Development of a National Forest Inventory for Carbon Accounting Purposes in New Zealand's Planted Kyoto Forests

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Abstract.—This article discusses the development of a monitoring system to estimate carbon sequestration in New Zealand's planted Kyoto forests, those forests that have been planted since January 1, 1990, on land that previously did not contain forest. The system must meet the Intergovernmental Panel on Climate Change good practice guidance and must be seen to be unbiased, transparent, and verifiable. At the same time, the system should meet a wider set of objectives for international forest reporting and forest health. The core of the system is to be a network of some 400 permanent sample points, established objectively on a 4- by 4-km grid coincident with an area of Kyoto forest. Each sample point is a cluster of four 0.04-ha circular plots installed in a design similar to that employed in the United States Forest Inventory and Analysis program. Sufficient data are collected at each point to enable the carbon density in each of the required reporting pools to be calculated or modelled. At a subset of points, integrated with an existing system implemented on an 8-km square grid over New Zealand's indigenous forest and shrubland, assessments of soil carbon and plant biodiversity are made. The intention is that the inventory will have a 3-year measurement cycle, with one-third of the points remeasured each year.

Introduction

New Zealand is committed to estimate greenhouse gas (GHG) emissions by sources and removals by sinks for reporting to the Conference of Parties of the United Nations Framework Convention on Climate Change. In accordance with Article 3.3 of the Kyoto Protocol, New Zealand has agreed to report, in a transparent and verifiable manner, GHG emissions by sources and removals by sinks associated with direct human-induced land use change and forestry activities, limited to afforestation, reforestation, and deforestation since 1990. Net carbon stock changes on land subject to afforestation (A), reforestation (R), and deforestation (D) must be estimated each year over the defined commitment period, the first of which is from January 1, 2008, to December 31, 2012, from information on land area (ha) and its corresponding carbon density (tC/ha) for each of five carbon pools.

Large-scale plantings of introduced tree species in New Zealand commenced in the 1920s. As of April 2004, the total area of exotic plantations in New Zealand was 1.82 million ha (MAF 2005). In addition, New Zealand contains approximately 6.25 million hectares of indigenous forests (i.e., natural forests containing tree species that are either indigenous or endemic to New Zealand) and 2.65 million hectares of shrublands, containing both indigenous and exotic species. Radiata pine (*Pinus radiata*) is the most common plantation species, with approximately 89 percent of the total plantation area comprised of this species. Other plantation species include Douglas fir (*Pseudotsuga menziesii*) and eucalypts (*Eucalyptus* spp.). A significant

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proportion of these exotic forests were planted since January 1, 1990, on land that previously did not contain forest. These forests are referred to as Kyoto-compliant forests. Between 1990 and 2004, it is estimated that approximately 600,000 ha of such forests have been established (MAF 2005).

New Zealand does not currently have a plot-based national forest inventory covering all of its forests. A plot-based system covering the indigenous forest and shrubland is in the fourth year of a 5-year implementation program. Information on the area and the amount of growing stock in exotic plantations by age class, species, and region is compiled in the National Exotic Forest Description (NEFD). The data presented in the NEFD are obtained from surveys that are sent out annually to owners and managers of larger forests (at least 1,000 ha in size), or biennially to owners and managers whose forests are between 40 and 999 ha. The response rate for these surveys is generally very high. For example, in the 2003 NEFD some 1,400 survey forms were mailed out to all owners of forests at least 40 ha in size; a 90 percent response rate was received, with a 99 percent response for owners with more than 1,000 ha. (MAF 2005). Since 1992, new planting that is not captured by these surveys of forest owners has been imputed from nursery surveys. Forest nurseries provide accurate estimates of the number of planting stock sold. Using assumed stocking rates and a number of other factors (e.g., restocking, blanking, and field wastage) the area of new forest planting is calculated. The total area of afforestation that has been imputed using data from nursery surveys is estimated to be around 180,000 ha.

