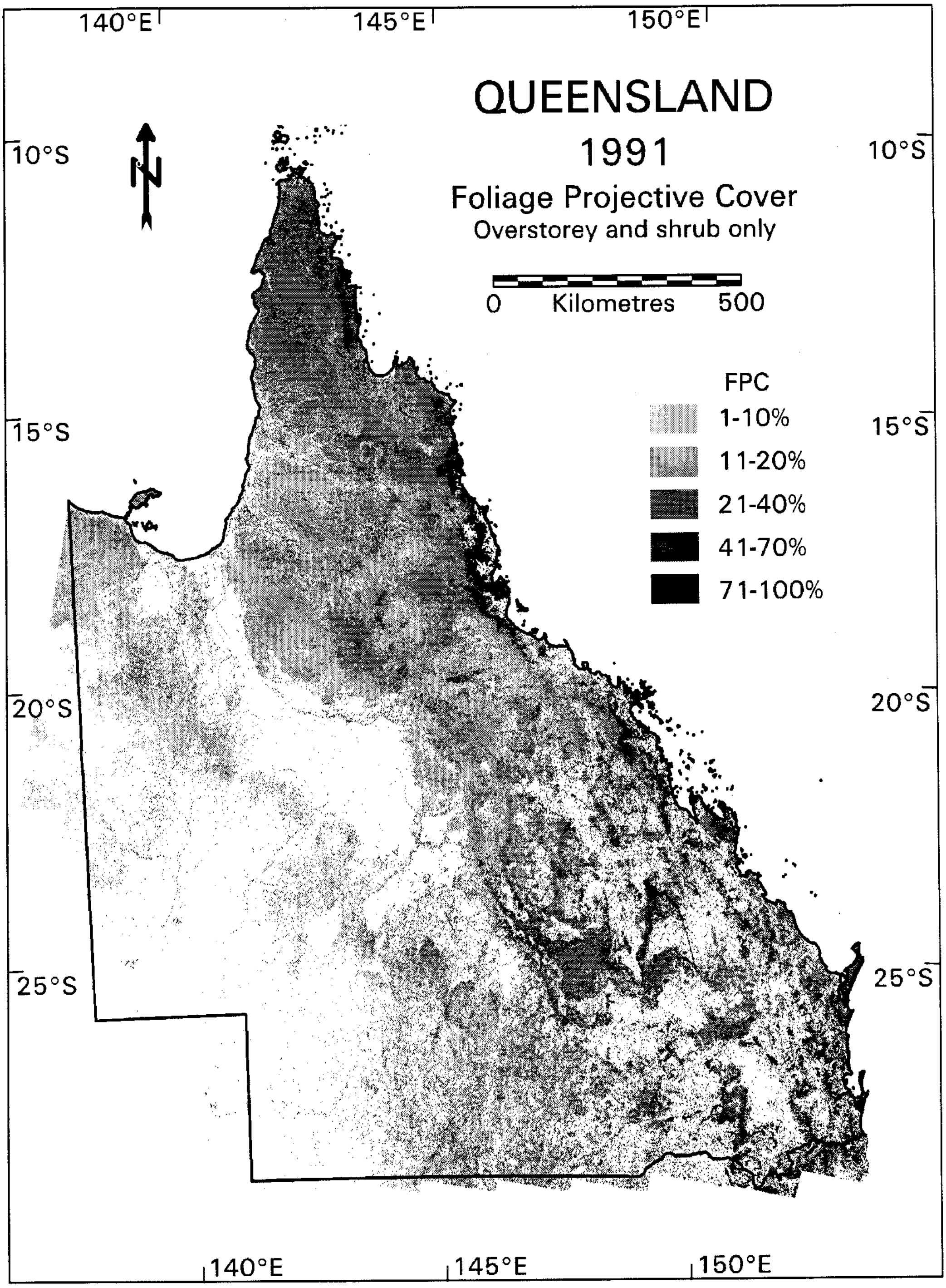

Fig. 1. Queensland land cover in 1991 mapped by Statewide Land cover and Trees (SLATS) project using Landsat TM imagery. Total wooded cover detectable using remote sensing was 84 M ha with approximately 76 Mha having foliage projective cover (FPC) ≥12% (equivalent to about 20% crown cover).

woody vegetation can be confidently distinguished from ground cover down to almost 5% FPC using 30 m resolution data. These areas contribute only a small fraction of total biomass cleared but are also mapped in the SLATS project. Analysis of the satellite imagery for 1991 shows that the total area of wooded vegetation in Queensland was 84 million ha with 76 million ha having FPC greater than or equal to 12%. FPC in this analysis refers to overstorey plus shrub layers.

Development of a relationship between FPC and basal area of woody vegetation based on site measurements (Kuhnell *et al.* 1998) enabled mapping of basal area (Department of Natural Resources 2000). Relationships between basal area and biomass have been developed to give an estimate of biomass cleared from the SLATS pre-clearing basal area maps (Department of Natural Resources 2000). A relationship between aboveground biomass and basal area of woody plants was derived from published and unpublished data from a large number of eucalypt, acacia and rainforest sites in Australia, including a large dataset from the Transect Recording And Processing System (TRAPS) program in Queensland (Back *et al.* 1999):

$$B_{ag} = 1.91A^{1.44} \qquad r^2 = 0.96 \qquad (2),$$

where B_{ag} is aboveground ground biomass and A is basal area.

While there was considerable scatter around this relationship at high basal areas, it provided a good fit within the range of basal areas of land use change in Queensland.

A preliminary relationship developed relating belowground biomass to above ground biomass gave results consistent with published root to shoot ratios (Department of Natural Resources 2000):

$$B_{bg} = 3.20\ BA_{ag}^{\ 0.46} \qquad r^2 = 0.81 \qquad (3),$$

where B_{ag} and B_{bg} are the biomass above and belowground, respectively.

