An analysis of carbon stocks and net carbon position for New Zealand sheep and beef farmland

Bradley Case and Catherine Ryan

Department of Applied Ecology, School of Science, Auckland University of Technology

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EXECUTIVE SUMMARY

1. There is currently considerable interest across New Zealand's sheep and beef sector in gathering the necessary information to help assess its roles and responsibilities regarding carbon accounting and greenhouse gas (GHG) mitigation. This report presents results of a spatial analysis of existing carbon stocks and a quantification of the net carbon position for this sector, based on information sourced from national spatial vegetation and landcover datasets, available vegetation plot data, and published information regarding carbon stock densities, sequestration rates, and GHG emissions.

Key findings

2. The sheep and beef sector comprises 40% of New Zealand's land area, and is currently responsible for about 20% of New Zealand's total, and 45% of its agricultural, gross emissions.

3. Using a GIS-based analysis with available national datasets, approximately 2 million hectares of carbon-sequestering woody vegetation was identified across sheep and beef lands, comprising just under 20% of the total *c.* 10 million hectare estate. This vegetated 20% of the estate is comprised of 8.2% indigenous forest, 5.5% mānuka/kānuka early successional forest, 3.3% exotic forest, 1.7% indigenous shrubland, and 1.3% exotic scrub.

4. In terms of existing carbon stocks, sheep and beef farms hold a total of approximately 1.295 million kilotonnes (kt) C in all above and below ground carbon pools, including estimates for pasture soils. About *c.* 12% of the New Zealand's woody carbon stocks, and over 40% of the country's total carbon stock (including both above and below ground carbon), is held on sheep and beef farmland.

5. Areas with the greatest above ground carbon quantities are located in Gisborne, Hawkes Bay and Manawatu-Whanganui regions in the North Island, with only very localised areas in north-eastern South Island containing comparably high carbon stock quantities.

6. Sheep and beef farms are, on average, 300 ± 1,469 ha in size and have a mean woody vegetation proportion of about 15% per farm, although this varies by region (5-37%); for most regions, farms have an average of 4% exotic woody vegetation as a proportion of area. The mean woody carbon stock per farm is 4.5 kt C.

7. Under lower-end and higher-end published carbon sequestration rate value scenarios, sheep and beef farmland has equivalent annual GHG sequestration of -10,394 and -19,665 kt CO_2e, respectively. On average, this equates to over 50% of New Zealand's estimated 2018 GHG Inventory total sequestration value. Total equivalent annual GHG gross emissions from various agricultural sources for sheep and beef farmland are +16,537 kt CO_2e. On balance, sheep and beef farmland have net annual GHG emissions that lie within a range between +6,143 kt CO_2e (positive net emissions) and -3,128 kt CO_2e (positive net sequestration).

Recommendations

8. Prioritise the development of a data collection protocol for sheep and beef farmland that would enable an accurate, sector-specific dataset to be compiled on vegetation components, their key attributes (species composition, age, condition, etc.), their carbon stocks (above and below ground), and their relative sequestration rates.

9. Prioritise a spatial vegetation mapping programme for sheep and beef farmland. Such data would form the basis for future GHG budget calculations, for assessing the quantification of carbon sequestration

potential for non-ETS eligible vegetation components, and for targeting revegetation interventions at a farm or landscape level in support of net GHG emission reduction.

RESEARCH CONTEXT AND AIMS

The interchange of carbon between the Earth's surface and the atmosphere, whether by natural or human-caused processes, governs the overall global carbon balance. Recent decades have seen an overall net increase in atmospheric carbon in the form of greenhouse gases (GHG) from fossil fuel burning and expanding animal-based agricultural practices (IPCC, 2019). Overwhelming evidence now indicates that the result of these net greenhouse gas emissions is a consistent, upward warming trend and increasing, extreme weather events (Mitchell et al., 2016). This has consequently led to widespread international recognition and discussions of global warming and its impacts, and commitments by some countries worldwide, to reduce their emissions and increase carbon sequestration, largely via the provision of carbon sinks through reforestation activities.

Aotearoa New Zealand has committed, as part of the Paris Agreement, to reduce net greenhouse gas emissions as part of its contribution towards keeping global warming well below 2°C, aiming to keep it to 1.5°C. Consistent with this commitment, New Zealand passed the Climate Change Response (Zero Carbon) Amendment Act in 2019, which requires a transition to net zero emissions of long-lived greenhouse gases by 2050 or sooner, assisting the country's transition to a low-emissions economy (Ministry for the Environment, 2019a). To date, emissions from different agricultural sources have mainly been quantified for national-scale reporting requirements as part of New Zealand's Greenhouse Gas (GHG) Inventory. Presently, the agriculture sector is the largest contributor to NZ greenhouse gases, contributing about 45% of gross emissions in 2018, to the amount of +37,088 kilotonnes of carbon dioxide equivalent (kt CO_2e) emissions (Ministry for the Environment, 2019b), using Global Warming Potential 100 (GWP100) as a metric of carbon dioxide equivalence for methane and nitrous oxide.

In addition to emissions, rates of carbon sequestration are also quantified at a country scale as part of the GHG Inventory framework; sequestration is estimated using the Land Use and Carbon Monitoring System (LUCAS) programme (Ministry for the Environment, 2019b). The LUCAS approach uses moderate-resolution (10-15m) satellite imagery to delineate broad land cover/land use types across the country, and their changes between 5-year reporting periods. Sequestration rates are compiled using biomass changes quantified within a system of vegetation plots, occurring primarily in indigenous forest areas, shrubland areas, and plantation forests, which are then applied to land cover/land use classes to estimate total carbon sequestration across terrestrial areas of New Zealand (Holdaway et al. 2017). Thus, the NZ GHG Inventory provides a national-scale summary of New Zealand's major carbon sources and sinks for domestic and international reporting purposes. However, the NZ GHG Inventory report does not identify the net carbon position (emissions minus sequestration) for different production sub-sectors (e.g. the sheep and beef farm sector), nor does it provide spatial information regarding the distribution of carbons stocks and the potential for future carbon sequestration.

An analysis by Norton and Pannell (2018) found that 17% of all New Zealand native woody vegetation is occurring on sheep and beef farms (*c.* 1.4million ha). However, in terms of assessing the carbon held in this woody biomass, few data are available. Agricultural lands are characterized by a wide variety of woody vegetation components that vary considerably in size, species composition, age, and degree of disturbance. Further these vegetation components are found in many forms, such as native remnants, exotic forestry blocks, amenity and riparian plantings, soil conservation plantings, shelterbelts, regenerating patches of shrubland (Norton and Read, 2013), each with different potentials for carbon storage and sequestration (Burrows et al. 2018). At present, there is a lack of thematically-detailed and high-resolution vegetation type data for New Zealand, and especially for the varied vegetation components on privately-owned land. Soil carbon stocks, and sequestration rates in particular, are challenging to quantify and the effects of animal-related disturbance, management activities and inputs, and environmental variation on agricultural soils magnifies this challenge (McNally et al., 2017).

Despite the challenges, the sheep and beef sector is currently motivated to estimate the current distribution of carbon stocks, and potential carbon sequestration, for the more than 10 million hectares of sheep and beef farmland. A spatial representation of the distribution of woody vegetation and carbon storage enables the identification of relatively lower-carbon stock locations across sheep and beef farmland and where there is the greatest potential for increasing woody vegetation and carbon sequestration to offset emissions at a national level. Such an assessment also provides a baseline upon which future carbon quantification research and actions could be based for sheep and beef farmland. Further, with improved knowledge about the relative prevalence of different woody vegetation types, and their carbon storage and sequestration potentials, there is an opportunity for sheep and beef farmers to offset their carbon emissions (e.g., within the Emissions Trading Scheme (ETS)), improve biodiversity, and enhance multiple ecosystem services.

Consistent with these motivations, this research aims to:

1. Undertake a review of published and un-published sources of information regarding carbon quantification
2. Classify and map vegetation types on sheep and beef farms using available vegetation and landcover spatial datasets.
3. Estimate, and spatially-map, current carbon quantities on sheep and beef farms.
4. Using available information, estimate the current net carbon position for sheep and beef farms in NZ (emissions minus sequestration).
5. Illustrate differences in vegetation distribution and carbon sequestration potential between national-scale spatial data and bespoke, fine-scale data derived from aerial imagery.

CARBON QUANTIFICATION: A BRIEF REVIEW

Woody vegetation mapping in New Zealand

Vegetation type strongly influences the amount and rate of carbon storage in vegetation. For example, tall naturally occurring indigenous forest can store on average twice as much carbon per hectare than exotic plantation forest over its harvest rotation timeframe (Ministry for the Environment, 2017); exotic forests managed on harvest rotations are also subject to further loss of carbon from frequent harvesting and replanting cycles (Buswell, 2016). Compared to mature native forest, which is estimated to have a neutral sequestration rate based on a national assessment of carbon analysis native forest plots (Holdaway et al., 2017), regenerating indigenous scrub, shrubland and forests sequester carbon rapidly as they grow (Stats NZ, 2019). However, relatively little is known about the quantities or types of vegetation occurring across New Zealand farms (Burrows et al., 2018) and the overall potential for this vegetation to offset emissions within the sheep and beef farm sector.

Given the importance of vegetation classification for carbon stock and sequestration assessment, we briefly summarise efforts to classify and map New Zealand vegetation and associated ecosystem types since the 1950's:

- National coverage **Forest Class Maps (FCM)** were compiled from the 1950's at a scale of 1:250,000 (NZ Forest Service Mapping Series, 6). Data were collected from ground and aerial surveys (1946-1955), and the maps qualitatively describe 18 broad forest classes (McKelvey and Nicholls 1957), which were later modified by Nicholls (1976).

