



# Maximising Forest Carbon: Carbon stocks of New Zealand's forests

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Yvette Dickinson, David Pont and Steve J. Wakelin



## Report information sheet

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# Executive summary

New Zealand needs to measure and report on carbon stocks, to meet our commitments to the United Nations Framework Convention on Climate Change (UNFCCC) and Paris Agreement, as well as underpin our Emission Trading Scheme. Forests form an important part of our carbon management strategies. This review was intended to summarise the current state of knowledge of our forest carbon stocks and stock changes, including in live and dead vegetation above- and below-ground, dead wood, forest litter and soils. However, in the course of the work we discovered that it is not possible to synthesise carbon stock estimates, due to numerous challenges in data availability and reconciliation. Therefore, this report covers the existence of underpinning data from which forest carbon stocks and changes can be assessed. Note, the methods by which data is acquired, and also translated into carbon estimates, is covered in the associated report to MPI titled “Maximising Forest Carbon: Review of methods for measuring forest carbon for national- and property-scale reporting”.

We reviewed relevant peer-reviewed literature (497 articles) and other scientific reports (72) recommended by carbon forestry experts in Scion, 33 experts and stakeholders from outside Scion and a search of Elsevier’s Scopus database.

Important considerations regarding data validity are:

- Multiple forest names and classification systems makes comparisons between forests challenging as it is not clear which forests are similar or dissimilar. Forest types have no uniform naming system (there is a standard and published system for indigenous forests but none for mixed or exotic forests) and natural vs anthropogenic regeneration is not clarified. Forest type is important to current calculations and regeneration type to forward projections of carbon stocks.
- The variety of approaches for quantifying forest carbon makes comparisons challenging, particularly for the numerous smaller studies that are available – there is a need for increased consistency. The Land Use and Carbon Analysis System and Emission Trading Scheme’s Field Measurement Approach are two different standardised systems which are not consistently used outside these programmes. Different studies/data sets take different approaches to delineating the breakdown of forest carbon stocks. In general, the majority of information is on stem biomass, and on above-ground biomass in general than below-ground, because these are the easiest carbon pools to measure.

There are five key datasets relevant to determining forest carbon stocks and stock changes of specific forest types in New Zealand:

- *Land Use and Carbon Analysis System (LUCAS)* managed by MfE, data since 1990, which includes plots repeatedly measurement since 2002. It is the most robust dataset with statistically rigorous sampling for measurement of forest carbon stock but is designed only to provide information at national scale c.f. forest types or property scale. It is also relatively recent, limiting consideration of carbon stock changes over time. It is consistent in its classification but its system is not used by others.
- *Emission Trading Scheme - Field Measurement Approach (FMA)* – MPI’s record of information submitted by forest owners to the Emission Trading Scheme for plots >100 hectares using standard protocols.
- *Permanent Sample Plot (PSP) database* – a forest inventory database held by Scion holding foundational data regarding >30,000 forest plots with standard data collection methods.
- *National Vegetation Survey Databank (NVS)* held by Manaaki Whenua Landcare Research, covering 120,000 vegetation survey plots over 50 years but with different data collection.
- *Tane’s Tree Trust’s Indigenous Plantation Database* – forest inventory information from indigenous tree species from >120 stands.

Other than LUCAS, the datasets are not intended to be nationally representative or represent every forest type.

In general, there is adequate information available to understand forest carbon stock and stock changes of the dominant exotic plantation forest types (radiata pine (*Pinus radiata*), Mexican white cedar (*Cupressus lusitanica*), Monterey cypress (*Cupressus macrocarpa*), brown barrel eucalypt (*Eucalyptus*

*fastigata*), shining gum (*Eucalyptus nitens*), Douglas-fir (*Pseudotsuga menziesii*), coastal redwood (*Sequoia sempervirens*)).

However, there is much less information available to ascertain carbon stocks and stock changes for less commonly planted exotic species, indigenous species and naturally regenerated/regenerating forests, e.g. a lack of field data for many species. Quantification of carbon stocks of naturally regenerated forest types is also challenging due to the great variation in forest composition and structure. Further, there is a lack of information regarding how forest management activities affect carbon stocks and stock changes, including silviculture and pest management. There is a lack of information as to how soil carbon changes when land use changes e.g. from pasture to forest. Process-based modelling – simulating underlying physiological mechanisms of carbon storage by plants based on existing data – may provide a way forward where data is sparse for a particular species or forest type.

# Maximising Forest Carbon: Current knowledge of carbon sequestration in New Zealand's forests

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# Introduction

New Zealand is a party to the United Nations Framework Convention on Climate Change (UNFCCC) and has ratified the Paris Agreement which took effect in 2020. As part of these international commitments, New Zealand must measure and report carbon sequestration and emissions across a wide range of sectors, including Land Use, Land Use Change and Forestry (LULUCF). Furthermore, the New Zealand government has set a national target of net zero greenhouse gas emissions by 2050 (excepting biogenic methane) to fulfill its international obligations. A range of national plans and programmes are being implemented to reach this target, including the Emission Trading Scheme (ETS). For both New Zealand's international commitments and our national programmes, there is a need to quantify the amount of carbon sequestration in New Zealand's forests at the national- and property- scales, respectively.

Over the last several decades there has been much research to support the quantification of carbon sequestered and stored in New Zealand's forest ecosystems. The objective of this review is to provide an overview of the existing information regarding how much carbon is sequestered in New Zealand's forests, including identifying:

- the species and forest types studied, including geographical extent;
- the management regimes or interventions investigated;
- the methodologies used to measure forest carbon stocks;
- the reported carbon stocks and changes over time, how this is presented and uncertainties; and,
- where multiple information sources have quantified carbon stocks and changes of the same forest type, indicate the range and variation of reported values.

For this review, forests were defined as an area of at least 1 hectare and 30 metres in width that is expected to have at least 30 per cent canopy cover and the potential to exceed 5 metres in height, consistent with the current definitions used in New Zealand's international reporting and the Emission Trading Scheme.

This review focuses on those studies which report forest carbon stocks or stock changes of the major carbon pools (e.g. above and below ground live biomass, coarse wood, forest litter, and soil) for New Zealand's forests. The forest sector has extensive research and information quantifying the above-ground volume and biomass within New Zealand's exotic plantation forests, with a focus on wood production and utilisation. While quantifying forest volume and biomass is a required precursor to calculating carbon stocks (see further discussion Fundamentals of measuring forest carbon sequestration and stocks), reviewing the large body of published forest productivity research was out of scope. Likewise, allometric relationships between forest volume and biomass, wood and carbon density measurements are critical to the calculation of forest carbon stocks, but directly reviewing the available information was out of scope for this review.

Due to logistical resource and time constraints, this review prioritises summarising information from systematic studies which attempt to quantify forest carbon sequestration across a representative geographic range. We have not attempted to include all small studies that quantify carbon in just a couple of pools and/or across a few sites. This review provides a New Zealand overview rather than a comprehensive, detailed catalogue of all forest carbon stock and stock change studies in New Zealand.

## Fundamentals of measuring forest carbon sequestration and stocks

Carbon is sequestered in all components of forest ecosystems ("carbon pools"), including in the live and dead vegetation above- and below-ground, dead wood, forest litter and soils. Furthermore, forest composition, structure and process vary greatly across the nation, depending on soil and climate conditions, and management. Forests range from relatively simple and homogeneous to

highly heterogeneous and complex. The ease of measuring carbon sequestration, and the amount of information already known varies greatly by both carbon pool and forest type.

Carbon contained in the forest is not measured directly – this would require detailed measurements of all branches, leaves, roots, dead wood and forest litter, as well as destructive sampling for wood density and carbon fraction of the components. This type of full inventory is not technically, logistically or economically feasible; instead, a sampling approach is used which gives an acceptable level of accuracy and precision at a much lower cost. These sampling approaches may use either conventional field measured data, remote sensing data, or a combination of both.