Correlations between above and belowground biomass have been noted previously and Eamus *et al.* (2002) derived a relationship for eucalypt trees in northern Australian woodlands. Applying equations (2) and (3) to basal area as mapped by SLATS gave an estimate of total aboveground biomass in the 76 million ha woody vegetation in Queensland in 1991 of 5100 million t with an additional 1500 million t below ground. This equates to total carbon stocks of 3300 million t assuming a carbon fraction in woody biomass of 50% (Gifford 2000).

Greenhouse accounting

Land clearing

Land clearing (LUC) represented a significant component of the total anthropogenic greenhouse emissions reported for Australia and for Queensland from 1990 to 1999 (Fig. 2). Estimates of emissions for Australia are published in the NGGI (AGO 2001a) and emissions for Queensland were calculated using the same methodology and data (AGO 2001b (1990, 1995, 1999), Henry unpublished (other years)). The rate of clearing in Queensland over this period is shown in Fig. 3 with the associated greenhouse emissions. Reported annual emissions from land clearing in Queensland declined by 9 million t CO_2-e [b] from 63.5 to 54.5 million t CO_2/a from 1990 to 1999. Current estimates have a high uncertainty and the NCAS programs may give revised LUC estimates.

The potential carbon loss from clearing may be considered equivalent to the biomass removed plus potential soil carbon loss minus sequestration by regrowth. Area of land cleared and pre-clearing biomass of vegetation are key parameters, but actual loss during any time period

[b] CO_2-e (CO_2-equivalent) emissions are calculated by conversion of trace greenhouse gases to equivalent molecules of CO_2 based on relative radiative forcings (global warming potentials).

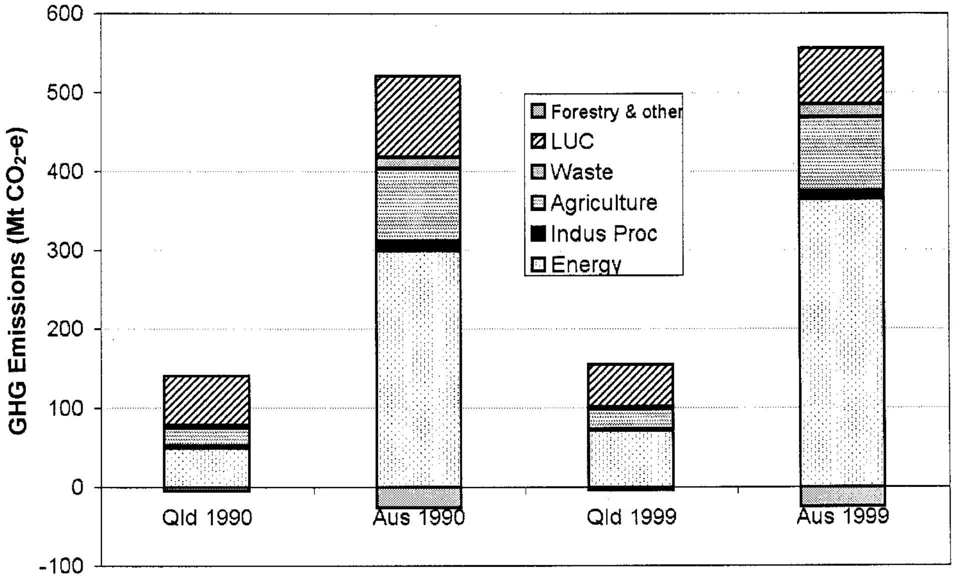

Fig. 2. Relative contributions of land clearing and forestry activities to the total reported greenhouse emissions for Queensland and Australia (AGO 2001a, 2001b). Total reported net emissions for Australia in 1990 and 1999 were 493.8 and 529.9 Mt CO_2-e, respectively and for Queensland 135.8 and 151.9 Mt CO_2-e, respectively. Land clearing contributed 20.9% and 13.5% of total reported net emissions for Australia in 1990 and 1999, respectively, and 46.8% and 35.9% of total reported net emissions for Queensland in 1990 and 1999, respectively.

following clearing will be modified by such factors as the clearing practice (whether cleared biomass is burnt or left to decay), post-clearing land use and management, and soil characteristics. Committed emissions or sequestration from past activities on the area must also be accounted. The impact of uncertainty in key parameters is discussed below and illustrated by the alternative estimate of emissions for Queensland in Fig. 3 made using preliminary revised data for biomass, soil carbon loss, regrowth and clearing practice. When released improved data and methods being developed by NCAS will improve confidence in estimates of emissions and also in estimates of projected impact on greenhouse emissions of changes in rates of land clearing.

Clearing rate: Biennial analysis of land cover change using Landsat imagery supported by extensive ground truthing in the SLATS project (Department of Natural Resources 1999a, 1999b, 2000) is providing accurate (± 8% at a 95% confidence interval) statistics on woody vegetation cover change typically down to 1 ha resolution. Change analyses have been published for 1991–1995, 1995-1997 and 1997-1999. For the crucial Kyoto Protocol baseline year of 1990, preliminary data are available from 1988 to 1991 imagery analysis to give the 1990 value shown in Fig. 3[1]. Clearing of woody vegetation for 1997-1999 averaged 425,000 ha/a with 86% being conversion to pasture, 10% for crops, and the remainder for non-agricultural use such as infrastructure, forestry and mining. Of the total clearing, 32.5% was assessed to be clearing of non-remnant (regrowth) communities (Department of Natural Resources 2000).