- The **Vegetative Cover Map of NZ** (Newsome, 1987) provided national coverage and described 30 'forest' or 'scrub' classes or gradations of these into each other or grasslands at a scale of 1:1000 000 with a minimum unit size of 500 ha. Underpinning data are primarily from the NZ Land Resource Information Survey (Blaschke et al. 1981) and extensive ground truthing. However, the resolution is insufficient to determine ecosystem types (Wiser et al. 2011).
- In the 1980's, the **NZ Protected Natural Area Programme (PNAP)** created 85 Ecological Regions and 268 Ecological Districts characterised by topographic, climatic, soil and biological features, and broad cultural patterns (Kelly and Park 1986). Ecological Districts provided a basis for survey to identify ecosystems for protection, however, the PNAP has focused on identification of ecosystems of highest ecological value resulting in an incomplete inventory (Park 2000, Singers and Rogers, 2014).
- Using satellite image classification, the **NZ Land Cover Database (LCDB)** was first-produced in the mid-1990's, providing a spatially-continuous coverage of broad land cover classes, including vegetation types (Dymond et al. 2017). This dataset has been regularly updated (~6 yearly) at four different dates: 1996/97, 2001/02, 2008/09 and 2012/13. While the LCDB dataset has been a substantial step forward in the classification and spatial representation of NZ vegetation, the thematic resolution is insufficient to determine indigenous vegetation types (Wiser et al., 2011), and only land cover features larger than one hectare are mapped. All indigenous forest is grouped into one class although there are several scrub and shrubland classes. The LCDB has a high overall mapping accuracy of more than 90% (Dunningham et al., 2000), but there is some uncertainty around how well it can report the area of individual classes or change in area of a class (Brockerhoff et al., 2008; Walker et al., 2008; Dymond et al., 2017).
- **Land Environments of New Zealand (LENZ)** identifies potential vegetation types by quantitatively correlating climatic, landform, lithology and soil variables with tree distributions (Leathwick et al., 2002). LENZ groups together sites with similar environmental conditions thereby enabling the delineation of land areas at a national scale that are likely to have had similar potential pre-human vegetation compositions (Leathwick et al. 2004).
- The **Terrestrial Ecosystem Classification (TEC)** (Singers and Rogers, 2014) is a national classification used widely by Regional Councils to derive potential, pre-human vegetation extents, which are used as a proxy for ecosystem types. The spatial extent of LENZ abiotic drivers (climate, landform, lithology and soils) provides a framework to place vegetation communities, drawn or derived from the literature (Singers and Rogers, 2014). The TEC has so far been taken up in nine of fourteen regions, with those councils developing their own spatial layers and ground verifying them.
- **Wiser et al.** (2011; 2013) provided the first statistical classification of NZ's woody vegetation. A fuzzy clustering methodology was applied to data from vegetation plots from the National Vegetation Survey (NVS) databank distributed across New Zealand's woody vegetation zones. Work is underway to create spatial layers to reflect the extent of classes (Wiser, *pers. comm.*). Notably, Wiser et al.'s vegetation classes reflect a relatively high prevalence of overall, seral (young, regenerating) vegetation across the plots. This is likely to also be true for vegetation on New Zealand farmland.
- Within the **LUCAS programme**, landcover elements on production land are classified into broad landcover types using satellite imagery in order to create the **Land Use Map (LUM)** dataset (Ministry for the Environment, 2012). The main types are grassland (either high- or low-producing), grassland with woody biomass, pre-1990 natural forest (discernable vegetation patches present before 1990 with a crown closure of >30% and the potential to grow into forest >5m tall), pre-1990 planted forest, and post-1990 forest (exotic and native). The main objective of this method is to track conversions in land use from one class to another across reporting periods and, thus, changes in sequestration and emissions for the GHG inventory using look up table 'emission factor' values.

Although significant progress has been made in characterising and mapping New Zealand vegetation since the 1950's, an accurate, ground-truthed, national spatial classification does not yet exist, nor has an inventory or classification of vegetation on NZ sheep and beef farms been produced. Thus, our methodology for country-wide carbon assessment for sheep and beef farmland has relied heavily on several of the datasets described above.

Quantifying carbon stocks and sequestration rates

The estimation of carbon stocks is the first step in quantifying the potential for carbon sequestration. Carbon stocks represent cumulative past carbon sequestration up to the time of measurement and are largely reflective of the spatial distribution of live woody vegetation biomass carbon and soil organic carbon components, which together represent the largest carbon sinks. Carbon stocks are related mainly to the species and ages of individual trees and shrubs comprising vegetation elements across farmland, as well as the environmental conditions, which affect both growth (and therefore sequestration) rates and soil variation (Burrows et al. 2018). Further, management activities (fertilizing, irrigating, tilling) and other disturbances (e.g., grazing and pest mammal herbivory) can have a range of impacts on both vegetation and soils and their corresponding carbon sequestration potentials. In woody vegetation, carbon is stored in live and dead biomass components, typically quantified for four main pools: aboveground live biomass, coarse woody debris (including aboveground standing dead trees and on-ground larger woody debris), litter (composed of fallen fine woody debris and leaf material), and belowground dead and alive root components (Holdaway et al., 2017). Most soil carbon is in the form of soil organic carbon, predominately in the top 30 to 50 cm of the soil profile under both woody and non-woody (i.e., pasture) vegetation (Welsch et al. 2019).

From a sequestration perspective, CO_2 is assimilated by vegetation (both woody and non-woody, although we focus in this study on the woody component) via photosynthesis, the net result of which is biomass accumulation, *c*. 50% of which is carbon. Thus, quantification of sequestered carbon per unit of time (e.g., per year) is underpinned by information regarding the amounts, types, ages, and spatial distributions of woody vegetation elements and their associated biomass carbon sequestration rates (Beets et al., 2014). Soil carbon stocks are relatively stable over time, and within a yearly time-frame sequestration is considered to be nil, unless there have been significant land use changes, or ongoing management activities such as tillage, that has affected soil carbon cycling processes (Schipper et al. 2017). Ongoing research (e.g., Whitehead et al., 2018) aims to fill in data gaps regarding management effects on soil sequestration rates that can be applied reliably across a large scale.

The quantification and spatial mapping of carbon stocks and sequestration rates associated with specific vegetation types in New Zealand has had relatively limited research effort and, up to present, there have been no published carbon quantification studies specifically for the sheep and beef sector. Much of the work on quantifying carbon stocks and sequestration rates for indigenous and plantation forest at the country scale has been carried out via the LUCAS programme, which collects data on forest carbon stocks and stock changes at five-year intervals to meet international reporting requirements (Ministry for the Environment, 2019b). Methods developed as part of this work, and informed by Kyoto Protocol guidelines, include: Coomes et al., 2002; Beets et al., 2012; Holdaway, et al., 2017, Paul et al. 2019a and Kimberley, et al., 2019. The most recent estimates for carbon stock and sequestration rates for the different forest types in all pools are:

- Pre-1990 natural forest: Carbon stock of 250.5 ± 14.9 tC ha^{-1} for tall forest, and 57.6 ± 8.5 tC ha^{-1} for regenerating forest, with a sequestration rate of 0.6 ± 0.3 tC $ha^{-1}y^{-1}$ in regenerating forests (Paul et al., 2019 – unpublished). However, carbon stocks were static as there was no significant carbon sequestration or loss in older forest (Paul et al., 2019 - unpublished).
- Post 1989 natural forest: most recent estimates are 28.9 tC ha^{-1} (Beets et al., 2014; Ministry for the Environment 2019b). Whilst the post-1989 carbon stock is low compared to that for pre-1990 natural forests, largely due to the young ages and small sizes the trees/shrubs comprising for the former, the

sequestration rate is higher with an average rate of 2.4 tC ha^{-1} yr^{-1} (Beets et al., 2014; Ministry for the Environment 2019b).

- Post-1989 plantation forests carbon stocks were estimated at 151.4 ± 21.5 tC ha^{-1} in December 2017 (Paul et al., unpublished, cited in Ministry for the Environment, 2019b). Based on MfE forest carbon stocks summary statistics for 2015, we calculated an overall sequestration rate for this class as 7.3 tC ha^{-1} yr^{-1}.
- The 'grassland with woody biomass' category is of particular interest because it is likely that a significant proportion of woody vegetation areas of sheep and beef farmland is associated with this category. This class comprises areas of shrubland or scrub less than 5 m tall, as well as sparse, taller woody vegetation, such as found in riparian plantings, shelterbelts, sparse trees within grasslands, and above-treeline shrubland. The 2019 GHG Inventory report presents carbon stocks for two sub-categories: transitional types (13.05 tC ha^{-1}) and permanent (60.57 tC ha^{-1}), with the former having a sequestration rate of 0.47 tC ha^{-1} yr^{-1}.

Some common farm woody vegetation features are too small to meet criteria for inclusion in LUCAS and are not reported on in the Emissions Trading Scheme (ETS). Burrows and colleagues (2018) provide a comprehensive literature review of available reference carbon stock value and sequestration rate information for non ETS land on farms including; wetlands, riparian strips, pole plantings, shelterbelts, and other retired land that is not eligible for ETS.

Methods for modelling soil organic carbon stocks in mineral soils, and changes in stocks between inventories, from existing soil plot data have been established as the Soil Carbon Monitoring System (CMS) component of the NZ Greenhouse gas inventory (e.g., Tate et al. 2005). The values used for steady-state soil organic carbon stocks within the GHG Inventory range from 91.9 tC ha^{-1} for Post-1989 forest to 105.98 tC ha^{-1} for low producing grassland (see MfE 2019b – Table 6.3.2). The default sequestration rate for soils under planted forest is 0.68 tonnes C ha^{-1} yr^{-1}. Additional to the national-scale estimation, a few studies have highlighted possible variation in soil carbon stocks and sequestration rates related to land conversion and management effects (e.g., Kirschbaum et al., 2009; Kirschbaum et al., 2012; Schipper et al., 2017).

Quantifying the greenhouse gas emissions component

Estimating GHG emissions from agricultural sector sources is complex. Biological emissions, which comprise the bulk of emissions from the agricultural sector, are quantified as part of the New Zealand GHG Inventory process and comprise estimates for methane sources from livestock digestion and nitrous oxide from animal manure and fertiliser for international reporting requirements (Ministry for Primary Industries, 2019). Estimates are derived from modelling of biological processes generating these emissions There are ongoing efforts to also model emissions at the farm scale using similar processes incorporated within models such as OVERSEER ® (Biological Emissions Reference Group, 2018). At the moment, the GHG Inventory provides the best-available published information.

STUDY METHODOLOGY

For this research, we first undertook a quantitative, spatial analysis of national spatial datasets to classify and map the extent of different vegetation types on NZ sheep and beef farms. The amount of biomass carbon and soil carbon was then estimated, and the approximate net carbon position of sheep and beef farmland was assessed using both lower-end and higher-end sequestration rates. All GIS operations were carried out with the ArcGIS Pro v. 2.2 (ESRI, 2018).

Classification and spatial mapping of the vegetation types on sheep and beef farms

Sheep and beef farm property boundaries were identified using the Agribase^{TM} dataset, a national spatial database of farm information (AsureQuality, 2018), providing the overall study area footprint for the analyses. Property boundaries of all privately-owned sheep and beef farms (33,860) were then spatially-overlaid in the GIS with the New Zealand Land Cover Database (LCDB, v. 4.1) polygon dataset, comprising the major land cover and vegetation types occurring across the country. The LCDB dataset was originally derived from the analysis and classification of SPOT-5 satellite imagery (10m resolution, collected in 2012/2013). This GIS operation provided a map of all land cover types (woody and pasture) occurring across sheep and beef farmland. The spatial distributions and amounts of five indigenous and four exotic LCDB woody land cover types on sheep and beef farms were identified for analysis, comprising: Indigenous Forest, Broadleaved Indigenous Hardwoods, Mānuka and/or Kānuka, Sub Alpine Shrubland, Matagouri or Grey Scrub, Mixed Exotic Shrubland, Gorse and/or Broom, Deciduous Hardwoods and Exotic Forest. The Exotic Forest class is predominantly radiata pine but includes a small proportion of other pine species, Douglas fir, cypress, larch, acacia and eucalypts. As the focus of this study was on woody vegetation, non-woody vegetation (e.g., in wetlands and tussock grasslands) were not included in our spatial analyses.

