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technical report no. 3

Woody Biomass: Methods for Estimating Change

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WOODY BIOMASS
METHODS FOR ESTIMATING CHANGE

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EXECUTIVE SUMMARY

The brief for this Consultancy was to assess the utility and quality of existing data, methods and techniques for 14 specific components of the estimation of biomass needed to address the 1990 baseline year requirements of the Kyoto Protocol. In addition, we were to consider the potential of emerging technologies for future improvements in the data needed to meet Australia's international obligations.

We have determined that data for the following components are readily available, although they may not always be accessible for political or commercial reasons:

- age class of plantations;
- growth increments of plantations;
- area of commercial plantations;
- area of plantations harvested; and
- area of plantations established.

For the following components, the information is difficult to obtain, but the contribution of the component to the 1990 baseline is so minor that approximations should be adequate:

- fuelwood extracted from managed forests;
- likely time to maturity, and biomass at maturity, of environmental plantings; and
- area of environmental plantings.

For the remaining components, to improve current estimates significant additional information and analysis is needed:

- growth increments of managed native forests no longer available for harvest;
- biomass removed, or put into decay, by previous land clearing;
- proportion of forest cleared that was mature and proportion that was regrowth;
- age and rates of accumulation of 'recleared' areas (i.e., regrowth that is being cleared);
- expansion factors, from rounded volume or wood product, to estimate total biomass removed and total biomass left to decay on site; and
- methods to calculate a continental biomass stock.

In most cases the missing information is related to improving knowledge of the allometric relationships between measurable attributes or available information and biomass. It is our view that precision of the final estimates hinges on two areas: the assigning of net primary productivity values to the various vegetation classes; and the partitioning of biomass to above- and below-ground. We believe that these areas, together with methods for quantifying the precision of estimates, should be given priority in the near future. Significant improvements in process modelling and satellite data collection systems over the next decade can be expected to allow major improvements in biomass estimations. It is these areas where most future work is needed.

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1.1 Likely time to maturity and biomass at maturity of environmental plantings

Determine from literature search and expert opinion the physiological age at maturity of a representative set of species commonly used in environmental plantings.

- From the allometrics literature or ground sampling, determine the biomass of mature individuals of a range of species commonly planted for environmental purposes.
- For typical arrangements of plantings, such as those for shelterbelts and salinity amelioration, determine typical biomass densities (i.e., tonnes / ha).
- Where environmental plantings are extensive, such as for salinity amelioration or carbon offset, support establishment of permanent growth plots and other forms of monitoring.

1.2 Age class of plantations

- Determine the age classes of plantations in 1990 from the NPI data.
- Check these data against the Carron Report and with growers. Patch gaps in knowledge, for example, areas that were harvested between 1990 and 1995 and not regenerated.
- Check whether information from the NFFI can provide estimates for small plantations existing in 1990.

1.3 Growth increments of plantations

- Ask growers to supply annual volume increment figures for 1990. To avoid duplication and maintain grower confidence concerning confidentiality, this would best be done through the NPI.
- Where this is not forthcoming, with knowledge of areas by age classes of plantations by NPI Regions, calculate total annual volume increments using the Indicative Yield Tables in Turner & James (1997). Volumes harvested should be estimated separately.
- Convert net total volume increments to biomass increments using allometric relationships from consultancy or literature.

1.4 Growth increments of managed native forests no longer available for harvest

- Request information – where, when, forest types and disturbance history – from State Forest agencies on annual transfers of forest to National Parks or other permanent reserves.
- Enquire from these authorities whether growth data are available, either from access to permanent plots or from yield tables.
- Establish relationships between volume and biomass, where necessary by sampling.
- Convert volume increments to biomass increments using allometric relationships.
- Investigate use of physiological models to provide biomass estimates from estimates of net primary production obtained via remote sensing.

2. LOSS OF BIOMASS

2.1 Biomass removed, or put into decay, by previous land clearing

- On the basis of literature and experimental evidence, determine the appropriate lag time for decay, recognising this may differ for different regions of the country.
- Evaluate Graetz's (1998) methodology by independent enquiry, and compare with alternatives such as using TM data as in the ALCC Project.

- Determine through a trial whether sampling over space and time would be more cost-effective than full censusing for decay attributes.
- Analyse data from remote sensing for land use change and estimate total area of change by region.
- Collect more data on biomass densities in areas currently being cleared and develop appropriate allometric relationships to estimate the total biomass cleared in each of the years up to 1990.
- Reduce this on a regional basis by the amount estimated to have been burnt immediately following clearing and the amount remaining as charcoal (carbon).
- Determine proportion of land cleared by various methods.
- Determine appropriate decay functions on a regional basis.
- Apply these to each year's estimate of biomass available for decay to obtain cumulative biomass loss due to decay in 1990.

2.2 Proportion of forest cleared that was mature and proportion that was regrowth

- Determine how long a period prior to 1990 should be considered for identifying recleared areas.
- Obtain suitable annual satellite data for the period prior to 1990.
- Map the areas of clearing in 1990 by annual differencing of TM or MSS images.
- By examining previous images, check whether cleared patches had been formerly cleared.
- Determine proportion of forest that had been recleared.

2.3 Ages and rates of accumulation of 'recleared' areas (i.e., regrowth that is being cleared)

- Determine age of regrowth cleared in 1990, either from aerial photographs, anecdotal information or, using sequential satellite imagery, by matching with areas previously cleared.
- Determine whether the Queensland biomass densities for recleared areas can be applied to other areas, through sampling where reclearing is still being conducted.
- If necessary, develop regional indicative yield models to determine the cleared biomass.
- Explore the potential of process modelling as opposed to indicative yield tables.

2.4 Expansion factors from rounded volume or wood product to estimate

(a) total biomass removed
(b) total biomass left to decay on site

- Ensure that the Allometrics Consultancy provides the means to estimate biomass from a large variety of input variables, for example, basal area at 0.3 and 1.3 m height, merchantable volume and canopy closure. If not, identify gaps and take steps to fill them.
- Search literature and canvas fire experts and state forestry agencies for information on debris following harvesting, relate it to harvesting methods and market circumstances on a regional basis, and derive factors.
- Apply factors to volumes (biomass) removed as products in harvesting in managed forests to gain estimate of total biomass removed in harvesting operations.

2.5 Fuelwood extracted from managed forests (native and plantation)

- Poll State Forest agencies and firewood merchants for estimates of fuelwood taken from managed forests.
- Use this information to deduce removals from private native forests and plantations.
- Convert from mixture of wet and dry tonnes to dry tonnes (biomass).
- Consult with ABARE / ABS to determine best way to collect relevant information in the future.

3. MAPPING OF BIOMASS

3.1 Methods to calculate the continental biomass stock

- Ensure that comprehensive independent accuracy assessments are carried out on the Graetz and ALCC mappings of continental vegetation, circa 1990.
- To produce the best possible map of 1990 woody vegetation, compare area and spatial estimates, by aggregated Carnahan types, from the various sources, then determine reasons for discrepancies and correct for them.
- Determine which vegetation types are lacking in representative biomass information and organise the collection of aerial and ground-based data according to a well-conceived multi-stage or multi-phase sampling scheme.
- Consider applying a factor to biomass estimates to account for different growth stages within strata.

3.2 Area of environmental plantings

- Determine the time horizon over which environmental plantings should be considered and also whether it is necessary to consider plantings that are not detectable in satellite data.
- Verify the accuracy of the ALCC mapping of environmental plantings.
- If it is considered desirable to supplement the satellite data, develop sampling strategies for acquiring the additional information.

3.3 Area of commercial plantations

- Determine areas of commercial plantation using the 1990 Structural Vegetation Maps from the ALCC Project.
- Compare digitally or visually with the NPI maps and check discrepancies with growers.
- Produce a map of commercial plantations for 1990.

3.4 Area of plantations harvested

- Request from growers, preferably through the NPI, information concerning harvesting which occurred in 1990.
- Consider checking grower information against TM data but realising that identifying harvesting by thinning will be difficult.

3.5 Area of plantations established

- Request from growers, preferably through the NPI, details of areas of new and re-established plantation created in 1990.
- Check the status of previous land use by reference to earlier TM data.

INTRODUCTION

Increasing concentrations of greenhouse gases in the atmosphere led to the development of the United Nations Framework Convention on Climate Change (UNFCCC) in 1994. The international negotiations that followed led to the Kyoto Protocol in 1997 under which developed countries agreed to targets to reduce their greenhouse gas emissions.
On ratification, the Protocol will require Australia to limit annual emissions in the commitment period, 2008-2012, to a maximum of 8% above 1990 levels.

Under the UNFCCC, Australia is required to prepare annual inventories of anthropogenic emissions of greenhouse gases by sources, and removals by sinks. Under the Protocol, by about 2001 when ratification is anticipated, Australia is required to present data to establish the level of carbon emissions in 1990. Because Australia is claiming that the Land Use Change and Forestry (LUC&F) Sector was a net emitter in 1990, it is essential that a "robust, transparent and verifiable record" of emissions and removals for land based sources and sinks in that year be prepared prior to 2001 (Australian Greenhouse Office 1998).