Biomass: The mean biomass density of vegetation cleared for the change periods 1991-1995, 1995-1997 and 1997-1999 was calculated to be 52.6, 55.7 and 56.2 t dm/ha. Frequency distributions of woody vegetation clearing against basal area showed that the basal area of

[1] The differences in estimates of clearing rate in Wilson *et al.* (2002: [this Volume]) to those presented here are the result of different methodologies (see Wilson *et al.* 2002 for explanation).

highest frequency of clearing increased from approximately 9 m^2/ha for the 1991-1995 cover change period, to 10 m^2/ha for 1995-1997 and to 11 m^2/ha for 1997-1999 (Department of Natural Resources 2000). Based on the relationships between biomass and basal area (Eq. 2), the aboveground biomass cleared annually for these three change periods was estimated to be 15.2, 18.9 and 23.9 million t dry matter (dm), respectively.

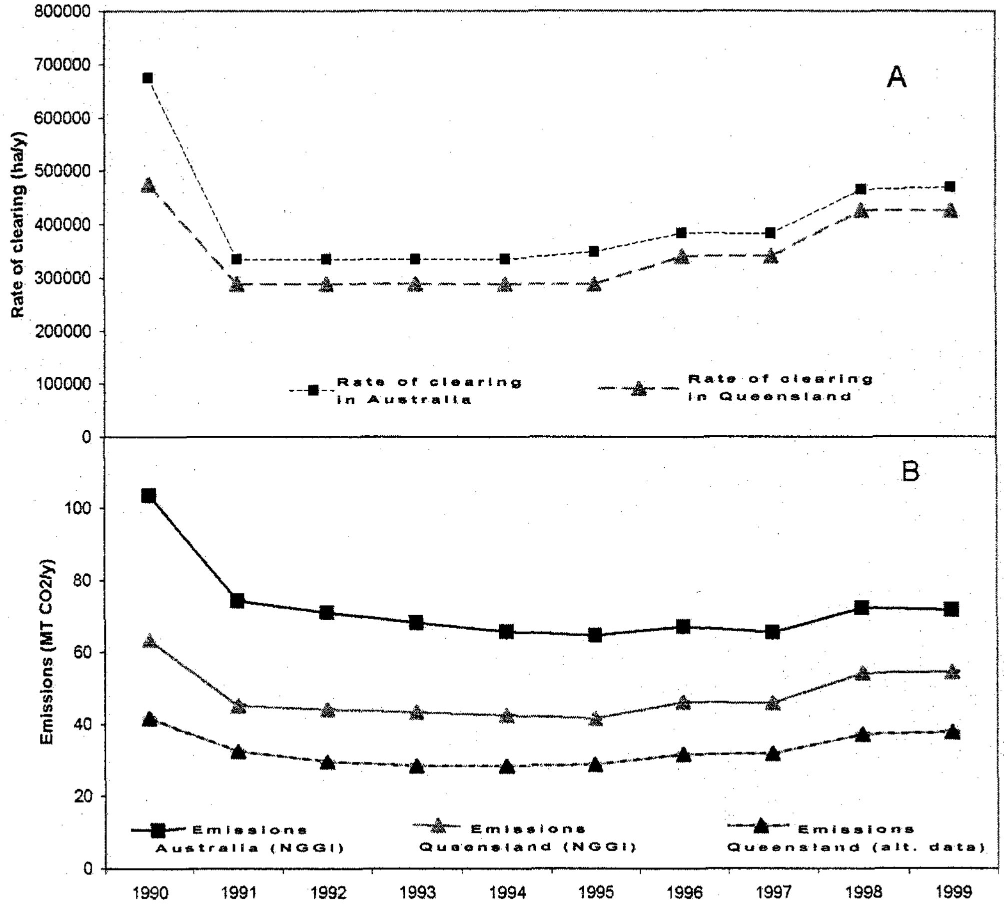

Fig. 3. Rate of tree clearing (A) and annual greenhouse gas emissions from tree clearing (land use change, LUC) (B) in Australia and Queensland. Values for rates of forest clearing and national estimates of emissions are those published in the National Greenhouse Gas Inventory (NGGI) (AGO 2001a). Estimates of emissions in Queensland (solid line) use the NGGI methodology (AGO 2001b for 1990, 1995, 1999; Henry unpublished for remaining years). To illustrate the uncertainty in estimates, emissions calculated using the same rates of land clearing for 1990 to 1999 but alternative data for some parameters including pre-clearing biomass, soil carbon change, regrowth clearing and proportion of the biomass burned soon after clearing are shown (Henry unpublished). [The differences in estimates of clearing rate in Wilson *et al.* (2002 [this Volume]) to those presented here are the result of different methodologies (see Wilson *et al.* 2002 for explanation).].

NCAS is developing a more comprehensive analysis of biomass cleared, but the current NGGI is based on stratification of pre-clearing vegetation into three broad forest classes - closed forest, open forest, and woodlands - with an average biomass density assigned to classes in each State (NGGIC 1998). This approach gave the total aboveground biomass cleared in Queensland in 1991-1995 and 1997-1999 as 17.6 and 25.9 million t dm, respectively, about 2 million t higher for each period.

Clearing practices and delayed emissions: The proportion of the biomass carbon on cleared land that is released to the atmosphere as CO_2 in the same year depends on the clearing practice. Remaining biomass decays over a period of time that will vary with species (wood density and composition), temperature, rainfall history and moisture. The current NGGI assumes that on average nationally 90% of cleared biomass is burned in the year of clearing with the remaining 10% decaying linearly over 10 years (NGGIC 1998). Preliminary surveys of coarse woody debris and evidence of fire during field checking for the SLATS project indicated that the proportion of biomass burned in the year of clearing in Queensland may be of the order of 30 to 40% (Queensland Department of Natural Resources and Mines, unpublished data). These proportions become significant where the rate of clearing changes in the years preceding the inventory period and changing the fraction of aboveground biomass burnt immediately after clearing from 90% to 40% in Queensland results in a change in estimated annual emissions for 1990 to 1999 of less than 10%. The period of decay will vary if termites are present, but preliminary evidence both from field observations and controlled experiments undertaken on behalf of NCAS is that the turnover time of coarse woody debris in the absence of such external factors is probably at least 25 to 30 years (Mackensen and Bauhus 1999).