A more accurate assessment of carbon storage for native forest patches on sheep and beef farmland required a knowledge of detailed vegetation types for each of the LCDB 'indigenous forest' polygons identified in the previous step (Wiser et al. 2011). To do this, we overlaid the Terrestrial Ecosystem Classification (TEC) dataset (Singers and Rogers 2014) with the outcome of the above step to identify 'potential', ecosystem-based indigenous forest types for each polygon. This dataset, created and used extensively by many Regional Councils, provides a spatial representation of potential vegetation polygons occurring on both public and private land along with an assigned ecosystem type attribute; the latter provides information about the potential plant community type at that location, derived from field surveys or the expected vegetation type given the local biotic and abiotic context (Singers and Rogers 2014). Thus, the TEC dataset enhanced the LCDB 'indigenous forest' polygons by enabling additional plant community attribution. Where potential spatial layers did not yet exist (for four of fourteen Regional Councils), detailed botanical reports, such as Tenure Review reports, Protected Natural Area reports and local species lists were used to manually identify indigenous forest types from LCDB maps overlaid with LENZ level 2 datasets. Additional datasets used to verify vegetation types include: FSL NZ Soil Classification, SMap Soil Drainage maps, and NZ Forest Service Maps. The Terrestrial Ecosystem Classification contains 152 ecosystems organised by climatic zones, except where other drivers have a greater influence (azonal types). For the purposes of our study, these more detailed ecosystem types were rationalized into 68 aggregate types to reflect vegetation and zonation found on sheep and beef farms; in addition to the seven LCDB-based landcover types not classed as indigenous forest, a total of 75 vegetation types were used for carbon stock quantification (**Table A1**).

Vegetation and carbon stocks for sheep and beef farmland

National-scale vegetation and carbon stock assessment

Data for 1183, 20 × 20-m woody vegetation survey plots from the LUCAS 8 × 8 km national vegetation plot grid network were obtained as a basis for estimating above ground live biomass carbon (AGC) values for potential indigenous forest types. From this dataset, data were compiled for live tree stems included tree species, heights, and diameters at breast height; wood density data was also obtained for 114 tree species (Holdaway et al. 2017). From this compiled dataset, aboveground live biomass carbon was estimated as per the general methodology presented by Beets et al. (2012). Above ground live biomass carbon content for each tree (kg C tree^{-1}) was estimated using species-specific allometric equations following Beets et al. (2012) and Holdaway et al. (2017) in the R statistical software version 3.6.0 (R Core Team, 2019). The tree carbon values produced by these equations assumed that 50% of tree biomass is carbon (Coomes et al., 2002).

Missing height values for some trees were estimated from tree diameters using a species-specific height diameter model following Holdaway et al. (2017). Tree carbon values were summed for all trees in each plot, converted from kilograms to tonnes (t), and divided by plot area in hectares to generate an above ground carbon (ABG) density value in t C ha^{-1}.

Plot location co-ordinates were overlaid with the TEC-derived vegetation type spatial layer (Section 4.1, above) in order to assign a potential vegetation type to each plot. As a result of this process, 658 vegetation plots were coincident with polygons classified using the Terrestrial Ecosystem Classification dataset, and these plots were used to derive carbon values for the majority of indigenous forest types. Estimated carbon values per type were then multiplied by the area (ha) of each vegetation type occurring on each sheep and beef farm to give total carbon per vegetation type. Aboveground biomass carbon values were derived from the average of the closest related classes for a small number of classes that had no LUCAS plot data; for the six other LCDB-based indigenous and exotic vegetation types, aboveground biomass carbon values were sourced from the literature. For the purposes of this report, we did not spatially-estimate carbon stocks for the root, deadwood, or litter components, although we do provide a total non-spatial estimate for these using published carbon density values multiplied by the total vegetation area. Belowground live biomass carbon was calculated as 20% of the above ground value (Beets et al., 2007);

We used soil carbon data compiled from 319 soil sample plots distributed across the country (**Fig. A1**) as a basis for quantifying reasonable steady-state soil carbon quantities for the top 30 cm of the soil profile. We quantified mean soil carbon stocks per region and for four vegetation types: pasture, indigenous forest, scrub, and exotic forest (**Table 1**); where there were missing, or not enough, plot samples for a given region, we in-filled these gaps with the overall mean for a given vegetation type across all regions.

Table 1. Soil organic carbon stock values (± 1 SD) for the top 0-30 cm of the mineral soil by region, under different four vegetation types, computed from LUCAS natural forest soil data collected from 319 sample plots across New Zealand during the 2002-2007 measurement period.

Region	Exotic Forest	Indigenous Forest	Pasture	Scrub
Auckland	87.1 (17.5)	108.4 (8.4)	102.6 (30.2)	122.0 (60.1)
Bay of Plenty	73.1 (16.6)	87.7 (29.4)	102.6 (30.2)	71.8 (45.0)
Gisborne	87.1 (17.5)	85.0 (35.1)	101.7 (19.4)	71.8 (45.0)
Hawke's Bay	87.1 (17.5)	110.5 (50.8)	107.4 (10.4)	103.2 (70.6)
Manawatu-Wanganui	87.1 (17.5)	133.6 (49.6)	102.6 (30.2)	71.8 (45.0)
Northland	105.7 (0.2)	102.8 (34.8)	102.6 (30.2)	71.8 (45.0)
Taranaki	87.1 (17.5)	103.4 (30.2)	102.6 (30.2)	71.8 (45.0)
Waikato	87.1 (17.5)	110.3 (52.2)	134.0 (21.7)	71.8 (45.0)
Wellington	87.1 (17.5)	70.7 (24.0)	102.6 (30.2)	71.8 (45.0)
Canterbury	87.1 (17.5)	36.5 (22.4)	92.6 (38.6)	51.9 (24.0)
Marlborough	87.1 (17.5)	86.0 (20.5)	102.6 (30.2)	76.2 (40.2)
Nelson	87.1 (17.5)	84.0 (49.7)	102.6 (30.2)	71.8 (45.0)
Otago	87.1 (17.5)	53.6 (23.7)	121.5 (41.8)	55.9 (31.2)
Southland	87.1 (17.5)	99.9 (65.5)	102.6 (30.2)	105.3 (57.7)
Tasman	87.1 (17.5)	67.4 (35.3)	102.6 (30.2)	71.8 (45.0)
West Coast	87.1 (17.5)	56.3 (39.0)	102.6 (30.2)	22.3 (12.7)

Farm-scale vegetation and carbon stock assessment

Using Agribase sheep and beef farm property boundaries and mapped vegetation and carbon stock data within the GIS, we quantified for each region in New Zealand: (i) mean farm size; (ii) the mean proportion of farms comprising exotic forest, indigenous forest, and indigenous and exotic shrubland and scrub; (iii) the mean total aboveground carbon stock (kt C) within each of these woody components per farm, and; (iv) the mean soil organic carbon stock per farm (including woody and pasture soil carbon).

Net carbon position assessment for sheep and beef farmland

Calculating net GHG emissions involves estimating relevant sinks (sequestration components) and sources (emission components) of carbon across sheep and beef farmland, with the 'net carbon position' computed as the difference between these two, indicating the overall net greenhouse gas exchange between land and atmosphere (Burrows et al., 2018). Carbon sequestration and emission rates are typically quantified on a yearly basis and are presented in the form of equivalent greenhouse gas units in tonnes of CO_2, per hectare, per year ($t{\cdot}CO_2e\ ha^{-1}\ yr^{-1}$). The carbon budget is calculated as the difference of the summed quantities of both emission and sequestration CO_2 equivalents (so-called 'emission factors'), with a positive quantity indicating an overall net emission scenario, and a negative result indicating an overall net sequestration scenario.

We compiled emissions estimates from 2018 NZ GHG Inventory data, provided by the NZ Ministry for Primary Industries, for the dominant methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) components related to agricultural practices on sheep and beef farmland. To quantify the sequestration component, we assembled published sequestration values from a range of sources for different vegetation/land cover types, providing both lower-end and higher-end estimates, assuming that this range would encompass the uncertainties associated with this exercise.

A carbon case-study comparison using vegetation mapped at a high resolution

As a comparison to the above national-scale analysis, we mapped vegetation in higher detail for a 55-km^2 area of farmland in the Kaipara district of the upper North Island. High-resolution (10-cm pixels) aerial RGB colour imagery and moderate-resolution (10-m pixels) Sentinel 2 multi-spectral satellite imagery from 2017 was downloaded from the LINZ data service website. These combined datasets provided a basis for an image classification procedure carried out within the eCognition image analysis software. The classification produced woody vegetation polygons grouped into 18 vegetation types and three canopy density classes.

Published carbon sequestration values obtained as above were applied to woody vegetation classes and aggregated up to the total area sampled and compared to those based on LUCAS-derived and LCDB vegetation polygons for the same area.

RESULTS

National-scale distribution of vegetation on sheep and beef farmland

The total sheep and beef farmland estate, as quantified using our methodology, was 10.2 million hectares in size, comprising about 38% of terrestrial land area in New Zealand. Of this 10.2 million ha, 80% was pasture (8.2 million ha), 8.2% indigenous forest (0.81 million ha), 5.5% mānuka/kānuka (0.56 million ha), 1.7% indigenous scrub and shrubland (0.17 million ha), 3.3% exotic forest (0.34 million ha) and 1.3% exotic scrub and shrubland (0.14 million ha). We note here that Statistics New Zealand and the Beef + Lamb NZ Economic Service Unit have recently estimated the total sheep and beef farm area in New Zealand as 9.1 million ha (e.g., Statistics NZ Agricultural Production Survey published result as at 30 June 2019). The use of Agribase farm parcel information as a basis for areal calculations in this study produces a slight variation from this figure due to how "sheep and beef farmland" has been defined based on information provided in this dataset and uncertainties related to the temporal accuracy of the data. However, in this report, Agribase was used for calculations as it included the necessary GIS information layers required for the spatial analysis.

Of the woody types, indigenous forest dominates in the North Island but gives way to locally dominant indigenous scrub and shrubland (matagouri and sub alpine shrubland) in more mountainous areas and flood plains of the South Island. Significant areas of seral indigenous scrub and shrubland (mānuka and/or kānuka) occur nationally (**Fig. 1**).