The Australian Greenhouse Office established a National Carbon Accounting System (NCAS) to help meet these requirements. The first stated objective of the NCAS is "to provide a database of Australia's land based sources and sinks of greenhouse gases, in CO_2 equivalents, to determine a baseline account of the 1990 stock of carbon in Australian terrestrial ecosystems and its rate of change" (ibid 1998).

Various workshops, conferences, publications, and research and development projects have confirmed that emissions in the Land Use Change and Forestry (LUC&F) Sector (see below) are multi-faceted and that determining the magnitude of stocks and fluxes is complex. However, it has also become clear that new technologies provide the means for significant improvements in estimating emissions and removals of carbon. Some of these methods have been put into place as responses to other national concerns such as sustainability and biodiversity protection. Thus, there are not only new technologies available, and enthusiasts with conflicting views, but potentially useful new data have already been collected. This consultancy arose out of a realisation that some collation and evaluation were needed before further resources were expended to collect new data or develop new methods.

COMPONENTS OF THE LAND USE CHANGE AND FORESTRY (LUC&F) SECTOR

The LUC&F Sector encompasses stocks and fluxes resulting from change in the woody vegetation of the landscape. Woody vegetation may be removed for agricultural or urban development, or as part of the cycle of harvesting for timber products. Cleared areas may be permanently put into pasture or cropping, or at some stage woody vegetation may regrow and be cleared again. Cleared vegetation is often burnt, so that some of it is immediately volatilised into greenhouse gases. A small proportion may be used as products such as farm posts and rails. However, much remains to decay over time, slowly releasing carbon to the atmosphere, or is converted into charcoal, which is highly resistant to decay and becomes incorporated into the soil carbon stock.

Harvesting of timber crops from forests results in removal of some of the biomass from the site to be sequestered into materials with various rates of carbon release. Nevertheless, considerable quantities of the above- and below-ground woody material is left behind to decay or be burnt, either purposely or accidentally. Deliberate burning may be for hazard reduction or to produce suitable conditions for regeneration and is therefore an important consideration in both emission and sequestration of carbon. Generally, forest will be re-established either naturally or artificially on these sites. In many countries, though not to a large extent in Australia, wood may also be removed from these managed forests for fuel which, when burnt, results in loss of CO_2 to the atmosphere.

New forests may be established on historically longterm agricultural lands. If they are established after 1990 ('Kyoto forests'), they may be included in carbon accounting for the Protocol. These plantations may be for commercial purposes or to achieve environmental amelioration or aesthetic improvement of the landscape. There is considerable political interest in these in Australia, not only for their carbon-sequestration role but also for a stronger timber and pulpwood resource base for industry, and for soil and climate amelioration.

A feature of land use change in Australia in recent decades has been the transfer of managed forest to conservation reserves. Until they reach ecological maturity, such forests will continue to be sinks for carbon.

The quantification of all these components on a national scale is daunting. The information available to quantify the stocks and fluxes for 1990 is highly variable in quality. Data vary from virtually non-existent to available but in units that have to be converted to biomass. Prospects are better for gaining information on most components in the future.

THE CONSULTANCY BRIEF

We were not required to comment on all components of the system but on those that appeared to be either exceptionally significant or exceedingly perverse. Specifically we were asked to consider issues related to:

1. Accumulation of biomass

- likely time to maturity and biomass at maturity of environmental plantings;
- age class of plantations;
- growth increments of plantations; and
- growth increments of managed native forests no longer available for harvest.

2. Loss of biomass

- biomass that would have been removed or been put into decay from previous land clearing;
- proportions of forest cleared that were mature and proportions that were regrowth;
- age and rate of accumulation of 'recleared' areas (i.e., regrowth that is being cleared);
- expansion factors from rounded volume or wood product to estimate total biomass removed and total biomass left to decay on site; and
- fuelwood extracted from managed forests.

3. Mapping of biomass

- methods to calculate the continental biomass stock (not just forest biomass)
- area of environmental plantings;
- area of commercal plantation;
- area of plantations harvested; and
- area of plantations established.

The brief was to prepare a report which:

- assesses the utility and quality of existing data, methods and techniques against each of the issues;
- considers the potential of emerging techniques and the required resources and time-lines associated with developing emerging methods/techniques;
- incorporates the results of consultations with industry and researchers; and
- proposes a summary plan of action for data collection and methods development to address the issues.

We were directed to specifically address these questions with respect to meeting the requirement to produce improved estimates for the 1990 baseline year, but also to comment on how high quality data might be achieved for the commitment period and beyond. Our recommendations apply mostly to achieving better 1990 data.

In order to gather initial impressions of the scope of the issues and the range of ideas on how to address them, we began the consultancy with a two-day workshop ('The Biomass Workshop') which was attended by 25 invited experts on various aspects of the problem. The list of attendees is appended to this report. Following that we met with five others who had been invited to the Workshop but were unable to attend. The principal consultant also made a one-day visit to the Queensland Department of Natural Resources. An earlier draft of this report was circulated to most of the above and comments were received from a number of them.

The report has been prepared by the principal consultant, Dr Brian Turner, and the subcontractor, Dr Kim Wells, but they wish to acknowledge the valuable assistance provided by the other ANU consultants, Professor Peter Kanowski and Drs Jürgen Bauhus, Geoffrey Cary and Cris Brack, attendees at the Biomass Workshop and those consulted since, and our AGO contact, Dr Gary Richards.

1. ACCUMULATION OF BIOMASS

1.1 LIKELY TIME TO MATURITY AND BIOMASS AT MATURITY OF ENVIRONMENTAL PLANTINGS

In a forest situation, maturity of an individual tree may be indicated by flattening out of the crown, and negligible growth in height and bole diameter. Increasing rates of decay and litterfall disintegration result in the mature tree having negligible net biomass increment. In shelterbelts or open grown situations, however, trees may continue to accumulate biomass for some time after their crowns appear mature. Typically, because there is more light available to them and lower branches are retained, trees in environmental plantings will take significantly longer to reach steady-state biomass condition than those in commercial plantations. Increasing maturity also results in a re-apportionment of biomass, e.g., more to flowers and fruits.

Data and methods

The likely time to maturity of environmental plantings will vary widely depending on the species, climate, arrangement of plantings and care given. The general climate can be inferred from the location, but historical information is needed to determine the other factors. Biomass at maturity might be established for small planted areas by sampling on a per tree basis, and for large plantings by extrapolation from local plantation wood production (yield) models where they exist.

Frequently, environmental plantings will be on less than optimal sites because their purpose is to ameliorate the site conditions. So, while time to physiological maturity for a radiata pine in a commercial plantation might be 50 years, shelterbelt pines in a windswept dry environment may not reach steady state in twice that time. Similarly, it is likely that for many eucalypt tree species the time to biomass maturity is of the order of 60-100 years or more, whereas for acacias and shorter-life trees and shrubs it will be less.

Biomass at maturity varies with the species – reflected in both tree size and wood density of components – planting formation and site.
In many cases it will be difficult to translate biomass to a value per hectare as the trees may be scattered irregularly or be arranged linearly. In some cases biomass per hectare may be inferred from canopy cover estimates (e.g., from satellite data) but this would require careful calibration using ground based measurement techniques ranging from destructive sampling to collection of basal area and height data. It is unlikely that relationships developed for commercial plantations or native forests will have much relevance: relationships may have to be established for specific arrangements of trees. Some allometric work indicates that relationships are not heavily species specific (de Gier & Sakouhi 1996) so it may be possible to estimate biomass even when species or even genera are not known. However, other workers in North America suggest that there are significant differences when large diameter trees of different species are compared (C. Brack, pers comm).

Under the new ‘Bush for Greenhouse’ program, active support is to be provided for the collection of information about biomass and carbon accumulation in carbon-offset plantings. This should enhance knowledge about time to maturity and biomass at maturity of environmental plantings.

Assessment

There is little empirical information on the time to maturity and biomass at maturity of environmental plantings that would be of use for estimating the 1990 flux. Such information could be collected now by sampling for major plantings. However, environmental plantings would not have been a major component of the 1990 flux and significant effort to gain improved estimates is probably not warranted.

Recommendations

- Determine from literature search and expert opinion the physiological age at maturity of a representative set of species commonly used in environmental plantings.
- From the allometrics literature or ground sampling, determine the biomass of mature individuals of a range of species commonly planted for environmental purposes.
- For typical arrangements of plantings, such as those for shelterbelts and salinity amelioration, determine typical biomass densities (i.e., tonnes / ha).
- Where environmental plantings are extensive, such as for salinity amelioration or carbon offset, support establishment of permanent growth plots and other forms of monitoring.

1.2 AGE CLASS OF PLANTATIONS

Areas of plantations of both softwoods and hardwoods in Australia at mid decade and end of decade can be calculated from five-year planting classes reported in the National Plantation Inventory (National Forest Inventory 1997). More than 90% of the area of plantations in Australia is thought to have been covered by this inventory, derived mostly from information supplied by growers. Small plantations, such as farm woodlots, were not covered, but are being targeted by the recently begun National Farm Forestry Inventory (NFFI). The area planted according to age class for most of Australia's plantations in 1990 can be derived from the NPI. As a check, a report on Australia's forest resources has been compiled for the Australian Forestry Council by L. Carron (Forest Resources Committee 1989), which also gives age by 5 year classes up to 1985. Information on areas planted since 1995 depends on the NPI being updated, which is presently intended at five years intervals. As a further check, an approach can be made to large public and private sector plantation owners, who are likely to keep an annual register of their plantation estates.

