Article

Multi-scale Forest Inventory and Modelling for Multi-purpose Management

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ABSTRACT

Forests provide many goods and services and the demands for quality information about forests are continuing to increase. These demands include detailed information about an increasing range of forest characteristics and resources - both wood and non-wood based - on small, nominated units of land. For example, Kyoto-type carbon credit schemes operating at a high tier, and therefore in the most valuable markets, require precise and unbiased estimation of carbon pools in forests at specific sub-hectare locations. Simultaneously, landscape-level management decisions, especially those related to biodiversity, may require information about stand characteristics and their spatial distribution over thousands of ha or km². Historical approaches for forest inventory were often classified into strategic/national, operational/regional or tactical/local scales to support management decisions at corresponding scales. However, recent trends of increased attention to the role of even individual forests in local and global economies and environments - evidenced by international conventions and agreements like the Montreal Agreement or Kyoto Protocol, and international monitoring of specific areas of deforestation and degradation - has reduced the usefulness of the strategic/operational/tactical separation. Strategic decisions made during international policy negotiations may significantly affect tactical or on ground decisions on specific forested lands, while conversely good but independent tactical decisions may put strategic management goals at risk. Disagreement amongst inventories at the various levels (e.g. where the sum of tactical inventories does not equal the strategic inventory) increases the probability for conflict between strategic and tactical management decisions. This paper summarises the framework used in the National Carbon Accounting System (NCAS) developed by the Commonwealth Government of Australia to support policy-development especially in relation to global climate change and forests. The framework allows for the integration of information captured through long-term satellite sensing, physiological and empirical modelling, field-based measurements and regional "text" information. Although policy-development is obviously at a "strategic" level, the framework is flexible enough to also provide information at sub-hectare levels and supports seamless tactical decision-making as well. The information provided supports Commonwealth policy development and this paper demonstrates how NCAS also provides valuable information for other management purposes ranging from tactical management of fuelwood and farm timbers at the scale of individual farm forests, through to landscape-level structural diversity and biodiversity management.

Keywords: Carbon accounting, multi-scale inventory, forest management, forest biodiversity

INTRODUCTION

Forest inventory and sampling textbooks have long concentrated on precise and unbiased estimation of the mean tree or hectare in a forest (e.g. COCHRAN, 1977). Simple random and systematic sampling approaches have been in existence for over a century, and were used to estimate population means for the extensive tracks of forest land opening up during the development of the USA and Australia. Long accepted theory and practice allows these methods to include predictions of sam-

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pling error and therefore some certainty as to how close the estimated value is to the *true* population mean value. Many inventories are designed in terms of this sampling error around the mean. It was relatively unimportant that the yields in any one year or over any sub-set of the forest were not similar to the population mean because it was anticipated that once the whole of the land had been treated, the true mean would be within the sampling error bounds. The non-importance of the estimates for forest sub-sections however is no longer the case. Forest inventory questions may no longer relate to total population or even strata means, but rather need to relate to questions about specific, small areas of the forest.

The scale at which inventory data is relevant to decision makers has changed. NORTON *et al.* (1990) conclude that even national scale data may be used to resolve forest resource issues for areas as small as a 'few hectares', while RICHARDS and BRACK (2004a; b) note that sub-hectare spatial resolution may be necessary to meet international conventions such as those stemming from climate change negotiations and the Kyoto Protocol. LUND and IREMONGER (2000) state that nearly "all natural resource issues, whether they are environmental, social, economic, ecological or political, are national as well as global issues" and therefore continental scale information is essential to put even local and regional decisions in context. Thus, information collected during an inventory may have application for decision making over a wide range of scales.

The multi-scale issue was a dominant problem during the design of the National Carbon Accounting System (NCAS) for Australia. While specifically designed to provide for a robust national account of Australia's greenhouse gas emissions (i.e. national scale information), the system was also required to support location specific management and to deal with monitoring changes from pre-1990 land use change events (i.e. fine scale information) (BRACK *et al.*, 2006). An early finding in the development of NCAS was that national sample-based measurements of carbon stock or stock change at the scales necessary for location specific management or to deal with monitoring were not feasible (BRACK, 2007). In response, a model-based system was adopted where the biomass (and change) was predicted for each "analytical unit" (cell) across the country. Project, regional and national accounts can be determined by aggregating the appropriate cell estimates. These estimates are based on a hybrid model that integrates empirical and process modelling with remotely sensed data and information about historical and proposed land management. In addition to the estimation of mean or total greenhouse gas emissions over projects or regional scales, NCAS also provides fine spatial and temporal resolution and a framework for reporting a breadth of data (climate, soils, productivity, land cover and management information). This comprehensive data and modelling capability has not previously been available in a single system (BRACK *et al.*, 2006).