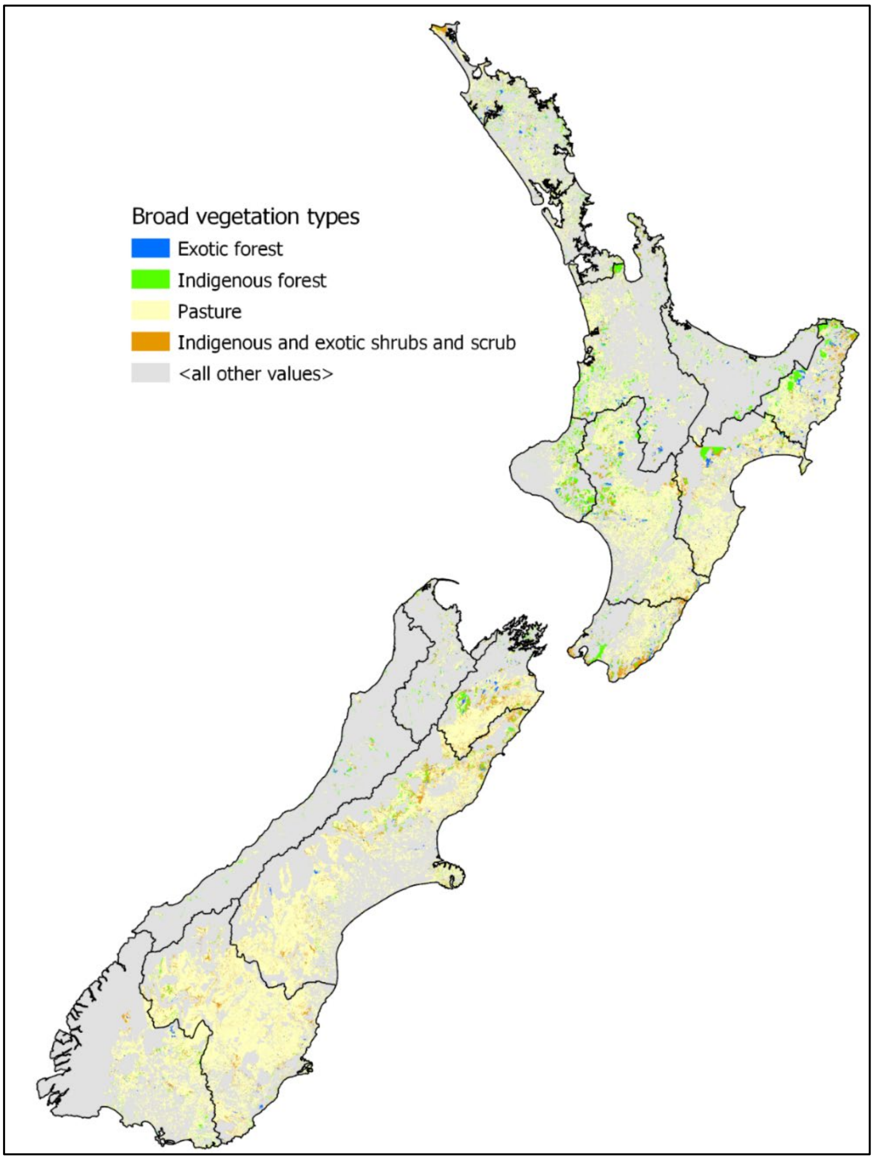

Figure 1. Distribution of broad woody vegetation types and pasture across sheep and beef farm areas. The majority of the 'indigenous and exotic shrub and scrub' type is mānuka/kānuka, as per LCDB v. 4.1.

A break-down of the 0.81 million ha of ‘indigenous forest’ into 75 ‘potential’ vegetation types using the Terrestrial Ecosystem Classification indicated that the five largest potential vegetation types comprise 51% of the total indigenous forest area (**Table A1**). The five types were:

- MF7 - Tawa, kamahi, podocarp forest (18.9%),
- WF13 - Tawa, kohekohe, rewarewa, hinau, podocarp forest (9.6%),
- CDF3 - Mountain beech forest (8.6%),
- WF11, Kauri, podocarp, broadleaved forest (8.2%),
- MF21, Tawa, kamahi, rimu, northern rātā, black beech forest (6.1%).

A further 15 classes comprised 37.5% of the total vegetation, each less than 5% in total. The remaining 48 classes made up the remaining 11.13% - each less than 1% of the total potential indigenous vegetation.

Carbon stocks in woody vegetation types on sheep and beef farmland

The total above ground carbon (AGC) in live woody vegetation on sheep and beef farms was 182,486 kt C; the mineral soil organic carbon (BGC) amounted to 1,042,736 kt C, comprising soils under both woody vegetation and pasture. Using available information, we estimated an additional 36,500 kt C of live root carbon, 20,500 kt of dead wood carbon, and 13,000 kt of litter carbon, for a total of 1,295,222 kt C.

Indigenous forest contained the highest proportion (54.1%) of total AGC of the woody vegetation types, followed by mānuka and/or kānuka forest (21.3%) and exotic conifer forest (16.7%) (**Fig. 2**).

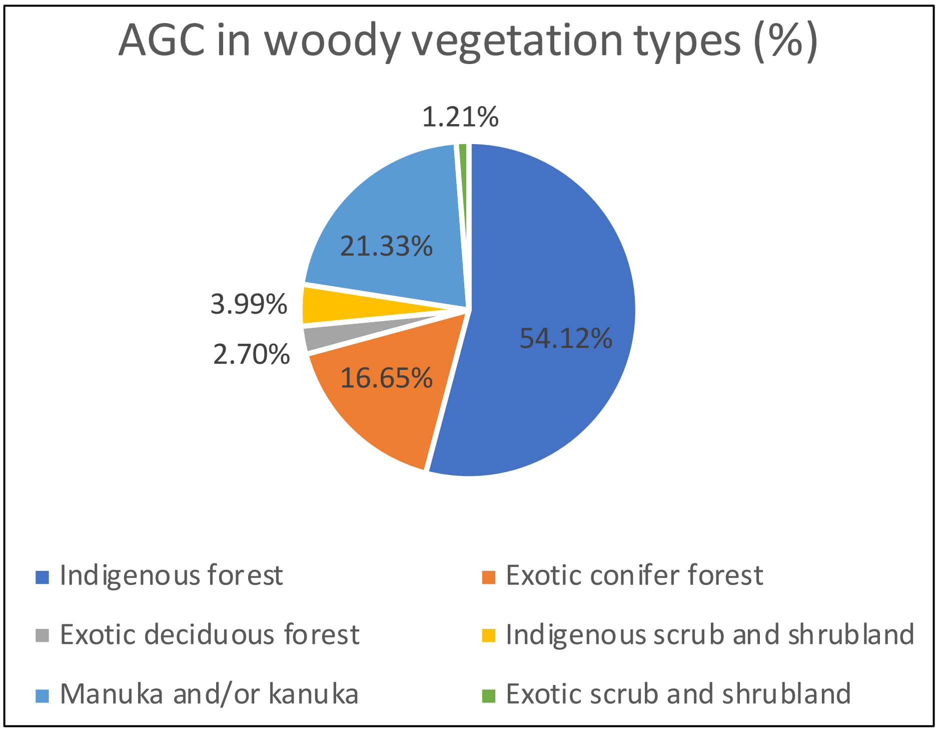

Figure 2. Proportion (%) of total above ground woody carbon stocks by vegetation class across New Zealand sheep and beef farmland.

Of the ‘potential’ indigenous forest types, MF7, Tawa, kamahi, podocarp forest contained the most AGC (10.2%), followed by CLF10, Red beech, silver beech forest (4.89%), then WF13, Tawa, kohekohe, rewarewa, hinau, podocarp forest (4.10%), CLF9, Red beech, podocarp forest (4.02%) and CDF3, Mountain beech forest (3.66%).

Spatial distribution of carbon stocks across sheep and beef farmland

Above ground woody biomass carbon is unevenly distributed across New Zealand, closely reflecting the relative amounts and distributions of vegetation types on sheep and beef farms; much of sheep and beef farmland has an AGC density of less than 20 t ha^{-1} (**Fig. 3a**) and total AGC quantities of less than 50 kt C (**Fig. 3b**) per 10×10-km regions. The regions with the greatest AGC quantities (between 500 and 1000 kt C) per 100 km^2 cells are located in Gisborne, Hawkes Bay and Manawatu-Whanganui regions in the North Island, with only very localised areas in north-eastern South Island containing comparably high carbon stock quantities (**Fig. 3a**).

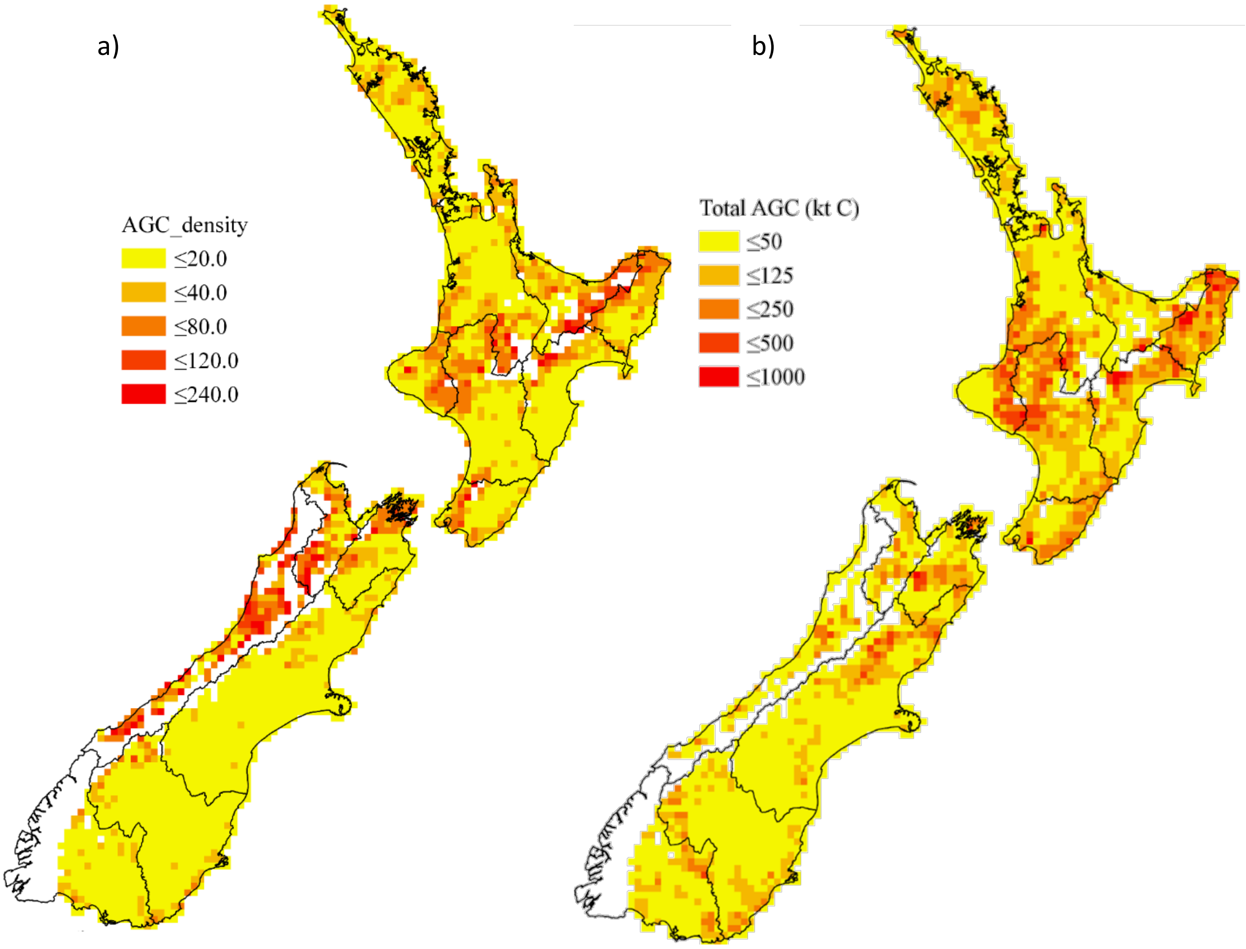

Figure 3. The distribution of above-ground woody carbon density (tC/ha) and total live aboveground woody biomass carbon stocks (AGC – kilotonnes of C) quantified for areas of beef and sheep farmland within 10x10-km grid cells. The high AGC density in the West Coast region in (a) is caused by a combination of relatively high woody vegetation density and small sheep and beef farm areas in the 100km^2 cells and is therefore somewhat misleading.

