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The inventory of carbon stock in New Zealand's post-1989 planted forest for reporting under the Kyoto protocol

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ABSTRACT

The United Nations Framework Convention on Climate Change (UNFCCC) requires reporting net carbon stock changes and anthropogenic greenhouse gas emissions, including those related to forests. This paper describes the design and implementation of a nation-wide forest inventory of New Zealand's planted post-1989 forests that arose from Land Use, Land-Use Change and Forestry activities (LULUCF) under Article 3.3 of the Kyoto Protocol. The majority of these forests are planted with *Pinus radiata*, with the remainder made up of other species exotic to New Zealand. At the start of the project there was no on-going national forest inventory that could be used as a basis for calculating carbon stocks and meet Good Practice Guidelines.

A network of ground-based permanent sample plots was installed with airborne LiDAR (Light Detection and Ranging) for double sampling using regression estimators to predict carbon in each of the four carbon pools of above- and below-ground live biomass, dead wood and litter. Measurement, data acquisition and quality assurance/control protocols were developed specifically for the inventory, carried out in 2007 and 2008. Plots were located at the intersection of a forest with a 4 km square grid, coincident with an equivalent 8 km square grid established over the indigenous forest and "grassland with woody biomass" (Other Wooded Land). Planted tree carbon within a ground plot was calculated by an integrated system of growth, wood density and compartment allocation models utilising the data from measurements of trees and shrubs on the plots. This system, called the Forest Carbon Predictor, predicts past and future carbon in a stand and is conditioned so that the calculated basal area and mean top height equals that obtained by conventional mensuration methods at the time of the plot measurement. Mean per hectare carbon stocks were then multiplied by an estimate of the total area of post 1989 forests obtained from wall to wall mapping using a combination of satellite imagery and ortho-photography.

The network of permanent samples plots and LiDAR double sampling methodology was designed to be simple and robust to change over time. In the future, using LiDAR should achieve sampling efficiencies over using ground plots alone and reduces any problems regarding restricted access on the ground. The network is to be remeasured at the end of commitment period 1, 2012, and the carbon stocks re-estimated in order to calculate change.

1. Introduction

New Zealand is a signatory to the Kyoto Protocol and the United Nations Framework Convention on Climate Change (UNFCCC). It has elected to maintain its net greenhouse gas emissions over the Kyoto Protocol's first commitment period (CP1, the 5 years from 1 January 2008 to 31 December 2012), at an average annual rate no greater than its emissions in 1990. New Zealand's initial assigned amount under the Kyoto Protocol for CP1 is recorded as 309,564,733 Mg CO_2 equivalent (CO_2-e). New Zealand prepares an annual inventory report of its greenhouse gases (Anon, 2011). In 2009, the gross rate of emissions per year had increased from 1990 by 11,500,000 Mg CO_2-e due to a long-term trend in growth in energy use, mainly from road transport and electricity generation. Under Article 3.3 of the Kyoto Protocol, carbon credits may be claimed for any net increase in carbon stocks through direct human-induced activities arising from Land Use, Land-Use Change and Forestry (LULUCF) (limited to afforestation, reforestation and deforestation), in those forests established on non-forest land after 1989, referred to as "post-1989 forests". Under Article 3.3, reporting afforestation, reforestation and deforestation activities occurring after 1989 is mandatory. New Zealand has elected not to report on activities covered under Article 3.4 (which includes the

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management of forests existing prior to 1990). It expects carbon credits from its post-1989 forests to more than compensate for the growth in emissions from transport and energy, enabling it to meet its Kyoto Protocol commitment without needing to purchase credits elsewhere.

Good Practice Guidance for LULUCF activities requires carbon stock changes to be estimated in an unbiased, transparent, and consistent manner, where uncertainties are determined and reduced over time (IPCC, 2003). Net carbon stock change in the post-1989 forests over CP1 will be evaluated at the end of the commitment period and subtracted from New Zealand's assigned amount at that time. Ongoing improvements to the inventory reporting, as required by Good Practice Guidance, imply that all inventory data is subject to change before the end of the commitment period. This paper describes the development of the large-scale national forest inventory system put in place to meet New Zealand's reporting obligations for planted post-1989 forests.

The paper describes the field protocols, the carbon models and the methods of obtaining LiDAR (Light Detection and Ranging) data and regression models in a double sampling scheme that assesses forest carbon stocks. It presents estimates of per hectare carbon stocks as at 1 January 2008 for the post-1989 forests based on the inventory conducted in 2007 and 2008. It does not cover in any detail the mapping procedures used to determine the post-1989 forest area in New Zealand by which the per hectare estimate will be multiplied to obtain the total carbon stock, nor does it cover the procedures to estimate soil organic carbon.

