SCIENCE FOR CONSERVATION 317

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newzealand.govt.nz

Department of Conservation
Te Papa Atawhai

Cover: Northern rata, Moehau Ecological Area, Coromandel Forest Park, January 2000. *Photo: DOC*.

Science for Conservation is a scientific monograph series presenting research funded by New Zealand Department of Conservation (DOC). Manuscripts are internally and externally peer-reviewed; resulting publications are considered part of the formal international scientific literature.

This report is available from the departmental website in pdf form. Titles are listed in our catalogue on the website, refer www.doc.govt.nz under Publications, then Science & technical.

ISSN 1177–9241 (web PDF)
ISBN 978–0–478–14941–8 (web PDF)

This report was prepared for publication by the Publishing Team; editing by Amanda Todd and layout by Lynette Clelland. Publication was approved by the General Manager, Research and Development Group, Department of Conservation, Wellington, New Zealand.

Published by Publishing Team, Department of Conservation, PO Box 10420, The Terrace, Wellington 6143, New Zealand.

In the interest of forest conservation, we support paperless electronic publishing.

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Abstract

There are strong financial incentives for accurately estimating potential Kyoto-compliant carbon sequestration on conservation land. However, estimation of potential carbon stocks is complicated, as it is unclear how the accuracy of estimates should be validated. One way of addressing this is to use several independent methods to estimate potential carbon stocks; the results can then be compared to indicate where uncertainty lies in predicting Kyoto-compliant carbon gain. In this study, the LUCAS vegetation survey plots were used in spatial predictive modelling to estimate current carbon stocks on conservation land in New Zealand. Three independent methods were then used to estimate potential carbon stocks, based on either regression models of potential forest cover using present-day forest survey data; spatial models of disturbance-adjusted carbon stock values for LUCAS plots; or a forest dynamics model that explicitly models changes in carbon. Kyoto-compliant lands were identified using the New Zealand Vegetation Cover Map. Conservation land was estimated to currently contain a total of 2578 Mt of C (9461 Mt CO_2e) in vegetation and soil. The three different methods provided estimates of Kyoto-compliant carbon gain ranging from 63 to 186 Mt of C (231–682 Mt CO_2e) as a result of land use change from non-forest to forest land. This equates to 3–8 years of New Zealand's total greenhouse gas emissions, based on estimated levels for 2005, and would take at least several centuries to be realised. Reasons for the variation in estimates, implications of results and limitations of the methods used are discussed. We acknowledge that uncertainties exist, primarily in the assumptions used to estimate total Kyoto-compliant forest areas and, to a lesser extent, extrapolation between plot-scale carbon measurements.

Keywords: carbon, Kyoto Protocol, conservation land, potential vegetation, spatial prediction, emission offsetting

Mason, N.W.H.; Carswell, F.E.; Overton, J.McC.; Briggs, C.M.; Hall, G.M.J. 2012: Estimation of current and potential carbon stocks and Kyoto-compliant carbon gain on conservation land. *Science for Conservation 317*. Department of Conservation, Wellington. 39 p.

1. Introduction

Lands managed for conservation purposes currently cover 35% of the New Zealand landscape (Ministry for the Environment 2007). These lands have various owners and managers, but the Department of Conservation (DOC) is the major stakeholder, managing approximately 8 million hectares. Conservation land management is crucial to the delivery of services that fuel the economy and support society (A. Morrison, Director-General, DOC, NZIF Conference, 15–18 May 2008, pers. comm.). The services of carbon storage and sequestration are among the most advanced in terms of quantification and economic valuation. New Zealand ratified the Kyoto Protocol in 2002, which conferred an ability for the country to gain credit from 'new' forests that were planted or naturally regenerated since 31 December 1989. The Government has since decided to devolve 'carbon credits' to private landowners for the duration of the Kyoto Protocol Commitment Period 1 (CP1), such that they can participate directly in carbon trading markets. Given that CP1 extends from 2008 to 2012, strong financial incentives currently exist for the accurate estimation of rates of Kyoto-compliant carbon sequestration.

While estimation of current carbon stocks is relatively straightforward through the use of present-day vegetation survey data, there is no obvious way to test the robustness of estimates of potential Kyoto-compliant carbon gain (i.e. potential increase in carbon storage due to cumulative sequestration). One way of addressing this uncertainty is to use several independent methods for estimating potential carbon gain. If independent methods produce similar estimates, confidence in these estimates is improved. If, on the other hand, they differ considerably, this will provide an indication of the range of possible values.

Carswell et al. (2008) previously estimated current carbon stocks on conservation land by applying mean carbon stock values to Vegetation Cover Map (VCM) classes (Newsome 1987). Potential carbon stocks associated with Leathwick's (2001) potential indigenous forest cover types were then predicted. Under New Zealand's interpretation of 'forest' within the Kyoto Protocol, lands eligible for afforestation/reforestation (Kyoto-compliant lands) are areas that, at 31 December 1989, supported less than 30% cover of species that could achieve a height of 5 m at maturity. For practicality, Carswell et al. (2008) identified Kyoto-compliant lands as those areas that were covered by VCM classes that were free of species that could potentially attain a height of at least 5 m. The estimate of potential Kyoto-compliant carbon gain was thus the difference between potential carbon stock in tall indigenous forest on Kyoto-compliant lands and estimates of average current carbon stocks for VCM classes, taken from Tate et al. (1997) and Hall et al. (2001). However, the estimate of gain was not time-bound—a zero rate of conversion of these lands from 'non-forest' to 'forest' between the time of VCM mapping and 1990 was assumed.

The current report provides an estimate of Kyoto-compliant carbon gain that improves on that given in Carswell et al. (2008) in two major ways. First, an unbiased estimate of current carbon stocks on conservation land was made by using data from a systematically sampled national-scale plot network known as the New Zealand Land Use and Carbon Analysis System (LUCAS; Payton et al. 2004). These data were combined with environmental and land cover information to produce a surface of current carbon stocks on conservation land (defined in this report as land managed by DOC). Second, we used three different methods to estimate potential carbon stocks:

1. Average carbon values associated with the predicted potential forest cover classes based on current tree species distributions presented by Leathwick (2001) (following the method of Carswell et al. (2008)).
2. Disturbance-adjusted carbon stocks estimated using the LUCAS data to quantify the effect of anthropogenic disturbance on carbon stocks, and to adjust carbon stocks recorded in LUCAS plots according to the effects of disturbance. These adjusted carbon values were then used to spatially predict potential carbon within conservation land.

3. Mean carbon values for potential vegetation biomes predicted by the LINKNZ model (Hall & McGlone 2006).

We report Kyoto-compliant carbon gain using each of these three methods and assess the magnitude of difference between estimates arising from each of the methods. LINKNZ models tree growth, death and competition based on observed species-specific growth rates, shade tolerance, and response to climatic, soil fertility and drainage gradients.

Since each of the three approaches incorporates independent information, we can be reasonably confident that we have obtained an accurate estimate if all three converge on a similar figure for potential carbon gain on conservation land. In contrast, any discrepancies may indicate where further work is needed.

2. Methods

2.1 Current carbon stocks

A map of current carbon stocks is required to provide an estimate of carbon contained by Kyoto-compliant lands, which is in turn required for comparison with estimated potential carbon stocks to produce estimates of Kyoto-compliant carbon gain. Current carbon stocks were estimated by regressing estimated carbon in live and dead vegetation within LUCAS plots (Payton et al. 2004) on a variety of spatial predictor variables. LUCAS plots were located at the intersection points on an 8 km grid that occurred in vegetation that was defined as either shrubland or indigenous forest by the Land Cover Database (LCDB1). At each location, a permanent 20 × 20 m plot was laid out, and data for estimating carbon stocks in woody vegetation were collected following the methods of Payton et al. (2004). Section 2.1.1 outlines how carbon stocks in LUCAS plots were estimated, and also describes the spatial predictors and modelling process used to produce a map of current carbon stocks.

2.1.1 Estimating carbon stocks in LUCAS plots

Carbon stocks in live and dead vegetative matter were calculated for five major categories: live trees, standing dead trees, coarse woody debris, continuous shrub cover and discrete shrub cover. Due to errors in LCDB1, some LUCAS plots occurred in non-woody vegetation. Such plots were included in the analyses, but were assigned a carbon value of zero, as the woody carbon stocks estimated by LUCAS were absent. It was necessary to include these plots in order to gain a non-biased estimate of carbon stocks within lands defined by LCDB1 as woody vegetation.

A total of 1243 plots were used to generate a surface of current carbon stocks for conservation land. We were unable to use the full LUCAS dataset due to restrictions on access to data.

On each plot, the height of the top of the crown and diameter at breast height (dbh—1.35 m above the ground) were measured for 15 individuals from each of the following groups, where present: broadleaved trees, conifers, tree ferns and dead standing stems. The sample included the full diameter range for each group, and included malformed stems. The sample also included all trees > 60 cm dbh or, where trees of this size were absent, the largest five trees on the plot. Where stems leaned more than 20° from vertical, lean angle was measured to the nearest 10°; height was then corrected by dividing the measured height by the cosine of the lean angle (where this angle was expressed in radians).

These height measurements were used to model the relationship between diameter at breast height and tree height. Two types of relationship were explored between diameter and height: linear (1) and log-linear (2):

$$\text{Height} = a + b \times \text{dbh} \tag{1}$$

$$\text{Height} = a + b \times \ln(\text{dbh}) \tag{2}$$

The relative ability of each model to predict height was assessed using the corrected Akaike Information Criterion (AICc; Burnham & Anderson 2002):

$$\text{AICc} = N \ln\left(\frac{\text{RSS}}{N}\right) + 2K\left(\frac{N}{N-K-1}\right) \tag{3}$$

where N is the number of trees, RSS is the residual sum-of-squares and K is the number of parameters included in the model.

An Akaike weight(W), which gives an estimate of the probability that a model gives the most parsimonious fit to the data, was calculated for each model, following the method described by Johnson & Omland (2004):

$$W_i = \frac{\exp\left(-\frac{1}{2}\Delta_i\right)}{\sum_{j=1}^{R} \exp\left(-\frac{1}{2}\Delta_j\right)} \tag{4}$$

where R is the number of models under consideration and Δ_i is the difference between the AICc value of model i and the minimum AICc value across all models. The sum of W_i values across all models adds to unity. The log-linear model was considered to be the default diameter–height relationship, and a $W_i > 0.7$ for the linear model was required for the log-linear to be rejected as the most parsimonious model.

This process was performed for each species for which we obtained over 30 height measurements. For all other species, height was estimated following the relationship between diameter and height for all stems within the database (i.e. all species in all plots grouped together) for which height measurements were taken. Where we measured more than 30 stems for a species and there was no evidence of a relationship between diameter and height ($P > 0.15$ for both linear and log-linear models), each stem was assigned the species' mean height. Modelled heights were applied to all stems for which no measured height was recorded, while measured stems retained their measured height value. Height was modelled separately for live and standing dead stems.

Live and standing trees

Trunk volume was estimated as a product of dbh and height, following the allometric relationship of Hall et al. (2001):

$$\text{Volume} = 0.0000598\ (\text{dbh}^2 \times \text{Height})^{0.946} \tag{5}$$

The biomass contained within each trunk was then calculated as:

$$\text{Stem Mass (kg)} = \text{Wood Density}\ (1.0 - 0.0019 \times \text{dbh}) \times \text{Volume} \tag{6}$$

This allometry was chosen for consistency with the methods used to estimate potential carbon stocks estimated from present-day tree species distributions and a process-based model of forest dynamics (outlined in sections 2.2.2 and 2.2.3, respectively). While it can give negative values for very large trees, this only occurs for trees > 5.1 m in diameter. The largest dbh value in the LUCAS dataset used for current carbon estimations was 3.2 m. If we take the example of rimu (*Dacrydium* *cuppresinum*), carbon is an increasing function of dbh until trees reach a dbh of > 3.6 m. Since this is larger than the largest tree in the dataset, we do not feel that the allometry will have biased our estimates.

Wood density values were obtained following the method described in Illic et al. (2000) from cores or discs collected opportunistically by Ian Payton, Landcare Research (pers. comm.), or were taken from Beets et al. (2009). Where values were available from both sources, the former source was used, as this dataset encompassed a larger range of species. Where multiple values for a species were available from this source, the mean was taken. For species where no density value was available, the mean density for the genus was used, and when no values were available for congeners, the mean density taken across all species was assigned. The biomass of branches > 10 cm in diameter and foliage was estimated following Hall et al. (2001):

$$\text{Branch Mass (kg)} = 0.03 \times \text{dbh}^{2.33} \quad (7)$$

$$\text{Foliage Mass (kg)} = 0.0406 \times \text{dbh}^{1.53} \quad (8)$$

Root biomass was assumed to be 25% of the live above-ground tree biomass, following Phillips & Watson (1994).

Tree biomass was assumed to be comprised of 50% carbon (Coomes et al. 2002). Standing dead stems were treated in the same way as live stems, except that branch and foliage biomass were assumed to be zero, and the proportion of biomass remaining for all species was assumed to follow the decomposition series (decay class I: 82% of live wood density; II: 66%; III: 47%). These values are averages taken across four species presented by Coomes et al. (2002). The proportion of carbon in decaying wood was assumed to be a constant 50% of total dry mass (values in Coomes & Beets (1999) range from 48.5% to 52.2%).

Only tree stems that were classified as 'alive' or 'dead' were included in the analyses of carbon; 'not found' (i.e. trees previously tagged in New Zealand National Vegetation Survey (NVS) plots but not in the LUCAS plots) were excluded. No epicormic or epiphytic stems were included in these analyses. No adjustments for biomass or carbon content were made for fused or multiple-stemmed individuals.

Total carbon contents of live and dead trees were converted from kg/0.04 ha to t/ha (Mg/ha) by multiplying by 0.025, summing individual tree values within each plot, and then cosine-correcting these totals for plot slope (i.e. dividing measured carbon by the cosine of the slope angle) to allow values to be applied to a mapped projection.

Coarse woody debris

Coarse woody debris (CWD) was recorded as fallen stems or branches (> 10 cm in diameter) within each 20 × 20 m LUCAS plot. The volume of individual CWD items was calculated as:

$$\text{Volume (m}^3) = (\pi l/32)((a+b)^2 + (c+d)^2) \quad (9)$$

where *ab* and *cd* are diameters at either end of the CWD item, and *l* is the length of the log. CWD biomass was calculated as the product of wood density and volume, where density was adjusted for each of three decay classes (as above for standing dead stems). No additional decay class modifiers were applied for climate or hollow v. solid logs because data on the influence of these factors are not available. Carbon stocks in CWD were multiplied by 0.025 to convert the figure into t/ha, and plot slope was corrected by dividing by the cosine of the slope.

Continuous shrub cover

Continuous shrub cover was defined as woody vegetation above 30 cm in height where individual plants or clumps could not be identified. Carbon stocks in continuous shrub cover were calculated using a combination of the volume of shrub cover within the 20 × 20 m plot and the density of biomass within destructively harvested samples from outside the plot, following the methods of Payton et al. (2004). Shrub volume was estimated in 0.2 × 0.2 m height–cover quadrats, where the vegetation height and the percentage cover were recorded using the following expression:

$$\text{Volume}\,(\text{m}^3) = \text{Area}\frac{1}{N}\sum_{i=1}^{N}\left[\text{Height}_i \times \frac{\text{Cover}_i}{100}\right] \quad (10)$$

where N is the number of height–cover quadrats, Height_i and Cover_i are the vegetation height (in metres) and percentage cover of quadrat i, respectively, and Area is the area in m^2 represented by the height–cover quadrats. Within the 20 × 20 m plot, 25 height–cover quadrats were used to estimate continuous shrub volume. Where a 4 × 1 m area of continuous shrub cover was harvested, 12 height–cover quadrats were measured to estimate the sample volume; when a 2 × 1 m area was harvested, six quadrats were used. Harvest carbon density was estimated as 0.5 × harvest dry weight, divided by harvest volume. Continuous shrub carbon in the 20 × 20 m plot was estimated as the product of shrub volume on the plot and harvest carbon density.

For some plots, height–cover quadrats were sampled within the 20 × 20 m plot but no harvest information was recorded. In these cases, the mean density across all recorded harvests was assigned to the estimated continuous shrub volume within the plot.

Discrete shrubs

Discrete shrub cover was defined as woody vegetation above 30 cm in height where individual shrubs or clumps of shrubs containing one or several species could be identified. Again, the methods of Payton et al. (2004) were used for data collection. Shrub volume was estimated using the equation for an elliptical cylinder:

$$\text{Volume} = \text{Height} \times \pi \frac{d_1}{2} \times \frac{d_2}{2} \quad (11)$$

where d_1 is the maximum diameter of the shrub and d_2 is perpendicular to d_1. Harvest carbon density was estimated as 0.5 × harvest dry weight, divided by harvest volume. Discrete shrub carbon in the 20 × 20 m plot was estimated as the product of shrub volume on the plot and harvest carbon density. Where a species was recorded as being present as a discrete shrub but had no corresponding harvest data, the mean density for that species across all discrete shrub harvests was applied. No discrete shrub measurements were made in forested plots.

Litter and soil carbon

Estimates of carbon contained in surface and buried litter for forest plots (all expressed as a percentage of live tree carbon) were obtained from Beets (1980). These litter values were used as the data on litter carbon from LUCAS plots were unavailable when the analyses were performed.

Estimates of soil carbon were obtained from Scott et al. (2002). While soil carbon is included in both current and potential carbon stocks, the layer is common to both, as we have not included drivers of soil carbon change. The reason for this is that there are very few data on the response of soil carbon stocks to changes in land cover type (Tate et al. 2003). As more data become available, it may be possible to model changes in soil carbon stocks in response to afforestation, but for now we must assume that they remain constant with vegetation change.