Assessment

Generally, data are adequate for estimating the age classes of plantations as they existed in 1990. The only gaps are likely to be for small areas on farms, not included in the NPI. These should be picked up in the new NFFI and it will be possible to back-estimate the 1990 age class information.

Recommendations

- Determine the age classes of plantations in 1990 from the NPI data.
- Check these data against the Carron Report and with growers. Patch gaps in knowledge, for example, areas that were harvested between 1990 and 1995 and not regenerated.
- Check whether information from the NFFI can provide estimates for small plantations existing in 1990.

1.3 GROWTH INCREMENTS OF PLANTATIONS

Regional growth rates for plantations in the broad, 'wood bowl' regions of the National Plantation Inventory are available as a result of work by Turner and James (1997). Plantation growth figures are also in James *et al*. (1995). More precise growth rates for individual plantations and possibly even for different site classes within plantations would be known to larger growers, and indeed would have been used to compile volume figures supplied to the NPI. However, these figures are 'in confidence', that is, not to be reported publicly unless aggregated with others at least regionally. Ample information is thus available to estimate volume growth rates for plantations to several levels of refinement according to need. These can be converted to biomass through allometric relationships that are fairly well known, especially for the major plantation species, radiata pine (Baker *et al*. 1984).

Assessment

Existing information is adequate for estimating volume growth increments for 1990 plantations, although use of some of the data may require the permission of growers. Reasonable allometric relationships exist for the major plantation species. No new field data collection appears warranted for this component.

Recommendations

- Ask growers to supply annual volume increment figures for 1990. To avoid duplication and maintain grower confidence concerning confidentiality, this would best be done through the NPI.
- Where this is not forthcoming, with knowledge of age classes of plantations by NPI Regions, calculate total annual volume increments using Indicative Yield Tables in Turner and James (1997). Volumes harvested should be estimated separately.
- Convert net total volume increments to biomass increments using allometric relationships from consultancy or literature.

1.4 GROWTH INCREMENTS OF MANAGED NATIVE FORESTS NO LONGER AVAILABLE FOR HARVEST

These forests comprise National Parks (or other conservation reserves) which were Managed National Forests (MNFs) until recently. It is assumed that these forests are progressing towards steady state and are actively sequestering carbon, unlike longterm reserves where sequestration is taken to be negligible. Clearly, forests should be included as MNFs until such time as they reach steady state. This may be anything from a decade to a century or more depending on the type of forest and intensity of silviculture previously practiced (selection or clearfelling). Although there have been transfers of forest from State Forest into National Parks since they were first established, the major shifts have occurred since the decision to conserve rainforest in NSW in 1982. This may be of the order of a million hectares by the time all Regional Forest Agreements (RFAs) have been negotiated. In the future there may also be some shifts of private MNFs to reserve.

Data and methods

In order to estimate the contribution of such forests to carbon sequestration in 1990 and beyond, it is necessary to know the types of forests, their growth stages and when the forests were transferred from the managed forest system to reserve. This information should generally be available from previous managers.

Growth increments might best be considered on a regional basis. In some cases it may be possible to determine increment by re-measuring permanent plots established in the forest before it changed conservation status. However, in most cases it will be necessary to assume increment will be similar to that for managed forest, of the same or nearly the same type, for which growth estimates are available. Assumptions about the time to reach steady state may have to be made on a regional basis, and then the transition modelled. There will usually be information about these forest areas, because often they will have been assessed before they became reserves. Some knowledge of species composition will be required so that assumptions can be made about wood density, in order to convert volume to biomass, and about merchantability standards, if the volumes are in merchantable units. The possibility of using dendrochronology to estimate past growth should be kept in mind. This is being used in conjunction with the Victorian Statewide Forest Resource Inventory to gather growth data where no permanent plot data exist, and has also been used in Western Australia (Rayner 1992).

The further development of physiological models based on remotely sensed data may make possible their use for determining the biomass of these forests. However, they will require field calibration, possibly from an enhanced network of permanent plots which could be the same as those established for soil carbon monitoring.

Assessment

Information on which forests should be considered as MNFs no longer available for harvest in 1990 should be available from State Forestry agencies. Information on volume increments should be just as readily available and in most cases the previous management agencies would be able to provide estimates without further field data.

However, allometric relationships between volume and biomass, both above- and below-ground, are lacking for many forest types, and will need to be established from field sampling. Exceptions are the ash forests of Victoria (Grierson *et al*. 1991– above-ground only) and some southern NSW forest types.

Recommendations

- Request information – where, when, forest types and disturbance history – from State Forest agencies on annual transfers of forest to National Parks or other permanent reserves.
- Enquire from these authorities whether growth data are available, either from access to permanent plots or from yield tables.
- Establish relationships between volume and biomass, where necessary by sampling.
- Convert volume increments to biomass increments using allometric relationships.
- Investigate use of physiological models to provide biomass estimates from estimates of net primary productivity obtained via remote sensing.

2. LOSS OF BIOMASS

2.1 BIOMASS REMOVED, OR PUT INTO DECAY, BY PREVIOUS LAND CLEARING

The estimation of CO_2 emissions due to land clearing must take into account not only the biomass burned in that year, but also the CO_2 released from decay of material left from clearing in previous years. It is important to take residues from previous clearing into account. Graetz (1998) estimates that around 40% of the total emissions from clearing over the period 1981-1990 resulted from lagged emissions, that is, those from decay of woody material and oxidation of organic matter in the soil.

The only exact method of estimation would be to partition the biomass cleared each year into biomass lost through burning, above- and below-ground residue, and any longer-lived products such as posts, rails and house stumps, and apply some decay function to this residual biomass. The number of years that the decaying component contributes would depend on the type of vegetation, the wood properties, presence of termites, the climate, and the position in which the wood is decaying. Wood in contact with the soil will decay faster than suspended material. Thus, the form of clearing – whether trees are felled or poisoned and left standing, or windrowed – will be an important determinant of the decay rate. Decay could take 50 years or so in the brigalow region of Queensland, where much of the current clearing is underway. However, if it is assumed that the decay function is negative exponential (i.e., in any given time step equal proportions of the remaining mass are lost, which results in initially high losses that gradually decline), the effect could be negligible after, say, 10 years.

It is known that sapwood decays rapidly, even in durable timbers. However, there is very little information on the pattern and time of decay of coarse litter from Australian woody vegetation. The rate and form of the decay function is the subject of a separate AGO consultancy with the Department of Forestry, ANU. An evaluation of the available literature carried out as part of that consultancy indicated that, in more than two thirds of all studies, the turnover time of coarse woody litter (the time until 95% of mass is lost) was more than 50 years.

Data and methods

To estimate the biomass that would have been removed or put into decay by clearing of woody vegetation prior to 1990 requires a time series of frequent snapshots showing vegetation cover over the whole continent. This can only be obtained from satellite data. NASA launched the first earth observing satellite in 1972, but information for the whole of Australia is available only from about 1980. Graetz (1998) used data from the Landsat MultiSpectral Scanner (MSS) (0.4 ha resolution) to estimate land clearing between 1982 and 1990 on a continental scale. He used a modelling approach based on rainfall and temperature to estimate above and below ground biomass prior to clearing via a median biomass figure for each MSS scene (Graetz 1999, pers comm). He believes that his method of change detection – selecting scene pairs of similar sun angle, normalising one to the other, differencing red responses and thresholding them – is effective and accurate in detecting clearing, but less so in detecting regrowth. Sensitivity analysis on the threshold levels suggests that they are robust. Some work is still in progress to determine whether the ‘speckle’, i.e., change within a single isolated pixel, is real or anomalous.

Graetz found some difficulty in separating clearing for agriculture from changes seen in the managed forest due to logging. Imposing a map layer that identifies forests by tenure, as available from NFI, should help overcome this problem. Further improvement might result from using a mask of woody vegetation, now available from the ALCC Structural Vegetation Map (see later), to concentrate analysis on that component. Graetz does not believe that the extra resolution and additional bands of TM data would improve the results obtained with MSS data, but Queensland and Western Australia researchers have found the mid-infrared band of TM to be useful for classification.

The second major change detection analysis was the ALCC Project, for the period 1990-1995 (described later), in which Landsat Thematic Mapper data (0.1 ha resolution) were used to map the change in land cover down to 1 hectare. Each State had different ancillary data sets to assist their analyses, so methods varied.

