New Zealand's National Planted Forest Inventory as part of the Land Use and Carbon Analysis System

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Abstract

New Zealand has implemented its Land Use and Carbon Analysis System (LUCAS) since 2007 to meet its reporting requirements under the Kyoto Protocol and United Nations Framework Convention on Climate Change (UNFCCC). An important part of LUCAS is a National Forest Inventory (NFI) that covers all plantation and natural forests and allows the estimation of annual carbon sequestration over time through the re-measurement of permanent sample plots. In LUCAS, information from the NFI is combined with a simulation approach that allows backwards and forwards prediction using additional long-term data sources to enable detailed annual reporting on planted forests. In this paper, we provide a general overview of the LUCAS system and the planted forest NFI, and give an example of how data in LUCAS was used for the international reporting of forest carbon sequestration. In future, changes in the approach may be required to accommodate changes in reporting requirements and inventory methods and potential divergence between purely plot-based and simulation approaches.

Introduction

New Zealand has implemented LUCAS to meet its reporting commitments under the Kyoto Protocol and the UNFCCC. Under the Kyoto Protocol, New Zealand is required to account for forest carbon stock changes from 2008 in post-1989 forests and from 2013 in pre-1990 forests (against a reference level). The UNFCCC requires reporting of carbon stocks and stock changes associated with land use and forestry from 1990.

IPCC Good Practice Guidance (Intergovernmental Panel on Climate Change (IPCC), 2003, 2006) provides two methods for estimating the annual carbon stock changes that must be reported in national greenhouse gas inventories for forest land. The default method requires biomass carbon loss to be subtracted from biomass carbon increment for each reporting year. Increments include biomass growth while causes of losses include harvesting and natural disturbances. The second method is the stock change method, in which annual biomass change is calculated as the difference between biomass estimated at two points in time. The stock change method is usually associated with NFIs (Cienciala et al., 2008).

Some countries estimate carbon stock changes through models rather than directly from inventory plot data, although NFI data may be used for certain aspects of their modelling framework. For example, the UK (Dewar & Cannell, 1992) and Australia (Richards & Evans, 2004) use a modelling approach to estimate carbon stock changes with various levels of input of NFI data during this process.

New Zealand also uses a modelling approach for estimating carbon stock changes in its planted forests. The LUCAS NFI can provide direct estimates of carbon stock for post-1989 planted forests in 2008 and 2012 and pre-1990 planted forests in 2010 (and soon for 2015) based on plot measurements. However these carbon stock estimates are not directly used for reporting. Instead the NFI permanent plot data is used to derive age-based yield tables for the reported classes of planted forests (post-1989 and pre-1990). The yield tables are combined with age class information from the National Exotic Forest Description (NEFD) (Anon., 2012), and mapped forest area and deforestation, to simulate changes in the carbon stock in planted forests over time. These estimates were used for both Kyoto Protocol accounting and for UNFCCC reporting and also allow scenario-based projections (Anon., 2016b).

New Zealand chose the simulation approach over the simple stock change method as there were no historical NFIs that would have allowed use of the stock change approach from 1990. Over time, data from the continuation of the unbiased representative NFI will allow the improvement of the simulation approach as longer forest data time series will become available to provide accurate estimates of carbon stocks and the state of planted forests in New Zealand. The current simulation approach produces a more realistic time series of the annual emissions and removals by the forest carbon pools that are required for reporting.

This is particularly important for New Zealand planted forests where activity data (afforestation, harvesting and deforestation areas) show a high degree of inter-annual variation and are the major drivers of carbon stock changes. This is not the case for most natural forests in New Zealand and the natural forest NFI is not discussed further in this paper. Details can be found in Coomes et al. (2002), Payton et al. (2004) and Holdaway et al. (unpublished).

This paper describes the LUCAS system and the embedded NFI and demonstrates how New Zealand derived the carbon stock changes in post-1989 planted forests for the period from 2008–2012 as an example of how this country meets its reporting obligations for Kyoto forests under the Kyoto Protocol and UNFCCC.