Manawatu-Whanganui has the greatest overall regional AGC stock, followed by Canterbury, Waikato and Gisborne (**Fig. 4**), while the largest regions by land area have the greatest total combined AGC and BGC (soil) carbon, namely Canterbury, Otago, Southland and Waikato (**Fig. 5**). Nelson, Tasman and Auckland, as the smallest regions, have the smallest above and below ground carbon stocks.

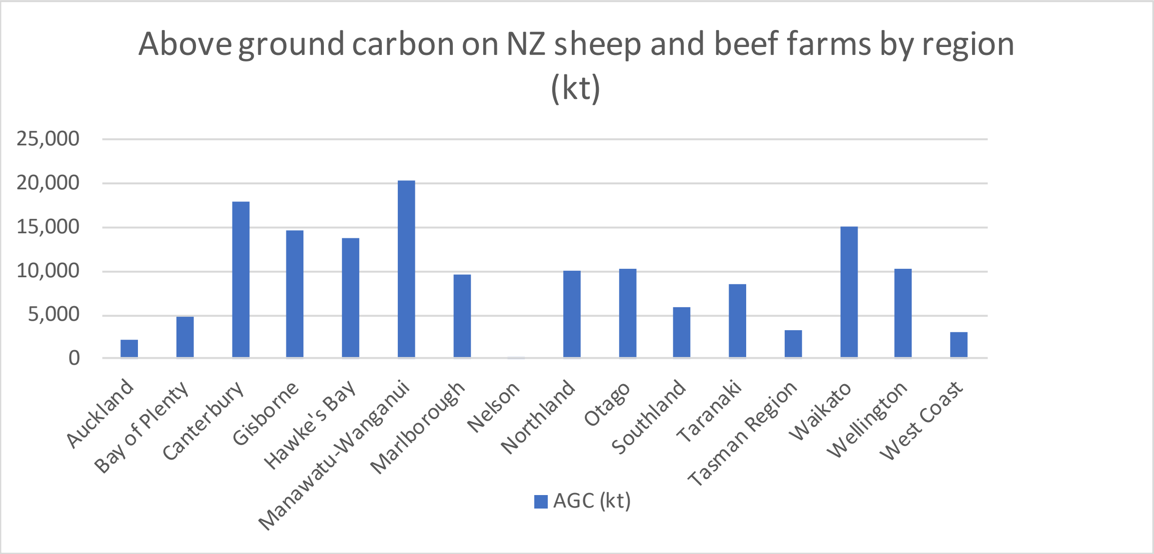

Figure 4. Regional breakdown of aboveground carbon (AGC - kt C) stock estimates, for sheep and beef farms across New Zealand.

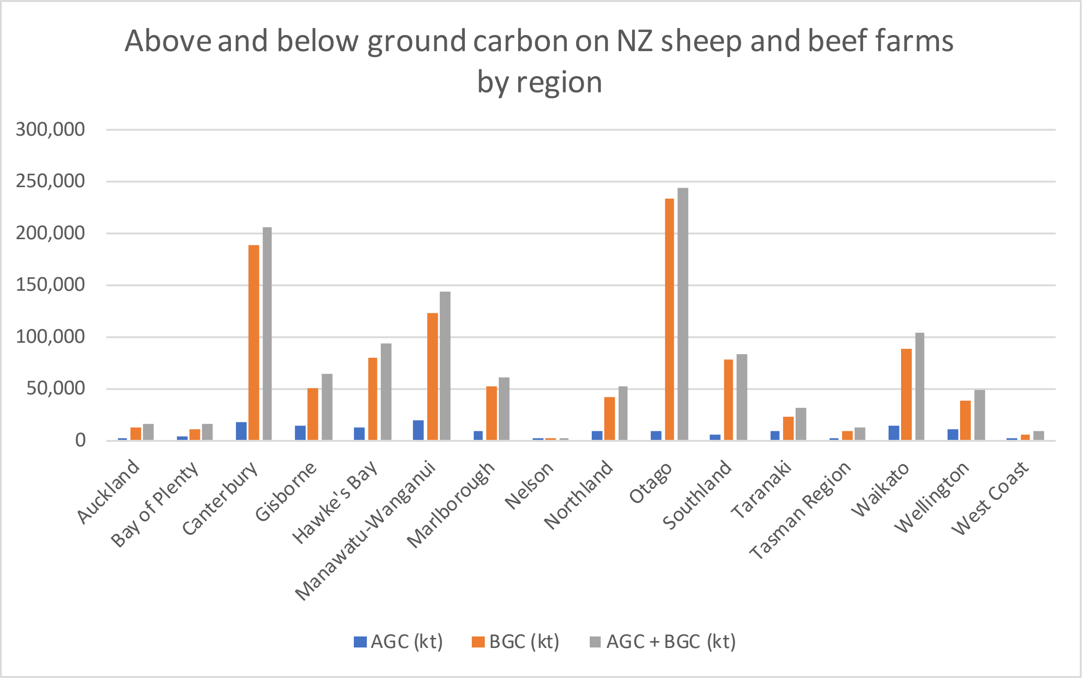

Figure 5. Breakdown of both aboveground carbon (AGC) and soil carbon (BGC) stock estimates, and their combined totals, for sheep and beef farms by regional council boundary across New Zealand.

Farm-scale vegetation and carbon stock analysis

The average size of sheep and beef farms across New Zealand, as per the Agribase dataset, was 300 ± 1,469 ha. On sheep and beef farms, the mean relative proportion of woody vegetation per farm was about 15%, although some regions (e.g. Gisborne, Northland, Taranaki, Nelson, West Coast) had much higher mean proportions per farm (**Table 2**). However, the relative distribution of woody biomass within exotic forest, indigenous forest, and shrub/scrubland components was highly variable by region; farms in some regions (e.g., Northland and Taranaki) had relative high proportions of indigenous forest, while farms in other regions (e.g., Gisborne and Nelson) had relatively higher shrub/scrubland biomass. With the exception of farms in the Nelson region, which comprised only 5,000ha of sheep and beef farmland, farms across all regions had less than 7% exotic forest on average, with an overall mean exotic forest proportion of 4% across all farms. Woody vegetation on farms contain, on average, 4.5kt of biomass carbon and follow similar trends to those for vegetation proportions by region; regions with the greatest combined woody and pasture soil organic carbon per farm are Marlborough, Gisborne, Otago, and Canterbury, with carbon stocks in the range of 40 to 100kt C per farm.

Table 2. Mean farm sizes, relative mean proportions of woody vegetation types, and mean carbon stocks on a per-farm basis tabulated for the 34,220 farm properties identified by the Agribase dataset across sheep and beef farmland.

Region	S&B total area (X 1000 ha)	Mean farm size (ha) (± 1SD)	Mean proportion (%) of farm area (±1SD)			Mean carbon (kt C) per farm (± 1SD)	
			Exotic forest	Indigenous forest	Shrubland and scrub	Woody AGC	Soil C (woody & pasture)
Auckland	134	46 (114)	3.6 (9.0)	7.2 (14.1)	5.1 (12.7)	0.6 (4.5)	4.6 (11.5)
Bay of Plenty	150	111 (427)	4.8 (11.3)	14.3 (22.3)	3.3 (10.0)	4.2 (23.2)	8.6 (32.6)
Gisborne	538	621 (1,540)	6.3 (13.7)	7.9 (14.2)	11.7 (18.9)	18.1 (78.5)	58.6 (142.2)
Hawke's Bay	772	363 (859)	5.0 (10.4)	3.0 (8.1)	3.6 (9.9)	6.5 (68.4)	37.8 (86.4)
Manawatu-Wanganui	1,205	266 (759)	4.0 (10.0)	5.5 (12.2)	3.1 (9.2)	4.6 (27.6)	27.4 (77.6)
Northland	469	125 (395)	4.2 (10.5)	14.3 (19.4)	9.1 (17.6)	2.2 (9.0)	11.3 (33.8)
Taranaki	236	205 (419)	3.6 (9.6)	13.1 (20.4)	4.4 (10.6)	8.6 (26.9)	20.3 (41.3)
Waikato	719	168 (417)	3.5 (9.5)	7.1 (14.2)	4.7 (12.9)	3.9 (21.5)	20.9 (49.6)
Wellington	416	259 (589)	5.8 (12.6)	5.6 (13.2)	7.6 (16.3)	4.9 (25.5)	24.3 (51.2)
Canterbury	2,142	482 (2,064)	3.6 (8.2)	1.3 (5.0)	3.4 (8.8)	3.8 (26.8)	42.5 (180.9)
Marlborough	536	1,039 (7,097)	6.7 (14.7)	7.2 (17.1)	8.5 (15.3)	16.7 (116.9)	100.3 (703.7)
Nelson	5	129 (270)	12.5 (18.1)	0.0	14.8 (20.4)	2.2 (4.4)	12.1 (25.8)
Otago	2,000	698 (2,106)	3.9 (9.3)	1.7 (6.5)	4.9 (10.3)	3.9 (18.8)	81.6 (245.8)
Southland	778	298 (1,529)	2.1 (6.3)	2.0 (6.6)	1.5 (5.7)	2.9 (18.2)	30.1 (153.9)
Tasman	96	124 (245)	6.2 (11.7)	8.6 (15.9)	7.3 (14.3)	5.3 (16.4)	11.3 (22.1)
West Coast	75	196 (408)	3.2 (8.5)	26.3 (26.6)	8.0 (14.1)	13.3 (38.3)	15.6 (32.6)
All regions	10,270	300 (1,469)	4.0 (9.9)	6.5 (14.3)	4.9 (12.4)	4.5 (32.8)	30.5 (146.6)

National-scale net carbon position estimate for sheep and beef farmland

Under lower-end and higher-end published sequestration rate values for different vegetation types and amounts, there is a total annual carbon sequestration on sheep and beef farmland of between -10,394 and -19,665 kt CO_2e (**Table 3**), equating to an approximate offset of 13.2% to 24.9% of the country's gross 2018 GHG emissions. Accounting for various agricultural GHG emission sources for sheep and beef farmland, total equivalent 2018 annual GHG gross emissions for the sheep and beef sector were +16,537 kt CO_2e, comprising about 20% of the country's and 45% of the agricultural sector's gross emissions. On balance, the net total net emissions for sheep and beef farmland ranges between net positive annual emissions of +6,143 kt CO_2e as a lower-end estimate, and net positive annual sequestration of -3,128 kt CO_2e as a higher-end estimate. Overall, these values equate to a potential offset in the range of 63% to 119% of the sheep and beef sector's 2018 GHG emissions.