Regrowth: Of the land cleared in Queensland between 1991 and 1999, 85 to 92% in each change period was for increased pasture production (Department of Natural Resources 2000). Unless active control is practised, regrowth of woody vegetation may occur on these areas. Of the 425,000 ha/a cleared in Queensland in 1997-1999, 138,000 ha/a was estimated to be non-remnant (regrowth) clearing. The *IPCC Guidelines* for national inventories provide a simple method for estimating net loss of carbon from clearing by including the removals due to growth of replacement vegetation (crops or pasture) in the year of clearing. The Australian NGGI also accounts for longer-term carbon sequestration by woody regrowth. A time series assessment of land cover change for Queensland from the early 1970s being undertaken by the Department of Natural Resources and Mines using Landsat Multispectral Scanner (MSS) imagery will improve understanding of the dynamics of woody vegetation in the rangelands and estimates of net emissions from clearing.

Soil carbon: Estimates of net soil carbon flux following clearing are one of the greatest sources of uncertainty in current land clearing inventories. Measurement of paired sites (environmentally and edaphically matched sites in adjacent cleared and uncleared areas) is being undertaken by NCAS to improve data on the magnitude and dynamics of soil carbon flux following land use change in Australia (Webnet Land Resource Services 1999).

The Australian NGGI has historically applied an average carbon content in the top 0 to 30 cm to each of the three broad forest categories - 120, 85 and 70 t C/ha for closed forest, open forest and woodland, respectively (NGGIC 1998). It was assumed that after clearing there was a 10% gain, 30% loss and 37% loss in soil carbon from the top 30 cm when forest was converted to improved pasture, unimproved pasture and cropping, respectively, based on IPCC default values. However, recent studies reporting lower values for both soil carbon content in natural forests and for the proportional change when forest is converted to unimproved pasture indicate that the data used may have overestimated soil carbon emissions following clearing. Analysis of soils under pasture, semi-arid grassland and woodland communities of Queensland gave values of organic carbon to 30 cm depth of 33 to 47 t C/ha (Dalal and Carter 2000, Harms *et al.* 2002). These are not inconsistent with the IPCC (1997) inventory default values for tropical dry areas of 40 to 60 t C/ha. Results of analysis of soils in paired sites in central and southern Queensland were variable, but overall soil organic carbon content in the top 30 cm was on average 7 ± 3% lower in sites cleared for pasture than in adjacent uncleared treed sites (Harms *et al.* 2002). Approximately half the 49 sites had been cleared for less than 10 years and the remainder for between 10 and 30 years but there was no clear relationship between the proportion soil organic carbon lost and time since conversion to pasture. Other studies have also found a response varying widely from significant loss to gains in soil carbon for conversion of forests to grazing lands (Howden *et al.* 1995), and grazing pressure following conversion may contribute to the variability (Ash *et al.* 1995). International publications have also indicated a variable though often relatively small impact on soil carbon of land use change, supporting the conclusion that the IPCC assumptions generally overestimate the impact on soil carbon stocks of conversion of forest to pasture (see review by Kirschbaum 2000).

Soil carbon loss for LUC was recalculated applying the lower values of native soil carbon content and change from the studies above for conversion to pasture in Queensland. The revised estimates show that the contribution of soil carbon to annual total land clearing emissions in Queensland for 1990 - 1999 may be approximately 10 to 13% (Henry unpublished) rather than 34 to 49% as calculated using the historic default parameters (AGO 2001b). There remains a high uncertainty in these estimates but they indicate that clearing of forests or woodlands for pasture has a lower impact on soil carbon than previously assumed and consequently the total greenhouse emissions would be lower than earlier estimates.

Managed native forests

Management of Queensland's native woodlands contributes to carbon emissions through land clearing, but also has a potential role in carbon sequestration. In Queensland the annual carbon flux on 4.6 to 4.7 million ha managed forests has been reported in accounting for *Changes in forests and other woody biomass stocks* for 1990 to 1999 giving a net sink for forestry of 6.2 million t CO_2 in 1990 and 4.4 million t in 1999 (AGO 2001b). The area reported is approximately equal to the 0.2 million ha plantations plus 4.6 million ha publicly owned forests managed for commercial production (Department of Primary Industries 1998), but DPI also reports that 60% of Queensland's native hardwood harvest is sourced from private native forests. The net human-induced greenhouse flux for managed forests is calculated according to IPCC guidelines as the difference in emissions due to decay or burning of harvested wood products, slash and fuelwood and annual sequestration due to growth. Asymmetry between the area of reported harvest volume from forest products statistics (emissions) and the area over which growth is estimated (removals) will introduce bias into accounting. However, the area of privately owned forests managed for timber production is not known (Department of Primary Industries 1998).