The data that are provided to the NEFD by large owners are considered to be very reliable. The data provided by many smaller owners or managers are of unknown quality, however, and, in general, their net stocked areas are thought to be overestimated. Much of the Kyoto-compliant afforestation that has occurred since 1990 is thought to have been carried out by these small-scale owners and may not be well represented by the NEFD. Therefore, to provide the necessary data to allow carbon stocks and stock changes to be estimated in accordance with the recently adopted good practice guidance for Land Use, Land-Use Change and Forestry (IPCC 2003), a means to inventory forests specifically designed for carbon monitoring is required.

This article will outline the development of New Zealand's proposed approach for an inventory of its planted Kyoto forests and describes some of the experiences gained from a pilot study that was conducted in the Nelson and Marlborough regions of the South Island.

Estimation of Forest Area

To meet its requirements under the United Nations Framework Convention on Climate Change and the Kyoto Protocol, New Zealand must determine the area of forest land. Under the Marrakesh Accords, countries must choose a definition of forest land from a predefined range of parameters describing minimum area, crown cover, and height at maturity *in situ*. New Zealand has provisionally adopted the following thresholds for the definition of forest land: a minimum area of 1 ha, crown cover of 30 percent, and a potential height *in situ* of 5 m. The exact approach for determining the area of Kyoto forest land is still to be finalized; however it is likely to be complete coverage mapping based on remote imagery, most probably acquired from satellites with some high-resolution aerial imagery. The recently completed Land Cover Database 2 (LCDB2) is based on a complete national coverage of Landsat 7 Enhanced Thematic Mapper Plus satellite imagery and has a target spatial resolution of 1 ha. It is recognised that the use of satellite imagery to determine the area of forest land is not without its problems, particularly in detecting changes in the area of forest land to a high degree of precision. It is envisaged that high-spatial resolution aerial photography will be used to provide past land use detail that is not provided by existing satellite imagery. For future land use and land use change mapping, high-spatial resolution satellite imagery may also be used.

Development of a Plot-Based Inventory System

At the national scale, New Zealand's woody vegetation can be thought of as being stratified into the following classes:

1. Indigenous high forest.
2. Shrubland (or other wooded land [OWL]).
3. Pre-Kyoto exotic forest.
4. Kyoto-compliant exotic forest.

The forest inventory approach adopted by the New Zealand Carbon Accounting System is to use a national grid-based network of permanent plots to provide a statistically valid, unbiased estimate of carbon stored in planted forests. Currently, a network of plots is being installed on an 8- by 8-km grid in indigenous forests and shrublands (Coomes *et al.* 2002, Payton *et al.* 2004). For Kyoto-compliant forests, a set of nested grids, coincident with the 8-km grid used to sample carbon stocks and plant biodiversity in indigenous forests and in shrublands, are placed over forests. This design is simple and robust to changes over time, permitting more complex statistical sampling designs and analyses to be imposed over the basic sample frame in the future, when necessary.

There are three proposed phases to the data collection.

Phase 1. Information on stand age, stocking, and management regime (e.g., thinning, pruning, forest health) is obtained for sample points on a 2-km grid[7] across the planted forest estate. This information is used (1) to determine the proportion of the planted forests that comply with the Kyoto Protocol definitions, and (2) for double sampling with regression estimation to improve the precision of estimates of carbon.

Phase 2. Data to estimate carbon stocks and forest health are obtained from sample points on a 4-km grid[7].

Phase 3. Additional soil carbon and plant biodiversity data are collected from sample points on an 8-km grid[7] (i.e., at approximately one-quarter of the phase 2 sample points). Protocols for soil carbon measurement are described in Davis *et al.* (2004), while those for assessing plant biodiversity are described in Payton *et al.* (2004).

Data in phase 1 of the system are collected via discussions with landowners or forestry consultants, while data in phases 2 and 3 are collected through a network of fixed-area plots. To minimize costs, it is proposed to visit only those points that have a high probability of sampling Kyoto forest.