2.1.2 Spatial predictor variables

Variables related to the environment (Table 1), land cover and the abundance of key groups of tree species were used as predictor variables in modelling total current and potential carbon. Using a geographic information system (GIS), we overlaid the LUCAS plot locations on maps of each of the predictor variables and extracted values for each plot location. Below, we describe the predictor variables, and justify their use where necessary.

Environmental

Environmental variables were generally obtained from the climate and soil maps underpinning the Land Environments New Zealand classification (LENZ; Leathwick et al. 2003a, b). Basic variables such as mean annual temperature (MAT), mean annual solar radiation (MAS), vapour pressure deficit (VPD), the ratio of rainfall to potential evapotranspiration (Rainfall:PET), soil fertility, soil age and drainage were included because of their influence on net primary productivity. Slope was included due to its influence on drainage and soil formation, and as an indicator of the probability of landslides. Average October wind speed (October Wind) was selected because the prevailing westerly winds are generally most intense during this month. Variations in mean temperature (T Seas) and solar radiation (S Seas) between months, and distance to coast were used as indicators of seasonality in temperature and solar energy input, respectively. Each of the environmental variables was mapped to a 100 m resolution.

Forest composition

Maps of the abundances (number of stems >30 cm dbh per hectare) of *Nothofagus* (summed over four species), Myrtaceae (summed over six species in *Kunzea*, *Leptospermum*, *Metrosideros* and *Syzygium*), and Podocarpaceae (summed over 12 species in *Dacrycarpus*, *Dacrydium*, *Halocarpus*, *Lepidothamnus*, *Manoao*, *Podocarpus* and *Prumnopitys*) were taken from Leathwick (2001) and Overton et al. (2009), to provide an estimate of the variation in species composition of forest canopy dominants. These were supplied as grids with 100 m × 100 m resolution.

Land Cover Database 2 (LCDB2)

LCDB2 cover class was used as a categorical land cover variable. Since the link between categorical predictor variables and the response can be unduly influenced by extreme values when categories contain few replicates, we lumped the LCDB2 classes represented by LUCAS plots (Appendix 1), so that each new class contained a reasonable number of plots (≥ 10). The LCDB2 was then converted from the polygon coverage in which it was supplied into a grid coverage at 100 m resolution and reclassified to reflect the new classes.

Native vegetation cover

A map of predicted naturalness of vegetation was created to estimate human effects on vegetation. This was done by combining LCDB2 with a layer of potential vegetation, taken from Leathwick et al.'s (2003a, b) potential vegetation of New Zealand, but modified to include new information on original and current wetland distributions, and the distributions of cover classes such as river gravel and bare alpine rock from LCDB2. The resulting layer was combined with LCDB2 to create a layer that contained all the unique combinations of LCDB2 and potential vegetation.

We then created a lookup table that gave the estimated proportion of native vegetation remaining for each combination of potential vegetation and current vegetation. The proportion of native vegetation was estimated using expert opinion, but values could also be defined or calibrated from data. Many of the combinations were uncommon and many constituted errors in predictions of either the potential vegetation (i.e. Leathwick et al. 2003a, b) or current vegetation (i.e. LCDB2).

To understand how this was done, it is useful to consider this table as an elaboration of the simple, one-column tables used in past studies to assess the amount of native vegetation remaining (e.g. Rutledge et al. 2004; Walker et al. 2006). These earlier tables assigned each LCDB current cover class as either 'native' or 'exotic'. The current table makes two refinements to this approach:

- We adopted a continuous measure of the proportion of native vegetation remaining, rather than using a simple, binary 'native'/'exotic' dichotomy. This allowed for mixtures of native and exotic vegetation.

- We included information on the predicted potential vegetation to interpret the amount of vegetation remaining in a particular land cover type. This was done because cover such as scrub or tussock grassland can contain a high proportion of native species despite it being induced by human influences such as fire or forest clearance. As a result, areas of scrub or grassland were considered to have more native vegetation remaining in places where that would be the potential natural vegetation than in areas that were predicted to be naturally (or potentially) forested.

The final result was a single grid, with values at each pixel estimating the naturalness of vegetation at that pixel, ranging from 0 (no native cover) to 100 (100% native cover). In addition, we ran neighbourhood smoothing analyses over the resulting grids to provide estimates of the amount of native cover in 300 m and 1000 m radii from each cell. These neighbourhood naturalness variables provided a disturbance context for each site. This is useful for reducing the errors associated with plot locations and GIS information, and takes into account the spatial contagion and neighbourhood effects that influence ecological processes and human activities (Overton & Lehmann 2003). To differentiate between these variables, we term the grid with % native cover values for each pixel LCDB2 Native Cover, while we refer to the smoothed layers as Native Cover 300 and Native Cover 1000 depending on the radius used for the local smoothing.

Ecosat woody vegetation

We used the Ecosat woody vegetation layer (Dymond & Shepherd 2004) as a source of information on the distribution of woody vegetation that is independent of LCDB2. This layer was produced from satellite imagery and classifies vegetation into woody or non-woody at 15 m-pixel resolution. We also performed neighbourhood analyses on this layer, using a 25 m-radius neighbourhood—larger neighbourhoods were trialled but ran into memory limitations, and were abandoned due to time restrictions. The grid resulting from the 25 m neighbourhood was resampled to 25 m pixels to make the size of the grid more manageable. The values of this grid were percentages ranging from 0 (no woody vegetation within 25 m) to 100 (all vegetation within 25 m radius is woody).

2.1.3 Production of a current carbon stock map

A map of current carbon stocks is required to provide an estimate of carbon contained by Kyoto-compliant lands, which is in turn required for comparison with estimated potential carbon stocks to produce estimates of Kyoto-compliant carbon gain. The generalised regression and spatial prediction package GRASP (Lehmann et al. 2003) was used to generate predictive models linking land cover and environmental variables (listed in Table 1) to plot-level total carbon stocks. GRASP employs Generalised Additive Models (GAMs) to allow flexibility in the shape of relationships between carbon stocks and predictor variables. The models were used to generate a spatial prediction (i.e. map) of total live and dead vegetation carbon (TCC) across all conservation land covered by the LCDB1 classes 'Indigenous forest' and 'Shrubland'. GRASP predictions were restricted to these cover classes as this is the sampling universe of the LUCAS plots. For the remainder of conservation land, the estimated mean vegetation carbon values for VCM classes used in Carswell et al. (2008) were applied, since VCM classes have estimated mean carbon stock values presented in Tate et al. (1997), which allowed these lands to be included in estimates of TCC. This in turn permitted estimation of potential carbon gain on these lands.

The graphs of the GAMs presented in this report (see section 3.1.3: Fig. 4) show the partial contribution of each predictor variable that was included in the final model. GAMs are additive models, and the overall model is obtained by summing the partial contribution of each predictor variable. The form of the partial contribution depends on whether the predictor variable is a continuous variable (e.g. MAT) or a categorical variable (e.g. LCDB2). For continuous predictor variables, GAMs use a scatter plot smoother to estimate a non-linear curve for the partial contribution. Sometimes statistical tests indicate that a curve is not justified and so a linear regression is used. The curves or lines are shown as solid lines, with point-wise standard errors

Table 1. Environmental predictor variables used to model total current carbon (TTC) and potential total carbon (PTC).

NAME	DESCRIPTION	UNITS	REFERENCE
MAT	Mean annual temperature	°C	Leathwick et al. (2003a)
T Seas	A measure of cold stress, relative to mean annual temperature	°C	Leathwick (2001)
MAS	Mean annual solar radiation	kJ/day/m^2	Leathwick et al. (2003a)
S Seas	Seasonality in solar radiation	kJ/day/m^2	
Rainfall:PET	The ratio of mean annual values of rainfall and potential evapotranspiration	N/A	Leathwick et al. (2003a)
VPD	Mean vapour pressure deficit	kPa	Leathwick et al. (2003a)
October Wind	Mean wind speed for the month of October	km/h	Leathwick & Stephens (1998)
Slope	Topographic slope	Degrees	Leathwick et al. (2003a)
Distance to Coast	Distance to coastline	km	This report
Soil Calcium	Categorical classification of soil exchangeable calcium	Ordinal ranking	Leathwick et al. (2003a)
Soil Age	Categorical classification of soil age	Ordinal ranking	Leathwick et al. (2003a)
Soil Nitrogen	Categorical classification of soil total nitrogen	Ordinal ranking	Leathwick et al. (2003a)
Drainage	Categorical classification of soil drainage	Ordinal ranking	Leathwick et al. (2003a)

indicated by the dashed lines above and below. For categorical predictor variables, the graph shows what is essentially an ANOVA for that variable, giving the mean contribution of each variable (the wide bars) with standard errors (SEs) indicated with dashed lines (upper and lower SE limits denoted by the narrow bars). The width of each mean bar is proportional to the number of samples in that category. Overall, the graphs of the GAMs show the regressions and ANOVAs that are added together to make the overall model.

GRASP models were constructed by backwards stepwise selection, with significance tests for variable removal having Poisson link functions (which are suited to modelling responses that have many small and few large observations). The following outputs are presented in this report:

- Final GAM, with the curve of the partial contribution of each predictor variable to the overall model.
- Model validation and cross-validation results, showing the plots of the observed versus the predicted values for each. The correlation between predicted and observed values was used to assess the model.
- Estimates of the relative contributions of each spatial predictor variable to the model. These were done both as drop and alone contributions to the model. The drop contribution of a spatial predictor variable is the difference in explained deviance between the final full model and a model with that variable excluded. The alone contribution of a spatial predictor variable shows the deviance explained by a model with only that variable in the model.

The final model was used to make spatial predictions for the response variable. Predictions were made by exporting lookup tables from S-Plus into Arcview, and using programs (scripts) written in Avenue (the Arcview programming language) to produce spatial predictions using the lookup tables and the grid layers of the spatial predictor variables.

We modelled TCC against various sets of predictor variables. Models that included variables measured on the plots (e.g. soil depth, disturbance) were used to assess the importance of these variables in predicting TCC. Models that included both variables measured on the plots and

GIS spatial variables were used to try to find the best predictive model for TCC. Only models that use spatial variables (i.e. those mapped in GIS layers) can be used for spatial prediction (extrapolation) of the models of TCC from the plots to other areas. Consequently, for brevity, only models with GIS variables used for spatial prediction are reported here (results of models including variables measured on the plots are available on request).

Validation and cross-validation are robust techniques for assessing the predictive performance and stability of models. Validation compares the correlation between the values observed on plots and those predicted by the model. A high correlation between observed and predicted values indicates good model prediction. Cross-validation is similar, and estimates that ability of the model to predict onto new data, and the stability of the model against perturbation of the data. Here we used k-fold cross-validation, where the data are subsetted into k groups (here we used five groups). Each group is alternately left out of the data and the model trained on the remaining k–1 groups, and predicted onto the group not used in the model. This is done until all points have predicted values, using models trained on other groups of data. Good models will have good correlations between observed and predicted values, with similar values of correlation for validations and cross-validations.

Kyoto-compliant lands were identified using VCM (Newsome 1987), based on the assumption that lands that were 'non-forest' in the 1980s would not have met the New Zealand definitions of 'Kyoto forest' by 31 December 1989, i.e. did not comprise 30% crown cover per hectare of species capable of achieving 5 m height at maturity in situ. All 'non-forest' VCM classes managed by DOC for conservation purposes were considered to be Kyoto-compliant. The current carbon surface produced by GRASP was applied to these Kyoto-compliant lands as an estimate of carbon stocks as of 1989. Carbon stocks contained in indigenous forest at 1989 were estimated as the sum of carbon stocks predicted by GRASP for conservation land covered by VCM indigenous forest classes F1–F8 inclusive.

2.2 Potential carbon stocks

Three independent approaches were used to estimate potential carbon stocks on conservation land. Here we provide a brief explanation of each.

2.2.1 Prediction from disturbance-adjusted carbon values in LUCAS

We investigated ways of modelling and predicting potential total carbon (PTC) for New Zealand. Models of TCC show a strong effect of human influence on total carbon. To try to remove this effect and arrive at models and predictions of PTC, we trialled two methods:

1. **Restricting the plot data to only those plots that lack human disturbance.**
   We used both plot information and GIS information to assess likely human disturbance. The plot information was the recorded 'cultural' information on fire, grazing, logging, etc. The GIS information was the native vegetation cover described in Section 2.1.2 heading 'Native vegetation cover'. Unfortunately, the resulting subset of data had very few plots in landscapes in many areas of New Zealand, and models and predictions based on this subset of data still showed strong evidence of human impacts, evidenced, for instance, by strong reductions in total carbon at the higher values of mean annual temperature (since intact, lowland forest remnants indicate that forests in warmer areas c.f. cool montane forests could potentially support very high carbon stocks; e.g. Hall et al. 2001). Accordingly, this approach was not pursued further and no results are reported here.
2. **Modelling the effect of disturbance on total carbon, and then 'adjusting' the observed values to remove the influence of disturbance.**
   We modelled total carbon observed on the plots against the plot disturbance ('cultural') variables and the GIS layers of native vegetation cover and the 300 m-neighbourhood smoothing of native vegetation cover (as outlined in section 2.1.2 under the heading

‘Native vegetation cover’). We quantified the disturbance effect on each plot as the mean of undisturbed carbon values minus the predicted carbon value. We then calculated adjusted carbon values by adding this estimated disturbance effect to the total carbon value observed on the plot. These ‘cultural variables’ have some limitations, as they include a degree of subjectivity in some instances, do not indicate the time or severity of disturbance, and do not account for herbivory by feral or wild mammalian herbivores.

2.2.2 Prediction of potential forest cover from existing tree species distributions

Leathwick (2001) predicted presence/absence of indigenous tree species at a 25 × 25 m scale based on their observed occurrences in the NVS database. Predicted potential forest assemblages were placed into groups using classification analyses (see Leathwick 2001). We reclassified these groups according to the forest classes of VCM (Newsome 1987), based on the relative abundances of three groups of species—*Nothofagus* spp., coniferous species, and angiosperms other than *Nothofagus* (Carswell et al. 2008: table 2). This allowed estimation of potential carbon stocks using the mean carbon stock estimates obtained for forest classes that were presented in Hall et al. (2001). This was also the approach used by Carswell et al. (2008) in predicting potential carbon stocks.

2.2.3 Prediction of potential forest cover using the LINKNZ ecosystem-processes model

The LINKNZ model (Hall & Hollinger 2000) was developed to simulate forest gap dynamics and stand development under New Zealand conditions, and is a generalisation of the LINKAGES model that was designed for the mainly temperate deciduous forests of eastern North America (Pastor & Post 1986; Post & Pastor 1996). LINKNZ contains several extensions that assist it in producing acceptable simulations for New Zealand’s temperate evergreen forests. In brief, the set of equations used to estimate light availability and canopy-gap decay rates were reformulated, and the ‘poor-growth’ conditions were altered to match the survival chances of several slow-growing major New Zealand species. In addition, a basic disturbance regime was added to simulate the effects of whole-stand disturbance by landslip, windthrow or fire on forest succession. We chose the LINKNZ model ahead of other potential process-based models since it is the only model we were aware of that was suitable for application at a national scale. Other models, such as SORTIE (e.g. Forsyth 2008), require further parameterisation effort before they can be applied nationally.

LINKNZ handles variation in rainfall by maintaining an explicit soil-moisture balance that accesses local data for monthly rainfall and temperature, soil moisture capacity, and soil wilting point. The model also incorporates a sub-model to track the litter decomposition–soil nutrient cycle and its impacts on stand succession, consistent with relationships presented in key studies on decomposition and soils (e.g. Aber et al. 1978; Pastor et al. 1984; Pastor & Post 1986). The positive feedback exhibited in the nutrient cycle is important because it allows the model to reproduce complex behaviour, in which variations in conditions can lead to forest successions diverging to alternative stable states.

We estimated potential carbon stocks from predictions at local sites using the ‘direct-extrapolation’ method (King 1991; Bugmann et al. 2000). Under this method, a spatially heterogeneous landscape or region is represented as a mosaic of discrete homogeneous landscape elements, with the aerial extent of each element being defined by traits that determine the property being modelled.

The New Zealand Land Resource Inventory database (NZLRI; Newsome 1992) provided a spatial representation of environmental heterogeneity at an appropriate level of detail for a national-scale study. This database subdivided the entire area of the North and South Islands into a total of 88 933 discrete homogenous landscape elements, ranging in area from < 1 ha to 61 266 ha. Stewart Island/Rakiura and the other outlying islands, which account for c. 2% of the total land area, were mapped into an additional 388 discrete landscape elements. The homogeneity of each of the landscape elements in the NZLRI database had been determined by an analysis of climate surfaces, soil, vegetation, slope, erosion and landform classes (Newsome 1992; Leathwick 2003a, b).

A set of 58140 landscape elements was obtained by overlaying an electronic map delineating land under public ownership and current management by DOC (supplied by DOC, August 2008) on the NZLRI database maps (Newsome 1992; Table 2). Landscape elements that were depicted by NZLRI as being unlikely to support significant amounts of woody vegetation were not sampled. This excluded elements defined by NZLRI as estuaries, ice, lakes, riverbeds, sand-dunes, dredge tailings and towns, and amounted to c. 9% of all elements or c. 8.8% of the conservation land area. In addition, a number of smaller landscape elements (<50 ha) in the North and South Islands were not modelled separately, but were merged with the most similar of their neighbouring elements, to reduce the total number of elements modelled. These elements (6.3%) covered 0.06% so that modelling them separately would have disproportionately increased the processing time required relative to the area they cover.

Forest development was simulated at a sample site located at the centroid of each landscape element and potential carbon stocks were calculated by multiplying mean sample stocks at the end of the simulation by the area of the element (King 1991). The potential total pool of live tree carbon for all conservation land was obtained by summing the estimated carbon stocks on each landscape element.