These figures indicate that growth on only approximately 6% of the 76 million ha forested land in Queensland is currently reported in the greenhouse inventory. However, since approximately 60 million ha woodlands is estimated to be managed for grazing, much of the area with woody cover is "affected by ongoing human interaction" and, therefore, could be included in greenhouse accounting (IPCC 1997) where data are available. As well as the change in carbon stocks that may be occurring in areas of privately owned forests harvested for native hardwoods, there is anecdotal evidence that vegetation thickening is occurring over large areas of woodlands managed for grazing. An understanding of the changes in carbon stocks occurring in managed native forests is required to understand the greenhouse implications of vegetation management practices. While the Australian NGGI currently reports change in stocks on only 10% (16.2 million ha) of the 157 million ha national forest estate, the national greenhouse inventory of U.S.A. includes all 302 million ha forested land in accounting (U.S. EPA 2000). Requirements for estimating and reporting greenhouse fluxes due to management activities are firstly transparent and verifiable data on carbon stock changes, and secondly assessment that the change in carbon stocks is due to human activities.

The magnitude of the carbon stock change in woodlands in Queensland managed for grazing has been quantified using data from a network of 57 permanent plots established progressively since 1982 by the Department of Primary Industries (Back *et al.* 1999). The average period of monitoring is 8.4 years with a mean annual increment in aboveground live plus standing dead carbon stocks of 0.53 t C/ha/a (Burrows *et al.* 2002). The sites analysed were shown to be representative environmentally and structurally of the 27 million ha grazed eucalypt woodlands in the defined study area of the State and the measured increase in carbon stock scales up to a significant sink (27 million ha x 0.53 t C/ha/a = 14.3 million t C/a). Allowing for proportional below-ground biomass increment using a root to shoot ratio to 1 m of 0.26 (Burrows *et al.* 2000), the 27 million ha eucalypt woodlands could represent a sink of 18 Mt C/a (66 million t CO_2/a) over the monitoring period which includes inventory years 1990 to 1999.

For greenhouse accounting, attribution of this large sink to natural factors or direct or indirect human influence is critical. However, attribution is difficult due to limited availability of long-term data and potentially also to the involvement of multiple factors that interact on different temporal and spatial scales to influence tree-grass balance in these communities (Burrows *et al.* 2002, Gifford and Howden 2001). Factors proposed to be significant in similar changes observed in savannas in North and South America and Africa (Archer 1995, Scholes and Archer 1997) include CO_2 fertilisation, climate variation, introduction of domestic livestock and change in fire regimes. Because of the potential importance of the sink, these alternative explanations are considered in some detail below with reference to the measured change in carbon stocks in Queensland's grazed eucalypt woodlands.

CO_2 concentration – Idso (1995) observed that the worldwide invasion of grassland by trees and shrubs that began *c.* 200 years ago has closely followed the post-industrial upward trend in the atmospheric CO_2 concentration. There has been limited ecophysiological evidence for CO_2 fertilisation conferring a long-term competitive advantage to C_3 trees and shrubs over C_4 grasses in mixed grass-tree communities (Polley *et al.* 1994, Anderson *et al.* 2001) and such an advantage does not explain the proliferation of woody species also observed in C_3 grasslands (e.g. mulga grasslands, Burrows *et al. 1990*). Where grassland fires occur, Bond and Midgley (2000) speculate that elevated atmospheric CO_2 concentrations may promote additional growth in woody sprouting species in savannas, but differences in vegetation structure on a local scale, including fenceline contrasts, cannot be explained on the basis of CO_2 concentration (Archer *et al.* 1995).

Climate – Fensham and Holman (1999) document a major dieback event in response to drought and have suggested that the observed proliferation of woody vegetation in northern Australia may be part of a normal tree mortality–regeneration cycle, primarily driven by rainfall variability. They also found no evidence that dieback was exacerbated by cattle grazing (see also Fensham 1998). In contrast, climate does not seem to have been a determining factor in the tree-grass balance in areas in the Western Division of New South Wales that were transformed from open grassy woodlands to denser shrub-woodland soon after the introduction of domestic livestock (Royal Commission 1901). These areas have remained or increased in woody plant dominance (Interdepartmental Committee 1969, Noble 1997), despite having been subjected to several periods of well above- and below- average rainfall over the past century.

The processes of regeneration and mortality in woodlands are strongly affected by temporal climatic variability especially at a 1–5 year timescale (Noble 1997, Fensham and Holman 1999). However, the validity of relying on the approximately hundred year instrumental record has been questioned by the reconstruction of longer rainfall records using paleoproxy evidence from coral fluorescence at the mouth of the Burdekin River in northern Queensland (Lough 1991). This analysis suggests climate variability on longer time scales, with evidence of drier 10-year and 30-year periods in the 1800s compared to the 1900s. Similarly in the 1900s, the period of 1920 to 1950 is generally recognised as relatively dry. These cycles associated with the Inter-decadal Pacific Oscillation (Power *et al.* 1999). It could be argued that changes in the tree-grass balance in woodlands could occur when major shifts of increased grazing pressure and periods of above average rainfall coincided (e.g. 1890s, 1970s). Modelling the impact of climate, fire and grazing pressure on the growth of trees and grasses in the eucalypt woodlands may clarify whether climate variation can induce a change from open grassland to woody domination in the absence of human influence through domestic grazing and management of fire regimes.

If the proliferation of woody vegetation in the grazed eucalypt woodlands of Queensland were part of a cycle of drought-induced tree death followed by slow recovery, evidence of past cycles would be expected in the stable carbon isotope ratios of soil organic matter. The C_3 and C_4 pathways of photosynthesis discriminate differently against the heavier isotope resulting in the characteristic $\delta^{13}C$ signature of C_3 ($\delta^{13}C \approx -27‰$) and C_4 ($\delta^{13}C \approx -14‰$) plant organic matter which is preserved in litter and soil organic matter providing a 'marker' of past composition. Results of an initial survey of sectioned soil cores (to 1 m depth) from sites in the grazed woodlands suggest a consistent dominance of C_4 grasses until the recent increase in C_3 productivity (Burrows *et al.* 1998), but no evidence of past phases of woody domination. Analogous C_4 $\delta^{13}C$ signatures in soils beneath invading C_3 *Prosopis* spp. in the desert grasslands of the south-west USA measured in conjunction with radiocarbon dating of the same carbon by Boutton *et al.* (1999) support the view that increase in woody C_3 vegetation is a recent (last 100 years) phenomenon.