Size of the Plot Network

The location of sample sites in planted Kyoto-compliant forests is determined by placing a 4- by 4-km grid over those LCDB2 classes thought to have a high likelihood of containing such forest (additional verification is done using recent fine-scale aerial photography). Assuming that the area of Kyoto-compliant post-1990 afforestation is 640,000 ha[8] (MAF 2005), then a 4- by 4-km grid is expected to yield on average 400 intersections (sample points). A subset of 100 of these points will be on the 8-km grid that is coincident with that used for the Indigenous Forest and Shrublands Carbon Monitoring System (Payton *et al.* 2004).

Using existing data from research monitoring plots, Goulding (2003) estimated that the coefficient of variation for stem volume in first rotation stands planted since 1990 (i.e., maximum age of 13) was 50 percent. By the end of the Kyoto Protocol Commitment Period 1 (CP1) trees planted since 1990 will range in age from 1 year up to 22.5 years and Goulding (2003) estimated that for stands aged between 4 and 23 years the coefficient of variation for stem volume increases to approximately 65 percent. Using these data and the assumption that the coefficient of variation for total carbon stocks is similar to that for stem volume, a network of 400 sites would produce an estimate of carbon stocks

[7] Nested grids that are coincident with the 8-km grid used to sample carbon stocks and plant biodiversity in indigenous forests and in shrublands.

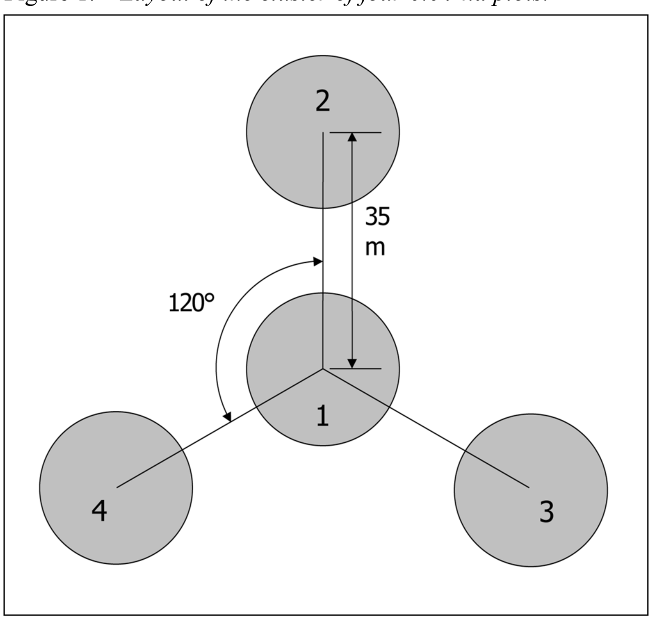
[8] The total area of post-1990 afforestation is approximately 670,000 ha; however, a proportion of this will not be Kyoto compliant as it occurred on land that already contained at least 30 percent canopy cover of a species capable of reaching 5 m in height.

that has probable limits of error (the ratio of the 95 percent confidence interval to the mean) of approximately 6 to 7 percent. Because these plots will be permanent, estimates of the change in carbon stocks over time will have a greater degree of precision associated with them than if they were computed from independent sets of temporary plots.

Plot Design

Much of the work that led to the final choice of plot design is described by Moore *et al.* (2004a), who examined the effect of plot size on the variability of the estimates of standing volume and carbon stocks as well as the within-site and between-site variation in these quantities. It was found that increasing the plot area above 0.04 ha did not further decrease between-plot variance, while that variance was unrelated to distance between plots within a stand over the range of distances examined (48 to 118 m). As a consequence of the study, it was recommended that each sample point consists of a cluster of four 0.04-ha circular subplots. The central subplot would be coincident with the intersection of the sample point; the centres of three other subplots located 35 m away and arranged at 120 degrees apart (fig. 1). This arrangement is similar to that adopted by the United States Forest Inventory and Analysis (FIA) (Bechtold *et al.* 2005, Scott 1993). The choice of 35 m as the separation distance between subplots was based on the need to increase the likelihood of obtaining differences in carbon density between subplots within a cluster, while at the same time trying to minimise the likelihood that subplots fall outside the target population.