Table 3. Estimates of aboveground and belowground CO_2 sequestration and gross greenhouse gas emissions (in kilotonnes of CO_2 equivalents) associated with the sheep and beef sector in New Zealand, and the net carbon position calculated as the difference of these values.

Sequestration component	Area (x 1,000 ha)	Sequestration rate (CO_2e t ha^{-1} yr^{-1})		Total sequestration (kt CO_2e)	Notes
Indigenous tall forest	812.2	Lower end	1.1	-893	Paul et al. 2019*[a]
		Higher end	3.3	-2,680	
Exotic conifer forest	310.1	Lower end	22.5	-6,982	Mean of ETS values for *P. radiata* at 20 years old
		Higher end	31.7	-9,836	Wakelin et al. 2016
Exotic deciduous forest	34.7	Lower end	4.4	-153	Burrows et al. 2018 – pole plantings
		Higher end	27.0	-937	ETS look-up value for exotic hardwoods at 20 years
Indigenous scrub and shrubland	170.0	Lower end	1.7	-289	Paul et al. 2019
		Higher end	6.5	-1,105	ETS look-up value for 'Indigenous Forest' at 50 years old*[b]
Mānuka and/or kānuka	562.3	Lower end	3.2	-1,799	Paul et al. 2019
		Higher end	5.3	-2,980	Carswell et al. 2014
Exotic scrub and shrubland	139.0	Lower end	2.0	-278	Carswell et al. 2009
		Higher end	15.3	-2,127	Carswell et al. 2013 – estimate for gorse
Pasture	8,233.2		0	0	Assuming no net sequestration*[c]
Soils	10,261.5		0	0	Assuming no net sequestration*[c]
	Total sequestration lower end			**-10,394 kt CO_2e**	
	Total sequestration higher end			**-19,665 kt CO_2e**	

Emissions component *[d]	**2017 Emissions (kt CO_2e)**	
Enteric fermentation	+13,792	
Manure management	+160	
Agricultural soils	+1,762	
Inorganic fertiliser	+446	
Liming and dolomite	+249	
Urea CO_2	+128	
Total emissions	**+16,537**	
Net carbon position – lower end	**+6,143**	kt CO_2 e yr^{-1} (net positive emissions)
Net carbon position – higher end	**-3,128**	kt CO_2 e yr^{-1} (net positive sequestration)

Footnotes for Table 3

[a] The latest LUCAS assessment (Paul et al, 2019) calculated a sequestration rate of 0.6 ± 0.3 tC/ha/year for indigenous forest falling outside of Public Conservation Land (ie., on farmland). The numbers presented here use the lower (0.3 tC/ha/year) and upper (0.9 tC/ha/year) confidence limits of this estimate as the lower end and higher end scenario sequestration rates for tall forest. These have been converted into CO_2 equivalents.

[b] As there are no readily available published values for 'indigenous shrubland' (excluding mānuka/kānuka, which is dealt with separately in our analysis), we have used the MPI age 50 look up table sequestration rate for 'Indigenous Forest' as the upper end value, which has been derived from data for regenerating indigenous shrubland (Ministry for Primary Industries, 2017).

[c] There is no definitive quantification of soil carbon sequestration rates for New Zealand. Generally, the evidence indicates that net sequestration is null for undisturbed soils, negative for managed pasture soils, negative for eroded soils, and potentially positive for soils where land conversion has occurred from grassland to forest. We have decided here to assume no net sequestration.

[d] Provided by MPI based on 2018 NZ GHG data.

Fine-scale case study comparison

Our landscape-scale (55km^2) Kaipara case study mapping exercise compared vegetation mapped using high-resolution (10-cm pixels) aerial colour imagery against vegetation data sourced from the LUCAS Land Use method (Sentinel 2 imagery only) and the most recent (2012/2013) LCDB 4.1 data (**Fig. 6**). The fine scale image analysis detected an additional 11.7% woody vegetation cover than the LUCAS method, much of which is younger regenerating vegetation, resulting in an estimate of nearly three times as much carbon sequestration. Compared to the LCDB approach, the fine scale analysis detected an additional 14.3% woody vegetation cover, resulting in an estimate of roughly one third more potential carbon sequestration **(Table 4).**

Table 4. Comparison of woody vegetation amounts mapped via classification of fine-scale aerial RGB imagery (fine-scale mapping) for a 55 km^2 sheep and beef farmland landscape area against woody vegetation data extracted for the same area from two national-scale land cover/land use datasets (LUCAS Land Use Map and LCDB 4.1 datasets). Also provided are comparisons of potential annual sequestration totals (kt CO2e) for the area calculated using the mapped vegetation types and areal proportions.

Quantified component	LUCAS LUM data	LCDB 4.1 data	Fine scale mapping
Total area sampled (ha)	5,453	5,453	5,453
Total vegetated area (ha)	1,660	1,668	1,668
Total area of woody vegetation (ha)	1033	888	1,669
Percent woody vegetation cover (%)	18.9	16.3	30.6
Annual C sequestration (kt $C0_2e$)	3.4	7.1	9.3

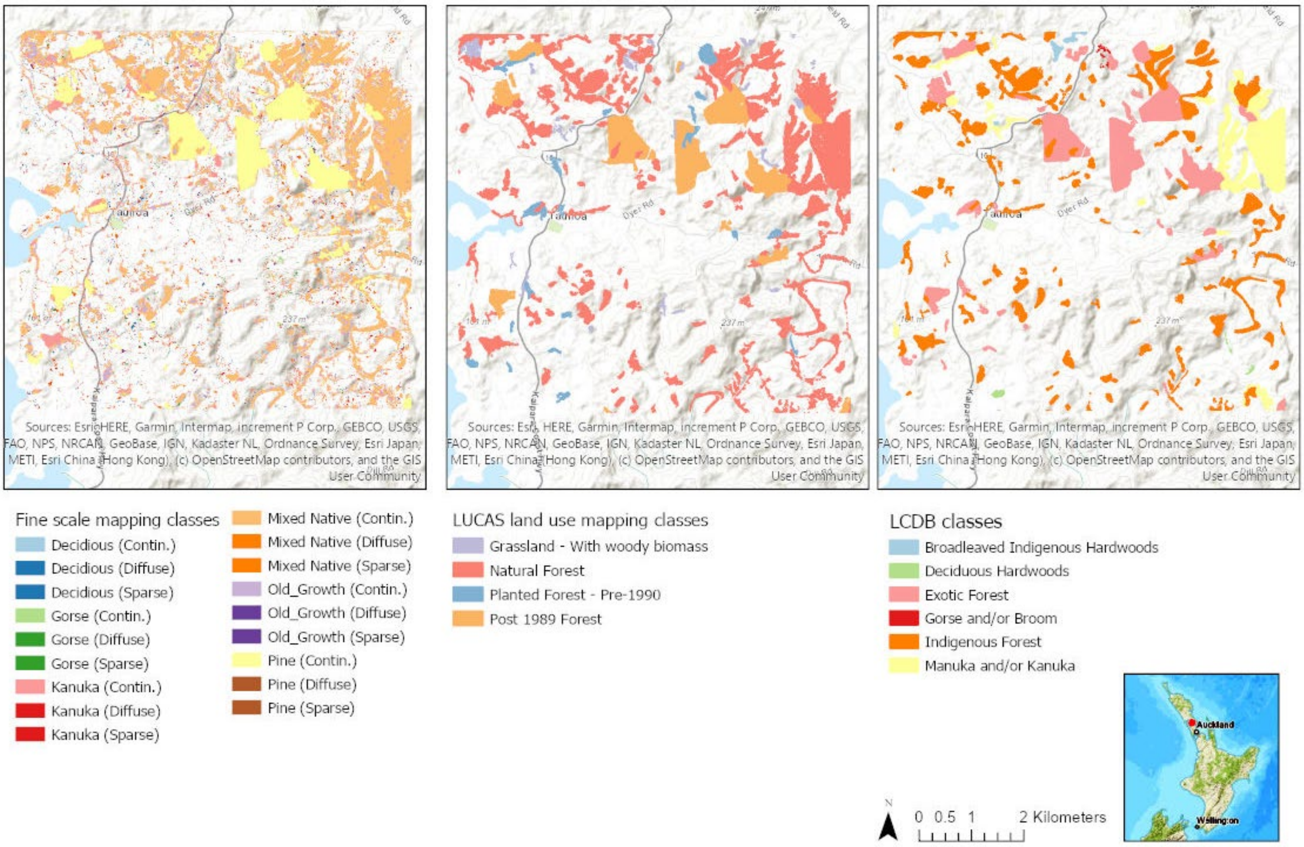

Figure 6. Maps showing spatial distributions of woody vegetation types for three different vegetation mapping efforts for a 55 km^2 case study sheep and beef farm landscape: using bespoke image classification of fine-scale aerial RGB imagery (left), using the LUCAS LUM dataset (centre), and using the NZ Landcover Database v. 4.1 (right).

DISCUSSION

This study has provided a spatial analysis of vegetation types, and a quantification of main above and below ground carbon stocks for these types, for New Zealand sheep and beef farmlands. Sheep and beef farmlands encompass a considerable area of woody vegetation, the vast majority of which is indigenous forest and early-successional indigenous shrubland. The state of the vegetation components classed as ‘indigenous forest’ is unclear, and likely comprises intact remnant forest fragments, remnant fragments that have been cut-over to some degree, grazed, or both, as well as some regenerating secondary forest (Norton and Reid, 2013). As these types of structural attributes impact significantly on carbon stock and sequestration potential, efforts to characterise and map vegetation attributes should be prioritised.

Relative to recent total carbon stock values reported by the Ministry for the Environment, the amount of carbon stored in sheep and beef farmland woody biomass represents c. 12% of the country’s woody carbon stocks, or c. 43% of the country’s total carbon stock, with the inclusion of soil carbon. There is a relatively unequal distribution of woody vegetation and carbon stocks among and within regions; as a proportion of region size, regions such as Gisborne, Whanganui-Manawatu, and Northland contain relatively higher stocks of farm biomass carbon while many of the South Island's regions in general have low carbon densities and total carbon stocks. The carbon maps depicted at the 10×10km grid scale provide relatively fine-scale information that could be used to assess where the greatest potential for revegetation activities and new carbon sequestration might exist across sheep and beef farmland. For example, areas where low carbon stock areas intersect with less productive farmland, such as that occurring in gully areas or on soils with low land use capability ratings, could be targeted for further revegetation. Conversely, higher carbon stock areas are likely able to provide viable seed sources for more passive forms of native revegetation into adjacent areas; this would provide the benefits of low-cost revegetation and potential income streams via carbon credits as these new forest patches establish. Carbon density maps also indicate where management is most needed to ensure mature/old growth forests are managed (e.g., exclusion of introduced mammalian browsers) to prevent them becoming sources of atmospheric carbon.