Grazing – Grazing by livestock preferentially depletes grasses relative to taller woody species, influences dispersal of seeds, alters the soil composition and structure, and is generally accompanied by a reduction in fire frequency and/or intensity. There is less fine grass fuel for burning and often active fire exclusion.

Increase in the woody component of savannas and grasslands has been observed to follow the introduction of domestic grazing (Madany and West 1983). Jeltsch *et al.* (1997) concluded that increased grazing intensity with the introduction of domestic cattle in the arid grasslands of southern Africa led to woody shrub encroachment and that this occurred under all rainfall conditions once stocking rates exceeded a threshold determined by long-term mean annual rainfall. Evidence that stocking rates have increased in excess of long-term sustainable carrying capacities since the 1970s has been shown for selected Queensland shires (Tothill and Gillies 1992). This increase was associated with retention of stock due to a rapid decline in international beef markets (1974), introduction of a cattle species (*Bos indicus*) better adapted to the harsh environmental conditions (1960s), and increased adoption of dry season feed supplementation (1960s, 1980s) (Ernst *et al.* 1975). Once the increase in trees and shrubs in woodlands and grasslands has been triggered, grazing pressure on the associated pasture inevitably increases, even if stocking rates are kept constant because of the negative curvilinear relationship between woody plant basal area and pasture yield (Burrows *et al.* 1990).

Fire – Fire can cause death of live trees, reduction in leaf canopy (thus affecting photosynthetic capacity and productivity) and/or removal of dead trees. Hence change in fire frequency can affect both live and dead tree biomass pools with the impact dependent on the intensity and seasonality of the burn. With the introduction of domestic livestock, wildfires are generally actively suppressed and fuel-reduction burning excluded to preserve grass for grazing. In addition, reduction of the amount and continuity of 'fine' fuels limits the opportunity for fires in grazed areas. Reduced fire frequencies have been implicated in the invasion by trees into grasslands in south-east Queensland (Fensham and Fairfax 1996). Fensham (1990) found the accession of dominant eucalypts from suppressed ground layer to saplings was statistically enhanced by 10 years of fire protection at a monsoon tropical site. Conversely, increasing fire frequency from triennial to annual burns has been shown to markedly increase mallee eucalypt mortality in western New South Wales (Noble 1989, 1997).

While increased atmospheric CO_2 concentration and climate affect growth and establishment of woody plants, the conclusion from numerous observations in arid and semi-arid savannas and woodlands globally is that a shift in the tree-grass balance towards a more woody structure is most likely triggered by intensification of grazing and suppression of fire (Scholes and Archer 1997, van Auken 2000).

Anecdotal evidence supports a link between the measured increase in woody biomass stocks in Queensland's woodlands and the reduction in fire frequency with introduction of domestic livestock but there are as yet insufficient data to establish a causal relationship between thickening and changed fire regimes. In the absence of comprehensive data we rely on mainly anecdotal reports of decreased fire frequency in the grazed woodlands but we know that since the 1940s machinery and equipment developments have greatly improved landholders' capacity to control or suppress fires. The natural fire frequency was estimated at every 1 to 3 years (Walker 1981), and management by tribal Aborigines probably resulted in more frequent burns (Pyne 1991). Observation of fire scars at woodland permanent monitoring sites and discussions with landholders indicate that present fire frequency at these sites is in the range of one fire every 10 to 25 years (Department of Primary Industries, unpublished). Survey statistics suggest that less than 30% of Queensland non-corporate broad-acre landholders currently use fire for woody plant control (ABARE 1999), supporting the notion of relatively low fire frequency.

To clarify factors determining the structure of woodland ecosystems in Queensland, further examination of the age and size-class distribution of the woodland communities in relation to the long-term climate, fire, and management histories is required. Proxy data such as charcoal records or evidence from tree rings or other growth cycles (Ward *et al.* 2001) may supplement photographic and anecdotal evidence of fire history in these regions. In addition, evidence from comparison of regularly burnt plots with those having long term fire suppression may be used to document responses in woody biomass and soil carbon stocks with fire suppression. Supporting evidence has been obtained from experimental plots in temperate (Tilman *et al.* 2000) and tropical African (Bird *et al.* 2000) savannas. These studies will support decisions on how much of Australia's forests and woodland area should be included in an inventory of human-induced carbon stock change for estimating greenhouse gas emissions and removals.

Kyoto Protocol accounting for land use, land-use change and forestry

Land use, land-use change and forestry activities will be included in accounting for the Kyoto Protocol if it enters into force, but in a less comprehensive way than in the NGGI prepared for UNFCCC reporting. Article 3.3 of the Kyoto Protocol deals with fluxes from areas of afforestation and reforestation arising from direct human action since 1990 on lands that were not forested on 1 January 1990. Credits are received for increases in carbon stock over commitment periods, the first of which is from 2008 to 2012. Areas deforested since 1990 are also measured but again only as stock changes during commitment periods.