Typically, a model-assisted design-based approach (Stahl, 2021) is taken for quantifying the carbon stocks within vegetation (live and dead, above- and below-ground). Generally, we measure the dimensions of the vegetation above-ground and calculate the volume of the vegetation (typically just stem dimensions and volume of trees). For field methods, these dimensions are collected in sample plots that are stratified by forest type. Alternatively, forest dimensions may be collected using remote sensing tools. Irrespective of how the forest dimensions data are collected, this above-ground volume is then converted to above-, below-ground or total biomass using allometric relationships. The allometric relationships are developed by undertaking intensive (often destructive) measurements from a small sample of trees, and statistically relating these to more easily measured variables such as diameter at breast height and/or tree height (e.g. Beets, et al., 2012). Next, the carbon stock is estimated using known wood density and carbon fraction (again, typically measured on a small sub-sample of trees). Similarly, litter and dead wood can be measured using field sampling techniques, and the calculated biomass used to estimate carbon stocks based on the density and carbon fraction derived from a subsample. The mean measured carbon stock of the sampled plots, and associated statistical uncertainty, can then be statistically expanded to the total area of the stratified forest types. The algorithms that associate carbon stock to vegetation volume are assumed to remain unchanged as long as climate has remained relatively steady and no ecological disturbances have occurred (i.e., wildfire, slip, disease etc.).

Carbon is also sequestered in soils, and this carbon pool may be measured using soil sampling approaches. Samples are taken down to a depth of 30cm depth and carbon content measured in the laboratory. Due to the complexity of quantifying soil carbon under forests, New Zealand doesn't currently directly measure this carbon pool to fulfill international reporting obligations, rather it is modelled. Furthermore, carbon sequestered in soils is not currently included in the Emission Trading Scheme.

Irrespective of the methods used, there are five principles that should be followed to ensure that the carbon inventory framework is robust and representative (Paul, Wakelin, et al., 2021). These principles apply at both the development of allometry and inventory phases:

- Accurate area estimation of the land on which woody carbon stocks are found and stock change occurs is required.
- Carbon stocks and stock change needs to be based on unbiased and representative sampling of the land area.
- Repeatable methods that provide precise and accurate estimates of carbon stocks and stock change are required.
- Models developed and applied need to be based on sufficient and representative data, and rely on the quality of input data.
- The costs of carbon stock and stock change estimation should not exceed the expected benefits.

## Review methods

To achieve our objective to provide an overview of the existing information regarding how much carbon is sequestered in New Zealand's forests we undertook several approaches to gather relevant information. Initially, the authors and colleagues within Scion who are carbon forestry experts recommended relevant publications for inclusion in this review (both peer-reviewed and other reports).

Further, a systematic search scientific literature using the Elsevier's Scopus database was undertaken to find relevant published literature, particularly literature which has been formally peer-reviewed. The search looked for the terms "New Zealand", "forest" and "carbon" in the title, abstract and keywords. A similar search was undertaken using Scion's internal literature database, to ensure previous work undertaken by Scion was included in the search.

In addition, we contacted 33 key experts and stakeholders outside of Scion who have undertaken relevant work, to request their assistance in locating relevant datasets and publications (Table 1 of Appendix A). These key experts included researchers employed by non-profit non-government organisations, carbon forestry industry, and scientists employed by universities and other Crown Research Institutes, including Manaaki Whenua Landcare Research, NIWA, Plant and Food. Studies recommended by these key experts and stakeholders were reviewed and included where relevant.

After initially assessing their relevance, we summarized the following information from each study, as applicable:

- A description of the forest type, and ECS used (if applicable).
- Whether the forest area would qualify as pre-1990, or post-1989 forest.
- Whether the forest was the forest planted, naturally-regenerated second-growth, or late-successional forest.
- The silvicultural system used to manage the forest. Specifically, whether the forest area is managed using an even-aged clear-cut system, a multi-aged continuous cover forestry system, managed as a forest reserve not intended to be harvested, or another system.
- The prevalence of the forest type across New Zealand, specifically the area covered by forest type if known and source of this information.
- Whether the data gathered was a representative sample of the forest type across its distribution in New Zealand.
- A description of the geographic coverage of the sample measured.
- The number of plots in sample (if applicable).
- The range of stand ages represented in the measured sample.
- A description of any specific silvicultural (forest management) techniques applied to the forest area, for example: site preparation, control of invasive mammals, control of competing vegetation, control of other invasive species, fencing and/or stock exclusion, thinning, or fertilisation.
- The field and analytical methods used to quantify the carbon stock or stock change.
- The specific carbon pools included in the measurement, which may include aboveground live (canopy and/or understory layers), belowground live, dead wood, forest litter, and soil.
- The forest carbon stock and/or stock change reported, including the units and measures of uncertainty.
- Whether the study was published in a peer-reviewed journal.
- Other pertinent information about the study that is relevant to this review.

General conclusions and apparent knowledge gaps were then identified from the summarized information.

There are several Ecological (or Ecosystem) Site Classifications (ECS) used in New Zealand, and numerous other *ad hoc* names used to describe the species composition of forests. The inconsistent use of forest type names creates challenges when trying to aggregate forest information from a variety of sources as we are unable to make comparisons of disparate forest types. For planted forests we used the dominant species planted to define the forest type. For native forests we used the classification system developed by Wisser, et al. (2011) and, Wisser and De Cáceres (2013) where possible; however, many information sources used a variety of other forest type naming conventions which did not correspond with this classification system. In these cases, we recorded the forest type as reported by the information source. **Caution should be taken when comparing studies to ensure that the forest types are compatible.** Furthermore, where disparate forest type naming conventions were used it may not be clear what the geographic coverage of each forest type is across the country, or the prevalence of that specific forest type.

We also defined naturally-regenerated forests are those that have become established without anthropogenic actions to plant seeds or seedlings, and could include, for example, forestlands with mānuka, kānuka, mixed-hardwoods, or totara (*Podocarpus totara*) (or other species) growing on previously cleared agricultural lands. Alternatively, late-successional forests are those which may

have been historically disturbed but were not cleared of forest. These forests have a canopy composed of mature, tall trees. There is a variety of similar concepts discussed in the published scientific literature, including “tall forest” and “old-growth” (Wirth, et al., 2009).

While the national Land Use and Carbon Analysis System (LUCAS) and the Emissions Trading Scheme’s Field Measurement Approach (FMA) have developed standard methods for quantifying forest carbon within New Zealand, outside of these two programmes there is a great variation in the methods used, including variation in the carbon pools quantified, specific sampling and measurement techniques, and choice of allometric relationships, wood densities, and carbon fractions. For this reason, **caution is needed when directly contrasting estimates amongst studies to ensure that they are compatible, and any comparisons are on an even-basis**. Due to the logistical constraints of this review, we simply present the values as published by the studies, with accompanying information about the methods used.

As discussed earlier, we focused on information sources that report carbon stock or stock change information. Studies reporting only forest growth or productivity of biomass or wood volumes were considered out of scope. Further, we did not focus on studies which developed or reported allometric equations, determined wood density or carbon fractions. While these are all critical steps to the estimation of carbon stock or stock change, they were out of scope for this review.

## Results and discussion

Our search of the published literature search in Scopus and Scion’s internal publication database identified numerous published studies that provided information quantifying forest carbon stocks or stock changes within New Zealand.