The most precise way to estimate CO_2 emissions associated with clearing would be to determine the total biomass cleared and its dispersal for each year up to the reference year. This would require a very large amount of computer processing and several analyst years. Despite employing the best processing systems, the analysis of remotely sensed data cannot be completely automated, and the input of knowledgeable resource analysts is indispensable if quality results are needed. Identifying all clearing on an annual basis would be quite difficult since many changes will be small in area and subtle, even though the differences in reflectance values might be very large for individual pixels. In addition, there will be difficulties in getting cloud-free scenes that coincidentally show maximum difference between woody vegetation and senescent grasses. However, for the purposes of estimating decay loss from biomass remaining after previous clearing, it may be sufficient to use sampling, although there are difficulties in establishing a reasonable stratification scheme. High rates of clearing in one timeframe will not necessarily be a good predictor for clearing in that area in future. Undertaking a census every 3-5 years could be a more efficient use of resources.

Clearing is often followed by burning and a portion of the biomass is converted immediately to greenhouse gases. Part of what remains is pure carbon with very slow decay rates. These proportions are likely to vary regionally, depending on type of vegetation, climate and clearing regime. Graetz (1998) makes some estimates of these proportions on a continental basis. In earlier estimates, time for decay of the residual fraction was assumed to be 10 years and linear, but in most vegetation types it is likely to be negatively exponential and much longer than a decade. A simple method for estimating parameters of the exponential relationship is suggested by Graetz (1998). However, it is unlikely that a single decay function for one regional vegetation type will be acceptable. The position in which the wood is left to decay – standing, suspended, charred, windrowed, or in soil contact, depending on the clearing method – strongly influences the decay rate, as does climate and the nature of decay organisms. Improvements on current crude models will require significant further research.

Assessment

Assuming exponential decay functions, a decision is needed on the number of years prior to 1990 for which clearing data is needed. Availability of remotely sensed data may preclude going back more than about 10 years, although coverage of some areas may be available from 1972. A decision must also be made on whether annual data is needed prior to 1990. We would suggest that a cost-benefit trial be conducted in a suitable region, sampling over space and time for decay quantification and comparing the results with those from total censusing. In the same trial, Graetz's method could be compared with ALCC methods. Once relationships have been determined, clearing from years prior to 1990 can be estimated as readily as those in the baseline year and subsequently. This would involve differencing pairs of annual images, using, for example, the criteria set up by Graetz (1998), or methods used by the states in the ALCC Project, and subsequent improvements.

Estimation of biomass removed in clearing prior to 1990 is another area for which empirical data are few. A reasonable first estimate would be current levels, for which there are survey data, for example, from the TRAP System in Queensland (Back *et al.* 1997). Nevertheless, it is likely that adjustment must be made for the fact that, even in one region, clearing practices and the type of vegetation involved will have been different prior to 1990. Clearly, there is a need for more empirical information on biomass densities in the regions where clearing is being practiced and on past vegetation management practices.

The estimation of rates of decay and how they vary across site and management attributes is a long term project and it is unlikely that there will be significant improvements in current estimation procedures in the next few years. Graetz's algorithm is simplistic, but an improvement on the current straight-line method. The suggested cost-benefit trial could include a component for determining whether the parameters of Graetz's model can be linked to management / site attributes.

Recommendations

- On the basis of literature and experimental evidence, determine the appropriate lag time for decay, recognising this may differ for different regions of the country.
- Evaluate Graetz's (1998) methodology by independent enquiry, and compare with alternatives such as using TM data as in the ALCC Project.
- Determine through a trial whether sampling over space and time would be more cost-effective than full censusing for decay attributes.
- Analyse data from remote sensing for land use change and estimate total area of change by region.
- Collect more data on biomass densities in areas currently being cleared and develop appropriate allometric relationships to estimate the total biomass cleared in each of the years up to 1990.
- Reduce this on a regional basis by the amount estimated to have been burnt immediately following clearing and the amount remaining as charcoal (carbon).
- Determine proportion of land cleared by various methods.
- Determine appropriate decay functions on a regional basis.
- Apply these to each year's estimate of biomass available for decay to obtain cumulative biomass loss due to decay in 1990.

2.2 PROPORTION OF FOREST CLEARED THAT WAS MATURE AND PROPORTION THAT WAS REGROWTH

It has been estimated that 42% of clearing in central Queensland is of regrowth (Carter *et al.* 1998), that is, vegetation that has been previously cleared and has grown back. This estimate is based of examination of three TM scenes and is not representative of all clearing. Nevertheless, it suggests that reclearing can be significant. Consequently, a substantial proportion of the land being cleared does not carry biomass at the mature rate but something significantly less. A second implication is that it may be claimed that land which is cycling between clearing, regrowth and reclearing is under a sustainable land use and is not a net emitter.

Data and methods

Estimation of the proportion of forest cleared that was mature and that which was regrowth in 1990 will firstly require identification of the areas and times of clearing. Methods for doing this from remotely sensed data are dealt with elsewhere in this report. To determine whether the land had been previously cleared, it is necessary to decide how far back before 1990 to look for previous clearing. Even though the practical problems are significant, if annual or at least frequent coverage by remotely sensed data is available, it is theoretically possible to examine the earlier status of each cleared patch. It is likely that this could not be done automatically on a pixel basis, so patches of clearing would have to be identified and their previous land use category determined. In some cases it might be possible to determine or check the previous status from historical records or anecdotal information.

Assessment

To define areas that have been recleared, annual sequences of remotely sensed data will be needed. For pre-1990, archived Landsat TM or MSS data is generally available for the continent back to about 1980, but may be patchy prior to that time. Procedures have been developed by State agencies to estimate change under the ALCC Project and an evaluation of the results is underway. However, some States, notably Queensland, have enhanced their capabilities and experience since that project. There seems to be no major technical impediment, but the logistics and need for human intervention in the decision processes suggest that the method will be expensive and require close monitoring.

Recommendations

- Determine how long a period prior to 1990 should be considered for identifying recleared areas.
- Obtain suitable annual satellite data for the period prior to 1990.
- Map the areas of clearing in 1990 by annual differencing of TM or MSS images.
- By examining previous images, check whether cleared patches had been formerly cleared.
- Determine proportion of forest that had been recleared.

2.3 AGES AND RATES OF ACCUMULATION OF 'RECLEARED' AREAS (I.E., REGROWTH THAT IS BEING CLEARED)

For the proportion of the land being cleared that does not carry biomass at the mature rate but something significantly less, actual biomass is dependent on the period and nature of the seasons since clearing, and the type of vegetation.

Data and methods

To help determine the range of regrowth biomass which might be encountered in reclearing, data similar to that collected in the 'TRAPS' program in Queensland (Back *et al*. 1997) is needed from other parts of the country. From an operational point of view, there is a minimum biomass (reflecting time elapsed since clearing) for reclearing. If biomass is too low, the regrowth is not dense enough to impede crop or pasture growth and thus warrant clearing. This may mean that the variation in recleared biomass is less than that of initial clearing, therefore fewer samples will be needed.

It is likely that both the mode and purpose of clearing have a bearing on biomass. To establish whether the type of clearing practice in 1990 was the same as that currently practiced, anecdotal information may be needed. Such information should be sought from local sources (e.g., the Western Lands Commission in NSW), and a decision reached on how to sample. This decision should also take into account differences in soil and vegetation type.

Based on these samples, regional yield tables showing the relationship between biomass and time since clearing could be developed for ecosystems different from those encountered in Queensland. The general form of this relationship should be sigmoid. However, in semi-arid regions growth is opportunistic and the relationship between age and biomass may not be very strong. It is possible that, after calibration, a process model, such as the latest form (3PG-Spatial) of the Physiological Processes for Predicting Growth model (Landsberg & Waring 1997), could provide the kind of estimates needed.

Another method might be to adopt a hybrid approach that uses a process model to stratify the landscapes into units within which empirical yield tables can be applied.

Assessment

If sequential satellite data are collected for delineating recleared areas, assuming the clearing event triggers the regrowth, the age of regrowth will be easily determined. This could be confirmed from records. For most regions, indicative yield tables will have to be constructed for ecosystems where reclearing occurs. If the range of biomass removed from recleared areas is relatively narrow, with quite minor additional ground sampling from areas currently being cleared, an average value for different regions could be established. A trial should be conducted of the applicability of appropriately calibrated, existing process models, either to directly estimate regrowth biomass or to create a stratification for sampling.

Recommendations

- Determine age of regrowth cleared in 1990, either from aerial photographs, anecdotal information or, using sequential satellite imagery, by matching with areas previously cleared.
- Determine whether the Queensland biomass densities for recleared areas can be applied to other areas, through sampling where reclearing is still being conducted.
- If necessary, develop regional indicative yield models to determine the cleared biomass.
- Explore the potential of process modelling as opposed to indicative yield tables.

2.4 EXPANSION FACTORS FROM ROUNDED VOLUME OR WOOD PRODUCT TO ESTIMATE:

(a) total biomass removed

Allometric relationships between volume and biomass are the concern of another AGO consultancy that is unfinished at the time of this report. It is assumed that the consultants will relate biomass to roundwood volume or units of converted wood product such as sawn timber. Total biomass removal could thus be estimated by applying an expansion factor to wood removals according to ABARE statistics. The factor might be region and / or species specific.