For the first commitment period countries may nominate which if any Article 3.4 additional activities from the broad categories of forest management, grazing land management, cropland management and revegetation they wish to count. For forest management, credit is given for all increases in stock arising from direct human management activities that have occurred since 1990. There was no reference to increases in the rate of uptake compared with the base year of 1990, thus a ceiling was placed on sequestration credits able to be gained from forest management for each country (Appendix Z, UNFCCC 2001). Australia accepted a zero credit for forest management. Credits for the remaining three additional activities use 'net-net' accounting i.e. the difference in annual flux between the commitment period and the base year. Once land is counted under Article 3.3 or 3.4, it remains in the accounting process for subsequent commitment periods. For countries like Australia, areas in these broad categories are large and changes in carbon stock densities may be small and difficult or costly to monitor (e.g. soil carbon in grazing lands). In addition, the magnitude and sign of the sink of these management activities will be affected by environmental and management factors, including wildfire, climate variability and climate change. The maintenance of sinks under future climate change may be determined largely by the response of heterotrophic respiration to global warming (Valentini *et al.* 2000, McMurtie *et al.* 2001). A further complexity is that the principles included in the Marrakech Accords state that the effects of indirect human factors (increased atmospheric CO_2 concentration, nitrogen deposition and age structure of forests) should be factored out of accounting. At present the scientific community has not determined how this can be achieved.

Article 3.7 provides for those countries, for which land use change and forestry was a net source of emissions in 1990, to count the emissions from land use change in the 1990 baseline for the purposes of estimating the assigned amount in the first commitment period. Thus, the higher the emissions from deforestation in 1990 and the greater the reduction in the commitment period relative to 1990, the greater the contribution to meeting the emissions target and the lower the abatement effort required from other sectors. The current reported emissions for 1990 LUCF are 80.5 million t CO_2-e (AGO 2001a) which means that Article 3.7 is triggered so adding 103.5 million t CO_2-e to Australia's baseline for the first commitment period. However, the Australian Government has yet to finalise the 1990 baseline inventory that will incorporate the revised estimate for LUCF. Burrows *et al.* (1998) have argued that the large sink due to vegetation thickening in the grazed woodlands should have been included in the inventory of anthropogenic greenhouse emissions. If included it would have been important in determining whether LUCF in Australia was a net source or sink in 1990 and hence the target negotiated by Australia in 1997 for the first commitment period under the Kyoto Protocol.

One area of greenhouse accounting that is under review internationally is that of degradation of forests. Through the IPCC, definitions and methodologies for reporting greenhouse emissions from human-induced degradation of forests are being examined. Vegetation management policy allows for permits to be issued for thinning of grazed woodlands to restore them to their former productivity. If there were a future requirement for Australia to report greenhouse emissions from this thinning an asymmetry in accounting would arise unless the anthropogenic component of the thickening sink were also reported.

Managing carbon stocks in Queensland's rangelands

A continued high rate of clearing of native vegetation is now widely accepted as a major issue for ecological sustainability and biodiversity regionally and globally (for example, Glanznig 1995), and it is probable that future natural resource management will include consideration of land clearing. Internationally, the UNFCCC has called on countries to recognise the synergies between the convention on climate change and conventions on biodiversity and desertification. The role of international climate change agreements in influencing regulation of land clearing and development of native vegetation management policy in Australia is not yet clear. This is partly due to the complex interactions between ecological, economic and social considerations, and partly due to the uncertainty in the science of climate change and greenhouse accounting, and in international agreements and domestic greenhouse policy.

Reduction in clearing of native vegetation in Australia has been widely discussed as a low-cost greenhouse gas abatement measure with wider environmental benefits (for example, ACF 2001). The challenge for scientists providing policy support and for government agencies dealing with natural resource management is to ensure ecological and economic sustainability in management of landscapes, often against a background of scientific uncertainty.

Options for management of natural resources for greenhouse benefit

Recognition in international climate change agreements of the role of terrestrial ecosystems in influencing global carbon balance may provide an additional value to native vegetation retention. However, the value of carbon as a tradeable commodity will likely remain uncertain until the Kyoto Protocol or an alternative international agreement with legally binding emissions targets and provision for trading in emissions permits and carbon sequestration credits enters into force.

Native vegetation management in Queensland is supported by State policies for vegetation management on freehold and leasehold land (Queensland Government 2000a, 2000b) with objectives to maintain biodiversity, ecologically sustainable productive potential and use of the land, and ecological processes. These objectives are consistent with understanding of the role of the terrestrial biosphere in the global carbon cycle. The Queensland Greenhouse Policy Framework (Queensland Government 2001) recognises that retention and planting of native and exotic forests and adoption of best practice farming and grazing techniques have the potential to significantly reduce greenhouse gas emissions. The National Greenhouse Strategy (NGS) (Commonwealth of Australia 1998) promotes greenhouse sinks and sustainable land management including developing and giving effect to national principles for sustainable management and retention of native vegetation (Measures 6.4 and 6.5).

Preserving or enhancing carbon stocks in rangelands can be considered as three broad activities:

1. Reduction in the rate of clearing of forests and woodlands for non-forest use;

2. Protecting and enhancing soil carbon stocks through management to reverse deteriorating land condition and protect against future land degradation;

3. Increase in standing biomass through tree planting or assisted establishment of native vegetation on previously cleared areas.

1. *Reduced land clearing*

Vegetation management policy restricts clearing of *endangered* ecosystems (<10% original extent remaining, or remnant vegetation of <10000 ha and 10-30% remaining) on freehold and leasehold lands and *of concern* remnant ecosystems (10-30% original extent remaining, or remnant vegetation of <10000 ha and >30% remaining) on leasehold lands and includes provision to protect areas vulnerable to degradation (Queensland Government 2000a, 2000b). The impact of the introduction of the *Vegetation Management Act 1999* on the rate of clearing will not be clear until land cover change analyses for periods after 1999 have been completed. There are large areas of wooded vegetation remaining in Queensland potentially able to be cleared, and the area of *not of concern* conservation status cleared in 1999 represented only 0.2% of the remaining *not of concern* remnant vegetation (Wilson *et al.* 2002 [this Volume]) (Table 1).