Forest model parameters and environmental data

LINKNZ requires information on species growth parameters in response to variation in climate, soil fertility and light intensity. Growth parameters for each species were obtained from Hinds & Reid (1957), Wilson (1982), Wardle (1984), Wardle (1991), and Lusk & Ogden (1992). This parameter set was used for all forest simulations apart from those for Stewart Island/Rakiura and its outlying islands. For Stewart Island/Rakiura, a subset of 42 species was selected from the full list, based on the field guide of Wilson (1982).

Monthly temperature and total monthly precipitation data (mean, standard deviation) were obtained from the spatially interpolated surfaces contained in the LENZ database. LENZ provides a 1 × 1 km climate grid over the North and South Islands, and a 100 × 100 m grid over Stewart Island/Rakiura and its outlying islands (Leathwick & Whitehead 2001; Leathwick et al. 2003a, b). Climatic parameters for each of the NZLRI landscape elements were obtained by calculating the mean of the climate grid estimates of all grid points falling within an element or, in the case of the smaller elements that lay between grid points, by the mean inverse-distance interpolation of the four closest climate grid points to the centre point of the element (Bugmann et al. 2000).

Table 2. Distribution of landscape elements over conservation land managed by the Department of Conservation as of 2008. Homogeneous elements from the New Zealand Land Resource Inventory database were chosen as the basis of a sample set for modelling potential forest biomass carbon over conservation land (Newsome 1992).

LOCALITY	TOTAL AREA (ha)	AREA MODELLED (ha)	TOTAL ELEMENTS	ELEMENTS MODELLED
North Island	2052389	1931847	24043	22036
South Island	6327337	5704083	33709	30528
Stewart Island/Rakiura and its outlying islands	154019	150484	388	365
Total	8533745	7786414	58140	52929

Soil parameters were estimated using field data and properties of representative samples of the 1246 soil classes defined in general soil surveys of the North and South Islands (as presented in New Zealand Soil Bureau 1957, 1968). The average depth of each soil type was taken from descriptions of the soil classes, and was defined as the distance from the surface down to either a base-rock material or an impermeable soil layer, such as an iron pan. Specific field capacity (cm) and wilting point (cm) for each soil type were estimated from soil texture per 300 cm of soil depth, following the general relationships given in Pastor & Post (1985). Estimates for soil organic matter and soil nitrogen were obtained from representative sample analyses of the soil classes (New Zealand Soil Bureau 1957, 1968). Percent soil organic carbon (SOC%) at soil depth d (cm) was predicted from the mean percent organic carbon in the soil A-horizon ($SOC\%_A$). Soil organic matter (SOM, Mg/ha) was then estimated from SOC%, depth of the A + B soil horizon (D, cm), and soil bulk density (β, Mg/m^3), by the following equation:

$$SOM = 1.7 \times SOC(D/2) \times D \times \beta \tag{12}$$

Finally, soil nitrogen (SN, Mg/ha) was estimated from SOM and the representative C:N ratio for each soil type (New Zealand Soil Bureau 1957, 1968):

$$SN = (SOM/1.7) * (N/C) \tag{13}$$

Soil parameters for Stewart Island/Rakiura and its outlying islands were derived using similar methods to those for the North and South Islands, but were based on the soil classes and soil map of Leamy (1974).

Because New Zealand canopy species tend to be slow-growing and can potentially live for several centuries (Hinds & Reid 1957; Wardle 1984; Lusk & Ogden 1992), the simulation period was set at 800 years, to let the later-successional species reach maturity and to allow the forest biomass to attain a long-term equilibrium level. The stochastic nature of the model requires that multiple simulations be undertaken to adequately represent the overall forest dynamics and to even out the effects of any anomalies. For this study, stand growth was simulated on 50 plots at each site, and mean values (with confidence limits) for live tree carbon were calculated at year 800. Sample plot area was one-twelfth of a hectare (c. 833 m^2), as an approximation of the canopy gap created by the death or removal of a large tree within mature forest. Initial site conditions on all sample plots were assumed to be receptive to seedling establishment, and initial stem diameters were stochastically determined within a range of 1.27–1.42 cm dbh (1.37 cm). All species available to the model were free to establish during a simulation whenever soil moisture, soil nutrients, light conditions and climate were suitable.

Carbon stock estimates

The forest model was extended to calculate whole tree biomass using the allometric equations developed to estimate the live tree carbon biomass of New Zealand tree species; these equations were taken from Hall et al. (2001) and are the same as those noted in section 2.1.1 for estimation of live tree carbon stocks in the LUCAS plots. Estimates of carbon contained in ground vegetation (i.e. vegetation < 2 m in height), and surface and buried litter for forest classes (all expressed as a percentage of live tree carbon) were obtained from Beets (1980). An estimate of mean carbon contained in coarse woody debris within native forests was taken from Peltzer & Payton (2006).

Total carbon stocks were estimated by adding the average coarse woody debris value for forests (21.9 tonnes per hectare; Peltzer & Payton 2006) and estimates of carbon contained in litter and ground vegetation (< 2 m in height) (1.05% and 1.01% of total carbon, respectively; Beets 1980), to the live tree carbon estimates provided by LINKNZ. These values were used since the complete LUCAS dataset was not available when the potential carbon stocks for LINKNZ were calculated. The mean CWD value given by Peltzer & Payton (2006) for indigenous forest is very close to that calculated for forest plots in the total LUCAS dataset (21 tonnes per hectare).

Estimation of carbon stocks by forest biome

To examine the variation based on predicted composition, the mean (± SD) potential live tree carbon stocks on conservation land were calculated for each forest biome across the NZLRI landscape elements in which it was predicted to occur by LINKNZ. Spatial variation was also examined by comparing mean estimates of carbon stocks among the three main land masses. Biomes for conservation land were obtained by using a GIS to overlay electronic maps of potential forest cover for the North and South Islands (Hall & McGlone 2006) on maps of potential live tree carbon stocks determined for this study. Potential forest cover for Stewart Island/Rakiura and its outlying islands was mapped into five major biomes following the methods described in Hall & McGlone (2006) for classifying forests into biomes based on plant functional types.

Potential carbon values for predicted non-forest areas

For conservation land predicted to support non-forest vegetation by LINKNZ, potential carbon values were assumed to be the same as current carbon values. Additionally, for lands predicted as 'non-forest' by LINKNZ but measured as currently supporting the LCDB1 classes 'Indigenous Forest' and 'Shrubland', the current carbon values predicted by GRASP from the LUCAS data were applied. For the remainder of non-forest classes on conservation land, vegetation carbon stocks for the relevant VCM class were used.

2.2.4 Estimation of Kyoto-compliant carbon gain

Kyoto-compliant carbon gain was calculated by subtracting the total current carbon (TCC) content of each pixel in Kyoto-compliant VCM classes from the corresponding potential total carbon (PTC) value. Differences were summed within each Kyoto-compliant class and across these classes to give subtotals and overall totals of Kyoto-compliant carbon gain. This also allowed estimation of the potential carbon gain per unit area (i.e. t/ha) within each VCM class and overall. This process was performed separately for the three independent methods of estimating potential total carbon.

3. Results

3.1 Current carbon stocks on conservation land

Total current carbon stocks (TCC) on conservation land were estimated to contain 2578 Mt of carbon or 9461 Mt CO_2e (CO_2 equivalents—the weight of carbon converted to an equivalent weight of CO_2) in live and dead vegetation and soil (Fig. 1). Below, we provide some summary statistics on carbon stocks and land cover-classification errors in LCDB1, as well as an outline of the results of GRASP models used to map TCC on conservation land.

3.1.1 Carbon stocks for expected LCDB1 cover classes

Of the plots analysed, LCDB1 classified 933 as indigenous forest and 311 as shrubland. Average carbon in live and dead vegetative material was 206 t/ha for forest plots and 49.6 t/ha for shrubland plots. On average, live stems > 2.5 cm dbh contributed by far the majority of carbon in plots classified as indigenous forest (185 t/ha) and shrubland (46 t/ha) (Fig. 2). Standing dead stems and coarse woody debris (CWD) contributed on average 21 t/ha to indigenous forest plots and 3.6 t/ha to shrubland plots.

3.1.2 Carbon stocks for observed LCDB2 cover classes

Comparison with land cover classification by LCDB1 with observed land cover shows that while indigenous forest was accurately mapped by LCDB1, a high proportion of plots classified as shrubland by LCDB1 were observed to support other types of land cover (Table 3). The majority of plots misclassified as indigenous forest by LCDB1 were observed to be either shrubland, planted forest or primarily pastoral (Table 3). The majority of plots misclassified as shrubland were observed to be forest (Table 3). On average, LUCAS plots observed to support indigenous forest had the greatest total carbon content (Fig. 3).

3.1.3 Comparison of carbon surface produced using GRASP with actual carbon stocks

Figure 4 lists the predictor variables included in the final model and shows the fitted relationship between them and total current carbon. Here it is worth noting that LCDB2 classes 'Indigenous Forest' and 'Planted Forest' tend to have much higher total carbon values than other classes; total carbon increases linearly with increasing Ecosat woody cover, the percentage of native cover in a 300 m radius of the plot and distance to the coast; and total carbon has a unimodal relationship with MAT.

LCDB2 class, Ecosat woody cover, MAT and drainage made the largest contributions to the final model (Fig. 5). However, only the first three of these variables had non-negligible predictive ability independent of all other variables in the model (Fig. 5 'Independent'). The unimodal relationship between MAT and TCC probably reflects the interaction between altitude and disturbance, where vegetation at lower altitudes is more likely to have experienced some form of human disturbance, while carbon stocks at higher altitudes are likely to be limited by environmental stress. The fact that the neighbourhood land cover variable (Ecosat Woody 25 m—the percentage of woody cover within a 25 m radius of the target pixel) added considerable predictive ability independently of the point-based land cover variable (LCDB2) may suggest two things: the neighbourhood smoothing may have helped to diminish the effect of errors in land cover classification on predictions; and the neighbourhood land cover may have influenced, or at least provided information about, the carbon stocks at a point. The strong ability of land cover variables to predict carbon stocks emphasises the importance of having accurate remote sensing information for estimating total carbon stocks on conservation land.

The final model had a Pearson r value of 0.662 (decreasing to 0.608 under cross-validation; Fig. 6). This small decrease indicates that the model is stable when predicting onto independent data.

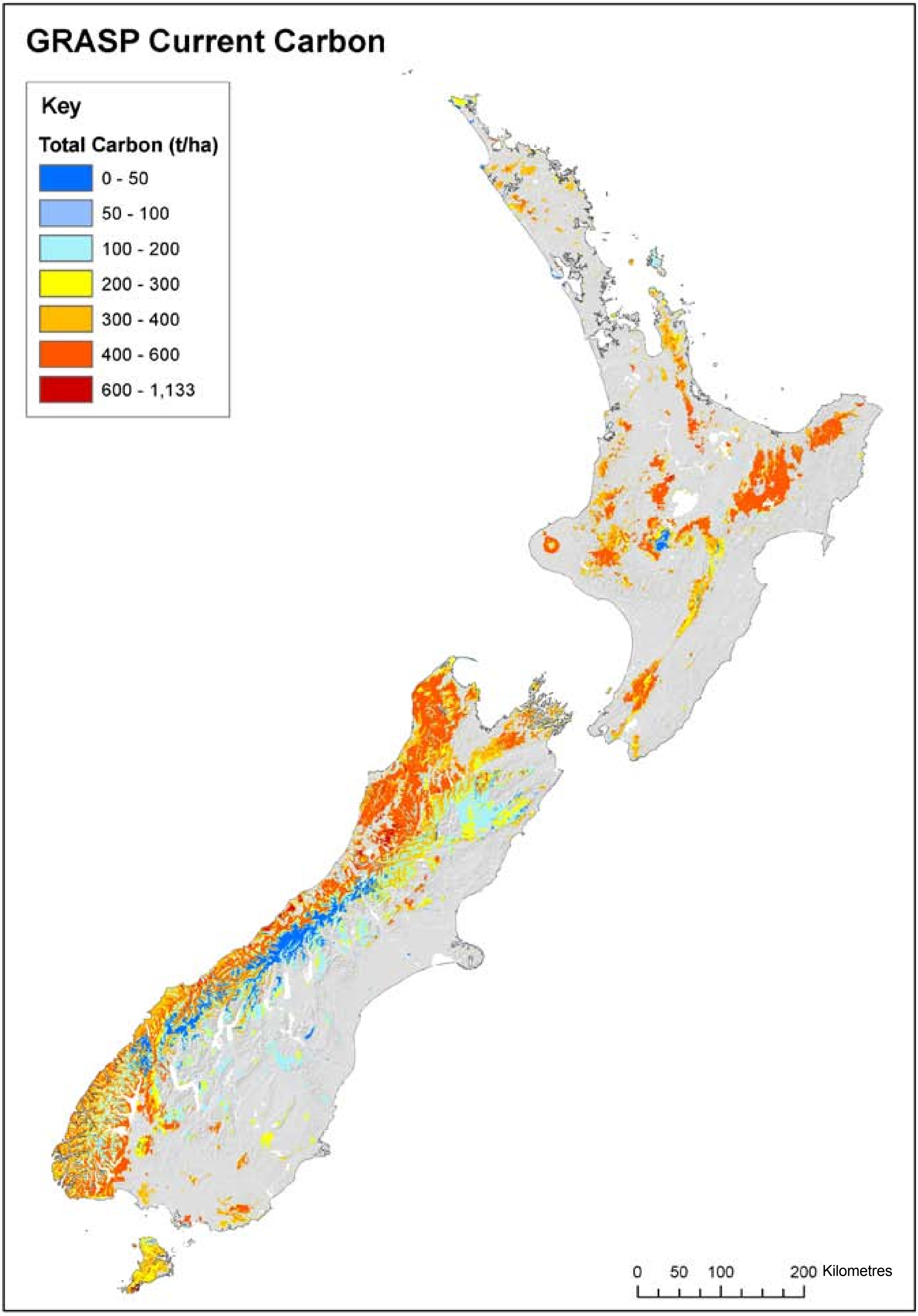

Figure 1. Total current soil and vegetation carbon on conservation land.

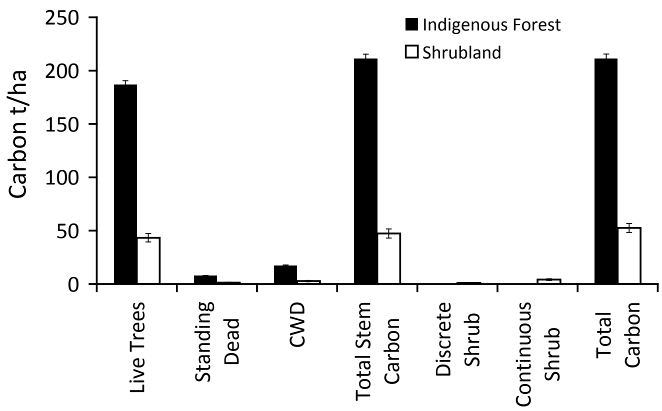

Figure 2. Mean (± SE) carbon stocks for LCDB1 classes 'Indigenous Forest' and 'Shrubland' as estimated using the LUCAS plots.

Table 3. Observed LCDB1 land cover class of plots classified as indigenous forest or shrubland in LCDB1.

OBSERVED LCDB1 LAND COVER CLASS	% LCDB1 FOREST PLOTS	% LCDB1 SHRUBLAND PLOTS
Bare ground	0.1	1.6
Coastal sands	0.1	0.3
Grassland	0.3	3.5
Indigenous forest	96.7	29.3
Inland water	0.0	0.6
Inland wetlands	0.1	0.3
Pasture	0.0	0.3
Planted forest	0.8	4.2
Primarily pastoral	0.9	6.4
Riparian planting	0.0	0.3
Scree	0.0	0.6
Shelterbelts	0.1	0.3
Shrubland	1.0	51.8
Urban	0.0	0.3

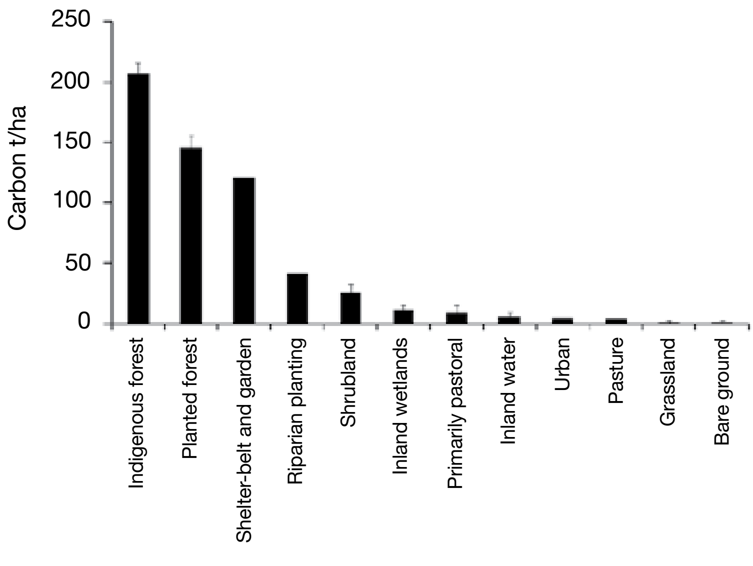

Figure 3. Mean (± SE) total current carbon stocks for each of the LCDB2 classes observed at LUCAS plots.