This paper outlines NCAS and provides examples of how the system has been integrated into forest inventory that sup-

ports forest management decisions at various scales.

NCAS DESCRIPTION

BRACK *et al.* (2006) provides a comprehensive description of NCAS. That paper also references some of the testing and model benchmarking for NCAS. There are essentially three major processes carried out for each analytical unit in the national coverage. The analytical units correspond to cells or pixels of about 625 m².

Identification of Woody Cover / Cover Change

Each unit is identified as "woody" or "non-woody" and any change between these states (i.e. trees removed or established) identified. The changes are identified from, currently, 18 national coverages of Landsat satellite data (MSS, TM, and ETM+) from 1972 to 2008 (CACCETTA *et al.*, 2003). Conditional probability networks are used to combine the information provided by this suite of temporal coverages and reduce the likelihood of mis-classifying a genuine change in woody cover (KESTEVEN *et al.*, 2003). The detection of non-woody to woody change allows the identification of a "starting point" from which new trees can be assumed to begin growing, while detection of the reverse change identifies the point where decay from the various biomass pools due to harvest or disturbance begins.

Determination of the Forest Productivity Index (FPI)

The FPI is a continuous variable ranging from 0–25 that is related to the potential net primary productivity (NPP) of a nominal tree species growing at a site for which it is well adapted. It is derived from a simplified or truncated version of the 3-PG (Physiological Processes Predicting Growth) model of LANDSBERG and WARING (1997). In essence, the maximum NPP at any point is related to the photosynthetically active radiation (APAR) absorbed by plant canopies, but this maximum may be limited by soil fertility, available moisture or temperature extremes. The productivity index is calculated for each unit over each month using monthly climate surfaces and national coverages of soil moisture holding capacity and fertility (BRACK *et al.*, 2006):

$$\text{FPI} = \text{APAR} \times T \times S \times W \times 0.01 \times (1 - F)$$

where T denotes a variable between 0 and 1 that reduces the potential FPI if the monthly temperature deviates substantially from a range of temperatures; S denotes a level of fertility (high, medium and low); these levels depend on soil type, before environmental modifiers are applied; W denotes a variable between 0 and 1 which is calculated from the most limiting factor of soil water content or vapour pressure deficit; and F denotes the ratio of the number of frost days per month to the number of days in the month. A long term average of the

Fig.1 Examples of national coverages produced by NCAS

monthly estimates of FPI was also determined as a general index of productivity (Fig. 1a). The complete version of 3-PG would require detailed species specific information to apportion the NPP into the various within-tree pools, but NCAS does not implement this part of 3-PG.

Estimate Biomass

The long-term (undisturbed) above-ground biomass at each unit is calculated from a correlation quantified between FPI and field measurements of biomass on undisturbed sites (RICHARDS and BRACK, 2004a) (Fig. 1b).

Where a change in the wood / non-woody classification has been identified for the unit, NCAS assigns a probable management regime for the unit using a region-based database of likely activities (e.g. proportion of the time land clearing was associated with post-felling burning or ploughing etc). The year of the change and the assumed activities are used as input into models that estimate the biomass in various pools and how these pools change on an annual basis through growth (proportional to the monthly FPI) or decay (RICHARDS and BRACK, 2004b) (Fig. 2).

USING CONTINENTAL COVERAGE DATA

While NCAS has developed national coverages for the FPI and certain other layers, the identification of disturbance is not available over the entire nation. Instead, disturbance identification has been prioritised towards regions of land-use change that will influence the national accounts for carbon sequestration / emission and reporting under the Kyoto Protocols.

Therefore coverages of disturbance on areas where there is no land-use change, e.g. harvesting on forest land which will remain as forest land, is not available. As a surrogate for this disturbance information, the following examples used measures of projected foliage cover (%) (PFC) derived from multiple satellite images or classifications of canopy structure derived from aerial photograph (API) determination. It was anticipated that, for a given FPI, a PFC close to 100% relates to forest stands with low and/or non-recent levels of disturbance, while PFC closer to 0% indicates heavy and recent disturbance. Similarly, eucalypt stands dominated by small and regular crowns indicates recovery from relatively recent disturbance, while stands dominated by large and irregular crowns indicates low levels of major disturbance.