Norton and Pannell (2018) showed that much of the woody vegetation on sheep and beef farms exists in lowland ecosystems that have little-to-no representation within public conservation land and is therefore critical for biodiversity conservation. Bearing this in mind, it would be useful for the sector to target future revegetation efforts within appropriate lowland ecosystem types that are under-represented or threatened, and which would also promote added benefits such as for the mitigation of water quality and erosion impacts (Case, 2020). For instance, a focus on revegetation and fencing of farm gullies, which are often marginal in terms of farm productivity and accessibility, would provide a practical starting place. Further, our break-down of indigenous forest areas on sheep and beef land into more defined 'ecosystem types' indicates that only a handful of the 60+ ecosystems are currently well-represented across the sector. Thus, it would be useful to consider how we could increase overall representation of New Zealand's lowland vegetation types as part of revegetation and biodiversity enhancement opportunities within all pastoral based farming systems.

Nonetheless, farmers will need to be properly supported to carry out such management interventions. At the farm level, farm environment plans or whole-farm plans provide a means to do this (Maseyk et al. 2019), supported by adequate assistance and funding by local and regional government. By and large, evidence suggests that the Emissions Trading Scheme (ETS) has not been a motivating instrument to reduce GHG emissions via revegetation on farms (Niles et al., 2016; Leining et la. 2019); however, if farmers could be recognised for non-ETS-eligible woody vegetation elements on their farms, there would be added impetus for exploring and implementing native revegetation that would have multiple ecosystem benefits. The recent 2019 Primary Sector Climate Change Commitment (He Waka Eke Noa) proposal provides an excellent partnership approach for mooting and pursuing such solutions.

Our analysis of the overall net carbon position of sheep and beef farmland provides evidence for both considered reflection and cautious optimism. Results suggest that, under a scenario where lower end published values for sequestration rates for the different vegetation types are used, sheep and beef farmland as a whole is a net source of greenhouse gases at the rate of +6,143 kt CO2e annually. Conversely, if higher end published values are used to provide the basis for calculating annual sequestration quantities, sheep and beef farmland emerges as a net GHG emission sink, at an annual rate of -3,128 kt CO2e. Thus, it is likely that the true annual sequestration rate is somewhere within these bounds. From a sequestration perspective, if we apply the mid-point value between our lower end and higher end annual sequestration scenarios, results indicate that sheep and beef farmland is potentially sequestering more than 50% of New Zealand's estimated total 2017 sequestered carbon, as reported in the GHG Inventory report (-23,958.4 kt CO2e). Indeed, over recent decades there have been significant eco-efficiency gains made across sheep and beef farm operations (Mackay et al. 2019), largely due to considerable reductions in both beef (-15%) and sheep (-54%) livestock numbers and a 35% reduction in sheep and beef pastoral land use (*pers. comm.*, Beef + Lamb New Zealand Economic Service & Insights). While some of this land area was converted to intensive dairy farming, a large proportion involved conversions to exotic forestry and new conservation areas, and reversions of marginal lands to scrub and other woody vegetation types. Thus, while the estimates presented here contain some uncertainty, the relatively high sequestration potential of sheep and beef farmland is conceivable given the relatively high density of woody vegetation on sheep and beef farmland (5-28% of farm property areas; mean of 15%), much of which is relatively high-sequestering early successional vegetation. This result suggests that the sector is contributing positively to national GHG goals.

Considering New Zealand's methane emissions from livestock alone, previous modelling has shown that by maintaining livestock numbers at 2016 levels into the future, a further 10-20% additional equivalent warming from the sector could be expected above 2016 levels by 2050 (Reisinger, 2018). To ensure no additional future warming due to methane by 2050, livestock methane emissions would have to be further reduced by 10-22% of 2016 levels. Such reductions would have to involve a combination of decreases in livestock numbers, improvements in productivity per animal, changes in stock and pasture management, potential advancements in methane inhibiting technologies, and increased sequestration in new biomass (Biological Emissions Reference Group, 2018). However, recent research suggests that the impact of methane emissions on potential warming is being overestimated in such traditional CO_2 equivalent 100-year Global Warming Potential (GWP100) calculations because methane is a relatively short-lived greenhouse gas (Allen et al., 2018; Cain et al., 2019). Consequently, it may be likely that any mitigation-based reductions in methane emission rates that can be achieved across the sector would ultimately result in better equivalent outcomes for New Zealand greenhouse gas budgets if calculations were based on current science (Allen et al. unpublished); this will have policy implications regarding whether, and when, agricultural emissions should be included in the Emissions Trading Scheme.

It is clear from our analysis is that published sequestration rate values for each vegetation type are wide-ranging and are specific to the context within which each study was undertaken. The MPI-ETS look up table figures for Indigenous Forest are currently widely used by government and industry for quantifying sequestration potential and carbon stocks for land and forest owners. However, it is important to note that the scientific basis for these values are unclear. The MPI look up table guide states that values for 'Indigenous Forest' are based on data from regenerating indigenous shrublands, predominantly mānuka and kānuka (Ministry for Primary Industries, 2017), rather than mature forest. The tables were primarily developed for the ETS and are applicable for post-1990 regenerating indigenous woody vegetation only. If a look up table derived sequestration rate (e.g., 6.5 kt CO2e/ha at 50 years of age) was applied to all indigenous vegetation characterised within this study, the result would be a significant overestimation of total sequestered carbon as it would assume that all indigenous woody vegetation was in an early regenerating rather than mature state. Therefore, sequestration rate information for this report was selected based on the latest scientific evidence available, matching the most appropriate rates to each vegetation type and stage of maturity. Future work is needed to help assess and refine the ages, regenerative states, and sequestration rates of all indigenous forest areas across sheep and beef farms.

The fine-scale vegetation mapping exercise for the Kaipara case study landscape highlights the thematic and spatial resolution limitations of existing national datasets for quantifying variability in woody vegetation composition and distribution. Our more detailed spatial mapping was able to account for smaller vegetation components, as well as provide greater detail regarding the composition and structural characteristics of vegetation typically occurring on farms. Reliable, high-resolution vegetation data underpins accurate GHG accounting exercises and there is certainly a need for this to be further investigated as farmers, and the farm sector in general, aim to meet reporting requirements into the future. While there is currently considerable interest on the part of farmers and the farming sector for computing greenhouse gas budgets for farms or farm sectors, much of this work remains in its infancy. Recent reports have been commissioned to assess potential approaches to emission reduction (e.g., Kerr, 2016; Biological Emissions Reference Group, 2018) and increased sequestration (Burrows et al. 2018) within the farming sector. Agricultural marketing companies such as Silver Fern Farms (M. Harcombe, pers. comm.) are recognizing the importance of carbon as part of formulating a marketing strategy associated with sustainably grown food and are starting to assemble their own GHG accounting data. As a result, it is likely that the need for detailed vegetation data (including sequestration rates) will be increasingly acknowledged in the next few years.

Uncertainties, limitations and caveats

There are a number of key sources of uncertainty that need to be considered when interpreting the results presented in this report. First, there are many uncertainties inherent to the spatial datasets used to map vegetation types and their areas across sheep and beef farmland. While, for example, there are relatively reasonable uncertainties associated with datasets such as LCDB (see Dymond et. al., 2016), the LCDB v. 4.1 dataset was produced in 2012/2013 and it is unknown the extent to which these landcover types have changed during the intervening seven years. Further, the more detailed vegetation typing of LCDB indigenous forest polygons, based on regional TEC data, has inherent uncertainty since it is based on potential types derived from literature, reflecting mature natural forest states, as compared to commonly found modified seral states. Nonetheless, the TEC remains one of a only a few national, spatial vegetation dataset that can be applied to this research question.

Second, uncertainties in both above and below ground carbon stock densities used in this work are equally hard to quantify. For instance, our method of spatially overlaying LUCAS plot data with TEC-based indigenous vegetation type polygons to quantify carbon densities for these types assumed that the vegetation typing for each polygon was relatively accurate, and that the LUCAS plot data provided a reasonable estimate of those types. The LUCAS plot network is biased towards natural and plantation forests, and so for sheep and beef farm vegetation polygons, there were few or no plots available and we had to use more generalised estimates. Carbon densities for the other LCDB vegetation types (i.e., not Indigenous Forest) were drawn from available published estimates which include estimates of expected precision; nonetheless, many of these studies were localized to a particular region of New Zealand or environmental context and so there is little known about the spatial uncertainties expected when applying these estimates to calculate carbon stocks across New Zealand. Nonetheless, while our calculated absolute carbon quantities may require further verification, we suggest that the relative patterns are reasonable and within the range of published carbon stock values.

Third, and even more pressing, is the need to quantify uncertainties associated with GHG emission and sequestration rates specifically associated with sheep and beef farmland; there is a paucity of information for both components. We relied on estimates sourced from the NZ GHG Inventory report and the few other published sources that have reported on sequestration rates for vegetation components relevant to sheep and beef farmland. We chose to deal with possible uncertainties in sequestration potential by providing both lower and higher end sequestration scenarios, assuming that the true value would likely fall within this range. Further field data collection is required to understand the variation in both the nature of vegetation across farmland and the rate at which these vegetation elements vary in their carbon sequestration rate depending on vegetation age, type, condition, and environmental context. Similarly, ongoing research in soil carbon sequestration is also needed to understand how environmental conditions and management actions lead to gains or losses in soil carbon through time. Additional sector emissions associated with other non-livestock components such as transport, machinery use, and losses of soil carbon after tilling and forest harvesting were not included in this study due to the difficulty in obtaining sector-related estimates; the refining of future accounting efforts would benefit from their inclusion. Recent atmospheric modelling approaches (e.g., Steinkamp et al. 2017) may provide new insights into the spatial distribution of CO_2 fluxes across New Zealand's land mass, enabling a possible comparison to the current plot-based methodology.

Clearly, ongoing research will be key to obtaining a comprehensive and more refined picture of GHG sources and sinks into the future.

Ultimately, error propagation methods, such as those presented by Holdaway and colleagues (2014), could be usefully applied to assess possible combined sources of error, including those associated with spatial data uncertainties. Such a complex undertaking was beyond the scope of this report and would require reliable, national-scale vegetation type and carbon sequestration rate datasets for sheep and beef farms.

RECOMMENDATIONS

1. Prioritise the development of a data collection protocol for sheep and beef farmland that would enable an accurate, sector-specific dataset to be compiled on vegetation components, their key attributes (species composition, age, condition, etc.), their carbon stocks (above and below ground), and their relative sequestration rates. The latter could be potentially achieved via the collection of tree cores, which could be assessed for tree ring growth rates for different species of varying ages, from a range of locations. Alternatively, and similar to the LUCAS plot network, a series of permanent sample plots would need to be established within which tree growth (and other attributes) could be tracked through time. Ideally, a combination of these two approaches would be appropriate.

2. Prioritise a spatial vegetation mapping programme for sheep and beef farmland. With adequate ground-truth data regarding existing vegetation types across different regions, aerial and/or satellite imagery can be trained to enable a classification of sheep and beef farm vegetation over large spatial extents. Such data would form the basis for future GHG budget calculations, for assessing the quantification of carbon sequestration potential for non-ETS eligible vegetation components, and for targeting revegetation interventions at a farm or landscape level in support of net GHG emission reduction.