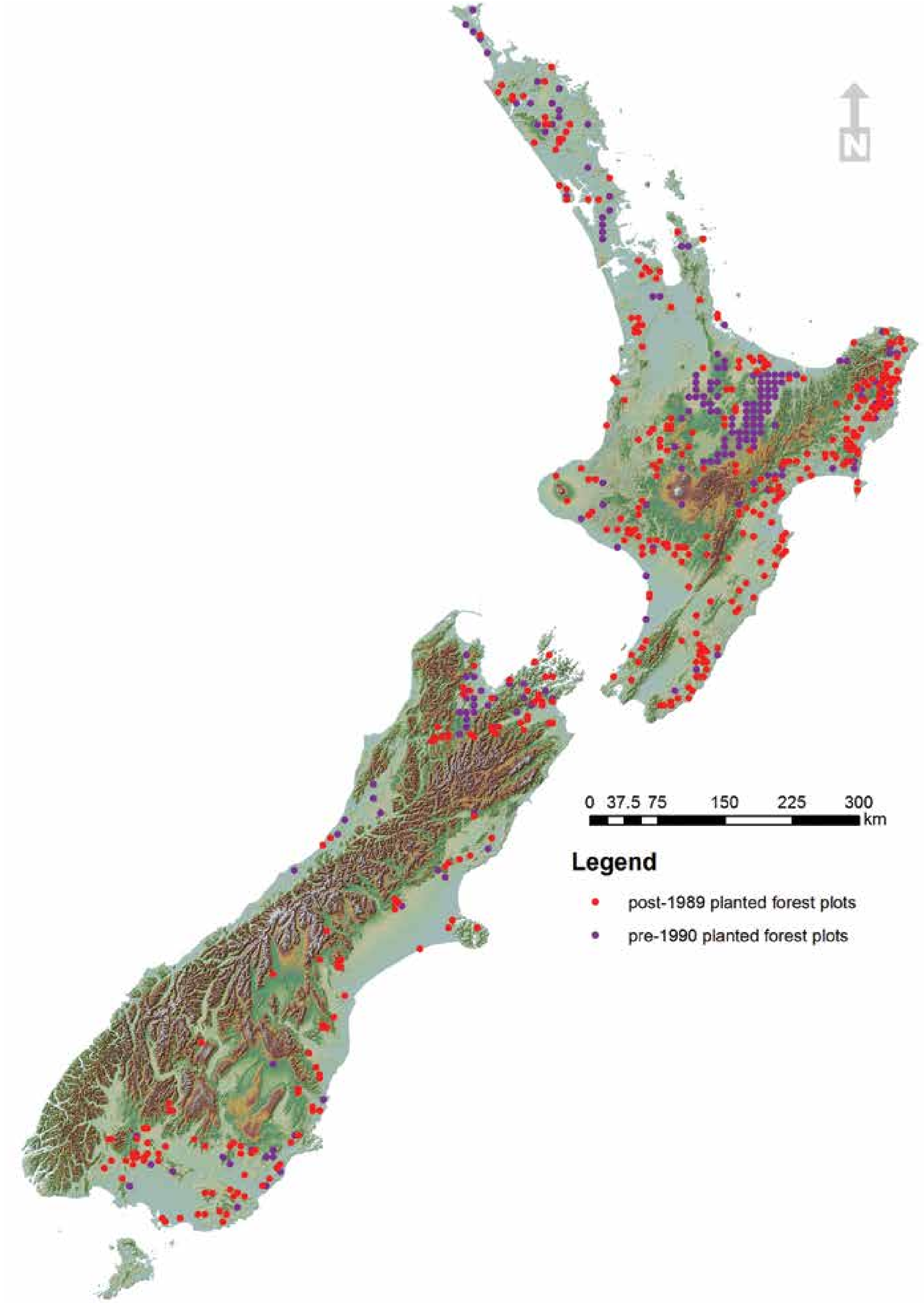

Figure 1: Map of locations of permanent planted forest plots measured periodically as part of the LUCAS National Forest Inventory (NFI)

National forest inventory as part of LUCAS

Until 2007, New Zealand was lacking a plot-based nationwide forest inventory covering all planted forests (Beets et al., 2010). This changed with the implementation of the NFI as part of the LUCAS system, which since its first measurement phase in 2007 has been continuously improved to provide unbiased and precise estimates of forest carbon stocks and their change. Four biomass carbon pools must be reported for post-1989 planted forests to meet the requirements for Kyoto Protocol and UNFCCC greenhouse gas inventory reporting:

- Above-ground live biomass (AGB)
- Below-ground live biomass (BGL)
- Dead wood (DW)
- Litter (fine litter, FL)

To estimate carbon stocks per hectare in the four pools, a number of tree and stand parameters are measured in the NFI (Beets et al., 2011a).