BRACK (2007) claimed it is "...difficult to conceive of any parameter of national interest that is not at least weakly related to one or more of these available auxiliary variables..." where the auxiliary variables were related to disturbance and the productivity of the stand as modelled by NCAS. Any such correlation can be used to improve the precision of the mean or total estimate for the parameter of national or region interest (HAMILTON and BRACK, 1999; BRACK, 2004). Given the complete spatial coverage of the auxiliary variables, the correlations can also be used to provide management relevant information at the project or fine scale. The following examples (Fig. 3) demonstrate how the information on disturbance and productivity has been used for multi-scale information to support management at multiple scales for a range of goods and services.

Fig. 2 Schematic of models used to estimate growth or transfer of carbon between pools in forests or agricultural lands (from RICHARDS and BRACK, 2004a)

Supporting Privately Managed Native Forests

Privately managed forest land (PMF) in the north east of NSW (Fig. 3, site 1) extends over 1.3 million ha and is gaining significance for their potential provision of commercial timber resources as well as their role in biodiversity. There was relatively little information about the PMF and the Bureau of Rural Sciences (BRS) of the Commonwealth Government commissioned an inventory to determine some basic resource data to assist in regional planning.

Previous experience in the privately managed forests of SE Queensland, immediately north of site 1 (Fig. 3), found that stratified random sampling, where strata were based on floristic or broad vegetation types was not effective in reducing sampling error. It was decided to use a multi-phase sampling approach with the long-term FPI data freely available from NCAS and FPC derived from a series of state-based remote sensing images as the auxiliary variables. The resolution of the FPC was 400×600 m, so the FPI for the analytical units were aggregated up into equivalent 400×600 m units, with the mean and variance estimated. Sixteen cluster plots were established across the range of FPI and FPC. Each cluster consisted of 25 angle-count sampling points (BAF=2). At three points within each cluster, fixed area plots were established where detailed tree measurements (including merchantable volume) and measurements related to structural diversity were collected. An

Fig. 3 Location of example study sites Numbers down the SE coast represent the example study areas discussed in this paper

Grey areas denote forested land along east coast of Australia.

additional 87 data points with merchantable volume (and precise location) collected previously were also made available.

The structural diversity measurements were related to a range of parameters identified by McELHINNY *et al.* (2006) as being related to fauna species diversity in peer-review publications: Perennial species richness; Lifeform richness; Stand basal area; Quadratic mean DBH (cm); Vegetation cover <0.5 m (%); Vegetation cover 0.5–6 m (%); Number of regenerating stems; Number of hollow-bearing trees; Number of live stems ha^{-1} > 40 cm DBH; Number of dead trees ha^{-1} ; Total log length (m); Total large log length (m); Litter dry weight (t ha^{-1}). The structural measurements allowed the creation of an index of stand structural diversity (McELHINNY *et al.*, 2005) where low scores represented stands with most of the measured parameters towards the lower range observed in the measured population. The maximum structural diversity index (25) could theoretically only be obtained if every measurement in the cluster were in the upper quartile of the observed distributions, and would represent a stand with a structural diversity that is very attractive to a wide range of fauna.

Multiple linear regressions were fitted with FPI (mean and variance of the analytical units) and PFC, including interaction terms, as the independent variables. The variance of the FPI analytical units was not significant in any model. Significant models ($p < 0.01$) with no observable deviations from normal and homogeneous distributions for the error, were fitted for cluster total volume, merchantable volume (Fig. 4a) and structural diversity index (Fig. 4b).

Estimates of the mean merchantable volume or structural index (and associated sampling error) can be made for the whole 1.3 million ha or any sub-regional by entering the corresponding mean FPI and PFC into the fitted linear models. The mean estimates for the sub-regions remain compatible with the overall regional values because of the structure of the linear model and because the FPI and PFC values are known for every individual unit in the region.

Individual land managers or Regional groups can use these maps to target areas of high biodiversity for protection or even low biodiversity for enhancement, as well as locating areas where commercial volumes of merchantable timber are available. They can also start to make meaningful trade-off calculations between the area they would need to harvest to generate minimum volumes of merchantable timber against relative changes in the structural biodiversity index. Such management analyses would not be possible if only mean values across the entire Region were the sole output from the inventory.