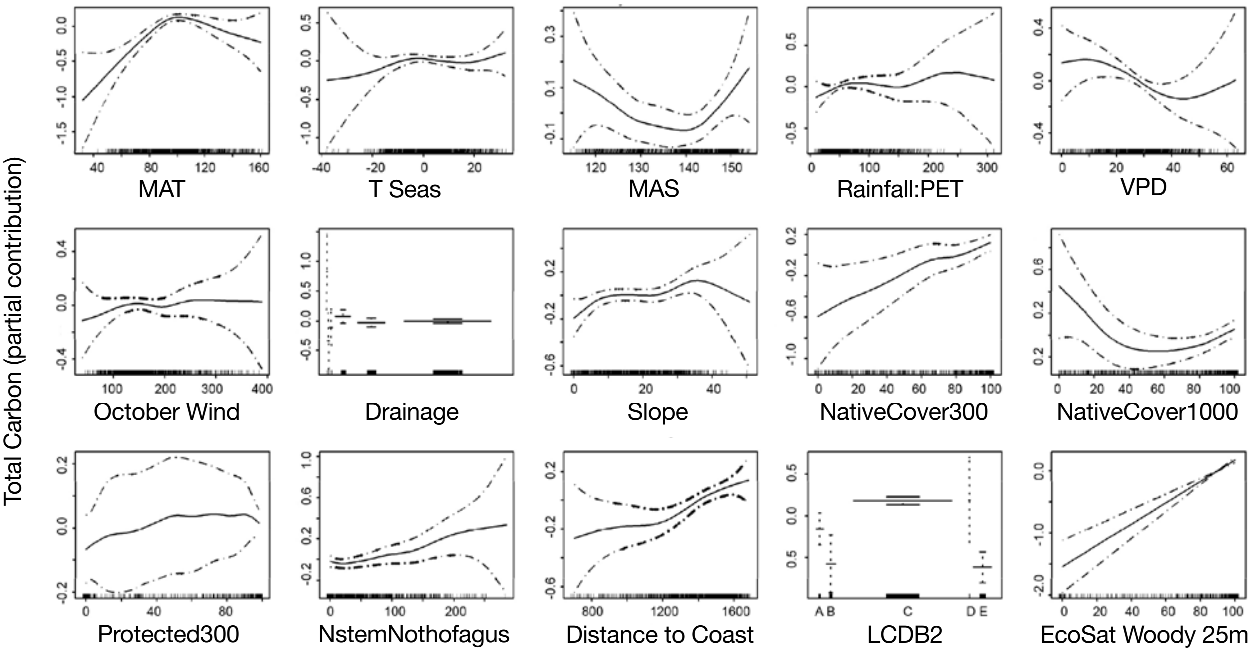

Figure 4. The GAM model of total current carbon, based only on variables available as GIS layers. The vertical axis shows the additive partial contribution of each variable to the overall model (see methods for a full explanation). For MAT, T Seas and October Wind, values have been multiplied by 10 for conversion to integers. LCDB2 classes are as follows: A 'Other'; B 'Herbfield, grassland or bare ground'; C 'Indigenous Forest'; D 'Planted Forest'; E Shrubland.

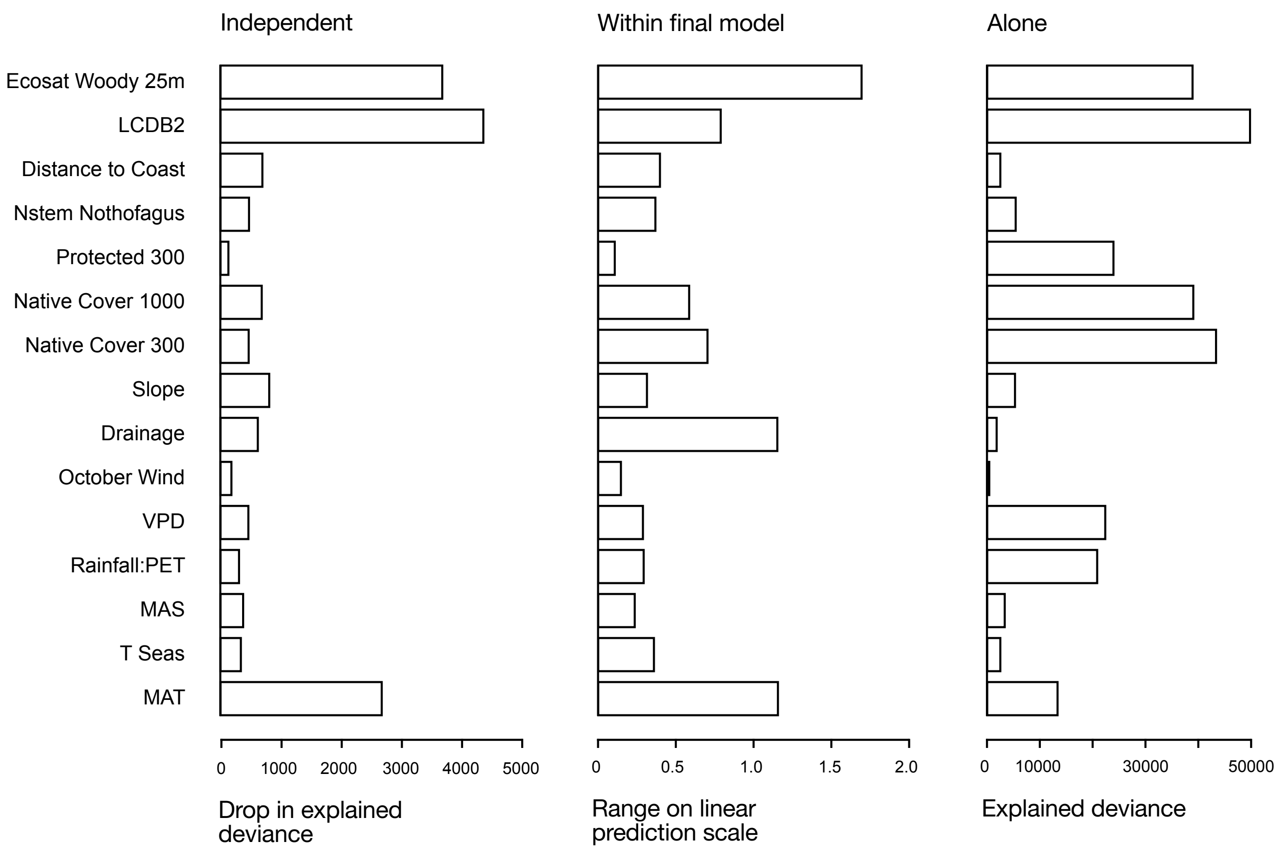

Figure 5. Relative importance of spatial predictor variables for explaining total current carbon. The independent contribution of a predictor variable is calculated as the difference in explained deviance between a model with that variable excluded and the final full model. The alone contribution of a spatial predictor variable shows the deviance explained by a model that only contains that variable. The contribution within the final model indicates the influence of each predictor when all other predictors are held constant.

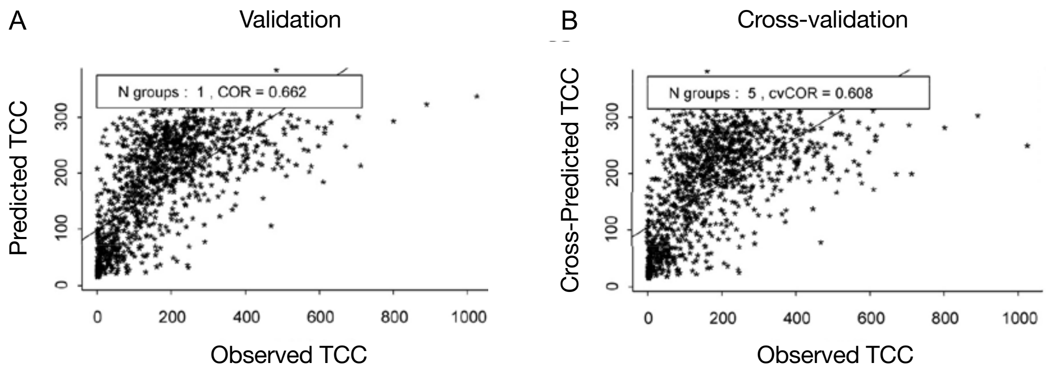

Figure 6. A. Validation and B. cross-validation of the total current carbon (TCC) model, using only GIS variables. Five-fold cross-validation was used, whereby the data were divided into five even-sized groups and total carbon for plots in each group was predicted by models constructed using plots in the other four groups.

3.2 Potential carbon stocks on conservation land

3.2.1 Prediction from disturbance-adjusted carbon values in LUCAS

Total current carbon (TCC) was lower for LUCAS plots on which disturbance was observed than on plots where there was no disturbance. This effect was seen for all types of disturbance, though was less noticeable for logging (Fig. 7). Total carbon increased linearly with %Native cover in a 300 m radius (Native Cover 300) and almost linearly with the native cover of individual pixels (LCDB2 Native Cover). %Native cover in a 300 m radius and %Native cover of individual pixels explained most of the variation in the model, while clearance, grazing and fire also explained a relatively large amount of variation. Similar patterns were observed for within-model contributions and independent (selection) contributions (Fig. 8). This indicates that the two spatial representations of disturbance were much more effective in revealing disturbance effects on TCC than the binary variables indicating the presence or absence of disturbance types assessed subjectively at LUCAS plot sites.

The correlation between observed and predicted values of TCC using the best fitting model (under cross validation) was 0.55 (Fig. 9A). Figure 9B shows disturbance-adjusted carbon values against those predicted by the disturbance model. It can be seen that a large number of data points sit to the extreme right-hand side of this graph, representing plots with no disturbance. The mean of these undisturbed plots is an estimate of overall total carbon in undisturbed plots. The points to the left of these extreme values represent plots with various levels of disturbance, which reduce their total carbon.

Figure 10 lists the variables included in the final model of potential (disturbance-adjusted) total carbon (PTC). It is worth noting the asymptotic relationship between mean annual temperature and PTC. MAT made by far the largest contribution to the model (Fig. 11), so the model may be considered to largely reflect its relationship with PTC. Once the effects of disturbance were removed, the correlation between observed and predicted PTC was quite weak (0.383; Fig. 12). There was also a moderate decrease in correlation under cross-validation, suggesting that the model was only moderately stable. The weak correlation between observed and predicted PTC values indicates that there is probably only a small amount of spatial variation in carbon stocks once disturbance effects have been factored out.

The final GRASP model of disturbance-adjusted LUCAS carbon stocks predicted that conservation land could potentially contain a total of 2677 Mt of carbon in soil and vegetation (Fig. 13). This is a total gain of 99 Mt over the current 2578 Mt of carbon on conservation land. Since GRASP was only used to predict carbon stocks, there is no way of knowing how carbon would be divided between forest and non-forest ecosystems.

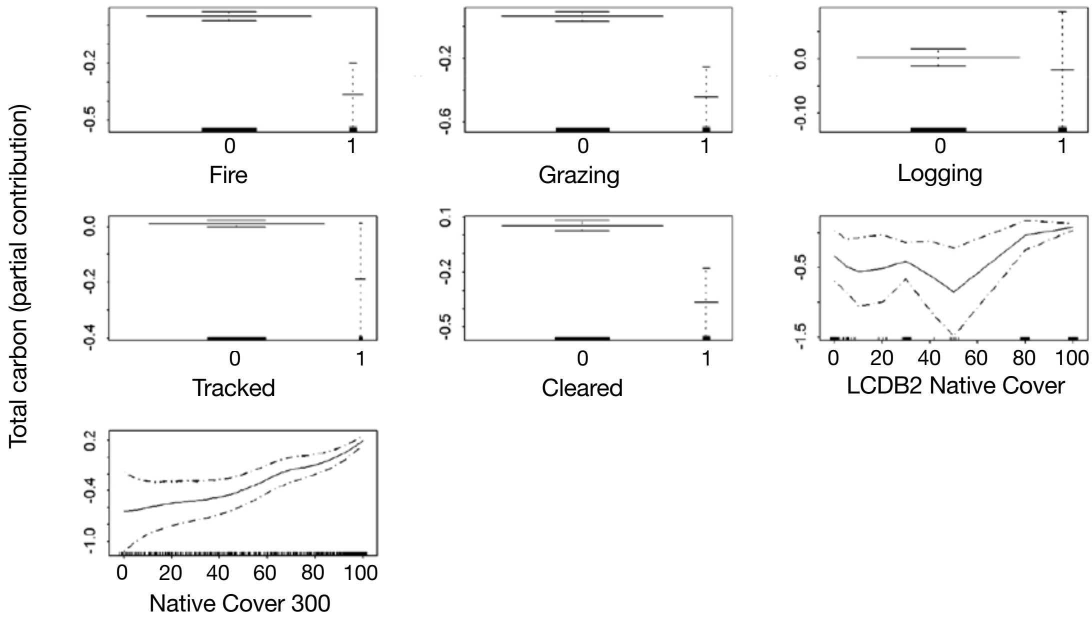

Figure 7. The GAM model of total current carbon, based only on disturbance variables. The vertical axes show the additive partial contribution of each variable to the overall model (see methods for a full explanation). For categorical variables, 0 indicates absence and 1 presence of the disturbance at LUCAS plots. LCDB2 Native Cover is the % native vegetation cover of individual pixels, while Native Cover 300 is LCDB2 native cover smoothed using a 300 m radius.

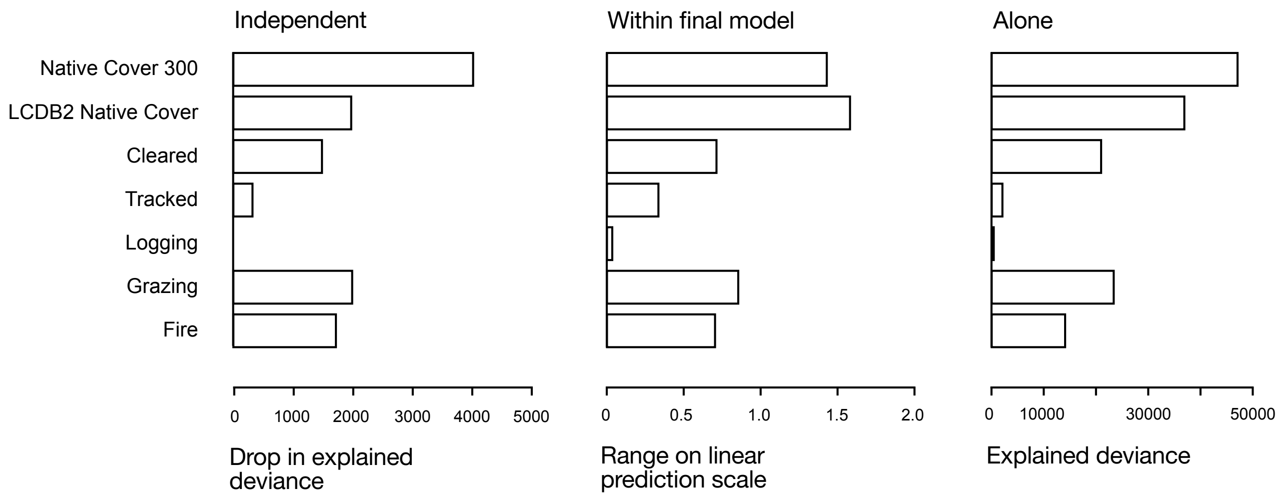

Figure 8. Relative importance of predictor variables in the disturbance model of total current carbon (TCC model). The independent contribution of a spatial predictor variable is the difference in explained deviance between the final full model and a model with that variable excluded. The alone contribution of a spatial predictor variable shows the deviance explained by a model with only that variable in the model. The contribution within the final model indicates the influence of each predictor when all other predictors are held constant.

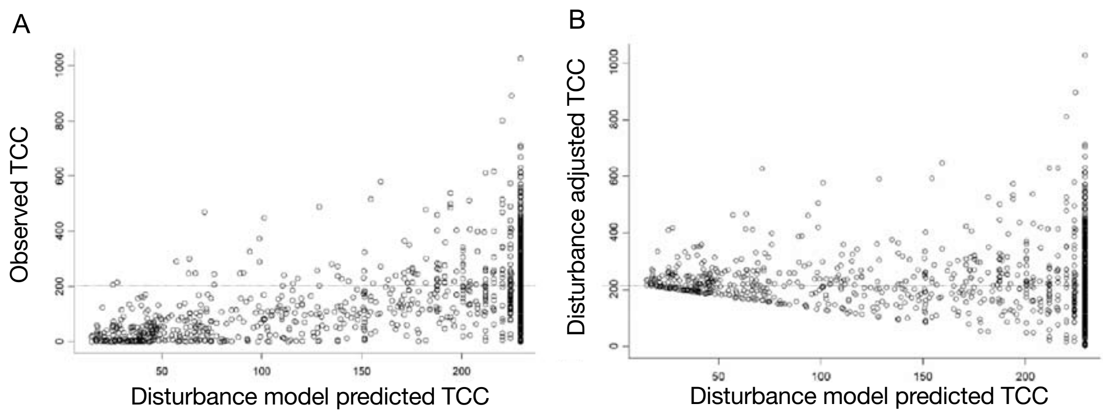

Figure 9. Relationship between A. predicted total current carbon (TCC) using the disturbance model and the total carbon observed on the plots; and B. disturbance-adjusted TCC values and values predicted by the disturbance model.