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SUPPLEMENTARY TABLES AND FIGURES

Table A1. Relative areas and carbon density (tC ha^{-1}) estimates (±SD) for mapped indigenous (in grey) and exotic vegetation types on sheep and beef farmland. Where LUCAS plots spatially-coincided with an indigenous vegetation type, a mean above ground live biomass value was computed for that type from plot data; where there were no plots associated with a vegetation type, a mean carbon density value (±SD) was computed using data for the broader ecosystem type (e.g., CDF) and applied to that type. For LCDB-derived vegetation types (except for subalpine shrubland), carbon stock density values were taken from the published literature.

Vegetation type	Sheep and beef area (ha)	Mean C density (t ha-1)	SD C density (t ha-1)	No. LUCAS plots
MF7, Tawa, kamahi, podocarp forest	158,918	117.2	99.9	89
WF13, Tawa, kohekohe, rewarewa, hinau, podocarp forest	80,368	93.2	59.5	34
CDF3, Mountain beech forest	72,212	92.4	49.4	17
WF11, Kauri, podocarp, broadleaved forest	69,118	66.8	76.3	34
LCDB Sub Alpine Shrubland	60,684	48.6	61.1	30
MF21, Tawa, kamahi, rimu, northern rata, black beech forest	51,135	108.2	64.2	9
CLF10, Red beech, silver beech forest	39,072	228.2	129.9	101
CLF9, Red beech, podocarp forest	37,623	194.8	166.5	47
MF8, Kamahi, broadleaved, podocarp forest	28,990	205.5	207.5	26
WF3, Tawa, titoki, podocarp forest	25,088	150.3	63.4	0
WF14, Kamahi, tawa, podocarp, hard beech forest	23,468	119.0	90.2	9
MF22, Tawa, rimu, northern rata, beech forest	22,254	152.4	80.8	12
CLF3, Podocarp, ribbonwood, kowhai forest	20,793	157.1	72.1	1
MF3, Matai, totara, kahikatea, broadleaved forest	18,640	20.7	24.6	1.5
CLF11, Silver beech forest	16,179	199.5	101.5	11
MF1, Totara, titoki forest	15,231	137.8	92.9	0
MF2, Rimu, matai, hinau forest	15,187	79.8	137.2	6
WF9, Taraire, tawa, podocarp forest	14,350	45.2	25.7	5
MF5, Black beech forest	13,796	27.9	92.9	1
MF16, Rimu forest	13,491	224.9	108.4	2
TI2, Kanuka, Olearia scrub/treeland	10,969	124.0	124.1	0
WF12, Kauri, podocarp, broadleaved beech forest	8,270	36.5	40.2	2
MF20, Hard beech forest	7,837	178.9	144.4	22
CDF7, Mountain beech, silver beech, montane podocarp forest	6,776	109.0	74.3	4
MF17, Rimu, kamahi, tawheowheo forest	6,493	150.5	118.0	3
MF11, Rimu forest	5,795	163.9	51.4	3
CLF12, Silver beech, mountain beech forest	4,871	180.1	54.0	10
VS6, Matagouri, Coprosma propinqua, kōwhai scrub [Grey scrub]	4,734	94.9	0.8	0
VS3, Manuka, kanuka scrub	4,571	95.7	0.8	0
WF4, Pohutukawa, puriri, broadleaved forest [Coastal broadleaved forest]	4,171	4.2	5.9	2
WF7, Puriri forest	4,155	88.7	14.1	0
CDF4, Hall’s totara, pahautea,kamahi forest	3,632	110.8	71.4	17
MF12, Rata, hard beech, kamahi forest	3,609	52.1	32.2	3
WF8, Kahikatea, pukatea forest	2,968	88.7	14.1	0

MF10, Totara, matai, kahikatea forest	2,772	391.3	92.9	3
WF2, Totara, matai, ribbonwood forest	2,280	88.7	63.4	0
CLF7, Rimu, kamahi, beech forest	2,039	176.7	124.1	0
TI4, Coprosma, Olearia scrub [Grey scrub]	1,985	124.0	124.1	0
CDF2, Dracophyllum, mountain celery pine, Olearia, Hebe scrub [Subalpine scrub]	1,963	88.2	84.8	0
CDF6, Olearia, Pseudopanax, Dracophyllum scrub [Subalpine scrub]	1,304	40.8	42.3	11
WF17, Northern rata, mahoe, nikau forest	1,274	88.7	63.4	0
VS2, Kanuka scrub/forest	1,211	94.9	0.8	0
MF6, Kohekohe, tawa forest	1,173	115.0	92.9	1
CLF1, Hall's totara, mountain celery pine, broadleaf forest	1,172	176.7	124.1	0
WF1, Titoki, ngaio forest	1,099	88.7	90.3	0
MF13, Kahikatea, northern rata, kamahi forest	1,015	137.8	92.9	0
CLF5, Matai, Hall’s totara, kamahi forest	981	17.4	124.1	1
MF24, Rimu, towai forest	771	79.3	51.0	2
TI1, Bog pine, mountain celery pine scrub/forest	767	124.0	124.1	0
CLF4, Kahikatea, totara, matai forest	683	176.7	124.1	1
CL3, Coprosma, Muehlenbeckia shrubland/herbfield/rockland	602	124.0	124.1	0
MF4, Kahikatea forest	569	137.8	92.9	0
CDF1, Pahautea, Hall’s totara, mountain celery pine, broadleaf forest	440	88.2	84.8	0
MF14, Kahikatea, silver pine, kamahi forest	358	137.8	92.9	0
WF5, Totara, kanuka, broadleaved forest [Dune forest]	343	88.7	63.4	0
CL1, Pohutukawa treeland/flaxland/rockland	260	124.0	124.1	0
WF15, Matai, totara, northern rata, titoki forest	130	88.7	63.4	0
MF25, Kauri, towai, rata, montane podocarp forest	102	137.8	110.4	0
CLF8, Silver beech, kamahi, southern rata forest	69	259.6	124.1	1
WF10, Kauri forest	69	194.4	63.4	2
CL2, Ngaio,taupata treeland/herbfield/rockland	56	124.0	124.1	0
WF16, Matai, northern rata, broadleaved forest	55	88.7	63.4	0
WF6, Totara, matai, broadleaved forest [Dune Forest]	50	88.7	81.2	0
VS5, Broadleaved species scrub/forest	15	94.1	0.8	0
TI3, Monoao scrub/lichenfield	12	124.0	124.1	0
TI5, Bog pine, mountain celery pine, silver pine scrub/forest	12	124.0	124.1	0
MF18-2, Silver pine, mountain beech, pink pine low forest	4	137.8	92.9	0
UM2, Conifer, beech, manuka forest/scrub, rockland	0	223.3	5.1	2
LCDB - Manuka and/or Kanuka	556,530	69.0	32.7	
LCDB - Exotic Forest	310,088	98.1	47.1	
LCDB - Gorse and/or Broom	103,994	14.9	3.3	
LCDB - Matagouri or Grey Scrub	86,992	13.0	0.7	
LCDB Sub Alpine Shrubland	60,684	61.1	48.6	30
LCDB - Mixed Exotic Shrubland	34,980		19.1	
LCDB - Deciduous Hardwoods	34,679	160.0	19.4	
Overall mean/total area (ha)	2,089,030	120.6		

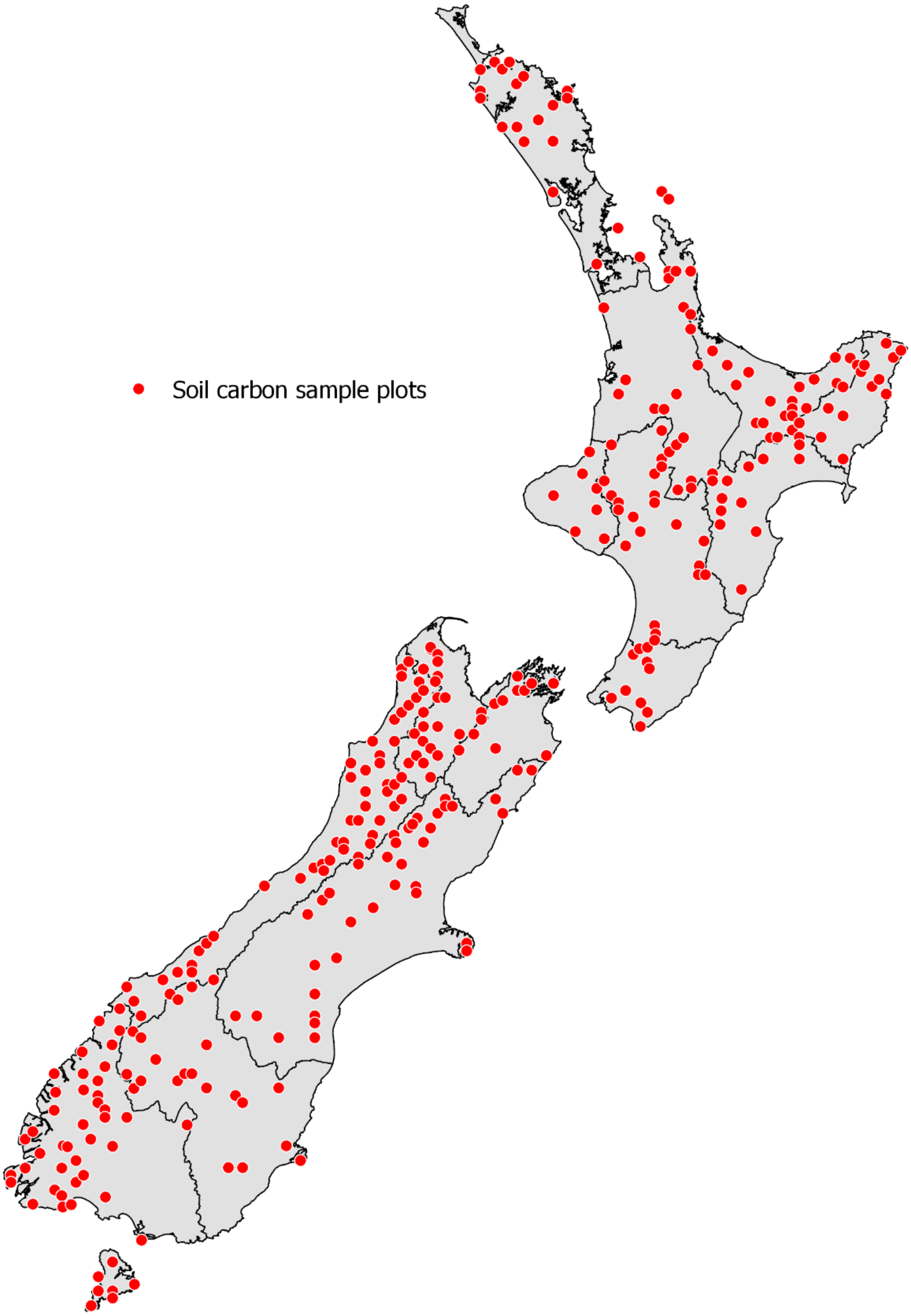

Figure A1. Soil carbon plot data used for soil carbon stock quantification in this study.