The search terms “New Zealand”, “Forest” and “Carbon” identified 569 publications since 1962 in Scopus (Figure 1). Of those 497 were peer-reviewed research articles, and a further 25 were published reviews of the literature. The number of publications grew from the 1960s to a peak of 35 publications per year at the end of the first commitment period of the Kyoto Protocol in 2012. Between 2005 when the Kyoto protocol was ratified, and 2012 there was an emphasis on fulfilling New Zealand’s international reporting obligations, with much research focused on quantifying carbon stocks and stock changes in vegetation at a national scale. Following this peak, the number of publications per year has generally declined, with fewer studies focused on quantifying forest carbon stocks in New Zealand being published. The cause of this decline is unclear but may be due to changes in the availability of research funding to support this area or, alternatively, reductions in science capacity in relevant areas.



**Figure 1.** Number of publications using the terms “New Zealand”, “Forest” and “Carbon” identified by Scopus by their publication date.

In addition to the publications identified by our literature search, we received 20 responses from the 33 key experts and stakeholders whom we contacted for recommendations. While many did not have relevant information to share or were unable to share their data, many responses highlighted relevant published literature; provided data from unpublished studies; or were able to advise us on studies that were currently underway. Further, a number of these key experts and stakeholders shared our request for assistance with their colleagues, or recommended others who we should contact. We followed up on these recommendations wherever possible. We are grateful for the rapid and generous responses of these key experts and stakeholders.

A summary of the studies we identified that quantify forest carbon stocks or carbon stock changes of forests within New Zealand is presented in Table 1 of Appendix B. The intention of this summary table is to present the information gathered within the logistical constraints of this review. ***While all efforts have been made to ensure that this summary is as comprehensive as possible, including all major information sources, it is not intended to be a definitive summary of all studies in New Zealand.*** It is likely that there are additional studies which have not been identified by the authors or through the survey of experts.

Below we summarise the key outcomes the studies identified in terms of the distribution of studies across forest types, stand ages, geography, forest management, and the carbon pools quantified. Further, we highlight four key comprehensive datasets which are particularly notable. These comprehensive datasets of carbon stocks and stock changes across a wide variety of forests in New Zealand use consistent methods, and therefore provide a rare opportunity to make comparisons and draw general conclusions.

## **Forest Type, Stand Age and Geographic Representation**

### ***The importance of Ecological Classification Systems***

Across the studies reviewed that summarize carbon stock or carbon stock changes in New Zealand forests there was considerable inconsistencies in the use of forest type terminology. These inconsistencies limit our ability to make comparisons and draw general conclusions regarding the amount of carbon sequestration measured across the disparate studies. Forest Types are defined by ECS.

Forests vary greatly in terms of their structure, composition and ecological processes. This variation tends to occur across gradients with poorly defined limits. Rather than forming discrete units with clearly defined forest type boundaries, forests variation tends to consist of gradual transitions. This variation is driven by underlying variation in the environment, and tends to follow variation in topography, soils, rainfall, temperature, and other environmental factors (Oliver & Larson, 1996). Native forests are particularly complex and heterogenous, ranging from relatively simple even-aged monocultures to highly-diverse forest stands with dense, multi-layered canopies. Both planted and native forests vary greatly across New Zealand. Ecologists and land managers have constructed ECS that “cut” these gradients of forest variation into discrete, management units. These ECS are human constructs designed to simplify the complexity of forest variation for forest management. There are a number of alternative ECS that have been developed over time, each designed to fulfil a specific purpose with varying advantages and limitations.

The way that the ECS divides the complex heterogeneity of forests into types may strongly influence the carbon stocks and stock changes measured. The choice of ECS influences the outcomes of forest studies, and careful consideration is needed to ensure that the ECS selected is fit for purpose. Generally, the intent of an ECS is to provide a description of a typical or average forest stand of that type; however, there is variation amongst stands that are grouped together under one forest type. For example, a “Broadleaved-Podocarp Forest (including kauri)” forest is not the same as a “Kāmahī-podocarp forest”. Likewise, a “Kāmahī-podocarp forest”, “Kāmahī-silver fern forest” and “Hard beech-kāmahī forest” are all different. While they may share some commonalities, there are important differences in terms of the environment, composition and structure of these forest types, and as a result the carbon stocks and stock changes are different.

When undertaking any forest inventory, whether for carbon stock or any other metric, the derived mean is only relevant for the statistical population that was sampled. Any estimates of uncertainty

indicate the distribution of the statistical population around the mean; however, specific stands of that forest type may still have values outside those bounds. However, mean value derived for a specific forest type is not relevant to any other forest types (even if their definitions may have shared species). Therefore, when attempting to compare or aggregate the carbon stocks and stock changes from different studies, it is important to ensure that the defined forest types are compatible, and the comparison is appropriate.

The common grouping of manuka (*Leptospermum scoparium*) and kanuka (*Kunzea ericoides*) into one category in a number of studies (Ausseil, et al., 2013; Trotter, et al., 2005; Watt, et al., 2012) is another example of where the lack of a robust ECS limits the utility of the information provided by studies. While these species appear superficially similar, they are genetically and ecologically distinct and do not form a logically consistent forest type. While mānuka is a shrub up to 10m tall, kānuka can become a tree up to 30m tall. While they may be found growing together, they have different ecological niches and are also found growing in different habitats. For this reason, the robust ECS of New Zealand's native woody vegetation developed by (Wiser & De Cáceres, 2013; Wiser, et al., 2011) separates these species into separate forest types (i.e. Kānuka forest and tall shrubland, Mānuka shrubland, and Wheki-mānuka shrubland). Studies that combine these disparate species together are unlikely to provide robust, representative information regarding their forest carbon stock across geographic and age ranges (particularly at older stand ages).

Furthermore, there is variation amongst forests grouped together within a forest type. While a forest stand may be classified as a particular forest type, it is unlikely to have precisely the mean carbon stock for that type. For national reporting purposes, it is satisfactory to use an ECS with broad forest type categories to provide information about overall national forest carbon stocks, and general trends at a coarse scale. However, for the ETS and other regulatory schemes, landowners and managers who are aiming to characterise a single forest stand, or forests at a property-scale will likely require more precision. To satisfy this need using standardised values (e.g., look-up tables), a more complex fine-scale ECS with a greater number of more narrowly defined forest types would be required. However, a finer-scale ECS also requires denser sampling with more data collected to accurately characterise each of the forest types across the gradient of forest composition, structure, age, silviculture, and environments. The appropriate balance between simplicity and precision will vary depending on what the information is going to be used for.

While many of the studies reviewed clearly stated which specific ECS they used and which forest type within that ECS they aimed to characterise, there were numerous studies (particularly smaller studies) which described the forest types studied using poorly defined terminology without referring to an ECS. ***It is not possible to make comparisons among studies that do not have clearly defined forest types because it is unknown which forests they typify. Further, it is not possible to make comparisons of forest types across different ECS because the delineation of forest types is not compatible.*** Fortunately, systematically designed studies with the purpose of characterising carbon stocks and stock changes across larger geographic areas tended to use a clearly-defined standard classification system, allowing for comparisons and generalisations to be drawn. For example, the LUCAS analysis which previously followed the ECS developed by (Wiser, et al., 2011) and Wiser and De Cáceres (2013) for native forests, and now also uses the broader classifications from the Land Cover Database (LCDB v5).

Due to the challenges of comparing across ill-defined forest types, it is difficult to draw conclusions about the distribution of information across geographic ranges and stand ages. Large, systematic studies such as LUCAS are able to provide information across the nation at a coarse scale, and robust estimates of forest carbon stocks nationally. However, there are a number of individual forest types that have few plots within the LUCAS system because they are relatively uncommon and the plot network is laid out on a regular 8 x 8km grid. Generally, the fewer plots measured for each forest type, the poorer our understanding of the variability of forest carbon stocks across space and time. For this reason, the LUCAS system uses a 4 x 4km grid (i.e., 4 times as many plots per 100 hectares) for planted forests to ensure a greater diversity of planted forests which potentially sequester carbon rapidly are well-represented. There are many smaller independent studies (i.e., those that focus on carbon sequestration on few sites); however, these studies are *ad hoc* and their distribution is patchy with sampling biases towards common, scientifically interesting, or easily accessible sites. Furthermore, the ECS, measurement methods, and carbon pools measured across these studies are inconsistent, limiting our ability to make comparisons and draw conclusions. Strategically increasing the density of plots in large systematic studies with consistent methods, such as the LUCAS system, will likely improve the representation of poorly

characterized forest types or forest types of greatest interest, and provide more robust information about the carbon sequestration at the forest, or property scale.