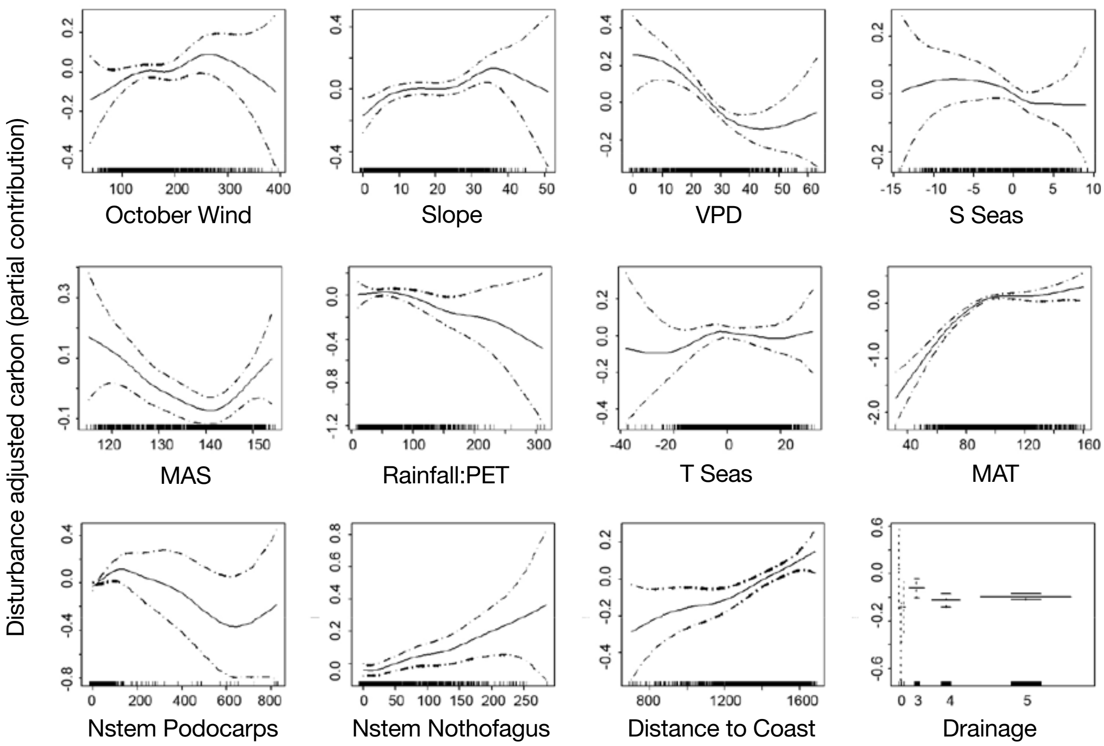

Figure 10. Additive partial contributions of predictor variables in the final GAM model predicting disturbance-adjusted carbon. The vertical axes show the additive partial contribution of each variable to the overall model (see Methods for a full explanation). For MAT, T Seas and October Wind, values have been multiplied by 10 for conversion to integers.

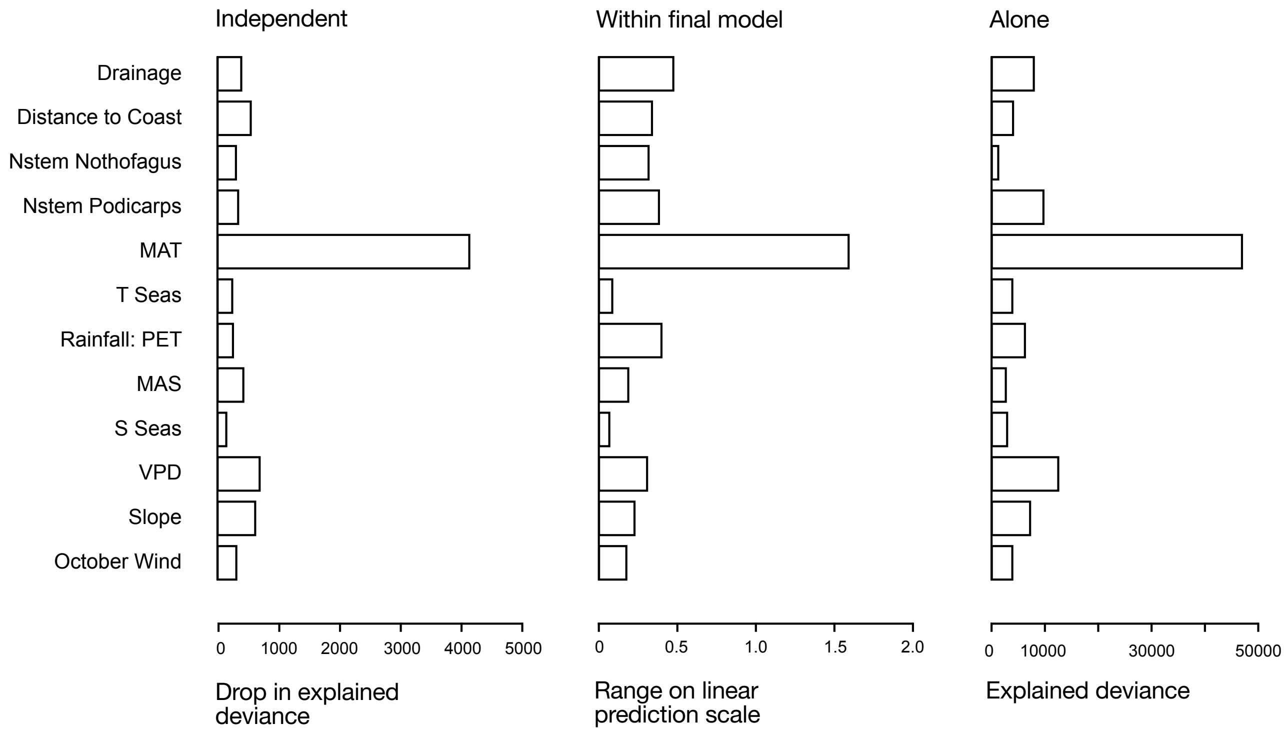

Figure 11. Relative importance of predictor variables for explaining potential total carbon (PTC). The independent contribution of a spatial predictor variable is the difference in explained deviance between the final full model and a model with that variable excluded. The alone contribution of a spatial predictor variable shows the deviance explained by a model with only that variable in the model. The contribution within the final model indicates the influence of each predictor when all other predictors are held constant.

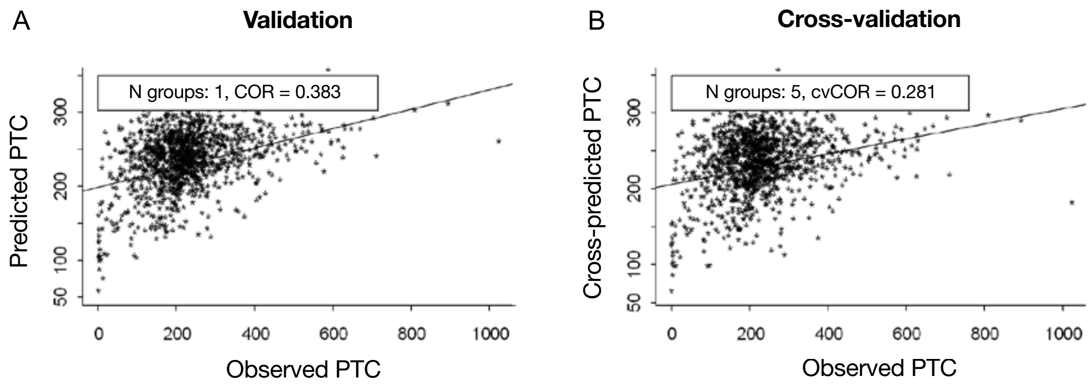

Figure 12. A. Validation and B. cross-validation of the potential total carbon (PTC, or disturbance-adjusted total carbon) model. Five-fold cross-validation was used, whereby the data were divided into five even-sized groups and total carbon for plots in each group was predicted by models constructed using plots in the other four groups.

3.2.2 Prediction of potential forest cover from existing tree species distributions

Estimates of potential carbon stocks based on the predictions of Leathwick (2001) indicated that conservation land could potentially contain 2628 Mt of carbon in vegetation and soil (Fig. 14). This is a total gain of 49 Mt over current levels.

3.2.3 Prediction of potential forest cover using the LINKNZ ecosystem-processes model

LINKNZ predicted a potential total vegetation and soil carbon value of 2664 Mt on conservation lands (Fig. 15), representing a total gain of 86 Mt. Considering that the LINKNZ and GRASP approaches to predicting potential carbon stocks were completely independent, it is remarkable that they gave such similar results.

LINKNZ predicted that 7.8 million hectares, or 97% of conservation land, could potentially support forest vegetation of some sort (Table 4), and would contain a total of 1386 Mt of carbon in live and dead vegetative matter (for an average of 178 t/ha of carbon when CWD, litter and ground vegetation carbon are added to carbon estimated by LINKNZ to be contained in trees). Encouragingly, an independent analysis of the carbon contained in all LUCAS forest and shrubland plots gave an average value of 173 t/ha (Beets et al. 2009). Our results suggest that indigenous forests on conservation land could potentially contain 461 Mt more carbon in live and dead vegetation than at present (i.e. total carbon contained in lands mapped as indigenous forest by the VCM)—though not all of this gain could contribute to emissions offsetting, as not all non-forest vegetation classes in the VCM are Kyoto-compliant, and some non-forest classes have high stocks of carbon. Despite this large predicted increase in carbon contained in forest, only a relatively small total increase in carbon was predicted. This is because LINKNZ predicts that almost all of the carbon on conservation land occurs in forests, but some of the forested areas predicted by LINKNZ have only marginally greater (and in some cases smaller) carbon stocks than the TCC predicted by GRASP for non-forest classes.

For each of New Zealand's three main islands, LINKNZ predicted that forest biomes containing some podocarp (species in the Southern Hemisphere conifer family Podocarpaceae) or kauri (*Agathis australis*) component had the highest mean carbon stocks, though in the South Island some of the high-carbon biomes also contained a beech component. The presence of conifers in the highest-carbon forests is to be expected, as they often form an emergent layer in mature forest, with a concomitant increase in wood volume (Lusk 2002).

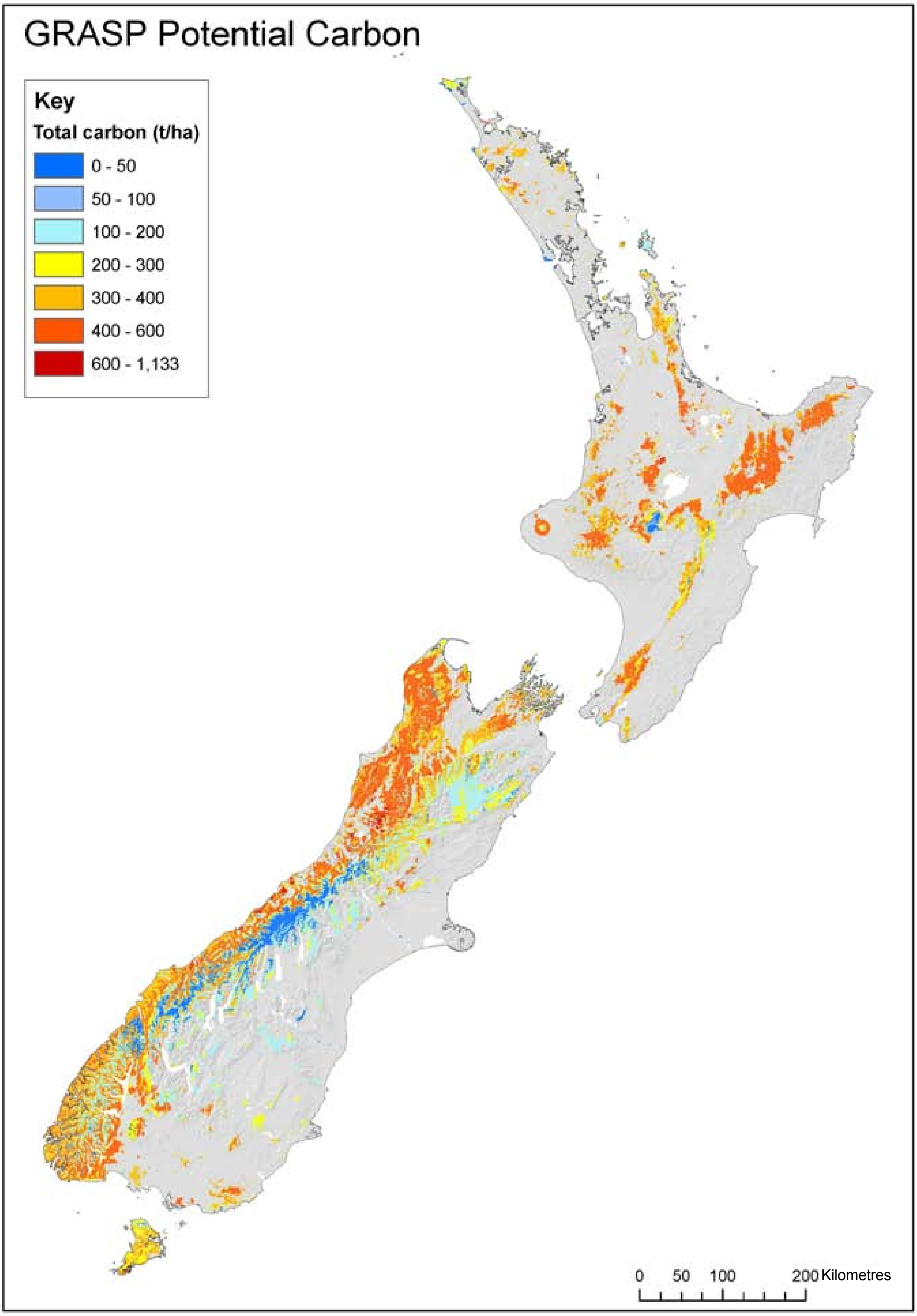

Figure 13. Potential carbon as predicted by GRASP predictions of disturbance-adjusted total carbon values for LUCAS plots.

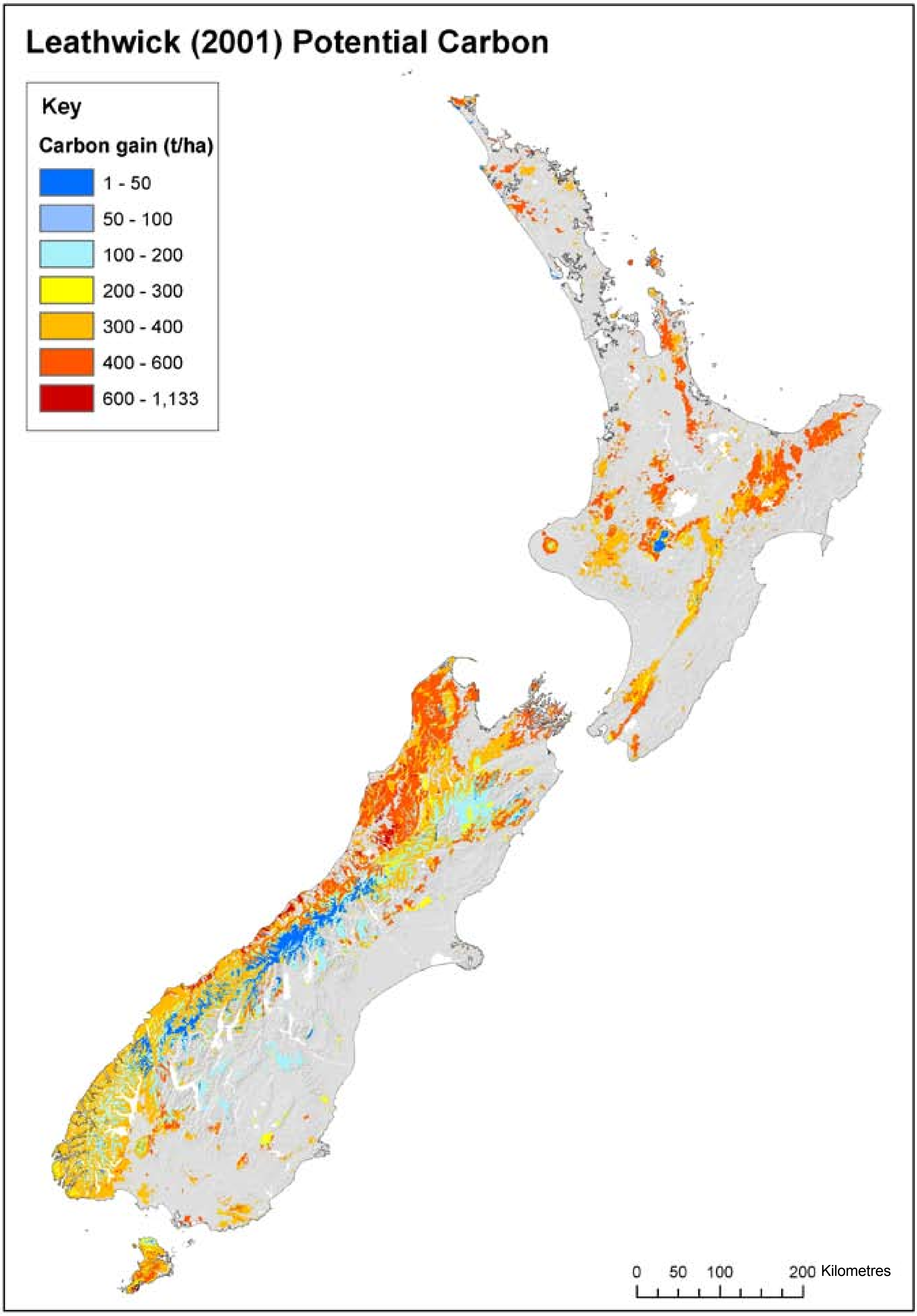

Figure 14. Potential carbon based on the predicted potential forest cover of Leathwick (2001) and mean forest type carbon stocks estimated by Hall et al. (2001).