(b) total biomass left to decay on site

The implication is that there is some relationship between the volume of products removed from a forest during harvesting and the amount of debris left to decay on site. To some extent this could be true, but the amount of debris will depend on the silvicultural system (e.g., clearfelling vs selection cutting), condition of the forest prior to harvesting, harvesting method, utilisation intensity and whether fire is used. State agencies sometimes assess biomass from the point of view of fuel loads, or amount of woody material that may potentially inhibit regeneration or harvesting of future crops in public forests, but such data are unlikely to be representative of all forest types, and usually include only fine fuels.

Assessment

The expansion factors used in earlier estimates that convert commercial volume measurements to biomass estimates are very approximate and improvements are desirable. Relationships between stem volume and total biomass for the major forest types in Victoria are reported by Grierson *et al.* (1991). There appears to be little data on biomass left to decay on sites after harvesting and more research is needed.

Recommendations

- Ensure that the Allometrics Consultancy provides the means to estimate biomass from a large variety of input variables, for example, basal area at 0.3 and 1.3 m height, merchantable volume and canopy closure. If not, identify gaps and take steps to fill them.
- Search literature and canvas fire experts and state forestry agencies for information on debris following harvesting, relate it to harvesting methods and market circumstances on a regional basis, and derive factors.
- Apply factors to volumes (biomass) removed as products in harvesting in managed forests to gain estimate of total biomass removed in harvesting operations.

2.5 FUELWOOD EXTRACTED FROM MANAGED FORESTS (NATIVE AND PLANTATION)

The amount of fuelwood used in Australia is relatively small compared with that in other countries and comes mainly from the cooler southern parts of the country. For reasons of accessibility, species preference and moisture content, most firewood is harvested from dead trees on semi-cleared farmlands rather than from managed forests.

Data and methods

Statistics on the amount of fuelwood harvested, particularly its sources, are difficult to gather. Fuelwood can be cut under permit on most public lands and leases managed by State Forest agencies, but usually the permit specifies only a general area in which to operate and perhaps a maximum quantity. This applies to both native forests and plantations. Perhaps half the firewood cut from managed forests comes from private forested lands and illegal operations in public forests. Nevertheless, fuelwood cut from managed forests would be less than that taken from farmlands where large isolated dead trees are an easily accessible source of dry wood. ABARE now collects information biennially on ‘energy wood’, meaning charcoal production, and ABS collects information on fuelwood consumption in their household survey (Love, pers comm). Several years ago, in connection with a proposal for fuelwood plantations in the ACT, a study was done of fuelwood use by Canberra households.

It would seem that the amount of fuelwood extracted from managed forests is not very large. If it appears worthwhile, a sample survey could be undertaken of fuelwood operators in major population centres in southern states. This would indicate the level of commercial activity, but would not yield an accurate total figure since it is likely that individuals also collect an equivalent amount or more each year. The latter would be difficult to survey unless it is done as part of the periodic census of households. The relevance to the 1990 baseline of data collected currently would have to be assessed.

We are aware of only one instance of long-term, localised, well-documented removal of fuelwood from any managed forest in Australia in recent years. This was mainly of jarrah wood blocks for conversion to charcoal for pig iron production at Wundowie in WA. The Wundowie processing plant closed down in the early 1980s.

At one stage the softwood processing plant in Mt Gambier, South Australia, generated electricity for both its own purposes and for feeding into the town grid. However, wood used in the boilers was from manufacturing plant waste, not purposefully removed from the plantations. Softwood is not a favoured fuel for household use, although a small amount is collected. Again, firewood permits issued by state agencies would not be an accurate guide to the amount of firewood that is actually taken from softwood plantations. As hardwood plantations grow older and more extensive, the amount of fuelwood collected from them may be more significant than from softwood plantations.

Assessment

The contribution of emissions from fuelwood to the 1990 baseline is likely to be much less than that from other sources. It is probable that the amount of fuelwood extracted from managed forests is relatively small and almost impossible to quantify. The best sources of information are likely to be State Forestry organisations and fuelwood merchants. Provided these sources can provide some information, albeit with a high level of uncertainty, it would not be justifiable to expend large resources to improve the estimates.

Recommendations

- Poll State Forest agencies and firewood merchants for estimates of fuelwood taken from managed forests.
- Use this information to deduce removals from private native forests and plantations.
- Convert from mixture of wet and dry tonnes to dry tonnes (biomass).
- Consult with ABARE / ABS to determine best way to collect relevant information in the future.

3. MAPPING OF BIOMASS

3.1 METHODS TO CALCULATE THE CONTINENTAL BIOMASS STOCK

Two useful points emerged at the Workshop from discussions on methods to calculate the total continental biomass stock. The first was that high precision is not needed in estimating continental biomass stock for the 1990 baseline year. Graetz (1998) makes the point that as far as the UNFCCC and NGGI needs are concerned, "the issues of consistency and transparency in the reporting of biomass carbon pools are more important than accuracy (except for verifiability)". The second was that the mapping of woody vegetation at the continental level has been done a number of times, independently, over the last decade or so. Tabular information about the forest estate is also available and that might prove useful.

In order to calculate the continental biomass stock, the nationwide area of woody vegetation must be estimated and then related to biomass.

Data and methods

Area of woody vegetation

There have been several recent attempts to map the present vegetation of Australia, all using satellite data to at least some extent.

Carnahan's (1976) Natural Vegetation (Series 2) map of the continent was the culmination of five years part-time work using numerous existing regional vegetation maps, personal observation and widespread consultation. It showed the vegetation as it was believed to have existed pre-European settlement, classified by modified Specht structural categories and by dominant genus in both overstorey and understorey. The Present Vegetation map (AUSLIG 1990) shows the vegetation as it existed in 1980-85, using similar categories to those used for the Natural Vegetation map. This mapping was based largely on visual analysis of Landsat 1:1,000,000 false colour composites and was used, together with the existing Natural Vegetation map, to produce a new Natural Vegetation map (Series 3) at a scale of 1:5 million.

Based largely on interpreted Landsat data, Wells *et al*. (1984) produced a coarse-scale continental map of degrees of loss of forest and woodland since settlement. Graetz (1998) produced his maps of land cover change between 1981 and 1990, and since settlement, from comparisons of the AUSLIG maps with 1990 Landsat MSS data. For each scene, he used a subjectively chosen threshold on the red band to separate the woody component. No independent review of these products has yet been conducted.

Under the Agricultural Land Cover Change (ALCC) 1990-95 project managed by BRS, the States produced the Structural Vegetation 1990 Map (Kitchin & Barson 1998; Bureau of Rural Sciences 1999). Primarily, this work was undertaken to establish the types of vegetation cleared in 1990-1995, in order to allocate a biomass value for emissions estimates. The basic information used by all States came from Thematic Mapper (TM) data from the Landsat satellites. The eastern States used the M305 data set constructed by the Murray Darling Basin Commission (Ritman 1995). Although there was some difficulty in finding suitable imagery – partly because 1990 was a relatively wet year in eastern Australia and it was thus difficult to separate the spectral signature of trees from that of green pasture, forcing the eastern States to use some 1991 data – all States were able to get complete coverage of areas with woody vegetation. The States employed various methods to analyse the data, but rigid performance criteria were set for the map products (Kitchin & Barson 1998). Most States have completed their analyses, but checking of the WA map is still in progress.

Between 1995 and 1998, a comprehensive independent accuracy assessment of the M305 data was performed (Volframs & Wilkins 1998). The accuracy of Queensland mapping was found to be greater than that for NSW and some parts of SA. This was attributed to the methodology used: supervised classification was more successful than manual interpretation of clusters derived from unsupervised classification. An external accuracy assessment on land use change mapping is to be conducted in the near future.

The National Forest Inventory produced their map of Australia's forest resources in 1997. The NFI database is compiled from data sources of varying scales, ranging from 1:25,000 API to 1-km AVHRR. It is a multi-scale database designed to incorporate into a common framework the best available information for any location. M305 landcover data are incorporated into the NFI, as are many data sources in common with those used in the ALCC project.

The definition of forest (or woody vegetation) used in these projects is the same as that used in this consultancy. There are, however, large areas of 'woody weeds', especially in Queensland, that are not covered by this definition and thus not included in the total biomass estimate.

The most recent initiative in mapping Australia's vegetation is the National Vegetation Information System (NVIS) being developed under the National Land and Water Resources Audit, a program of the Natural Heritage Trust. The NVIS is designed to be a repository of vegetation information, including "a database describing present and pre-1750 vegetation, using existing information" at 1:100K for the Intensive Land Use Zone, to be completed by February 2000 (see Vegetation Management Theme-Work Plan, National Land and Water Resources Audit 1999).

For the time around 1990 the most reputable data set for the calculation and prediction of volumes is that gathered by the RAC Forest and Timber Inquiry (1990-92). This is actually made up of two data sets, one compiled by Zammit, entitled "A Survey of Australia's Forest Resources" (Resource Assessment Commission 1992), and another containing the information on age classes of forests used by the INFORM model to predict future commercial wood volumes. This data set superseded the statistics on Australia's forests published by the Forest Resources Committee (1989), sometimes called the Carron Report, which represents the best estimates of the State Forestry organisations at that time. By applying the RAC volume estimates to structural types within the NFI, BRS has produced a biomass map for commercial forest types. Extrapolation beyond this was not feasible.