Figure 1.—*Layout of the cluster of four 0.04-ha plots.*

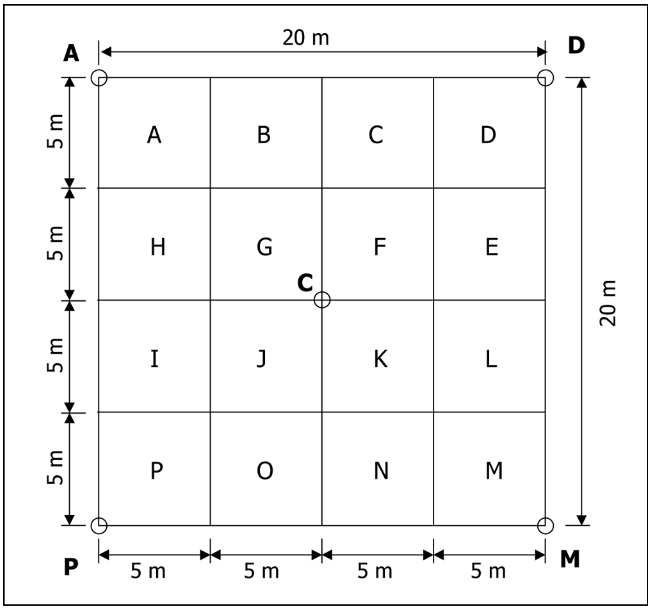


In New Zealand, many of the Kyoto-compliant forests are small (< 50 ha) and, therefore, it is likely that a number of subplots will straddle the boundary between planted forest and adjacent nonforest land-cover classes. Unlike the case of a single plot that straddles multiple conditions (where techniques such as the "mirage method" can be used to correct for the part of the plot which falls outside the target population), it is not possible to rotate subplots into a single uniform condition (i.e., planted forest) as this will generate a bias by altering the selection probabilities of trees, especially those near the edge (Williams *et al.* 1996).

To overcome this problem, New Zealand will adopt the same approach recommended for the FIA (Hahn *et al.* 1995, Scott *et al.* 1995). When a subplot straddles two or more conditions, field crews record the two azimuths where the condition-class boundary crosses the subplot perimeter. This is called the "fixed-radius, mapped plot" design. The plot level estimators (e.g., basal area, volume, stand density) are computed on the basis of the revised plot area and procedures for estimating means and variances are given in Van Deusen (2004).

For those sites that lie on the 8-km grid (i.e., phase 3), an additional 20-m square plot is installed at the center of the cluster for the purposes of recording plant species composition (plant biodiversity) by height tier. The plot is subdivided into 16 5- by 5-m subplots (fig. 2), with 24- by 0.75-m^2 circular subplots established to measure understory/seedling vegetation. The emphasis is on ensuring that biodiversity data collected from planted forest stands are compatible with equivalent data sets obtained from the inventory of indigenous forests and shrublands (Payton *et al.* 2004).

Figure 2.—*Layout of the 0.04-ha (20- by 20-m) square plot used for plant biodiversity measurement.*



Vegetation Measurements

The key purpose of the inventory is to collect sufficient information to allow the average carbon density (i.e., tonnes of carbon per hectare) of New Zealand's Kyoto-compliant planted forests to be estimated. The good practice guidance for Land Use, Land-Use Change and Forestry inventories (IPCC 2003) recognises five carbon pools that need to be reported on: (1) above-ground live, (2) below-ground live, (3) dead wood, (4) litter, and (5) soil. In the current New Zealand Carbon Accounting System, pools (1) and (3) are estimated directly from field measurements, while the remaining three pools are modelled. Soil modelling (pool 5) requires soil data collected from a proportion of the plots. The approach for measuring pools (1) and (3) is briefly described in the following section.