### ***Planted versus naturally regenerated and mixed forests***

Similarly, there are challenges arising from the classification of vegetation into planted and naturally regenerating categories in current studies (e.g. LUCAS). These categories are used in New Zealand's international reporting to characterise forests at a national scale, but may not be meaningful for other purposes, such as quantifying forest carbon stocks at finer scales (e.g., for individual stands or properties). While the delineation of planted forest types by the dominant species planted may appear relatively straightforward, there is a great deal of variation in planted forests that is not well represented by this approach. In particular, forest stands with a mix of planted vegetation and natural regeneration may arise in a wide range of circumstances and may be relatively common across the landscape but are not well represented in this dichotomous categorisation (e.g. naturally regenerating wilding exotic conifers and willows, planted native tree plantations with naturally regenerating understorey, the use of planted nurse crops to encourage natural regeneration, underplanting within natural vegetation including shrublands, forests transitioning from exotics to native species, and failed plantation establishment with invading natural vegetation). ***The poorly defined terminology regarding stands of mixed planted and naturally regenerated stands is reflected in the relatively little carbon stock and stock change information found for these forests.***

Generally, natural regeneration of forest stands takes more time and is more variable than plantation forest establishment. Natural regeneration relies on ecological process for seed production and dispersal which are highly complex and variable (e.g., flowering, pollination, seed-set, and seed dispersal), with many opportunities for failure due to abiotic or biotic site conditions. Natural regeneration is also reliant on the seed successfully arriving at a suitable micro-site for germination, establishment and growth, which is strongly influenced by site conditions, competition from pre-existing vegetation, and weather conditions at critical times. Due to the complexity of these ecological processes, it is difficult to project growth of natural regeneration and develop models of their carbon sequestration. There is some existing information about key naturally regenerated vegetation types (e.g. mānuka/kānuka and shrublands discussed below), however, these studies often suffer difficulties with poorly defined ECS as discussed above.

Note: Burrows (2018) provides a relevant review of the carbon sequestration potential of a range of vegetation types on agricultural lands, including both planted and natural regenerated vegetation such as wetlands, riparian strips, pole plantings, shelterbelts, small woodlots, and retired lands not eligible for ETS. In many cases Burrows (2018) relies on surrogate information due to a lack of specific data for each type.

### ***Exotic plantations***

Generally, there is more information available and greater certainty regarding the volume and biomass of exotic plantations than for naturally regenerated and native forest types, due to the interest of the forest industry in these species over the last ~100 years. There is an extensive published literature focused on the influence of genetics, environment and silviculture on the growth and yield of New Zealand's exotic plantations, particularly focused on the commonly planted species including (but not limited to) radiata pine (*Pinus radiata*), Mexican white cedar (*Cupressus Lusitanica*), Monterey cypress (*Cupressus macrocarpa*), brown barrel eucalypt (*Eucalyptus fastigata*), shining gum (*Eucalyptus nitens*), Douglas-fir (*Pseudotsuga menziesii*), and coastal redwood (*Sequoia sempervirens*). Likewise, empirical (including machine learning) and process-based models of growth and yield are available for many of these species. A review of this information would require considerable resources and is out of scope of this review. Volume and biomass information is required by the industry for the sustainable management of forests for wood production. In addition, this data is also a critical first step required for the calculation of carbon stock information (along with allometry, wood density and carbon fraction information). Given the wealth of information regarding growth and yield for these species, it is not surprising that ***there is more information available regarding the forest carbon stocks and stock changes for common exotic plantation forests than for other forest types*** (see Appendix 1 Table 1).

Models that can predict carbon stock of forest stands on a range of sites have been developed for radiata pine, Douglas-fir, cypresses, and eucalyptus species, including the Forest Carbon Predictor model (Beets, et al., 2018; Beets, et al., 2011; Beets, et al., 1999) which incorporates the earlier C-Change model. This model was originally developed for radiata pine, and was later adapted for the other species. Additionally, commercially available forest growth and yield models such as Integral Forecaster have incorporated these models and are able to simulate and provide estimates of volume, biomass and carbon stock. Process-based models which are capable to providing carbon stock and stock change estimates have also been parameterised for a number of species, including: radiata pine, brown barrel eucalypt, white stringybark eucalypt (*Eucalyptus globoidea*), Douglas-fir, and coastal redwood (Meason, et al., 2011; Meason & Mason, 2014). National spatially-explicit models of forest carbon stocks by shining gum, Mexican white cedar and Monterey cypress, and coastal redwood were developed by (Lin, et al., 2020) and for coastal redwood and radiata pine by (Watt & Kimberley, 2022).

These models tend to be limited to providing projections of forest carbon stock over the first several decades. The forest industry tends to harvest trees when they reach economic maturity after which the growth of financial returns decline based on investment analyses. Because the industry tends to harvest before ecological maturity, there is a lack of robust information about growth and yield of old plantation forests. Furthermore, New Zealand plantation forestry is relatively young by global standards with the earliest plantations only established ~130 years ago. Therefore, there is relatively little information regarding the forest carbon stocks of exotic plantation stands beyond ~50 years old for species such as radiata pine, Douglas-fir, and the non-durable eucalyptus. For species that have only become of interest to the forestry industry recently, this may be as short as 25 years (e.g. the durable eucalypts). **Compared to the extended time scales of forests, we are only able to make forest carbon stock projections over a relatively short timeframe for exotic plantations.**

Summary information for a subset of exotic forest stocks has also been released by the Emission Trading Scheme (ETS) as part of a public consultation process (Ministry for Primary Industries, 2022). This information includes carbon stock information for post-1989 indigenous forests based on data in their Forest Measurement Approach (FMA) database collected from forests which are greater than 100 ha enrolled in the ETS. This summary information suggests that the measured area-weighted mean carbon stocks and stock changes of post-1989 radiata pine, Douglas-fir and other exotic hardwood species up to age 50 is much higher than that estimated by the current look-up tables used by owners with less than 100ha in the ETS. However, this information was not published in a peer-reviewed science journal, and the statistical methods used to derive this information are not reported. It is unclear if the information is more broadly representative of these forest types.

Previous reports review the available information for a range of species, and identify the specific information needs for developing better understanding of forest carbon stocks (Beets, Meason, et al., 2014; Hock, et al., 2017; Todoroki & Meason, 2012). While these reports don't specifically report carbon forest stock values, they provide a systematic analysis of the available supporting information which allow carbon stocks to be calculated, including information regarding forest productivity, allometry, wood density and carbon fractions.

### **Indigenous vegetation**

Indigenous vegetation may include late-successional forest that is relatively undisturbed (e.g., large tracts of the crown's conservation estate), restoration planting, indigenous plantations for timber harvest, or other indigenous trees in the landscape. Generally, there is less information available regarding the forest carbon stocks and rates of change for this indigenous vegetation relative to the exotic plantations discussed above. Furthermore, quantifying the forest carbon stock of indigenous forests is more challenging due to the great heterogeneity in forest structure and composition, and challenges with defining forest types (as discussed above).