2. Background

To estimate carbon stocks and stock changes in its post-1989 forest, New Zealand has implemented its Land Use and Carbon Accounting System (LUCAS), managed by the Ministry for the Environment. The forest area is defined by a GIS-based, wall-to-wall map created using historical aerial photographs and satellite images. Mean per hectare carbon stocks and sequestration in the planted forests are estimated by using a double sample of a network of ground permanent sample plots and airborne LiDAR plots arranged on a 4 km grid overlying the mapped area.

New Zealand's 1.8 million hectares of planted forests are composed predominantly of radiata pine (*Pinus radiata* D. Don) (89%), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) (6%), with the remainder made up of Eucalyptus and other exotic species (Anon, 2010a). These forests have been established mainly for timber production, with the merchantable trees known as "crop trees". The stands are even aged, moderately fast growing, (average merchantable mean annual increment 17 m^3/ha/year, under bark, country-wide over the rotation, for the stands now being harvested Anon, 2010a). They are intensively managed, often with several live-branch pruning and non-extractive "thinning to waste" operations at early ages that result in large amounts of woody debris. Unstocked gaps within production forests can quickly be colonised by exotic "weed" species such as gorse (*Ulex europaeus* L.) and broom (*Cytisus scoparius* (L.) Link) and by regenerating native shrubs and trees such as kanuka (*Kunzea ericoides* (A. Rich.) Joy Thomps.). and manuka (*Leptospermum scoparium* (Labill.) J.R. Forst. and G. Forst.). These plants exhibit a range of form, from individual woody stems to multiple-stemmed bushes, sometimes with very large numbers of individual stems per hectare. Over time, an under-storey of tree ferns (*Cyathea* and *Dicksonia* spp.) can establish naturally, particularly when the over-storey trees are widely spaced.

At the start of the development of LUCAS, there was no formal, ongoing national forest inventory (NFI) that completely covered the total New Zealand forest area to provide the data required to meet LULUCF reporting requirements (Beets et al., 2010). An annual postal survey of the larger forest owners is carried out by the Ministry of Agriculture and Forestry that collates information on planted forest areas by age classes in a National Exotic Forest Description (NEFD) Anon, 2010a. Periodically, yield tables (merchantable volume by age) are derived for the major production tree species $\times$ silvicultural regime combinations by surveying the corporate forest owners who manage approximately two thirds of the total area. The accuracy of the results of these surveys is weakest for the non-professionally managed small forests and woodlots that comprise the bulk of the post-1989 forests, and the survey would not meet the Good Practice Guidance for reporting under Article 3.3 of the Kyoto Protocol.

Under the Kyoto Protocol, New Zealand has defined its forests as having the ability to attain at least 5 m in height *in situ* with at least 30% canopy cover on a minimum area of 1 ha and a width greater than 30 m. Urban trees, shelterbelts, orchards and horticultural trees are not included in the forest definition.

Five carbon pools must be reported for the post-1989 forests:

- Above-ground live biomass (AGB), living stems, branches, foliage.
- Below-ground live biomass (BGL), living roots.
- Dead wood (coarse woody debris, CWD) not contained in the litter, either standing, lying on the ground, or in the soil.
- Litter (fine litter, FL) litter, fumic, and humic layers.
- Soil organic carbon to a specified depth.

The soil organic carbon pool is currently estimated by a separate, independent system within LUCAS. To estimate carbon stocks per hectare in the other four pools, trees and stand parameters are measured in the ground plot network. The data are processed using a forest carbon modelling system called the Forest Carbon Predictor. The first measurement of permanent sample plots on the 4 km square sampling grid was carried out during the winters of 2007 and 2008 with the objective of estimating per hectare carbon stocks as at 1 January 2008. Future inventories of the permanent plot network, the next scheduled for 2011/2012, will provide direct estimates of carbon sequestration.

The first inventory was carried out during a period when the mapping of the post-1989 forest area was not fully completed. Furthermore, field access to these mostly privately-owned forests was not guaranteed and there was a serious threat that permission for access would be withheld. Therefore, although the original intention had been to use ground-based measurements only, it was decided to use airborne scanning LiDAR to characterise all 4 km grid locations identified as being potentially within the post-1989 forest and to obtain ground-based tree measurements for a sub-sample of these locations. Average carbon stocks could then be estimated using double sampling regression procedures, even if ground access to some locations was not possible. This approach depended on there being good relationships between LiDAR metrics and carbon stocks. This was tested using two pilot studies. The second of these conducted in the central North Island of New Zealand is described by Stephens et al. (2007) and showed that total carbon could be predicted by LiDAR metrics with a good level of precision (R^2 = 0.80). A number of non-New Zealand studies have also demonstrated the potential of airborne LiDAR for forest carbon inventory (Drake et al., 2002; Nelson et al., 2003; Patenaude et al., 2004).

3. Methods

3.1. Development of a systematic sampling design

Permanent sample plots were installed rather than independent sets of temporary plots. Apart from improving the efficiency of