To acquire nationally-representative, unbiased estimates of carbon stocks in planted forests the inventory has a systematic sampling design taking the form of a random grid. The grid provides sufficient ground plots to account for the often fragmented and scattered nature of planted forest in New Zealand, which only cover a small proportion (6–7%) of the 27 million ha in this country. The random grid has a mesh size of 8 x 8 km for pre-1990 forests (natural and planted) and a superimposed finer grid of 4 x 4 km for the post-1989 planted forests (see Figure 1). The smaller grid was chosen because post-1989 planted forests are generally small and fragmented. Permanent sample plots were installed and include forest edge situations for representativeness (Hahn et al., 1995; Van Deusen, 2004; Bechtold & Patterson, 2005).

Changes in the initial plot design (Beets et al., 2011a) led to a circular single-plot of 0.06 ha at each sample location with a re-measurement period of five years (Beets et al., 2012). Improvements in mapping and remote assessments of locations also resulted in the inclusion of 112 previously unmeasured plots in the second post-1989 planted forest inventory phase in 2011/12. The additional plot locations were identified after the first inventory phase following the completion of the wall-to-wall mapping, which was carried out in parallel to the initial inventory due to time constraints.

A mapped plot approach Zarnoch and Bechtold (2000) was utilised to allow for the estimation of the net-stocked area by excluding areas such as unplanted gullies, forest roads, skid sites and edge situations where boundaries between land uses occur within plots. The derived net-stocked area was the basis for estimating the per hectare metrics used to calculate yield and carbon stocks, and is assumed to approximate the area reported by forest companies in the NEFD (Anon., 2012).

Complementary to the ground sampling, LiDAR (Light Detection and Ranging) data was acquired to serve in a double-sampling design to improve carbon stocks estimates in post-1989 and pre-1990 planted forests (Beets et al., 2011a, 2012). Such a double-sampling approach was possible as we were able to develop strong relationships between a number of LiDAR metrics and ground plot-derived carbon stocks for the first time in New Zealand (Stephens et al., 2012). LiDAR is now commonly used within forestry for biomass and volume estimation, e.g. Watt et al. (2013). The full potential of the LiDAR double sampling approach was realised in the pre-1990 planted forest inventory for the first time in 2010 (Beets et al., 2012).

Modelling carbon stocks – plot and national level

Carbon stocks in the live and dead pools of the planted trees are estimated from the individual ground plot measurements using the validated Forest Carbon Predictor Model Version 4.10 (Beets et al., 2011b). This model provides estimates of carbon in the above-ground live biomass, below-ground live biomass, dead wood and litter pools from the plot data at the time of measurement and predictions at other ages over multiple rotations. The model integrates a number of models:

- The 300 Index Growth Model for *Pinus radiata* (Kimberley et al., 2005), and the 500 Index Growth Model for *Pseudotsuga menziesii* (Knowles, 2005)
- Stem wood density models for *P. radiata* (Beets et al., 2007a) and *Ps. menziesii*
- The C_Change compartment model (Beets et al., 1999).

As well as the estimation of carbon in managed and tended trees, the additional carbon stocks in large shrubs and naturally regenerated native or exotic trees with a stem diameter at breast height (DBH) ≥2.5 cm were estimated. This was done using allometric equations based on the DBH and height of the individual plants as described previously in Beets et al. (2011a).

A ratio estimator approach (Zarnoch & Bechtold 2000; Bechtold & Patterson, 2005) was used to calculate national averages of carbon stocks, their change and an overall national average yield table for the two planted forest classes. This approach uses the carbon stock or sequestration per plot, summed across all plots, divided by the summed net-stocked area sampled.

As the measurement date of plots periodically assessed in the inventory does not directly coincide with reporting dates, short-term projections or back-casting of plot estimates were required. Data is reported as at 31 December, so plots measured during the winter season needed to be projected forwards or backwards to the end of the calendar year. Because of the periodic nature and timing of the inventory cycle, little extrapolation to the reporting dates was required. The resulting estimates for the reporting dates can be assumed to be reasonably accurate, based on the independent model validation work conducted previously (Beets et al., 2007b).