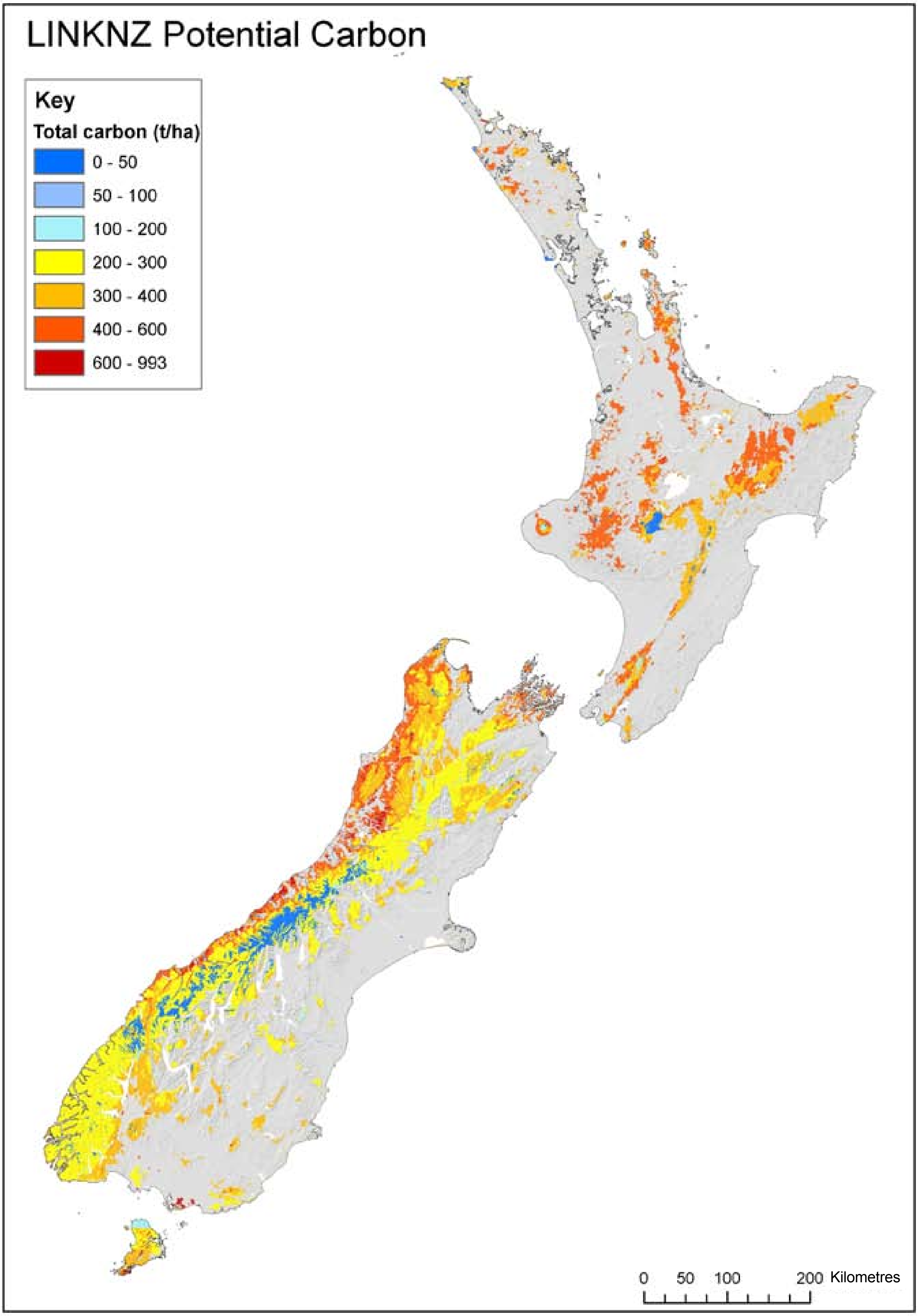

Figure 15. Potential carbon based on the predicted potential forest cover of LINKNZ.

Table 4. Mean and standard deviation of carbon stocks predicted by LINKNZ (see section 2.2.3, 'Carbon stock estimates') for the forest biomes identified by Hall & McGlone (2006). Values were taken across NZLRI polygons within conservation lands represented by each biome and weighted by polygon area. Carbon content of coarse woody debris (CWD) was taken from Peltzer & Payton (2006), and litter and ground vegetation carbon were obtained from Beets (1980), since LINKNZ estimated only carbon on live trees. Addition of carbon in these components allows comparison with Total Current Carbon estimated from LUCAS plots.

NORTH ISLAND BIOMES	AREA	C				
		MEAN	SD	+ CWD	+ LITTER	+ GROUND VEG
	(1000 ha)	(t/ha)	(t/ha)	(t/ha)	(t/ha)	(t/ha)
TEMP-MED-PODCP-FOREST	508.8	221.5	27.2	243.4	256.7	260.0
KAURI-PODCP-FOREST	0.4	216.8	12.9	238.7	251.7	254.9
TEMP-MED-PODCP-BROAD-FOREST	556.7	211.9	29.1	233.8	246.6	249.8
KAURI-FOREST	3.1	203.1	42.1	225.0	237.2	240.3
TEMP-MED-PODCP-BEECH-FOREST	58.5	184.0	40.1	205.9	217.1	219.9
KAURI-PODCP-BROAD-FOREST	46.6	177.4	35.0	199.3	210.1	212.8
TEMP-PODCP-KAURI-BROAD-FOREST	47.2	171.1	21.2	193.0	203.5	206.1
TEMP-MED-PODCP-BEECH-BROAD-FOREST	124.2	166.0	25.6	187.9	198.1	200.7
TEMP-DRY-PODCP-FOREST	126.1	162.2	14.3	184.1	194.1	196.6
TEMP-DRY-PODCP-BROAD-FOREST	33.0	159.1	14.7	181.0	190.8	193.3
TEMP-DRY-PODCP-BEECH-FOREST	15.8	138.6	16.6	160.5	169.3	171.4
KAURI-BROAD-FOREST	30.6	127.1	63.4	149.0	157.1	159.2
COOL-DRY-BEECH-PODCP-FOREST	7.0	125.4	15.2	147.3	155.3	157.3
COOL-MED-BEECH-PODCP-FOREST	207.5	121.7	17.4	143.6	151.4	153.4
COOL-MED-BEECH-FOREST	11.6	121.5	12.0	143.4	151.2	153.2
COOL-MED-BEECH-PODCP-BROAD-FOREST	154.7	115.6	14.9	137.5	145.0	146.9
ALL BIOMES	1931.8	184.5	47.6	206.4	217.6	220.4
SOUTH ISLAND BIOMES						
TEMP-MED-PODCP-FOREST	610.2	220.8	31.6	242.7	255.9	259.2
TEMP-MED-PODCP-BROAD-FOREST	204.8	217.6	26.5	239.5	252.6	255.8
TEMP-MED-PODCP-BEECH-FOREST	95.9	167.4	29.2	189.3	199.6	202.2
TEMP-DRY-PODCP-FOREST	74.8	166.7	20.5	188.6	198.9	201.5
TEMP-MED-PODCP-BEECH-BROAD-FOREST	263.9	161.1	27.5	183.0	193.0	195.5
TEMP-DRY-PODCP-BEECH-FOREST	5.3	148.4	16.5	170.3	179.5	181.9
COOL-MED-BEECH-PODCP-FOREST	2 185.2	123.4	14.2	145.3	153.2	155.2
COOL-MED-BEECH-FOREST	42.3	123.1	12.3	145.0	152.9	154.9
COOL-DRY-PODCP-FOREST	11.2	122.3	16.1	144.2	152.0	154.0
COOL-MED-PODCP-BEECH-BROAD-FOREST	807.1	115.4	13.5	137.3	144.8	146.7
COOL-DRY-PODCP-BEECH-BROAD-FOREST	3.1	113.8	19.2	135.7	143.1	145.0
COOL-DRY-PODCP-BEECH-FOREST	85.2	108.5	20.9	130.4	137.5	139.3
COOL-MED-BEECH-BROAD-FOREST	321.1	104.8	32.1	126.7	133.6	135.4
COOL-DRY-BEECH-BROAD-FOREST	625.7	97.7	26.5	119.6	126.2	127.8
COOL-DRY-BEECH-FOREST	362.1	74.6	49.5	96.5	101.8	103.1
COOL-MED-BROAD-FOREST	6.2	9.5	17.8	31.4	33.1	33.6
ALL BIOMES	5704.1	131.8	47.4	153.7	162.1	164.2
STEWART ISLAND/RAKIURA BIOMES						
COOL-MED-PODCP-FOREST	15.8	164.6	13.6	186.5	196.7	199.2
COOL-MED-PODCP-BROAD-FOREST	38.0	136.3	26.4	158.2	166.8	169.0
TEMP-MED-PODCP-BROAD-FOREST	92.4	123.8	22.5	145.7	153.6	155.6
TEMP-DRY-PODCP-BROAD-FOREST	4.1	121.2	5.7	143.1	150.9	152.8
COOL-MED-BROAD-FOREST	0.1	58.7	7.3	80.6	85.0	86.1
ALL BIOMES	150.5	131.1	25.9	153.0	161.3	163.4
ALL CONSERVATION LAND	7786.4	144.9	47.0	166.8	175.8	178.1

Table 5. Area covered by Kyoto-compliant VCM classes in 1990, and their current and potential carbon and carbon gain according to the GRASP model of disturbance-adjusted carbon stocks of LUCAS plots.

VCM CLASS	VCM CODE	AREA (1000 ha)	CURRENT C (Mt)	POTENTIAL C (Mt)	CHANGE C (Mt)	CHANGE C (t/ha)
Orchards or vineyards & pasture	C1	0.53	0.10	0.17	0.08	148.90
Horticultural crops & pasture	C2	0.19	0.03	0.06	0.03	147.47
Improved pasture	G1	66.74	13.90	24.16	10.26	153.71
Unimproved pasture	G2	23.48	4.88	7.94	3.06	130.52
Short tussock grassland	G3	119.62	23.36	38.88	15.52	129.77
Snow tussock grassland	G4	829.14	129.57	167.25	37.67	45.44
Short tussock–snow tussock grassland	G5	202.33	36.79	54.88	18.09	89.42
Red tussock grassland	G6	9.10	2.03	3.33	1.29	141.88
Grassland & cassinia scrub	GS3	1.67	0.29	0.51	0.23	135.16
Tussock grassland & subalpine scrub	GS4	749.61	138.99	181.01	42.02	56.06
Grassland & *Dracophyllum* scrub	GS5	33.21	6.55	10.28	3.73	112.40
Grassland & gorse scrub	GS6	8.14	2.14	2.93	0.80	97.70
Grassland & matagouri	GS7	37.75	7.34	12.53	5.19	137.55
Grassland & sweet brier or sweet brier & matagouri	GS8	42.14	8.46	14.52	6.06	143.79
Subalpine or alpine herbfield	M1	134.88	14.92	19.10	4.18	31.00
Wetland communities	M2	46.11	19.50	27.42	7.92	171.77
Sand-dune communities	M3	11.03	0.73	2.47	1.74	157.86
Pakihi heathland communities	M4	24.14	9.19	11.57	2.38	98.61
Subalpine scrub	S3	93.51	26.63	26.43	–0.20	–2.13
Gorse scrub	S4	1.44	0.39	0.51	0.11	78.28
Total		2434.75	445.79	605.96	160.17	65.79

3.3 Potential carbon gain on Kyoto-compliant conservation land

For each of the three potential total carbon (PTC) modelling approaches outlined above, the estimated Kyoto-compliant carbon gain is larger than the total gain, as each approach predicted lower PTC stocks for some areas that currently support forest. Below, we detail the results for estimated Kyoto-compliant carbon gain using each of the three models.

3.3.1 Prediction from disturbance-adjusted carbon values in LUCAS

Models of disturbance-adjusted LUCAS carbon stocks estimated 160 Mt of Kyoto-compliant carbon gain on conservation land (Table 5, Fig. 16). The biggest gains were in Snow Tussock Grassland and Tussock Grassland and Subalpine Scrub VCM classes. The highest rates of carbon gain per unit area were in crop and pasture and tussock classes (C1, C2, G1, G2, G3, G6), Grassland–Shrub classes (GS3 and GS5, 7 and 8), Sand Dunes and Wetlands.

3.3.2 Prediction of potential forest cover from existing tree species distributions

Predictions based on Leathwick's (2001) potential forest cover estimated 63 Mt of Kyoto-compliant carbon gain on conservation land (Table 6, Fig. 17). The biggest gains were in Short Tussock Grassland and Tussock Grassland and Subalpine Scrub VCM classes. The highest rates of carbon gain per unit area were in crop and pasture and tussock classes (C1, C2, G1, G2, G6), Grassland–Shrub classes (GS3 and GS5–GS7), and Gorse scrub.

3.3.3 Prediction of potential forest cover using the LINKNZ ecosystem-processes model

LINKNZ estimated 632 Mt of total potential carbon for Kyoto-compliant lands (Table 7, Fig. 18), giving a total Kyoto-compliant carbon gain of 186 Mt at an average rate of 77 t/ha.

Of the Kyoto-compliant VCM classes, Horticultural Crops and Pasture, and Orchards, Vineyards and Pasture had the highest potential rate of carbon gain per area (Table 6). Grassland (G1–G3 and G5), Grassland–Shrub communities (GS3, GS6–GS8), shrubland (S4) and wetland

Table 6. Area covered by Kyoto-compliant VCM classes, and their current and potential carbon and carbon gain based on predicted potential forest cover of Leathwick (2001).

VCM CLASS	VCM CODE	AREA (1000 ha)	CURRENT C (Mt)	POTENTIAL C (Mt)	CHANGE C (Mt)	CHANGE C (t/ha)
Orchards or vineyards & pasture	C1	0.53	0.10	0.17	0.08	148.90
Horticultural crops & pasture	C2	0.19	0.03	0.06	0.03	147.47
Improved pasture	G1	66.74	13.90	24.16	10.26	153.71
Unimproved pasture	G2	23.48	4.88	7.94	3.06	130.52
Short tussock grassland	G3	119.62	23.36	38.88	15.52	129.77
Snow tussock grassland	G4	829.14	129.57	167.25	37.67	45.44
Short tussock–snow tussock grassland	G5	202.33	36.79	54.88	18.09	89.42
Red-tussock grassland	G6	9.10	2.03	3.33	1.29	141.88
Grassland & cassinia scrub	GS3	1.67	0.29	0.51	0.23	135.16
Tussock grassland & subalpine scrub	GS4	749.61	138.99	181.01	42.02	56.06
Grassland & *Dracophyllum* scrub	GS5	33.21	6.55	10.28	3.73	112.40
Grassland & gorse scrub	GS6	8.14	2.14	2.93	0.80	97.70
Grassland & matagouri	GS7	37.75	7.34	12.53	5.19	137.55
Grassland & sweet brier or sweet brier & matagouri	GS8	42.14	8.46	14.52	6.06	143.79
Subalpine or alpine herbfield	M1	134.88	14.92	19.10	4.18	31.00
Wetland communities	M2	46.11	19.50	27.42	7.92	171.77
Sand-dune communities	M3	11.03	0.73	2.47	1.74	157.86
Pakihi heathland communities	M4	24.14	9.19	11.57	2.38	98.61
Subalpine scrub	S3	93.51	26.63	26.43	–0.20	–2.13
Gorse scrub	S4	1.44	0.39	0.51	0.11	78.28
Total		2434.75	445.79	605.96	160.17	65.79

Table 7. Area covered by Kyoto-compliant VCM classes, and their current and potential carbon and carbon gain according to LINKNZ.