The most robust information available for indigenous forest types is from LUCAS based on >1200 plots in New Zealand's native forests (Paul, Kimberley, et al., 2021). This forest inventory programme was specifically designed to provide accurate measurement of forest carbon stocks at a national-scale for international reporting, with data collected from plots on an 8 x 8km grid. While

it provides forest stock measurements at a national scale to the appropriate accuracy for international reporting, there are a number of forest types within LUCAS that have less than <10 plots nationally. With such low sample sizes, it is unlikely that LUCAS can provide representative measurements of the mean forest stock or fully reflect the full variation of these specific forest types (for example Matai forest, Towai-tawa forest, and Matagouri shrublands). Furthermore, LUCAS was established in 2002 and is unable to provide information regarding changes over longer time-scales (>20 years). Much of the reviewed carbon forest stock information for indigenous forests tends to be focused on pre-1990 late-successional stands. The prevalence of information from late-successional stands reflects the age distribution of New Zealand's extant indigenous forests with much of the indigenous forest managed as forest reserves within the crown's conservation estate. It is challenging to measure the precise age of these forest stands because late successional stand which have not been disturbed by external factors (such as windthrow, land clearance, or volcanic eruption) for a long-time frame and therefore contain a mix of tree ages with young regenerating tree mixed and older mature trees. The lack of precise forest age information prevents us from being able to use this data as a chronosequence (i.e., substituting space for time) to examine carbon stock changes over time.

Generally, there are fewer forest growth models available for indigenous forest types. The few that are available are particularly focused on just a handful of species, for example naturally regenerated mānuka or kānuka (Watt, et al., 2012), black beech (*Nothofagus solandri*) (Ganivet, et al., 2017), podocarp-hardwood in Waitutu forest (Kunstler, et al., 2011); and planted totara (Bergin & Kimberley, 2003; Wade, 2020) and kauri (Steward, 2011; Steward, et al., 2014). A full review of forest growth models is out of scope of this report however, it should be noted that these forest growth models tend to be parameterised from a limited number of sites, and don't tend to be sensitive to the variation in growth across site and climate conditions. In addition, there is relatively limited allometric information available for indigenous species, with notable studies by Beets, et al. (2012), Schwendenmann and Mitchell (2014), Mason, et al. (2014), Marden, et al. (2018) and Easdale, et al. (2015). Beets, et al. (2012) provides allometry for the 15 indigenous species, however it is based on relatively small sample sizes of less than 20 trees per species (as few as 1 sample for one of the species) across up to 5 sites. Likewise, Schwendenmann and Mitchell (2014) provides allometry for a range of native species based on a small number of samples from one (urban) site. The small sample sizes, and relatively few sites represented suggest that this allometry is unlikely to be representative of the full range of variation across New Zealand. Further, Easdale, et al. (2019) summarizes root biomass allometry from 12 studies in New Zealand. A full review of the available allometric relationships available in the published literature are out of scope for this report.

As a result of the limited availability of forest growth information and models, and allometry information, ***there is relatively less information available regarding carbon stock changes over time for indigenous forests in contrast to exotic plantations.***

There are several notable studies that have examined forest carbon stocks and stock changes in indigenous plantations. Lin, et al. (2020) developed a spatially explicit model of forest carbon stocks for planted totara and mānuka. In addition, Kimberley, et al. (2021) and Kimberley, et al. (2014) present information for several indigenous species based on data from the Tane's Tree Trust's Indigenous Plantation Database; however, these are not published in peer-reviewed science journals and the statistical methods used to derive this information are not reported. It is unclear if the sampling design used by Kimberley, et al. (2021) and Kimberley, et al. (2014) are representative of indigenous plantations across the full variation of site conditions across New Zealand.

Further, there is limited information available regarding the forest carbon stocks of indigenous forests planted for restoration, however these studies tending to be focused on relatively few sites and specific forest types (Schwendenmann & Mitchell, 2014; Yarur Thys, 2021). These restoration plantings tend to be planted at higher tree densities (or stockings) and often have mixed species compositions, in contrast to indigenous plantations.

Several notable studies focused on forest carbon stocks and stock changes in naturally regenerating stands include, estimates of carbon stocks within shrublands composed of gorse, broom, mānuka, tauhinu and other species (Beets, Kimberley, et al., 2014; Carswell, et al., 2013); and mānuka and kānuka (Ausseil, et al., 2013; Trotter, et al., 2005; Watt, et al., 2012).

Summary information has also been released from the ETS FMA data as part of a public consultation process (Ministry for Primary Industries, 2022). This summary information suggests that the area-weighted mean carbon stock and stock changes of post-1989 indigenous forests up to age 50 is much lower than that estimated by the current look-up tables for forests less than 100ha in the ETS. However, this information was not published in a peer-reviewed science journal, and the statistical methods used to derive this information are not reported. It is unclear if this data is representative of these forest types nationally.

## **Carbon Pools Measured, and Methods Used to Quantify Carbon Sequestration and Stocks**

Total forest carbon stocks are composed of several carbon pools. The specific delineation of the carbon pools and the carbon pools quantified can vary among studies. LUCAS follows international reporting standards, breaking total forest carbon stocks into above ground live biomass, below ground live biomass, deadwood, forest litter, and soil carbon stocks (to 30cm deep). Other studies and developed models may report data in additional pools, such as needles, branches, stem, coarse and fine roots, coarse and fine forest litter, etc. Furthermore, they may choose to break the pools down by canopy trees and understory shrubs (e.g., Forest Carbon Predictor model). ***It is not possible to make direct comparisons or aggregate studies where the carbon pools quantified are not compatible.***

Generally, there is much more information for stem biomass than the other above-ground components, including the understory, across all forest types. The above-ground biomass is relatively easy to measure accurately, compared with other carbon pools. This is the reason that many studies use existing allometric relationships to estimate the other carbon pools based on measurements of the above-ground stem biomass. In contrast, there is relatively little information regarding below-ground biomass, deadwood and forest litter carbon pools across all forest types due to the challenges of directly measuring these pools.

Currently, LUCAS does not directly quantify forest soil carbon stocks due to the challenges of quantifying this; rather, a simple model is used to estimate the carbon stored in the top 30cm of forest soils. Soil carbon is assumed to be soil carbon stocks are constant under a consistent land use. Deep soil carbon below 30cm is not currently quantified due to the lack of information about this layer; however, it is hypothesized that an additional 35% carbon may be stored in soils below 30cm (Byers, et al., 2023). It is unclear how this deep soil carbon may change overtime, or with changes to land management.

Most studies utilise field methods to measure vegetation dimensions such as diameter at breast height (dbh), and tree height in sample plots. The size, shape, number and placement of plots varies greatly depending on the purpose of each study, resulting in variable levels of statistical uncertainty. There are a handful of key comprehensive datasets with large numbers of field plots utilising standardised methods (e.g. LUCAS, ETS FMA, and PSP; described below).

Many species have limited allometric information available, particularly many of the indigenous or uncommon exotic species. Typically, the development of allometric relationships that estimate vegetation biomass or carbon content from field measurements (such as dbh and tree height) requires very intensive measurements of sampled trees. For example, whole trees may have to be cut down, divided into their constituent parts (e.g., stemwood, bark, leaves, and branches), weighed, and their carbon fraction determined. Allometric equations to estimate belowground biomass or carbon require excavating the root system. Sampling large numbers of trees for all species across a wide range of site conditions and ages is prohibitively expensive, and there are many species which have allometry based on few trees or no allometry at all. Some studies therefore use allometry developed from other regions, related species, or unrelated species that look superficially similar. It is likely that the true allometric relationships vary among the species and that this approach introduces bias into the forest carbon stock estimates. Frequently there is little scientific evidence to support the choice of allometry developed for other species or regions.

## Forest Management impacts on carbon stocks

A general review of the impact of management on forest carbon stocks and stock changes globally has been published by (Ameray, et al., 2021). This published review provides a useful summary of the current scientific knowledge, and identifies knowledge gaps for boreal, temperate and tropical forests.