The design and analysis also allows the construction of national carbon yield tables for the planted forest class of interest. The plots used in generating carbon yield tables are the same as those used to estimate carbon sequestration for reporting periods, with the exception that plots that had been recently harvested or planted were excluded.

Simulation of carbon stock changes for reporting

Emissions and removals in planted forests are calculated in the LUCAS Calculation and Reporting Application (CRA) by combining the carbon yield tables with mapped planted forest area and deforestation, and NEFD (Anon., 2015) derived age class, harvesting and new planting data (Anon., 2016). This provides estimates of carbon gains and losses for planted forests by year and carbon pool. Total planted forest area and deforestation are obtained from wall-to-wall mapping at 1990, 2008 and 2012 (Anon., 2016). Data from the NEFD (Anon., 2015) is used to allocate this area to age classes and provide afforestation for years where it is not mapped. The modelling process tracks forest areas by age class over time, simulating historic afforestation, harvesting, replanting and deforestation activity. Deforestation is modelled as an instantaneous loss of all carbon on-site, while harvesting is assumed to result in an instantaneous loss of harvested wood (estimated as 70% of above-ground biomass), with the remainder assumed to decay over time. Harvested wood products are modelled by a separate independent model based on national production and export statistics, according to guidance prepared by the IPCC (2006, 2014).

Post-1989 planted forest carbon stocks and stock change for 2008/2012

The estimates of carbon stocks by pool for the net-stocked area of New Zealand's post-1989 planted forests as at 31 December 2012, and the estimates for sequestration over the five-year first commitment period, are shown in Table 1. Stocks as at 1 January 2008 were estimated by subtracting sequestration from the 2012 stocks. Carbon sequestration occurred exclusively through crop-tree growth and corresponding increases in above and below live biomass. The dead wood and litter pools declined slightly over the period and were therefore a small source of carbon.

A comparison was carried out between the simulation approach and the direct plot-based estimate of carbon sequestration to validate and check the simulation approach. The comparison by pool is shown in Table 1. The simulation approach returns higher estimates for all biomass pools. The total sequestration estimate is within 1.1 tC/ha over the commitment period. The simulation approach also contains higher error than direct plot-based estimation due to estimated uncertainty in the model and the NEFD-derived activity data.

Discussion

The UNFCCC created a need for New Zealand to report carbon stocks and stock changes within forests. This need was initially met using existing data sources and models, principally the NEFD, but the introduction of binding commitments under the Kyoto Protocol provided the impetus for the development of a system to provide unbiased, nationally-representative estimates that would meet best practice standards. The LUCAS planted forest NFI was developed to meet these requirements.

As New Zealand did not have an existing ground-based NFI, expertise and capability had to be developed and methods tested during the implementation of the system. The NFI has been continuously improved for cost efficiency, to provide additional information and to reduce measurement and sampling error. Initially the priority was sampling post-1989 forests because accounting for stock changes in pre-1990 forests was not mandatory under the first commitment period of the Kyoto Protocol. Plot sampling and wall-to-wall mapping are complementary and need to be synchronised as best as possible (IPCC, 2003). However time and budgetary constraints meant that initial sampling in 2007/08 had to be undertaken in the absence of completed wall-to-wall mapping. The addition of 112 plots in the 2011/2012 re-measurement phase of the NFI was critical as it removed a previously undetected bias in the estimation of carbon stocks and carbon sequestration. This occurred because these plots represented post-1989 planted forests with reduced growth that were previously not included in the calculations described in Beets et al. (2011a).