VCM CLASS	VCM CODE	AREA (1000 ha)	CURRENT C (Mt)	POTENTIAL C (Mt)	CHANGE C (Mt)	CHANGE C (t/ha)
Orchards or vineyards & pasture	C1	0.53	0.10	0.18	0.09	164.74
Horticultural crops & pasture	C2	0.19	0.03	0.07	0.04	200.61
Improved pasture	G1	66.74	13.90	23.39	9.49	142.17
Unimproved pasture	G2	23.48	4.88	8.19	3.31	140.86
Short tussock grassland	G3	119.62	23.36	38.40	15.04	125.76
Snow tussock grassland	G4	829.14	129.57	186.38	56.80	68.51
Short tussock–snow tussock grassland	G5	202.33	36.79	60.32	23.53	116.31
Red-tussock grassland	G6	9.10	2.03	2.76	0.72	79.32
Grassland & cassinia scrub	GS3	1.67	0.29	0.55	0.27	158.70
Tussock grassland & subalpine scrub	GS4	749.61	138.99	189.40	50.42	67.26
Grassland & Dracophyllum scrub	GS5	33.21	6.55	8.99	2.44	73.54
Grassland & gorse scrub	GS6	8.14	2.14	3.04	0.91	111.34
Grassland & matagouri	GS7	37.75	7.34	11.99	4.64	123.02
Grassland & sweet brier or sweet brier & matagouri	GS8	42.14	8.46	14.28	5.82	138.00
Subalpine or alpine herbfield	M1	134.88	14.92	20.63	5.72	42.38
Wetland communities	M2	46.11	19.50	26.03	6.53	141.64
Sand-dune communities	M3	11.03	0.73	1.23	0.50	44.94
Pakihi heathland communities	M4	24.14	9.19	11.41	2.22	91.98
Subalpine scrub	S3	93.51	26.63	24.26	–2.37	–25.38
Gorse scrub	S4	1.44	0.39	0.59	0.20	136.60
Total		2434.75	445.79	632.09	186.30	76.52

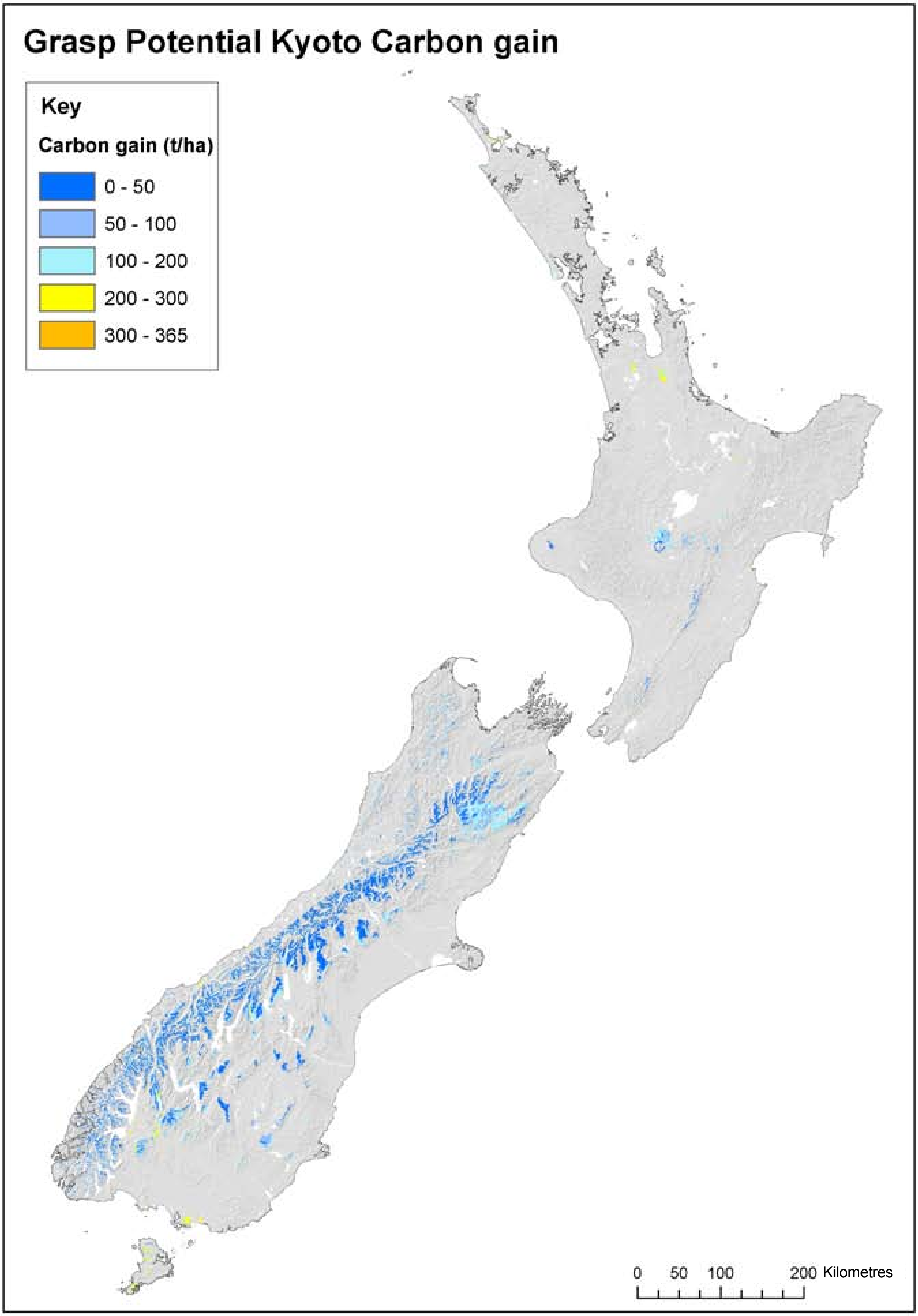

Figure 16. Potential Kyoto-compliant carbon gain based on the GRASP disturbance-adjusted carbon stocks predictions.

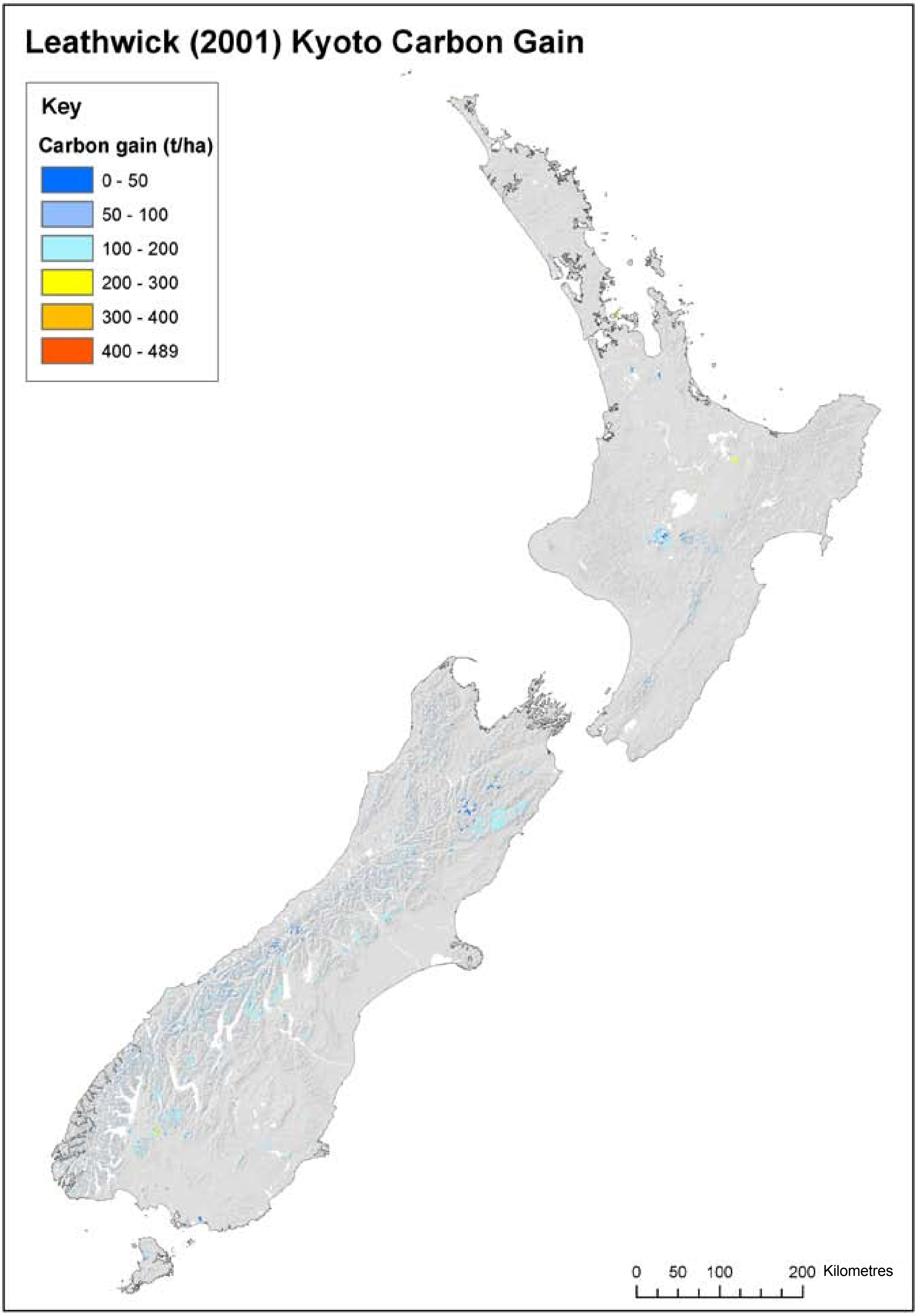

Figure 17. Potential Kyoto-compliant carbon gain based on the potential forest cover of Leathwick (2001).

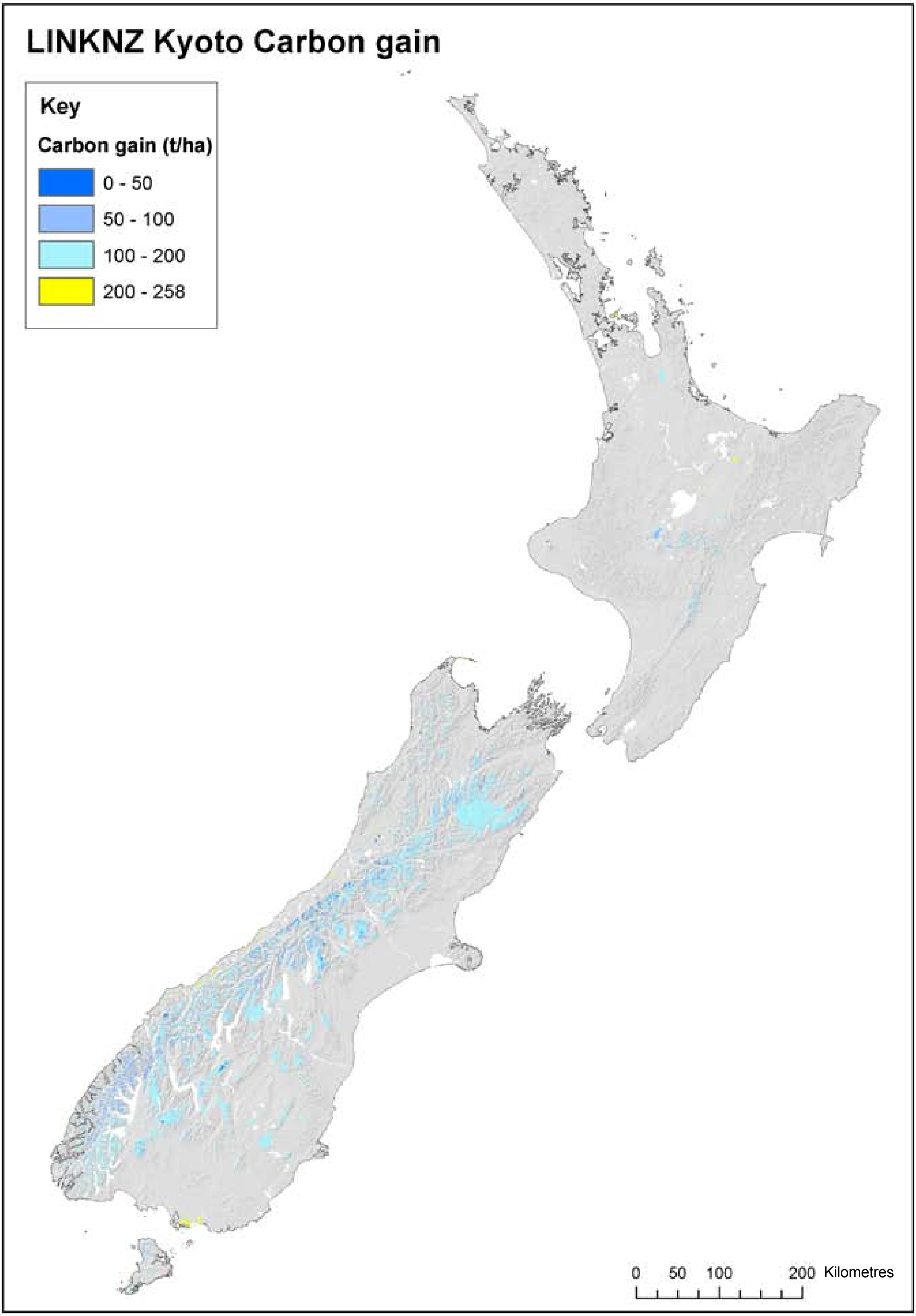

Figure 18. Potential Kyoto-compliant carbon gain based on the potential carbon stocks predicted by LINKNZ.

communities (M2) all had average potential carbon gain rates of greater than 100 t/ha. G4 and GS4 had the greatest total potential carbon gains (57 and 50 Mt, respectively) due to the very large areas they cover (792 000 and 738 000 ha, respectively). Only one Kyoto-compliant class, Subalpine Scrub, had a potential loss of carbon (2.37 Mt). This resulted from GRASP predicting higher carbon stocks than LINKNZ for some areas covered by this class.

4. Discussion

The results show that the method used can have a large effect on estimated potential carbon stocks. The potential Kyoto-compliant carbon gain of 186 Mt estimated using LINKNZ and 160 Mt using the disturbance-adjusted LUCAS carbon stocks are considerably greater than the 72 Mt estimated by Carswell et al. (2008) and the 63 Mt estimated in the present report using Leathwick's (2001) potential forest cover. The difference between the LINKNZ and Leathwick (2001) estimates is largely due to LINKNZ predicting a greater potentially forested area than Leathwick. LINKNZ predicted 55 Mt more carbon gain in the Snow Tussock Grassland VCM class and 33 Mt more in the Tussock Grassland and Subalpine Scrub class. It should be noted that woody colonisation of these currently non-forested vegetation classes is likely to occur over centuries, rather than decades. Current barriers to colonisation include lack of seed source, low temperatures and high water deficit. Pollen records and macrofossil evidence suggest that Leathwick's (2001) estimate of potential forest cover in the drier areas of the South Island rainshadow was conservative (Hall & McGlone 2006). LINKNZ, on the other hand, agrees much more closely with these other forms of evidence (Hall & McGlone 2006), suggesting that the higher levels of carbon gain predicted by LINKNZ for the two aforementioned VCM classes may, in the long term, prove to be more realistic than the relatively modest gains predicted by the Leathwick (2001) based estimate.

Modelling of potential carbon stocks by adjusting the measured carbon stocks in LUCAS plots for disturbance effects produced an estimate that was 26 Mt, or 14%, lower than that obtained from LINKNZ. While this is not a huge difference, neither is it negligible. Most of this difference was due to LINKNZ predicting larger gains in the Snow Tussock Grassland (15 Mt more) and Tussock Grassland and Subalpine Scrub (8 Mt more) classes. Some of this difference may also have been due to a lack of undisturbed LUCAS plots in fertile lowland environments, which may have very high carbon stocks. Given the importance of mean annual temperature in the spatial prediction of disturbance-adjusted carbon stocks, and the asymptotic relationship between the two, it is possible that incorporating data from intact lowland forest ecosystems might increase disturbance-adjusted estimates in lowlands.

4.1 Implications for emissions offsetting

Based on LINKNZ, we estimate that afforestation/reforestation of conservation land could at best result in an additional 682 Mt CO_2e being stored, while estimates based on disturbance-adjusted LUCAS carbon stocks give a potential sequestration value of 586 Mt CO_2e. If we assume a 200-year time period to attain this stock (based on carbon gain during succession observed by Mason et al. (2011)), the average annual gain is only 3.4 Mt. Given that total gross emissions for New Zealand in 2005 were 77.2 Mt CO_2e in greenhouse gases, the potential gross offset is at most approximately 4%. However, given that current indications suggest that New Zealand may be a net seller of units at the end of the first Kyoto Protocol commitment period (Ministry for the Environment 2009), this 'surplus' of units, sold at $20 per tonne could potentially realise an additional $68 million of revenue to support conservation outcomes.

Since the LINKNZ simulations were run for a period of 800 years, it is possible that some of the projected Kyoto-compliant carbon gain will not be realised for several centuries. Further, much of the projected carbon gain predicted by both methods occurs in VCM classes where growth rates are slow (due to water limitation or low temperatures) and environmental conditions may be marginal for forest. Consequently, these estimates would best be interpreted as the maximum long-term carbon gain due to afforestation on conservation land. It would be useful to link projected Kyoto-compliant carbon gain with environmental variables that are known to affect plant growth, or estimates of potential indigenous forest productivity, to identify areas where gain could be achieved with minimal management effort. Potential forest productivity could be estimated using LINKNZ or other process-based forest gap models, from satellite imagery (as in Baisden 2006), or from stem growth models developed from remeasured forest plots. Potential forest productivity is only currently available from satellite imagery, and this was only a preliminary effort (W.T. Baisden, Geological and Nuclear Sciences, pers. comm.), so further work would be required to improve the accuracy of predictions.

4.2 Limitations of the approach and data sources

4.2.1 Predicted carbon stocks

The fact that GRASP predicted carbon stocks in LUCAS plots with only moderate accuracy is a reflection of both the complexity of processes that contribute to variation in carbon stocks and the limitations of the spatial information available for these factors. For instance, there is little available information on key disturbance events at a national scale (e.g. fire and earthquakes), and there is only patchy information on human disturbance due to logging, though we have some tools to estimate the impact of forest clearance on vegetation cover. Disturbance factors seem to provide reasonable explanatory power in predicting carbon stocks, and maps of these might improve spatial prediction. We note the importance of remotely sensed land cover variables in predicting total current carbon (TCC) in the final GRASP model. This underlines the importance of having accurate spatial land cover information when mapping carbon stocks. While evidence from the LUCAS plots indicates that the LCDB was able to differentiate between indigenous forest and other cover types very well, it appeared to have limited power in differentiating between shrubland and other vegetation types.

4.2.2 Potential forest cover

The amount of potential forest predicted by LINKNZ was possibly overly generous in some areas that were covered by unusual vegetation types. For example, LINKNZ predicted large carbon gains in many wetland areas. While it is possible that some of these areas, such as Awarua Bog in Southland, would have supported forest before human settlement and could potentially do so in the future, other areas, such as Kopuatai Peat Dome on the Hauraki Plains, are highly unlikely to support forest under present-day climatic conditions (Beverley Clarkson, Landcare Research, pers. comm.). The formation of peatlands is poorly predicted by climatic and topographic variables in New Zealand, so it is understandable that LINKNZ might predict potential forest cover for wetlands where this is highly unlikely. Also, while the Land Resource Inventory polygons used incorporated information on soil type, extremely low nutrient and low-pH peatlands were poorly mapped. There may be other rare ecosystems (Williams et al. 2007) that LINKNZ also predicted could support forest, but which are unlikely to under present climatic conditions. However, it is likely that this bias will have had only a minor effect on the overall estimation of Kyoto-compliant carbon gain due to the small area likely to be covered by rare ecosystems. These finer scale inaccuracies are to be expected when modelling at a national scale, and underline the need to investigate specific Kyoto-compliant areas closely before planning management actions to enhance carbon gain. As improved maps of rare, non-forest ecosystems are produced, it will be easier to exclude rare ecosystems from predictions of potential forest cover using LINKNZ.