### ***Planted Forests – Above ground biomass, below ground biomass, dead wood and forest litter carbon stocks***

An understanding of how stand development can be manipulated by forest management activities to achieve desired outcomes is fundamental to the management of planted forests in New Zealand. Plantations are intensively managed and management decisions are backed by research into all aspects of silviculture including site preparation, establishment methods, initial stocking, pruning, timing and intensity of thinning, fertiliser application, weed and pest control, final crop stocking and rotation length (reviewing this information is beyond the scope of this report). Most of this research has been conducted on radiata pine managed as even-aged stands with clearfelling at ages 25-35, as this species makes up about 90% of the plantation forest resource (Forest Owners Association, 2023). A relatively smaller amount of research has been undertaken regarding the effects of silviculture on other species of interest to the forest industry, including Douglas-fir, cypress species, non-durable eucalyptus species, and coastal redwood, with a particular focus on the influence of weed control, initial stocking and thinning (i.e. stand density management) and rotation length on productivity. Fertilisation and pruning are rarely carried out for these forest types and impacts are not well understood. Relatively, very little information is available regarding the influence of silviculture on other exotic plantation forests.

The information available regarding the influence of silviculture on productivity of exotic plantation species has been built into the available growth and carbon models. These models have been developed using the Permanent Sample Plot database (discussed below), and a number of replicated experimental field trials comparing different forest management interventions have been established across New Zealand over the last ~130 years. For example, stand density management and pruning can both be modelled across a range of sites in the Forest Carbon Predictor and Forecaster for radiata pine, Douglas-fir, cypresses, and eucalyptus species. Likewise, the impact of stand density management on forest carbon stocks across sites can be modelled in process-based models such as 3-PG (Landsberg & Waring, 1997) and CABALA (Battaglia, et al., 2004) for radiata pine, Douglas-fir, cypresses, eucalyptus, coastal redwood and totara. Stocking and rotation length can also be incorporated into the spatially-explicit national models for shining gum, Mexican white cedar, Monterey cedar, and coastal redwood developed by (Lin, et al., 2020).

An online Carbon Calculator for indigenous plantations has been developed by Tane's Tree Trust and is publicly available<sup>1</sup>. Care should be taken when using this calculator to estimate carbon stocks, as the calculator does not accurately incorporate forest management actions. For example, forest carbon stock estimates produced by the model increase directly-proportional to increases in stocking; however, it is well understood that the allocation of carbon within a tree changes (i.e. tree shape or allometry changes with stocking), and mortality due to self-thinning increases as forest stocking increases. Therefore, this calculator will provide erroneous estimates of forest carbon across stocking levels.

Conventionally, forest modelling has used empirical algorithms that are reliant on developed statistical relationships between forest structure variables (e.g. dbh, and height) using current or historical data (primarily from the Permanent Sample Plot database). They assume that the forest stands will behave (i.e., grow) similarly to the data trend used to develop the empirical equation. As such, empirical forest growth models are best used for forest stands with similar characteristics, including climate, as those used to develop the empirical algorithm. Using the empirical model outside the conditions under which it was developed (e.g. new sites, climates, genetics or management) adds error and uncertainty into the projections. Therefore, we have less confidence

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<sup>1</sup> <https://toolkit.tanestrees.org.nz/carbon-calculator/>

in the ability to model volume and carbon in situations not encountered in the Permanent Sample Plot database, such as:

- extremes in site quality
- new genetics
- very low, very high or irregular stockings
- irregular stand shapes such as shelterbelts with a high proportion of edge trees
- multiple thinning, or continuous cover forestry (including managed or unmanaged transitions to native forest)
- long rotations
- growth under changing climate and CO<sub>2</sub> levels
- growth after an ecological disturbance
- less common combinations of any of the variables affecting growth rates.

In contrast, process-based (or physiological) modelling takes a different approach and therefore does not require the same assumptions. Rather than modelling forest growth based on relationships derived from historical inventory data, process-based modelling approaches seek to simulate the underlying physiological mechanisms of forest ecology. Therefore, these models are broken-down into a number of interacting sub-models. Each of these sub-models describe how various aspects of tree physiology are influenced by environmental factors, and how these physiological processes interact with each other. The sub-models are developed using statistical analysis of detailed measurements of tree physiology under experimental conditions. Because process-based models project the growth of a forest stand based on these underlying physiological processes, they have a greater ability to project growth under a wider range of novel conditions using a relatively modest dataset compared to empirical modelling approaches. However, process-based models are more challenging to use, requiring expertise in forest physiology, and there are few examples of process-based models that have been parameterized for New Zealand's forests. The majority of these examples are for commonly planted exotic species.

Opportunities to increase the carbon stored in pre-1990 radiata pine plantations through management changes were explored for MPI in a recent report (Manley, 2021). Management interventions which may increase mean forest carbon stocks include extending rotations, increasing stocking, changing species or genetic improvement for replanted stands, as well as better weed and pest management, and optimising fertiliser regimes.

### ***Natural Forests – Above ground biomass, below ground biomass, dead wood and forest litter carbon stocks***

Naturally regenerated forests in New Zealand are not subject to the same intensity of direct management as exotic or indigenous plantations. The area of natural forest undergoing harvesting operations (including thinning), or supplementary planting is very small. Where active management takes place, it is usually confined to the control of introduced pests, including possums and ungulates, and research focuses on longer-term ecological processes. The conceptual models developed by (Wyse, et al., 2018) for beech-dominated and conifer-angiosperm forest illustrate the complexity of forest dynamics, and suggest where browsing mammals may hinder succession.

Easdale and Burrows (2021) summarised what is known about the opportunity to modify carbon stocks in pre-1990 native forests through management. Management options include:

- Fencing to exclude stock and deer;
- Wild animal control;
- Releasing from competition and supplementary planting; and,
- Transferring highly modified landscapes back to indigenous forest with active forest management practices developed for native tree species (i.e. forest or ecological restoration).

Data is limited, and a key issue is the timing of the response i.e., whether it is significant in the context of climate change mitigation efforts this century, or only in longer-term ecological timeframes.

Allen, et al. (In press) reviewed 26 paired ungulate exclosures (fenced areas which exclude ungulates) and unfenced controls after varying time periods of over 20 years. Total ecosystem carbon stock was found to be similar inside and outside exclosures. Exclosures increase the abundance of small trees, but these account for only small proportion of total ecosystem carbon. To some extent unpalatable species can compensate for the damage to species favoured by browsing mammals. Large trees account for the majority of carbon stocks and carbon stock change, and these are not affected by browsing ungulates over the time scale observed. Over a much longer timeframe, control of ungulates is critical to ensuring regeneration as large trees die and gaps in the canopy are created. This means that while removal of ungulates may allow an immediate increase in small tree biomass, this increase will not necessarily be sustained. When canopy gaps provide the opportunity for small trees to sustain their growth and become replacement canopy trees, their sequestration is offset by emissions from the dead trees they are replacing.

The high diversity and generally slower sequestration rates in native forests make it difficult to detect a change that can be attributed to management. Nevertheless, there are specific examples where management is likely to make a measurable difference. Hackwell and Robinson (2021) hypothesised that because the forest types experiencing carbon loss reported by Paul, Wakelin, et al. (2021) included kamahi (*Weinmannia racemosa*), it was likely that possum browsing was the cause. If so, targeting possum control in these forests could provide a carbon response.

Natural regeneration on some sites is limited by the absence of nearby seed sources and site conditions (particularly on drier sites with exotic grasses and other weed competition). In some cases, early successional shrubs and small trees, such as mānuka or kānuka may develop, but a lack of nearby forests prevents succession to a mixed forest type previously found in the area (also called arrested succession). Alternatively, a planted nurse crop of shorter lived, smaller trees with sparse crowns may help natural regeneration by creating a forest microclimate preferred by some tree species, and encouraging seed arrival by providing perching sites for seed-dispersing birds. Supplementary planting or manual seeding may be useful in these cases, but data is limited (Easdale & Burrows, 2021).