For measurement purposes the above-ground live carbon pool is subdivided into four subpools. These are assessed using either height and diameter measurements (trees and tree ferns, saplings and seedlings) or height and cover measurements (shrubs, ground cover).

- Trees are defined as woody stems > 25 mm diameter at breast height (d.b.h.) (1.4 m).
- Saplings are woody stems > 1.4 m tall, but < 25 mm d.b.h.
- Seedlings are woody stems < 1.4 m tall.
- Shrubs are plants > 0.3 m high that lack the monopodial form typical of trees, saplings, and seedlings. For the purpose of estimating carbon they may be woody (e.g., gorse) or nonwoody (e.g., pampas).
- Ground cover refers to vegetation (woody or nonwoody) < 0.3 m high.

The d.b.h. of each standing tree on the plot is measured and its bearing and horizontal distance from the plot center recorded. A subsample of up to 16 trees per species spanning the range of d.b.h. values is selected for measurement of total height, green crown height, and pruned height.

Dead wood includes standing and fallen dead stems, thinned trees, broken tops, stumps, etc., (including remnants of previous land covers) that have a diameter ≥ 10 cm. In intensively managed plantations, most dead wood originates from thinning operations. Therefore, the dead wood is assessed using the same protocols as for standing trees, but with a suitable allowance made for decay. Immediately following an operation, particularly one in which the felled trees are not extracted but left *in situ* (i.e., precommercial thinning or "thinning to waste"), the amount of dead wood may be substantial, but this decays rapidly.

Remeasurement Frequency

The growth rates of New Zealand's exotic forests are often higher than those for forests in areas such as the United States and Scandinavia, as is the intensity of management. (In New Zealand there can be up to three green-branch pruning lifts and two thinning operations before a stand is 10 years old.) Therefore, it is proposed that the remeasurement interval should be 3 years. (Note: the current standard remeasurement interval for permanent sample plots in New Zealand is 1 to 3 years.) If the interval is longer, changes to stand structure and levels of growing stock could be significant and difficult to estimate.

It is proposed that the system be an annualised inventory (Van Deusen *et al.* 1999), with one-third of plots measured each year. Under the annual approach some new data are available each year. It will be important for New Zealand to have current data on a regular basis to assess its national carbon balance leading up to and during CP1. In addition, the continuity of work should make it easier to retain experienced people and reduce the need to recruit and train new people, and the costs of conducting the inventory will be spread over the measurement cycle.

During the first year of implementation of the inventory, estimates of carbon stocks will only be able to be estimated from the current year's measurements. In subsequent years, however, data will be available from multiple years. While the simplest way to calculate annual estimates of carbon stocks is to use only the data from those plots measured in the current year, their precision will be lower because of the reduced sample size (i.e., only one-third of plots are measured in any one year). The approach for producing estimates of carbon stocks and stock changes using data from multiple years has not been decided on. It is likely, however, that New Zealand will use an imputation approach with appropriate growth models used to update information from plots measured in previous years.

Testing of the Approach in a Pilot Study

A pilot study was carried out within the Marlborough, Nelson, and Tasman Districts of the South Island to address many of the issues relating to estimation of the carbon pools and fluxes in Kyoto-compliant planted forest lands, and to make recommendations for a national inventory based on precision, cost, and effort (Moore *et al.* 2005). A total of 32 sites were sampled in August and September 2004—23 on the 4-km grid (phase 2), and 9 on the 8-km grid (phase 3), which is also used for the inventory of indigenous forests and shrublands. At each site a standard series of measurements was made as described in the relevant field manual. From these measurements, the amount of carbon (t/ha) in pools (1) through (4) was predicted for each plot using the C_Change model (Beets *et al.* 1999), and for pools (1), (2), and (3) using a series of allometric equations in order to provide a comparison with values from the model. The change in carbon stocks in pools (1) through (4) during the first Commitment Period of the Kyoto Protocol was also predicted using a combination of the C_Change model and appropriate growth models.