Options for reducing land clearing (and hence associated greenhouse emissions) within the period of one to two decades relevant to the first Kyoto Protocol commitment periods have been openly debated in the media. These options include voluntary agreements between government and landholders for a cap on total remnant clearing or financial incentives to retain vegetation (see for example *Australian Financial Review* 24 August 2000, *Queensland Country Life* 16 Nov. 2000, *The Courier Mail* 27 April 2001, *The Australian* 31 July 2001).

2. *Enhanced soil carbon stocks*

A major determinant of soil carbon levels in rangelands is grazing pressure (Ojima *et al.* 1993). Grazing affects carbon and nutrient cycling to the soil, partitioning of above- and below-ground carbon, soil temperature and compaction, disturbance of surface soil and infiltration characteristics. Heavy utilisation results in loss of perennial grass cover. Management to restore cover including adjusting stocking rates for climate variability (Ash *et al.* 1995, Johnston *et al.* 2000) is likely to have a positive impact on both productivity and soil carbon sequestration. In the degraded grazing lands of northern Australia, adoption of reduced stocking rates has been estimated to have the potential to increase carbon sequestration in the top 10 cm soil by 0.24 t C/ha/a, a total of 315 million t C, over 30 years (Bolin and Sukumar 2000).

Table 1. Annual clearing rate (1997-1999) expressed as a percentage of the total area of each conservation status still present in 1999. This clearing occurred prior to the Vegetation Management Act (VMA) (1999). (Data derived from Wilson *et al.* 2002 [this Volume]).

VMA conservation status	1999 annual clearing expressed as a % of total remaining area		
	Total	Freehold	Leasehold
Endangered	4.5	7.3	2.0
Of Concern	2.8	4.9	1.2
No concern	0.2	1.0	0.1
Remnant	0.3	1.5	0.1

Grazing land management, cropland management and revegetation e.g. saltbush and leucaena planting for fodder, are eligible additional activities under the Kyoto protocol if parties elect to count them in the first commitment period. Although these activities could provide significant soil carbon sequestration for parties electing to count them, the issues discussed above relating to monitoring costs, variability and permanence of the potential sink need also to be considered. If the Protocol enters into force, Australia's decision on ratification and the inclusion of grazing land management in accounting is likely to impact on future vegetation management decisions in Queensland's grazed woodlands.

3. *Afforestation and Reforestation*

Direct human-induced tree planting on land not forested in 1990, including agroforestry, environmental tree planting, e.g. for salinity or erosion control, and plantation establishment for timber or aesthetics, will be eligible sink projects under the Kyoto Protocol. The carbon sequestration may be counted under Article 3.3 (reforestation or afforestation). Plantings since 1 January 1990 that do not meet the area or size thresholds in the definition of forest can potentially count as revegetation under Article 3.4. Carbon sequestered in eligible forests under the Protocol may also potentially be traded in an international emissions trading scheme. Expectations of the value of carbon credits have been lower since the withdrawal of the U.S. from the Kyoto Protocol and acceptance of liberal allowances for sinks in Marrakech effectively reduced demand and increased supply of carbon credits. However, trading in carbon credits outside the Kyoto Protocol has already occurred and may continue. The Australian Government has stated that a mandatory domestic trading scheme will not be introduced until a) the Kyoto Protocol enters into force, b) Australia has ratified the Protocol, and c) there is an international trading scheme:
(http://www.greenhouse.gov.au/emissionstrading/).

The potential value of carbon sequestration credits in meeting possible international obligations and as a tradeable commodity may combine with other commercial or environmental benefits to influence management decisions by landholders. To facilitate investment in carbon sequestration credits, it is necessary to have a) legal recognition of carbon rights, b) an accepted standard for carbon accounting and third party verification of accounting, and c) a trading framework or agreed contract. Steps towards establishing the requirements for trading of carbon credits in Queensland have been made. Legal recognition of carbon rights on freehold land in Queensland was introduced in the *Forestry & Land Title Amendment Bill 2001* that establishes the rights for carbon on freehold land as a *profit a prendre*. Carbon sequestration rights on freehold land may now legally be registered on the land title as a commodity that can be traded. Standards Australia is developing an interim Carbon Accounting Standard to give confidence to both project proponents and prospective investors in carbon sequestration credits in afforestation and reforestation projects.

Conclusions

International concern about the risks of human-induced climate change is likely to result in a future economy that is 'carbon-restricted'. Management to increase carbon stocks in the terrestrial biosphere has the potential to offer cost-effective, short-term greenhouse abatement options to enable time for development of technologies to reduce total fossil fuel emissions. Against the background of international agreements to reduce greenhouse emissions there is likely to be increasing pressure on landholders in Queensland to reduce rates of tree clearing to increase carbon stocks in landscapes and also to provide additional environmental benefits such as biodiversity protection and prevention of land degradation. Improved scientific understanding of the dynamics of carbon in natural and managed ecosystems, and of the impacts of climate variability and climate change on ecosystem function will reduce the uncertainty in estimates of greenhouse emissions and the potential savings in emissions from activities such as reduction in clearing. Research and measurements are addressing key areas of uncertainty in greenhouse accounting for land-based activities including for land cover, land cover change, land use, carbon stocks of existing vegetation, and response of soil carbon and belowground processes. In Australia, there is a commitment through the National Carbon Accounting System and the Cooperative Research Centre for Greenhouse Accounting to improve the capacity to monitor land-based greenhouse stocks and fluxes.

The ultimate objective of greenhouse science and international climate change agreements is a reduction in global greenhouse gas emissions to achieve the UNFCCC objective of preventing dangerous anthropogenic interference with the climate system. The UNFCCC states that this objective *should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.*

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