### ***Impact of forest management on soil organic carbon stocks in planted and natural forests***

Currently New Zealand's greenhouse gas inventory reporting assumes that soil carbon stocks are constant under a constant land use, and transitions to a new steady-state level over 20 years when there is a change in land use (Ministry for the Environment, 2022). In practice, soil carbon stocks would be expected to increase when forests are established on recent soils, such as sandy, pumice and alluvial soils, but show a decline when forests are established on ex-pasture sites. The impact of harvest and site preparation practices has been studied in plantations in connection with long term sustainability and soil characteristics, and there is ongoing research on the role of carbon storage in forest soils at deeper levels than the 10cm or 30cm typically sampled.

Currently the understanding of soil carbon changes in response to land use change or under a constant land use due to management is not considered to have advanced enough to be incorporated in carbon reward schemes (Mudge & Schipper, 2021).

### **Key comprehensive datasets**

There are several comprehensive datasets that are particularly important and warrant specific discussion. Because they use a consistent methods to collect and catalogue relevant data across a wide range of forest types and geographical locations, they provide an exceptional opportunity to understand carbon stocks and stock changes across New Zealand. In contrast, the inconsistencies in methods used and variation in the delineation of forest types, make the systematic compilation and analysis of numerous smaller, localised studies of forest carbon stocks impossible.

### ***Land Use and Carbon Analysis System (LUCAS)***

New Zealand's Land Use and Carbon Analysis System (LUCAS) is managed by the Ministry for the Environment (MfE). This system was established to enable New Zealand to fulfil its international carbon accounting and reporting obligations under the UNFCCC. LUCAS includes a number of

components to track national Land Use, Land-Use Change and Forestry (LULUCF) components of New Zealand's carbon budget over time since 1990. One component of this system is a Natural Forest Inventory network of repeatedly measured plots located on a stratified-random 8km x 8km grid across natural and planted forests, and shrublands nationally which began in 2002. A finer grid of 4km x 4km has been superimposed for post-1989 planted forests, to ensure adequate sampling. The plot design consists of nested subplots for different components of the forest, with the largest being a 0.06ha circular plot. Within these plots all live trees above and below-ground, dead wood, fine debris, forest litter are measured, and carbons stock calculated following standard procedures (Ministry for the Environment, 2018). In total there are ~1257 plots installed in native forests between 2002 and 2007, and a further ~300 plots installed in post-1989 planted forests.

This dataset was developed specifically for the reporting of forest carbon stocks and stock changes at a national level using international best-practices, and therefore represents the single-most important source of robust, representative data for understanding the carbon sequestration of New Zealand's forests. However, it was developed for reporting carbon stocks at a national scale, with a density and distribution of plots which is most efficient and effective for deriving estimates at that scale. The LUCAS system was not developed for to specifically quantify forest carbon stocks at finer project-scales, or for understanding carbon sequestration of specific forest types. The random-stratified sampling on a grid is ideal for quantifying overall carbon at a national scale, but may poorly represent carbon sequestration in forest types that make up a smaller proportion of the landscape and are therefore represented by few plots. This includes forest types that are currently uncommon nationally but are likely to be planted more widely in the future.

Estimates for forest carbon stocks and stock changes derived from the LUCAS National Forest Inventory dataset have been included in our review of the available data.

### ***Emission Trading Scheme - Field Measurement Approach (FMA)***

New Zealand's Emission Trading Scheme (ETS), and the preceding Permanent Forest Sinks Initiative (PFSI), are regulatory mechanisms which allow forest owners to claim carbon credits (New Zealand Units, NZUs) as their forests grow over time. For forest owners with more than 100 hectares registered in the scheme, it is mandatory to quantify the carbon stock and stock change using prescribed field inventory methods, described as the Field Measurement Approach (FMA). These forest owners are then required to submit this information for the Ministry for Primary Industries (MPI) periodically to be able to claim and trade their carbon credits.

The Ministry for Primary Industries generally does not release FMA information publicly; however, in 2021 the ministry released area-weighted averages of carbon stock by age for radiata pine, Douglas-fir, exotic softwoods, exotic hardwoods and indigenous forests up to 50-years derived from this dataset, as part of a public consultation regarding policy changes related to these schemes<sup>2</sup>. These estimates for forest carbon stock and stock changes have been included in our review of the available data.

While generally not publicly available, this dataset represents a potentially important source of robust data for understanding the carbon sequestration of new New Zealand forests, particularly focused on those forest types and locations that are most likely of interest for carbon forestry projects. While this database is not a representative sample by forest type or geographic location, the data is collected using robust, standardised methods allowing it to be compiled and analysed across forest types and locations. It also reflects the site, species, and management decisions of these owners and the sequestration achieved by their forests.

### ***Permanent Sample Plot (PSP) database***

The Permanent Sample Plot (PSP) database is a forest inventory database held by Scion. While it does not directly collect or hold information regarding forest carbon stock and stock changes, it is a critical dataset which has been foundational for a number of studies included in this review, and may be a potential source of data for future analyses. The PSP database holds information from over 30,000 plots, including over 10,000 current repeatedly measured plots and ~20,000 that are

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<sup>2</sup> Managing exotic afforestation incentives by changing the forestry settings in the NZ Emission Trading Scheme consultation

abandoned or historic records from as early as the 1920's. This dataset includes historic and current forest research trials managed by Scion and encompasses a wide variety of forest types, forest management treatments, and full geographic range. In addition, a number of forest industry companies may elect to store their forest inventory data in the PSP database; however, they maintain ownership and control of this data.

All data held in the PSP database is measured and recorded using a standard protocol. While distribution of plots in terms of forest type and geographic region is unlikely to be representative of all forests nationwide, the size of this database and collection of data using robust standardised methods allow it to be systematically analysed to provide information about productivity of planted forests in terms of biomass and wood volumes. With the addition of appropriate allometric, wood density and carbon fraction information, carbon stock and stock change information can be derived.

Estimates for forest carbon stocks and stock changes derived from the PSP database in several studies have been included in our review of the available data.

### ***National Vegetation Survey Databank (NVS)***

The National Vegetation Survey Databank (NVS) is held by Manaaki Whenua Landcare Research. Similar to Scion's PSP database, NVS is a repository for vegetation data collected across a wide range of studies for varied purposes; however, the data held within NVS is focused on indigenous forests and grasslands (although other ecosystems and exotic species are included), primarily describing species occurrence and abundance across New Zealand. Furthermore, while this repository does not directly collect or hold forest carbon stock and stock change information, it has been used for a variety of studies included in this review and is a potential source of data for future analyses.

NVS holds data from over 120,000 vegetation survey plots spanning 50 years, including 25,000 from permanently marked plots. This data includes surveys completed by the New Zealand Forest Service (prior to its abolishment in 1987), the Department of Lands and Survey, the Department of Scientific and Industrial Research Botany Division, Department of Conservation, regional councils, universities, private consultants, and Manaaki Whenua Landcare Research staff. The data is held by NVS through agreement, and the ownership and public access rights to data varies among the agreements.

In contrast to Scion's PSP database, the data contained within NVS is not collected using a standard protocol, and there is great variation in the methods used to collect the data. Of the 120,000 plots stored in NVS, 57,000 are point-based compositional and structural descriptions of vegetation that records relative abundance in fixed structural tiers. Generally, this type of information is not as useful for calculation of forest carbon stocks and stock changes as it is not quantified in a way that can be directly converted to vegetation volume or biomass. In contrast, 19,000 are fixed area permanent plots that could potentially be used to derive carbon stock and stock change information with the addition of appropriate allometric, wood density and carbon fraction information. These plots were collected using varying methodologies, plot sizes and shapes, and care should be taken to ensure that derived forest carbon stock information is compatible across the studies.