Biomass Density

Given that actual ground measurements are restricted to a few areas of the continent, Graetz (1998) points out that there are two ways of estimating biomass. One method is to stratify the total area of woody vegetation into classes that are relatively homogeneous with respect to biomass, for example, structural vegetation types, and then attribute a biomass density, for example, tonnes per hectare, to each. The other is to use some kind of process model to estimate the amount and spatial distribution of biomass, predicted from known causal variables.

Graetz considered that a relationship could be established between above- and below-ground biomass density and the annual mean soil moisture index (AMMI), which is available for the continent at about a 25 sq km pixel scale via the BIOCLIM/ESOCLIM package developed at CRES at the ANU. The parameters for the relationship were estimated from existing (sparse) data and expert knowledge. It was shown that this at least gave spatially continuous estimates of biomass which in aggregate were relatively close to the NGGI estimates. However, studies elsewhere have shown that, unless disturbances such as fire are taken into account, this approach to the estimation of maximum potential biomass will overestimate actual biomass (e.g., Kurz *et al.* 1998).

In terms of biomass estimation, stratifying woody vegetation by structural categories is more useful than by floristics. Fortunately, it is relatively easy to detect broad differences in vegetative structure from remotely sensed data. The experience of the Murray Darling Basin study (M305 project) was that it was not feasible to achieve acceptable mapping success using the 20 or so Carnahan woody classes with Landsat TM data. Classes were therefore aggregated for the ALCC Structural Vegetation and NFI mapping. If appropriate allometric equations are available, biomass can be estimated via some measure of crown cover derived from satellite or aircraft data.

The degree of classification of vegetation in the ALCC Structural Vegetation 1990 map varies from State to State. Initially, attributes were to be given to contiguous areas of greater than 50 ha, but this has been reduced to 30 ha in some States. For the areas mapped under the M305 project, only density (crown cover classes), genus and growth form (tree, tree mallee, shrub, etc) are recorded. The minimum attributes for the new data set were to be the M305 attributes + height. NFI attributes (crown cover, genus and major species, growth form, height and biomass) were also acceptable (Kitchin & Barson 1998). However, no States included biomass in their Structural Vegetation data set and basal area is used as an attribute in Queensland only.

To use the stratification approach it is necessary to estimate an average biomass density for each of the strata (vegetation classes). When stratification does not include stage of development categories, this may be particularly difficult. To account for the lesser biomass present in managed forest, one solution may be to reduce biomass estimates for steady state forests in each category by a factor determined from subjective sampling within strata. Data to estimate biomass is available for Central Queensland (the TRAPS project) and from research projects in other, mostly commercial, forests. For example, the data collected by Keith in *Eucalyptus obliqua* forests and by Attiwill in *E. regnans* (Grierson *et al*. 1991).

If new data are to collected, as seems necessary for biomass density estimation, a stratification based on IBRA regions (Thackway & Cresswell 1995) would be logical, as these are designed to take into account broad bioclimatic differences. However, alternatives such as using BIOCLIM exist.

It is expected that the Allometrics Consultancy will provide some guidance on biomass estimation. Biomass prediction will have to handle a range of attributes for input to the allometric models. Inevitably, new field data will be required, to establish biomass levels in some strata and in different growth stages within strata, and to verify that estimates established for a stratum in one part of the country are applicable in another. A mixture of ground and aerial plots may prove to be optimal, with the number of aerial plots being much higher than the number of ground plots (multi-stage or multi-phase sampling). The intensity of sampling needed will depend on the precision desired. Aircraft (fixed-wing and rotary) fitted with laser altimetry (LIDAR) and cameras may provide the best means of gathering data from the air. Tickle *et al*. (1998) demonstrated the utility of such a system for collecting information on tree height, canopy density, stocking, growth stage and floristics. Such a system, when combined with limited ground calibration, offers the capacity to collect information at a fraction of the cost of traditional ground survey. In future, remotely sensed data might be used to detect life stage, but this would be difficult or impossible for 1990.

Data from forest management agencies will allow prediction of merchantable volumes from their ownerships, principally the publicly owned forests, and allometric relationships will be required to convert this to above- and below-ground biomass. Biomass on privately-owned MNFs may need to be extrapolated from that on the publicly-owned forests, using remotely sensed data to detect their life-stage, or perhaps from a process model such as 3PG-Spatial, calibrated by data from nearby public forest management plots. However, it is likely that past management on private MNFs will have been quite different from that on public forests and this will have affected growth rates. This difference would need to be taken into account in any modelling approach.

The input of satellite data to process models would be particularly important if they were used for predicting biomass in sub-climax, grazed woodlands, where models based on site potential, rather than actual growth, would be inappropriate.

Assessment

Given the existence of several mapping projects, it would not be cost effective to carry out a new continental vegetation survey based on remotely sensed data for the determination of carbon stocks in 1990. Instead, projects concerned with mapping continental vegetation at or about 1990 (often using partially common data) should be carefully evaluated and the most reliable data sets selected for estimating biomass. Where gross differences occur between data sources, either in the location of the vegetation or in its attributes, these should be checked by field or aerial reconnaissance and corrected. The sparsity of biomass density data suggests that resources need to be focussed on amplifying the distribution and intensity of this information, which is fundamental to developing knowledge of total carbon stocks.

Recommendations

- Ensure that comprehensive independent accuracy assessments are carried out on the Graetz and ALCC mappings of continental vegetation, circa 1990.
- To produce the best possible map of 1990 woody vegetation, compare area and spatial estimates, by aggregated Carnahan types, from the various sources, then determine reasons for discrepancies and correct for them.
- Determine which vegetation types are lacking in representative biomass information and organise the collection of aerial and ground-based data according to a well-conceived multi-stage or multi-phase sampling scheme.
- Consider applying a factor to biomass estimates to account for different growth stages within strata.

3.2 AREA OF ENVIRONMENTAL PLANTINGS

We have found no consistent records of environmental plantings, certainly none prior to 1990. Organisations such as Greening Australia do not have this information. Some Landcare groups might have some records, but there will be no consistency. The National Plantation Advisory Committee (1991) report lists programs promoting on-farm planting (Appendix C4) and there is a table (table 9, Appendix C5) which shows areas planted under various assistance schemes. However, environmental planting (categorized by Jones 1988) is not differentiated from commercial planting. In the past, surveys have been done in some States, but they have not been comprehensive (e.g., Jones 1988; Hassell & Associates 1998).

The ALCC project separated out environmental plantings (referred to as on-farm tree planting) from plantations of less than 20 hectares not in forest tenure. Problems in using satellite data, besides the small size of such plantings, are the time lags before such plantings show up on imagery, and the difficulties of distinguishing environmental plantings from commercial plantations, orchards or natural regrowth. The generally small size of environmental plantings is confounded by planting arrangement: they are often linear (shelterbelts, roadside plantings and riparian zones), making them difficult to distinguish on Landsat TM.

Interpretation of satellite imagery (Landsat TM or SPOT) will invariably give an underestimate of the area of environmental plantings, not only because of the problems mentioned above, but because there is also substantial risk of missing recent plantings because of lack of contrast with surrounding grass or vegetation. To help overcome the latter difficulty, scenes from dry months should be used in preference to scenes from wet months. However, this is not always possible to achieve – for example, it has been noted that 1990 was an especially wet year in eastern Australia.

Once verified, it would be sensible to link the ALCC data set with the NFI database, to provide, *inter alia*, a means of tracking which forests are 'Kyoto forests'.

In order to estimate biomass contributed by environmental plantings it will be necessary to know both their stage of growth and their real extent. It should also be decided how long prior to 1990 environmental plantings should be considered. A desirable period might be the time taken to reach maturity (i.e., steady state with respect to carbon emissions / absorption), but this is dependent on many factors. A more reasonable time might be that over which it is possible to have annual or frequent time sequence satellite data.

Assessment

There is little information available concerning the locations of plantings for environmental purposes in 1990. Areas previously established if of adequate extent have been recorded in the ALCC Structural Vegetation mapping as a separate class but many plantings will have been excluded because they were too small in extent or too narrow in shape. It is widely believed, however, that the role of environmental plantings in the 1990 flux is minor compared with other changes and that the expenditure of major resources to improve current C mapping of environmental plantings is not warranted.

Recommendations

- Determine the time horizon over which environmental plantings should be considered and also whether it is necessary to consider plantings that are not detectable in satellite data.
- Verify the accuracy of the ALCC mapping of environmental plantings.
- If it is considered desirable to supplement the satellite data, develop sampling strategies for acquiring the additional information.

3.3 AREA OF COMMERCIAL PLANTATIONS

Commercial plantations should be easily identified from Landsat TM data used by the ALCC Project to construct the Structural Vegetation Map 1990. They should be checked against the NPI report of 1997, which contains spatial information about an estimated 90% of the plantation estate in 1994. Where confusion exists, it should be relatively easy to get confirmation from growers. NFFI has just started collecting information about the smaller plantations not covered by the NPI: ALCC imagery may well be useful.

Assessment

Adequate information exists to estimate the area of commercial plantations in 1990 with reasonable certainty. The exception is small areas of plantation of less than a few hectares in size.