Perhaps a greater source of possible overestimation of potential forest cover using LINKNZ could be the absence of dispersal processes from the model. For each polygon modelled, all species had an opportunity to colonise and establish, irrespective of whether a seed source was available or not. Dispersal limitation could be a major barrier to afforestation in regions where forest is absent or very rare. Nevertheless, active restoration efforts could help to overcome dispersal limitation, so LINKNZ provides a useful indication of potential carbon stocks whether afforestation is possible via natural dispersal or active management.

4.2.3 Kyoto-compliant carbon gain

Another limitation of the present approach was that each polygon predicted to support forest by LINKNZ was assigned the mean carbon stock value (weighted by polygon area) for the predicted biome, taken across all the polygons occupied by that biome on the island in question (means were weighted by polygon area). While this would not have affected the estimation of total potential forest carbon stocks, it may have had some effect on Kyoto-compliant carbon gain and certainly will have affected the estimated potential carbon gain for particular areas. To gain a more accurate estimation of Kyoto-compliant carbon gain and to provide more reliable information on potential carbon gain for particular areas, each polygon should be assigned its own carbon stock value, rather than the mean for the biome.

The present estimation of Kyoto-compliant carbon gain was also compromised by the lack of coherent land cover information linking LUCAS plots to land cover in 1990. While the VCM provided a reasonable indication of Kyoto-compliant vegetation, greater accuracy in mapping Kyoto-compliant lands is desirable. Ideally, the observed land cover of LUCAS plots would be expressed in terms of the land cover classes used in the 1990 base map, to enable predictions of 1990 carbon stocks using the LUCAS plots.

4.3 Implications for future work

The current work could be improved in a number of ways, mainly relating to data sources. Firstly, the estimation of current carbon may have been more accurate if the 1990 LUCAS base map had been used—unfortunately, this had not been released in time for incorporation in this report. However, preliminary analyses suggest a rate of land cover change of less than 1% between 1990 and 2008 (J.D. Shepherd, Landcare Research, pers. comm.), so this effect should be quite minor. Similarly, mapping of Kyoto-compliant conservation land would have been more accurate had the LUCAS base map been available, though it is unclear whether estimating Kyoto compliance using the VCM will have caused over- or under-estimation of Kyoto-compliant lands.

The estimate of potential carbon provided by LINKNZ could be improved by updating maps of edaphic factors, which would enable the exclusion of areas unlikely to support forest. An alternative would simply be to exclude areas where non-forest vegetation is thought to exist due to unusual edaphic conditions. There may also be some potential to refine LINKNZ, since considerable work has been conducted on basic demographic processes in indigenous forests since LINKNZ was constructed (e.g. Coomes & Allen 2007; Hurst et al. 2007), which could increase the accuracy of species parameter estimations (e.g. growth response to climate, soil fertility and shade). It would also be interesting to incorporate dispersal processes in estimating potential carbon stocks using LINKNZ or a similar process-based model.

Our understanding of basic relationships between environmental variables and potential carbon stocks is limited by a lack of data on carbon stocks for intact lowland forest ecosystems. In current LUCAS plots, a unimodal relationship between mean annual temperature and carbon in vegetation was observed, probably reflecting an increase in disturbance with decreasing altitude. However, even when current carbon stocks were adjusted for disturbance, an asymptotic relationship was observed between temperature and potential carbon stocks. It is unclear whether this is a real relationship, or an artefact of the least disturbed, highest carbon systems occurring at moderate altitudes. Targeted work on intact lowland forests, especially on fertile soils, is required to gain an accurate estimate of potential carbon stocks in these environments.

5. Recommendations

The authors make the following recommendations:

- Maps of Kyoto-compliant carbon gain should be cross-referenced with maps of potential forest productivity to identify areas where high potential carbon gain may be realised rapidly. This will require the production of spatial layers of potential indigenous forest productivity.
- The LUCAS 1990 base map should be used to identify Kyoto-compliant-carbon conservation land.
- Dispersal processes should be incorporated into LINKNZ or an alternative process-based model to estimate potential rates of natural indigenous afforestation.

6. Acknowledgements

We thank the Ministry for the Environment for granting access to the LUCAS plot survey data and wood density values, the Department of Conservation for funding (Investigation No. 4040), and Susan Wiser for reviewing a draft of the report.

7. References

Aber, J.D.; Botkin, D.B.; Melillo, J.M. 1978: Predicting the effects of different harvesting regimes on forest floor dynamics in northern hardwoods. *Canadian Journal of Forest Research 8*: 306–315.

Baisden, W.T. 2006: Agricultural and forest productivity for modelling policy scenarios: evaluating approaches for New Zealand greenhouse gas mitigation. *Journal of the Royal Society of New Zealand 36*: 1–15.

Beets, P.N. 1980: Amount and distribution of dry matter in a mature beech/podocarp community. *New Zealand Journal of Forestry Science 10*: 395–418.

Beets, P.N.; Kimberley, M.O.; Goulding, C.J.; Garrett, L.G.; Oliver, G.R.; Paul, T.S.H. 2009: Natural forest plot data analysis: carbon stock analyses and remeasurement strategy. Scion Client Report No: 42782. Scion, Rotorua, New Zealand.

Bugmann, H.; Lindner, M.; Lasch, P.; Fleschsig, M.; Ebert, B.; Cramer, W. 2000: Scaling issues in forest succession modelling. *Climatic Change 44*: 265–289.

Burnham, K.P.; Anderson, D.R. 2002: Model selection and multimodel inference: a practical information-theoretic approach. 2nd edition. Springer, New York, USA.

Carswell, F.E.; Mason, N.W.H.; Davis, M.R.; Briggs, C.M.; Clinton, P.W.; Green, W.; Standish, R.J.; Allen, R.B.; Burrows, L.E. 2008: Synthesis of carbon stock information regarding conservation land. Landcare Research Contract Report: LC0708/071. Landcare Research, Lincoln, New Zealand.

Coomes, D.A.; Allen, R.B. 2007: Effects of size, competition and altitude on tree growth. *Journal of Ecology 95*: 1084–1097.

Coomes, D.A.; Allen, R.B.; Scott, N.A.; Goulding, C.; Beets, P. 2002: Designing systems to monitor carbon stocks in forests and shrublands. *Forest Ecology and Management 164*: 89–108.

Coomes, D.A.; Beets, P. 1999: Monitoring carbon in indigenous forests and scrublands: a test of methods and logistics along a South Island transect. Unpublished Contract Report JNT9899/124 for the Ministry for the Environment, PO Box 10-362, Wellington, New Zealand.

Dymond, J.R.; Shepherd, J.D. 2004: The spatial distribution of indigenous forest and its composition in the Wellington region, New Zealand, from ETM+ satellite imagery. *Remote Sensing of Environment 90*: 116–125.

Forsyth, D.M. 2008: Deer herbivory impacts research at Waitutu: synthesis and parameterisation in Sortie-ND/NZ. Landcare contract report: LC0708/098.

Hall, G.M.J.; Hollinger, D.Y. 2000: Simulating New Zealand forest dynamics with a generalized temperate forest gap model. *Ecological Applications 10*: 115–130.

Hall, G.M.J.; McGlone, M.S. 2006: Potential forest cover of New Zealand as determined by an ecosystem process model. *New Zealand Journal of Botany 44*: 211–232.

Hall, G.M.J.; Wiser, S.K.; Allen, R.B.; Beets, P.N.; Goulding, C.J. 2001: Strategies to estimate national forest carbon stocks from inventory data: the 1990 New Zealand baseline. *Global Change Biology 7*: 389–403.

Hinds, H.V.; Reid, J.S. 1957: Forest trees and timbers of New Zealand. *New Zealand Forest Service Bulletin 12*.

Hurst, J.M.; Richardson, S.J.; Wiser, S.K.; Allen, R.B. 2007: Growth, mortality and recruitment of New Zealand's indigenous timber species. Landcare Research Contract Report: LC0708/19. Landcare Research, Lincoln, New Zealand.

Ilic, J.; Boland, D.; McDonald, M.; Downes, G.; Blakemore, P. 2000: Wood density phase 1—state of knowledge. Australian Greenhouse Office, National Carbon Accounting System. *Technical Report No. 18*. 218 p.

Johnson, J.B.; Omland, K.S. 2004: Model selection in ecology and evolution. *Trends in Ecology & Evolution 19*: 101–108.

King, A.W. 1991: Translating models across scales in the landscape. Pp. 479–517 in Turner M.G.; Gardner, R.H. (Eds): Quantitative methods in landscape ecology. *Ecological Studies 82*. Springer, New York, USA.

Leamy, M.L. 1974: Soils of Stewart Island (Rakiura) New Zealand. *New Zealand Soil Survey Report 22*. New Zealand Soil Bureau, Wellington, New Zealand.

Leathwick, J.R. 2001: New Zealand's potential forest pattern as predicted from current species–environment relationships. *New Zealand Journal of Botany 39*: 447–464.

Leathwick, J.R.; McGlone, M.; Walker, S.; Briggs, C. 2003a: Predicted potential natural vegetation of New Zealand, poster and GIS file. www.landcareresearch.co.nz/databases/LENZ/products_poster.asp.

Leathwick, J.R.; Morgan, F.J.; Wilson, G.H.; Rutledge, D.; Wardle, P.; Johnston, K.; McLeod, M.; Kirkpatrick, R. 2003b: Land environments of New Zealand: Technical Guide. David Bateman, Auckland, New Zealand.

Leathwick, J.R.; Stephens, R.T.T. 1998: Climate surfaces for New Zealand. Landcare Research Contract Report, LC9798/126.

Leathwick, J.R.; Whitehead, D. 2001: Soil and atmospheric water deficits and the distributions of New Zealand's indigenous tree species. *Functional Ecology 15*: 233–242.

Leathwick, J.; Wilson, G.; Rutledge, D.; Wardle, P.; Morgan, F.; Johnston, K.; McLeod, M.; Kirkpatrick, R. 2003c: Land environments of New Zealand. David Bateman, Auckland, New Zealand.

Lehmann, A.; Overton, J.McC.; Leathwick, J.R. 2003: GRASP: Generalized Regression Analysis and Spatial Prediction. *Ecological Modelling 160*: 165–183.

Lusk, C.H. 2002: Basal area in a New Zealand podocarp-broadleaved forest: are coniferous and angiosperm components independent? *New Zealand Journal of Botany 40*: 143–147.

Lusk, C.H.; Ogden, J. 1992: Age structure and dynamics of a podocarp-broadleaf forest in Tongariro National Park, New Zealand. *Journal of Ecology 80*: 379–393.

Mason, N.W.H.; Carswell, F.E.; Richardson, S.J.; Burrows, L.E. 2011: Leaf palatability and decomposability increase during a 200-year post-cultural woody succession. *Journal of Vegetation Science 22(1)*: 6–17.

Ministry for the Environment 2007: Environment New Zealand. Wellington, New Zealand.

Ministry for the Environment 2009: Net position report 2009. Wellington, New Zealand.

New Zealand Soil Bureau 1957: General survey of the soils of North Island, New Zealand. *Soil Bureau Bulletin 5*. Government Printer, Wellington, New Zealand.

New Zealand Soil Bureau 1968: General survey of the soils of South Island, New Zealand. *Soil Bureau Bulletin 27*. Government Printer, Wellington, New Zealand.

Newsome, P.F.J. 1987: The vegetative cover of New Zealand. *Water and Soil Miscellaneous Publication 112*. National Water and Soil Conservation Authority, Wellington, New Zealand.

Newsome, P.J.F. 1992: New Zealand land resource inventory. *DSIR Land Resources Technical Record 81*. New Zealand Department of Scientific and Industrial Research, Lower Hutt, New Zealand.

Overton, J.McC.; Barker, G.M.; Price, R. 2009: Estimating and conserving patterns of invertebrate diversity: a test case of New Zealand land snails. *Diversity and Distributions 15*: 731–741.

Overton, J.McC.; Lehmann, A. 2003: Predicting vegetation condition and weed distributions for systematic conservation management: an application of GRASP in the central South Island, New Zealand. *Science for Conservation 220*. Department of Conservation, Wellington, New Zealand. 57 p.

Pastor, J.; Aber, J.D.; McClaugherty, C.A.; Melillo, J.M. 1984: Aboveground production and N and P cycling along a nitrogen mineralization gradient on Blackhawk Island, Wisconsin. *Ecology 65*: 256–268.

Pastor, J.; Post, W.M. 1985: Development of a linked forest productivity-soil process model. Report ORNL/TM-9519. *Oak Ridge National Laboratory Environmental Science Division Publication 2455*. Oak Ridge, Tennessee.

Pastor, J.; Post, W.M. 1986: Influence of climate, soil moisture, and succession on forest carbon and nitrogen cycles. *Biogeochemistry 2*: 3–27.

Payton, I.J.; Newell, C.L.; Beets, P.N. 2004: New Zealand Carbon Monitoring System indigenous forest and shrubland data collection manual. Caxton Press, Christchurch, New Zealand. 68 p.

Peltzer, D.A.; Payton, I.J. 2006: Analysis of carbon monitoring system data for indigenous forests and shrublands collected in 2002/03. Landcare Research Contract Report: 0506/35/139. Landcare Research, Lincoln, New Zealand.

Phillips, C.J.; Watson, A.J. 1994: Structural tree root research in New Zealand: a review. *Landcare Research Science Series 7*. Landcare Research, Lincoln, New Zealand.

Post, W.M.; Pastor, J. 1996: LINKAGES—an individual-based forest ecosystem model. *Climatic Change 34*: 253–261.

Rutledge, D.; Price, R.; Heke, H.; Ausseil, A. 2004: National analysis of biodiversity protection status: methods and summary results. Landcare Research Contract Report number 0405/042 to the Ministry for the Environment.

Scott, N.A.; Tate, K.R.; Giltrap, D.J.; Smith, C.T.; Wilde, R.H.; Newsome, P.F.; Davis, M.R. 2002: Monitoring land use change effects on soil carbon in New Zealand: quantifying baseline soil carbon stocks. *Environmental Pollution 116*: S167–S186.

Tate, K.R.; Giltrap, D.J.; Claydon, J.J.; Newsome, P.F.; Atkinson, A.E.; Taylor, M.D.; Lee, R. 1997: Organic carbon stocks in New Zealand's terrestrial ecosystems. *Journal of the Royal Society of New Zealand 27*: 315–335.

Tate, K.R.; Scott, N.A.; Saggar, S.; Baisden, W.T.; Trotter, C.M.; Wilde, R.H. 2003: Land use change alters New Zealand's terrestrial carbon budget: uncertainties associated with estimates of soil carbon change between 1990–2000. *Tellus Series B—Chemical and Physical Meteorology 55*: 364–377.

Walker, S.; Price, R.; Rutledge, D.; Stephens, R.T.T.; Lee, W.G. 2006: Recent loss of indigenous cover in New Zealand. *New Zealand Journal of Ecology 30*: 169–177.

Wardle, J.A. 1984: The New Zealand beeches: ecology, utilisation, and management. New Zealand Forest Service, Wellington, New Zealand.

Wardle, P. 1991: Vegetation of New Zealand. Cambridge University Press, Cambridge, UK.

Williams, P.A.; Wiser, S.; Clarkson, B.; Stanley, M.C. 2007: New Zealand's historically rare terrestrial ecosystems set in a physical and physiognomic framework. *New Zealand Journal of Ecology 31*: 119–129.

Wilson, H.D. 1982: Stewart Island plants: field guide. Field Guide Publications, Christchurch, New Zealand. 528 p.

Appendix 1

Lumping of LCDB2 classes

LCDB2 CLASS	LUMPED LCDB2 CLASS
Built-up Area	Other
Dump	Other
Transport Infrastructure	Other
Lake and Pond	Other
River	Other
Estuarine Open Water	Other
Broadleaved Indigenous Hardwoods	Hardwood
Deciduous Hardwoods	Hardwood
Urban Parkland / Open Space	Herb/Grass/Bare
Surface Mine	Herb/Grass/Bare
Coastal Sand and Gravel	Herb/Grass/Bare
River and Lakeshore Gravel and Rock	Herb/Grass/Bare
Landslide	Herb/Grass/Bare
Alpine Gravel and Rock	Herb/Grass/Bare
Permanent Snow and Ice	Herb/Grass/Bare
Alpine Grass / Herbfield	Herb/Grass/Bare
Short-rotation Cropland	Herb/Grass/Bare
Vineyard	Herb/Grass/Bare
High Producing Exotic Grassland	Herb/Grass/Bare
Low Producing Grassland	Herb/Grass/Bare
Tall Tussock Grassland	Herb/Grass/Bare
Depleted Tussock Grassland	Herb/Grass/Bare
Herbaceous Freshwater Vegetation	Herb/Grass/Bare
Herbaceous Saline Vegetation	Herb/Grass/Bare
Flaxland	Herb/Grass/Bare
Fernland	Herb/Grass/Bare
Indigenous Forest	Indigenous Forest
Major Shelterbelts	Planted Forest
Afforestation (not imaged)	Planted Forest
Afforestation (imaged)	Planted Forest
Forest Harvested	Planted Forest
Pine Forest—Open Canopy	Planted Forest
Pine Forest—Closed Canopy	Planted Forest
Other Exotic Forest	Planted Forest
Orchard and Other Perennial Crops	Shrubland
Gorse and Broom	Shrubland
Manuka and/or Kanuka	Shrubland
Matagouri	Shrubland
Sub Alpine Shrubland	Shrubland
Mixed Exotic Shrubland	Shrubland
Grey Scrub	Shrubland
Mangrove	Shrubland