Farm Scale Volume Estimation

Southern Tablelands region in NSW covers approximately 150×300 km and includes a vast amount of dry sclerophyll forest (DSF) (Fig. 3, Site 2). The majority of these forests exist in a degraded state and could easily be improved in value, both ecologically and economically, through some form of silvicultural

intervention. Significant areas of DSF are included in farms and rural blocks where landholders have a range of rationales for owning their private native forests. Most small land holders, for example, attribute the most important uses of native forests were enjoying its aesthetical and environmental benefits, while those with larger areas were likely to value their native forests for utilitarian purposes such as strategic grazing and timber production for on-property use (including firewood) and commercial timber production (MAY, 2006). However, there is concern that these private landholders do not utilise their DSF resources in an efficient or effective way (STATE CATCHMENT MANAGEMENT CO-ORDINATING COMMITTEE, 2003). This under-utilisation is due to the individual landholders having a poor or incomplete knowledge of their own resources and the processing sector also unable to determine a well established and accepted method of quantifying timber available over the region from private property growers.

This project used FPI coverages available from NCAS and local knowledge about disturbance history. Historical information, including remotely sensed information, was relatively scarce in this area, so local farm owners were simply required to divide stands into two relative classes – regrowth after disturbance (stumps or other evidence of major disturbance present) and no recent disturbance. The objective was to provide farm-scale estimates of total volume of trees and the potential size of commercial activities, and the involvement of the farm manager was considered most appropriate for the disturbance classification. Again, it was important that these farm-scale estimates could be aggregated to different potential supply zones to support processing sector planning.

The first stage in developing farm-scale timber volume information was the development of a stand volume function that could be used by farmers who had no forest mensuration training. Using intensively measured tree volume data from sites that covered the range of FPI, a VBAR (Volume to Basal Area Ratio) approach was developed where the slope of the VBAR was correlated to the FPI ($R^2 = 0.98$) (Fig. 5a). Once reliable VBAR values were available and localised by FPI at a target location, the total volume was estimated for a large number of sites across the Southern Tablelands Region where stand basal area was known. These data were used to develop a correlation between FPI, disturbance and total volume ($R^2 = 0.61$), which could then be used to produce a map of volume for the Region (Fig. 5b). A logistic regression was also fitted to estimate the number of trees that contained a solid-wood timber product as a function of FPI and disturbance ($R^2 = 0.91$). Farmers were encouraged to use the map and number of product trees to determine if the DSF on their farm was likely to support commercial activities (e.g. number of likely commercial trees exceeded a minimum level, with the minimum level set by the distance to access points). If there were a significant likelihood of a commercial activity, those farms could use the VBAR (Fig. 5a) and some simple angle-count inventory methods to confirm the availability of commercial quanti-

Fig.4 Maps of predictions based on multiple linear regressions using FPI and PFC

Fig.5 Stand-level estimates of volume for individual points across the Southern Tableland DSF

ties of timber.

As in the first example, estimates of the mean volume or number of solid-product trees (and associated sampling error) can be made for the whole Southern Tablelands or any sub-regional by entering the corresponding mean FPI and disturbance classifications into the fitted models. The mean estimates for the sub-regions remain compatible with the overall regional values because of the structure of the linear model and because the input values are known for every individual unit in the region.

CONCLUSIONS

Multiple coverages by satellites, long-term monthly climate surfaces and broad scale soil fertility maps have been brought together to create indices of forest growth at fine scale - both spatial and temporal. The fine-scale site quality index - FPI - integrates a wide range of physiological characteristics related to growth over the entire continent and has been made freely available. When combined with some measure of disturbance, FPI can be integrated into multi-phase sampling designs to produce estimates of volume (total and commercial) and biodiversity for specific locations which can be aggregated for reporting at a wide range of scales. The multi-phase sampling examples provided that use FPI and disturbance allow much more precise estimates of total values than those of stratified random sampling. The multi-phased approach also allows for estimates at specific spatial locations, which are superior to the stratified random sampling equivalent of assuming all points in a stratum are assigned the stratum mean value.

Further work may enhance the power of incorporating the fine temporal and spatial data that is increasing available through national projects like NCAS.

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(Received 23 September 2009)

(Accepted 30 September 2010)