Recommendations

- Determine areas of commercial plantation using the 1990 Structural Vegetation Maps from the ALCC Project.
- Compare digitally or visually with the NPI maps and check discrepancies with growers.
- Produce a map of commercial plantations for 1990.

3.4 AREA OF PLANTATIONS HARVESTED

The best source of data on the location and extent of plantations harvested in 1990 is the compartment records of plantation owners and managers. These would also reveal the type and degree of harvesting. The accurate location of clearfelled areas could be confirmed by satellite imagery, by comparing 1989 and 1990 data, but the detection and mapping of thinned blocks is more problematic. Discriminating between non-commercial and commercial thinnings could be difficult, but is important in terms of biomass movement.

Assessment

Information on plantations harvested in 1990 could be determined from differencing remotely sensed data, but would be more easily obtained from growers, provided they are willing to release such information. It would seem unlikely they would withhold 1990 information. Data on areas thinned might be less easily obtained by either method.

Recommendations

- Request from growers, preferably through the NPI, information concerning harvesting which occurred in 1990.
- Consider checking grower information against TM data but realising that identifying harvesting by thinning will be difficult.

3.5 AREA OF PLANTATIONS ESTABLISHED

Statistics on plantations established in 1990, will include re-establishment planting, that is, replanting following clearfelling of the previous tree crop, and planting on land formerly used for agriculture or grazing, or which supported native forest.
Areas planted after 1989 on formerly cleared lands are especially important, since these constitute the so-called 'Kyoto forests' for which carbon credits may be claimed.

Details about area planted, and sometimes location, of post-1989 plantations would be available from growers' compartment records for larger plantations; however details for smaller commercial plantations, principally those on farms, may not be available. Where they are missing, data could be collected using sequential aerial photos or perhaps satellite imagery. A difficulty with the latter is that it may be five or more years after planting before new plantations are discernible.

Assessment

Areas planted in a particular year are not easily detected from remotely sensed data unless it has very high resolution (better than 1 m), and this was not available from satellites in 1990.
Such information would have to come from growers, but they would need to differentiate between new plantations and re-establishment.
In view of the 'Kyoto forest' implications, some growers may be reluctant to divulge this information for post-1989 new plantings.

Recommendations

- Request from growers, preferably through the NPI, details of areas of new and re-established plantation created in 1990.
- Check the status of previous land use by reference to earlier TM data.

4. FUTURE DATA COLLECTION SYSTEMS

4.1 REMOTE SENSING (SATELLITE) SYSTEMS

Many new earth-observing satellite systems have recently been launched or are about to be. These will provide enhanced capabilities for gathering information about woody vegetation, including the ability to infer both structural and floristic attributes (Turner *et al*. 1998). The following is a non-exhaustive summary of how they might be used in the future to assist in data gathering for vegetation mapping and biomass estimation. Frequently, a combination of techniques will provide optimal information.

The longterm multispectral capabilities of SPOT and Landsat have been enhanced with the latest launchings. SPOT 4 joined the earlier SPOT 1 and 2 in space in early 1998. Its sensors have the same spatial resolution as the earlier instruments – that is, 20 m for the green, red and near infrared bands, and 10 m for the panchromatic – but there is an additional shortwave infrared band which is already demonstrating improved capacity for discriminating between vegetation types. With three satellites in orbit, and their pointable optics, it is now possible to get daily three-dimensional coverage at this resolution on request. The VEGETATION instrument on SPOT 4 provides 1-km resolution data over four bands, chosen specifically for vegetation mapping.

Continuous Landsat Thematic Mapper (TM) coverage has been available in Australia since 1982. The launch of Landsat 7 in April 1999 means that continued Landsat coverage is ensured for at least the near term (Landsat 5 is still functioning). Landsat 7 carries the Enhanced Thematic Mapper (ETM), which provides the same data type as TM (i.e., 7 bands and 30 m resolution), with the addition of a 15 m panchromatic band for extra spatial definition.

High spatial resolution is promised for some private-sector satellites, one of which failed after launch in December 1998. These will have 1 to 5 m resolution but limited spectral bands. SPOT 5 will have 2.5 m resolution. The launch of an Australian satellite (ARIES) is being frustrated by lack of funding, but hope continues that it will be launched in the next few years. ARIES will have hyperspectral capability but 30 m resolution, making it potentially useful for improved floristic discrimination.
The MODIS instrument due to be launched by NASA in 1999 will have moderate hyperspectral capability, but spatial resolution of about 250 m.

The capabilities of radar from space have rapidly improved since the Radarsat-1 launch in 1995. Synthetic Aperture Radar (SAR) in multi-bands and polarisations is available from the European ERS satellites, and there are numerous examples of the use of satellite SAR data combined with Landsat or SPOT data. For instance, the use of SPOT, Radarsat and ERS data in inventorying Sarawak timber resources (Nezry & Demargne 1998), or recent testing of methods of mapping above-ground biomass of woodlands in Queensland using JERS-1 SAR and Landsat TM data (Lucas *et al*. 1998, 1999). The interpretation of forests using radar data alone has continued to be difficult, but the availability of a greater range of data has given analysts the means to try new techniques. There is promise that the ability of different radar bands to penetrate canopy to varying degrees will lead to the achievement of biomass mapping from space.

Spaceborne laser scanning is another technology that is close to fruition. The Vegetation Canopy Lidar (VCL) satellite is due for launching in August 2000. The VCL will sample the entire globe at 2 km intervals across track and continuously along track. The data will be able to be used for individual sites or gridded to 2 km resolution for the globe. In addition to direct measurement of ground elevation and tree height to 1m precision, the VCL will record the complete time varying amplitude of the return signal of each laser pulse, which is related to vertical canopy architecture. This will provide the potential to classify the successional stage of the forest. When combined with other satellite data, it may be possible to determine whether the greenness signal is coming from trees or from understorey flushes.

Lastly, extensive airborne LIDAR research is currently being undertaken by Queensland Department of Natural Resources and BRS. CSIRO EOC is currently developing ground-based LIDAR systems. BRS and CSIRO EOC are in the early stages of collaboration with the VCL program in relation to calibration and validation in Australia.

4.2 REMOTE SENSING (AERIAL) SYSTEMS

Normally, satellite-platform sensors are tested in aircraft, which makes the capabilities indicated above available at much higher resolutions. One metre resolution or less is available from multispectral digital cameras or video, and hyperspectral data can be captured by the Australian Hymap or Canadian CASI systems at 2 to 5 m resolution. These systems are ideal for capturing sample data where it is necessary to see individual tree crowns. Lucas *et al.* (1999) report on the use of NASA JPL AIRSAR data to establish relationships between different radar bands and biomass components in Queensland woodlands. In conjunction with LIDAR data, that can capture elevational information at high precision, it is possible to get accurate crown dimension and tree height information for biomass estimation. This is in addition to the routine aerial photography that has played, and continues to play, such an important role in describing and mapping Australia's vast landscape.

4.3 MODELS

It has been suggested above that modelling of changes in biomass stocks may be an appropriate approach, to extract information and reduce the intensity and frequency of ground-based or remotely sensed inventory. To estimate the volume increment of their forests, increment models have been developed by all State Forest agencies and large plantation growers. In most cases, these are highly sophisticated empirical models based on a network of repeatedly-measured sample plots. In some cases, Queensland for example, the estimation of biomass is built into these directly, and in other cases allometric relationships will need to be established to convert commercial volume to biomass.

However, for the vast proportion of the area of forest these data do not exist. For these it has been suggested that process models, driven by environmental variables and calibrated in various ways to account for different vegetation types and histories, have longterm potential. The best known models are probably 3PG (Landsberg & Waring 1997) and 3PGS (Coops *et al.* 1998), which uses satellite-derived data to set the initial conditions and environmental variables to drive the increments. In the last two years, these models have been implemented at local to continental scales in Australia and elsewhere. The models have now been integrated into a GIS environment and called 3PG-SPATIAL. While there is no doubt that the approach has demonstrated its potential, it has been calibrated for only a few species. Considerably more data and experimentation will be needed to make it useful for biomass accumulation prediction in the drier woodlands, especially where the driving variables may be different than those for the commercial forest areas.

4.4 GROUND SAMPLING METHODS

Recent developments in sampling theory are making possible much more efficient sampling of vegetation to estimate biomass. Probability sampling and importance sampling enable model-builders to collect data without bias in the parts of the population where it is most needed to develop allometric relationships. Similar approaches can be used to build sampling schemes that use a judicious combination of aerial and satellite data to provide estimates of biomass with a minimum of expensive field measurements. The best example of the use of these techniques is in the Victorian Statewide Forest Resources Inventory currently in progress.

4.5 OTHER VEGETATION MONITORING PROGRAMS

Attention has been drawn in this report to a number of Commonwealth funded activities which have resulted from a need for vegetation data at the national level. These include the AUSLIG Atlas of Australian Resources, the National Forest Inventory, National Plantation Inventory and National Farm Forest Inventory within BRS, the National Greenhouse Gas Inventory and various activities of ERIN within Environment Australia, and the recent National Land and Water Resources Audit's National Vegetation Information System.

Many forest inquiries which have contributed to the available data pool, not least the RAC Forest and Timber Inquiry and the RFA process, could also be listed.