Similar to the PSP database, the distribution of plots across forest types and geographic locations is *ad hoc* and is therefore unlikely to be representative of all forests nationwide; however, it remains an important potential source of biomass information due to its large size.

### ***Tane's Tree Trust database***

Tane's Tree Trust holds a database of forest inventory information collected from plantations of native tree species across New Zealand. The Tane's Tree Trust Indigenous Plantation Database is based on two surveys of native tree plantations undertaken by Forest Research Institute (FRI) in the mid-1980's (Pardy, et al., 1992), and Tane's Tree Trust (Bergin & Kimberley, 2012; Kimberley, et al., 2014; Kimberley, et al., 2021), with additional inventory data added over time.

While the database contains information from over 120 stands including up to 60 different native tree and shrub species with an age range of 3-110 years, the distribution of these plots is

opportunistic and therefore does not represent the full climatic and geographic range of sites likely to be planted with indigenous species. The number of plots for each species range from approximately 6 to 112. Details of the silvicultural management of the stands is unknown. Furthermore, while many plots were collected using the methods of Ellis and Hayes (1997), the specific inventory design and methods vary making intercomparison difficult.

Estimates for forest carbon stocks and stock changes reported by Tane's Tree Trust from their Indigenous Plantation Database have been included in our review of the available data; however, the methods used to collect data and calculate these estimates have not been published or peer reviewed.

## Conclusions

There is great variation in the availability of forest carbon stock information across forest types in New Zealand. While there is adequate information to understand forest carbon stock and stock changes of the dominant exotic plantation forest types, there is much less information for less commonly planted exotic and indigenous species. Furthermore, the quantification of carbon stocks of naturally regenerated forest types is challenging due to the great variation in forest composition and structure, and there is relatively little information regarding the forest carbon stock of many of these forest types.

Caution must be taken when using data from existing studies to estimate forest carbon stock. The methods and forest type delineations used by different studies varies greatly depending on the purpose of each. Due diligence is required before comparing or aggregating data from different sources to ensure that they are compatible (i.e., equivalent forest type and carbon pool definitions). Further, care must be taken to ensure that the data is collected using scientifically defensible methods and with adequate number, size and placement of plots to represent of the forest type across the full range of environmental conditions. Furthermore, the choice of allometric relationships used to estimate carbon stock from field measurements should be appropriate to the species and site conditions. For many species, appropriate allometry is not available.

There are numerous smaller studies that have quantified forest carbon stocks or stock changes focused on a smaller number of sites. Each of these studies has a different focus or purpose, and therefore they use a variety of field and analytical methods. The opportunistic use of existing data collected within numerous small studies for other purposes is unlikely to result in a balanced sampling design that is representative of the full variation. It is not possible to opportunistically aggregate the data across these numerous fragmented smaller studies to quantify forest carbon stocks because they use a wide variety of incompatible methods and assumptions.

Alternatively, there are five key comprehensive datasets that each contain a large number of sample plots across forest types and geographic locations which may provide useful information. Of these datasets, LUCAS is the most robust, using a rigorous statistical sampling design to measure forest carbon stock and stock changes to fulfil international reporting obligations. However, LUCAS is designed to provide information at a coarse national scale rather than information about specific forest types or at a fine property scale. This National Forest Inventory system may be augmented with additional plots to provide greater representation and statistical certainty for relatively uncommon forest types, as has already been done for post-1989 planted forests. The remaining key comprehensive datasets, including the ETS FMA, PSP, NVS, and Tane's Tree Trust Indigenous Plantation Database also have the potential to provide additional information regarding forest carbon stocks of specific forest types; however, the data they contain is opportunistically gathered rather than systematically designed to be nationally representative, and it is unlikely that they represent the full range of variation for each forest type. Thoughtful analysis of these datasets and, in some cases, augmentation with additional plots to ensure representativeness, will be required if they are to be used for this purpose. It may be possible to aggregate these larger datasets, where the ECS, forest management techniques and measurement methods used are compatible. Further, access to proprietary data may need to be negotiated.

The use of process-based (or physiological) modelling may provide a way forward where the available data for a particular species or forest type is relatively sparse. Furthermore, process-based modelling may be able to provide information regarding the likely future forest carbon stocks under projected climate change conditions which is not possible using empirical modelling. Conventionally, forest modelling has used empirical techniques that are reliant on developed statistical (or more recently machine learning) relationships between forest structure variables using current or historical data, and therefore has required a relatively large datasets across the full range of variation to ensure the model is representative. Empirical techniques assume that future forest stands will behave similarly to past or current forest stands, and that the underlying relationships and conditions will not change. Process-based models aren't constrained by the same assumptions. They take a different approach by seeking to simulate the underlying physiological mechanisms of forest ecology. Process-based models are composed of a number of interacting sub-models, each of which describe how various aspects of tree physiology are influenced by environmental factors, and how these physiological processes interact with each other. Because process-based models project the growth of a forest stand based on these underlying physiological processes, they have a greater ability to project growth under a wider range of conditions using a relatively modest dataset compared to empirical modelling approaches. Process-based models are challenging to parameterise and use because they require expertise in forest physiology along with robust data that describe the physiological processes.

There has been considerable research into the forest carbon stocks, and stock changes of New Zealand's forests over the last several decades. The information that has been generated has allowed New Zealand to provide scientifically defensible reports of the national forest carbon stock and stock changes to fulfil our international obligations. While there remain knowledge gaps which hinder the ability of landowners and managers to report forest carbon stocks and stock changes at the forest stand or property scale, these challenges can be resolved with the strategic allocation of resources focused on the research needed.

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# Appendix A

**Table 1.** Experts and stakeholders contacted to request information related to the carbon sequestration of New Zealand's forests.

<b>Name</b>	<b>Organisation</b>	<b>Response</b>
Rob Allen	Retired; Independent Consultant	-
Peter Beets	Retired Scion	-
Peter Bellingham	Manaaki Whenua Landcare Research	✓
Peter Berg	Tane's Tree Trust	✓
Bradley Case	Auckland University of Technology	-
John Craig	Tahi & Green Inc Ltd	-
Grant Douglas	AgResearch	-
Tomas Easdale	Manaaki Whenua Landcare Research	-
Len Gillman	Auckland University of Technology	✓
	Auckland University of Technology; Te Punaha Matatini	
David Hall		✓
Jenny Hurst	Ministry for the Environment	✓
Mark Kimberley	Retired, but now independently consulting	-
Sebastian Leuzinger	Auckland University of Technology	✓
Janice Lord	Otago University	✓
Cate Macinnis-Ng	University of Auckland	✓
Alan Mark	University of Otago; Forest and Bird	✓
Euan Mason	University of Canterbury	-
Norm Mason	Manaaki Whenua Landcare Research	✓
Ian McIvor	Plant & Food	✓
Trevor Jones	Plant & Food	✓
Sara Mikaloff-Fletcher	NIWA	-
Paul Mudge	Manaaki Whenua Landcare Research	✓
	Retired University of Canterbury; Independent Consultant	
David Norton		-
Sarah Richardson	Manaaki Whenua Landcare Research	✓
Cate Ryan	Auckland University of Technology	-
Louis Schipper	University of Waikato	✓
Luitgard		
Schwendenmann	University of Auckland	✓
Warwick Silvester	Tane's Tree Trust	-
Rowan Sprague	CarbonCrop (CarbonCo Ltd)	✓
John Wardle	Woodside Forest; Forest and Bird	✓
Graham West	NZ Farm Forestry Association	-
David Whitehead	Manaaki Whenua Landcare Research	✓
Susan Wiser	Manaaki Whenua Landcare Research	✓

# Appendix B

**Table 1.** Summary of identified studies which quantify carbon stocks and/or stock changes of forests in New Zealand.

Please see the accompanying excel spreadsheet:

[Maximising Forest Carbon current carbon stocks and existing data in NZ forests](#)