Results

In general, field teams had little difficulty with the measurement protocols. Some problems arose, however, with the measurement of coarse woody debris and the assessment of crown transparency. There were also some issues with the identification of forest land from LCDB2, with 4 of the 32 sites actually occurring on nonforest land (mainly pasture). Because the planted Kyoto forest estate consisted of many small blocks that were dispersed, plots that straddled boundary conditions were reasonably common; this straddling occurred at 14 of the 32 sites.

Both methods of calculating carbon stocks, the allometric and modelling approaches, produced similar estimates of the amount of carbon in the various pools, indicating that the carbon calculation protocols are robust. These estimates were specific to the region over which the pilot study was conducted and should not be considered representative of all Kyoto-compliant forests in New Zealand. Analysis of sampling precision for the pilot supported earlier suggestions that the carbon stock could be estimated nationally using this design to within ± 7 percent of the mean.

From data collected on plant biodiversity, it was found that radiata pine stands contained an average of 25 ± 2.5 (n = 23) plant species per plot, with no suggestion of differences between Kyoto-compliant and non-Kyoto-compliant stands. Forty percent of the plant species in the radiata pine plots were New Zealand natives. As with the overall plant species diversity, native plant biodiversity varied widely between the radiata pine stands that were sampled (0 to 78 percent) and did not appear related to stand type.

As a result of the pilot study a number of refinements have been made to the field procedures, but the basic design of the inventory is unchanged. The national implementation of the inventory was due to commence in winter 2005, which would have permitted a full cycle of measurement to be completed before the start of the first Kyoto Protocol Commitment Period in 2008. A number of issues over access to private land, however, have delayed the national implementation. If these issues can be overcome before December 2006, then plots will be established over a 2-year time span, but will be remeasured on a 3-year cycle. If access to private land is not forthcoming, then the inventory may have to be redesigned to allow estimates of carbon stocks to be obtained from airborne remote sensing (e.g., high-resolution laser image detection and ranging coupled with color infrared aerial photography).

Discussion and Conclusions

The New Zealand Carbon Accounting System has been designed to provide national estimates at a "reasonable" level of precision compared to cost. Sampling on a 4-km square grid across Kyoto compliant forests should result in some 400 sample sites. Employing clusters of 4- by 0.04-ha plots should result in an estimate of the national Kyoto compliant forest carbon stock per hectare to within ± 7 percent. Indications are that an estimate of the change in stocks over the commitment period may be obtained with more precise confidence limits, given that it will be derived from remeasurements of permanent sample plots (Moore *et al.* 2004b). It is also a very "basic" design that can stand alone or be used to provide information for more complex inventory methods that may answer specific questions. It has the potential sometime in the future to be statistically integrated with remotely sensed images in a combined system that will provide more detailed, spatially explicit information or results at a subnational or regional level more precisely than from plots alone. While the design of the inventory itself is relatively simple, the statistical techniques required to analyse the data, particularly determining the precision of carbon estimates, are more complex. To obtain estimates of the carbon stocks and change with their variances, analysis of the data has to account for clusters of mapped plots, missing plots, rolling estimators/imputation, and the use of double sampling with regression estimators. It is therefore important that New Zealand maintains strong links with scientists in other countries who are involved with national forest inventories, particularly those in the United States due to the similarities in the systems, to keep abreast of advances in methodological and analytical approaches.

The system also has the potential to contribute to a range of national and international reporting requirements should the measurement procedures be extended beyond the minimum set required to estimate carbon stock. These include internationally derived requirements associated with sustainable forest management (e.g., New Zealand is a participant in the Montreal Process) and conservation of biological diversity (e.g., the Convention on Biological Diversity). Within New Zealand, the system could contribute data for the National Exotic Forest Description, Ministry of Agriculture and Forestry, and for Environmental Performance Indicators, Ministry for the Environment.

It is anticipated that over time the plot-based inventory will be extended to all planted forests, which will provide the data to enable full carbon accounting of all forest lands

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