In addition, each State has some responsibilities for monitoring land use change and vegetation mapping in their own jurisdictions. It seems inefficient that these activities all occur without much coordination, and each request for new information, such as biomass stocks, requires a new project to be instituted. There seems no logical reason why one of these existing programs should not be given the responsibility to acquire national biomass information and to produce the statistics required by the AGO on a regular and continuing basis. It is noted that neither NFI nor NLWRA, which currently has responsibility for providing this information, are permanent programs and the custodianship of these data should be in the hands of some enduring organisation.

5. CONCLUDING REMARKS

There is no doubt that improved methods and better data are now available to estimate the national woody vegetation stocks and fluxes for the 1990 baseline year and earlier. Fourteen different components of the complex system have been individually considered with respect to their capacity to provide data that is transparently determined and verifiable to the National Carbon Accounting System, in order to meet Australia's international obligations. Recommendations have been made for further data collection, model development or technology enhancement, to gather the required information for the base year 1990. In making these recommendations, care has been taken to balance the costs of new data against the value of that information, and to take into consideration the importance of the various components to the final estimates of carbon balance. It is emphasised that efficiencies can be gained by appropriate use of modern sampling theory and by minimising duplication of effort.

In terms of data for the 1990 baseline, we have determined that data for the following components are readily available, but may not always be accessible for political or commercial reasons:

- age class of plantations;
- growth increments of plantations;
- area of commercial plantations;
- area of plantations harvested; and
- area of plantations established.

For some components the information is difficult to get, but the contribution of the component to the 1990 baseline data is so minor that approximations should be adequate. These are:

- fuelwood extracted from managed forests;
- likely time to maturity and biomass at maturity, of environmental plantings; and
- area of environmental plantings.

For the remaining components, significant additional information and analysis is needed to gain improvement in current estimates:

- growth increments of managed native forests no longer available for harvest;
- biomass that would have been removed, or been put into decay, from previous land clearing;
- proportions of forest cleared that were mature & proportions that were regrowth;
- age and rates of accumulation of 'recleared' areas (i.e., regrowth that is being cleared);
- expansion factors from rounded volume or wood product to estimate total biomass removed and total biomass left to decay on site; and
- methods to calculate a continental biomass stock (not just forest biomass).

In most cases the information needed is related to improving knowledge of the allometric relationships between measurable attributes such as forest area, basal area and height of vegetation, or available information such as commercial volumes and the above- and below-ground biomass. This suggests that a detailed gap analysis is required to determine in which regions data are lacking, followed by a multi-stage national data collection effort to fill the gaps. Our preliminary investigation suggests that the major gaps relate to the freehold and leasehold forests of all states and, in particular, to the woodland forests cleared in 1990. The exception is Queensland, for which some data exist. A stratification on IBRA regions would provide a logical basis for field data collection.

It is our conviction, after consulting experts within Australia and the international literature, that the precision of the final estimates hinges on the attributing of net primary productivity values to the various vegetation classes, and the partitioning of biomass to above- and below-ground.

Further, inadequate attention has been paid to the estimation of the precision of biomass estimates, and to the evaluation of the propagation of error resulting from scaling up from tree to regional level, although the difficulty of doing this is recognised. We believe that these are the areas that should be given priority in the near future.

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GLOSSARY AND ABBREVIATIONS

AGO. Australian Greenhouse Office

ALCC Project. The Agricultural Land Cover Change Project, administered by Dr Michele Barson, in BRS.

Allometrics Consultancy. Consultancy called by the Australian Greenhouse Office to assess the data and methods available in Australia to convert measurements available for trees and forests to above-ground or total biomass.

AVHRR. Advanced Very High Resolution Radiometer, provides twice-daily data in several spectral bands at 1.1 km resolution.

Biomass density. The quantity of biomass per unit area (usually expressed as kg / m^2 or tonnes / hectare).

BRS. Bureau of Rural Sciences (formerly Bureau of Resource Sciences) of the Commonwealth Department of Agriculture, Fisheries and Forestry, Australia (AFFA) (formerly Department of Primary Industries and Energy).

CSIRO EOC. Earth Observation Centre of the Commonwealth Scientific and Industrial Research Organisation.

Environmental Plantings. For the purposes of this report, environmental plantings are defined as plantings of trees or woody shrubs which will achieve a height of 2 m or more and have been planted for purposes other than commercial gain. They include shelterbelts, plantings for salinity amelioration, ornamental or aesthetic plantings and agroforestry, where the returns from trees are incidental to the benefits in other respects.

Forest. Forest is defined here as woody vegetation having, at maturity, a ground cover of at least 20% and a height of 2 m or more. This is consistent with definitions used by the National Forest Inventory but may differ from that eventually adopted by the IPCC.

IPCC. Intergovernmental Panel on Climate Control.

Managed Native Forests (MNF). Managed forests are defined as "any forest subject to periodic or continuing human intervention that affects carbon stocks" (NGGI 1997). Managed native forests are defined here as native forests from which commercial wood products are periodically removed on a sustainable basis and which are legally and operationally available for such purposes. They include state and private forests containing native naturally-growing species. National Parks, conservation reserves and informal reserves such as streamside buffers for example are not MNFs.

Maturity. In this report maturity of a forest or tree implies a steady state with respect to biomass. Flattening out of the crown, negligible height growth and slowing down of bole diameter growth usually indicates the maturity of an individual tree. This is accompanied by increased decay and litter fall, resulting in negligible net biomass increment.

MSS. MultiSpectral Scanner, usually referring to that on the Landsat satellites.

NCAS. National Carbon Accounting System, Australian Greenhouse Office.

NLWRA. National Land and Water Resources Audit, a program of the Natural Heritage Trust.

NFFI. National Farm Forestry Inventory, a program of the Commonwealth Bureau of Rural Science.

NFI. The National Forest Inventory or the program of that name within the Commonwealth Bureau of Rural Sciences.

NPI. The National Plantation Inventory is a sub-program of the NFI.

NPP. Net Primary Productivity

RAC. Resource Assessment Commission, a series of enquiries conducted into major resource issues of the late 1980s-early 1990s set up under Commonwealth legislation.

Regrowth. Naturally regenerating vegetation on land previously partially or wholly cleared.

RFA. Regional Forest Agreement arising from the National Forest Policy Statement of 1992.

TM. The Thematic Mapper on the Landsat satellites.

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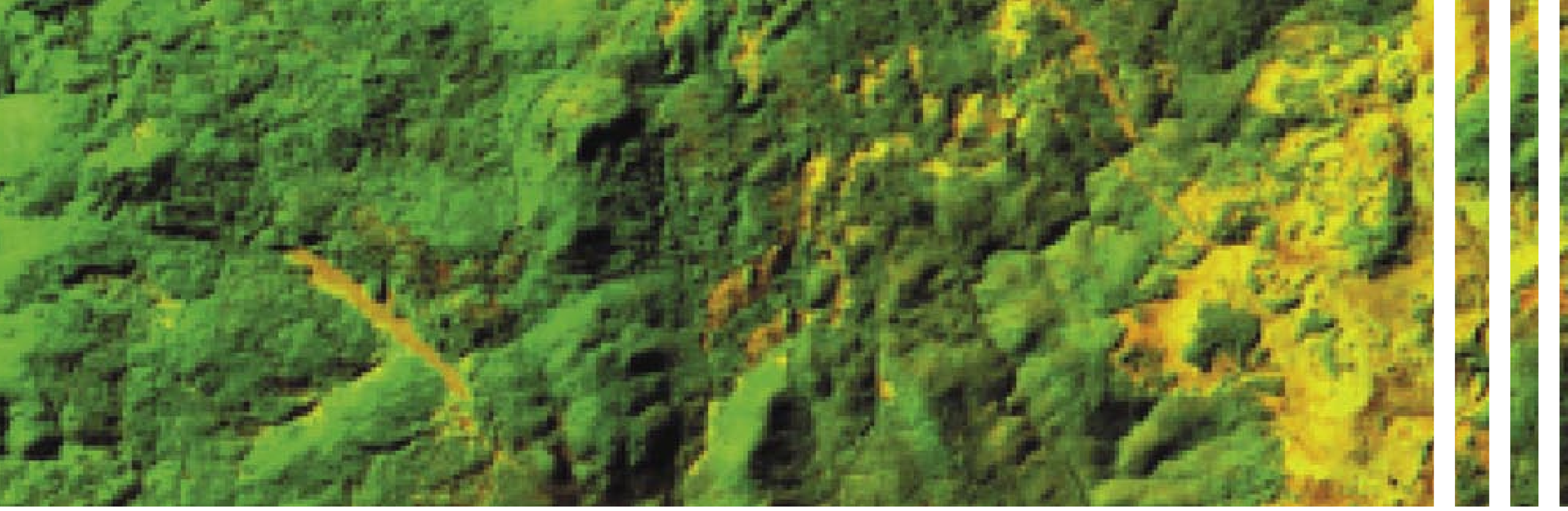
10. National Carbon Accounting System: Phase 1 Implementation Plan for the 1990 Baseline
11. International Review of the Implementation Plan for the 1990 Baseline (13-15 December 1999)



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