A double sampling approach based on LiDAR was utilised as it provides plot metrics if access is declined or not possible. LiDAR acquisition for planted forests has proven to be a valuable approach, for example,

Table 1: Total carbon stocks and sequestration (tonnes/ha) by pool for post-1989 planted forests using direct plot-based estimation and simulated sequestration

Component	Plot-based carbon stocks as at 1 January 2008		Plot-based carbon stocks as at 31 December 2012		Plot-based carbon sequestration 2008/2012		Simulation-based carbon sequestration 2008/2012	
	C tonnes/ha	95% CI	C tonnes/ha	95% CI	ΔC tonnes/	95% CI	ΔC tonnes/	95% CI
Total	77.7	±7.1	129.3	±6.5	52.0	±2.7	53.1	±7.3
AGB	48.5	±5.0	91.8	±5.0	43.2	±2.7	43.3	±7.5
BGB	10.7	±1.1	19.5	±1.1	8.8	±0.6	8.9	±7.1
DW	8.3	±1.2	7.9	±1.2	−0.6	±1.1	0.3	±7.1
Litter	10.2	±0.9	10.3	±0.7	−0.2	±0.7	0.6	±7.1

improving the accuracy of carbon stock estimates in pre-1990 planted forests (Beets et al., 2012) and reducing the bias in post-1989 planted forests.

The simulation approach to estimate annual stock changes in post-1989 planted forest integrates datasets additional to the plot-based estimates and allows for projections and backcasting of estimates through time. It also provided a degree of consistency with the simulation approach used for New Zealand's UNFCCC reporting before the introduction of the NFI, as described in Ford-Robertson et al. (2000). New planting, age class and harvesting area estimates come from the NEFD (Anon., 2015a) and the total forest area and deforestation area is from the LUCAS land use map. The plot-derived yield tables are combined with these data in the simulation approach. This allows the modelling of annual estimates from 2008 for Kyoto Protocol accounting and 1990 for UNFCCC reporting, and can provide future projections.

The simulation approach returned higher estimates for above-ground and below-ground biomass compared with the direct plot-based approach, which is likely to be caused by recent planting in the simulation approach that is not fully captured by the plot network. The deadwood and litter pools are also greater in the simulation approach to a lesser extent. This is likely the result of forest harvesting between 2008 and 2012 that is not fully accounted for in the plot network. When all pools are combined the total estimate is within 1.1 t C/ha over the commitment period. However the estimates may diverge through time as post-1989 planted forest reach harvesting age and future calibration of the simulation approach may therefore be required.

Forest mapping is an ongoing exercise as area is afforested and deforested, previously unidentified forests are included, and forests are reclassified as planting date is corrected. The ground-based inventories in this analysis were completed in 2012 and some areas may not yet be sampled. This has the potential to bias the total carbon stock changes if additional areas are different to the ground sampled areas that provided the ground measurements for stock and yield table calculations. However we expect that this bias will be small as only minor area changes are expected. The number of potential additional plots would be very small and should not diverge significantly in their carbon sequestration rate.

A more fundamental issue with the use of a single yield table is that it does not take into account genetic improvement over time or changes in management or site productivity that affects sequestration rates. There is potential to develop the simulation approach further, for example, by using different yield tables for individual planting year cohorts.

The Paris Climate conference (COP21) in December 2015 created the first universal, legally-binding climate deal adopted by 196 countries. New Zealand's submitted 'Nationally Determined Contribution' is to reduce greenhouse gas emissions to 30% below 2005 levels by 2030. Forestry is potentially one of New Zealand's largest and least-cost abatement opportunities, and the government has signalled that they want forestry to continue to assist in meeting our international emissions reduction targets. Accounting rules for the post-2020 period have yet to be negotiated and may require changes in the NFI approach.

Conclusions

Carbon stocks and sequestration, and associated yield tables on a net-stocked area basis were successfully estimated in New Zealand's NFI using ratio estimators for the multiple available datasets. The use of multiple datasets improves the accuracy of this country's post-1989 planted forests estimate under the UNFCCC and the Kyoto Protocol. The inclusion of additional plots established in 2011/2012 corrects for a previous bias from an unrepresentative sample. The simulation approach has been used to produce accurate and unbiased estimates of carbon sequestration in post-1989 planted forests and enabled New Zealand to meet its requirements under the Kyoto Protocol (IPCC, 2006; Anon., 2015b).

The NFI brings New Zealand up to a forest reporting standard comparable with other developed countries (Tomppo et al., 2010). The periodic re-measurement of the established network of ground plots every five years will provide valuable data to quantify and describe the status and trends in all New Zealand's exotic forests (Beets et al., 2011a, 2012). The NFI is already utilised to report metrics other than carbon in the Montreal Process and Forest Resource Assessment reports (Anon., 2015a, 2015c).

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