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Executive summary

Carbon stocks and stock changes in forests in New Zealand are monitored through the LUCAS National Forest Inventories which underpin reporting for the annual greenhouse gas inventory. There is increasing interest in the carbon stocks and stock changes over time in vegetation outside forests, for two reasons. Firstly, this information is required for greenhouse gas inventory reporting completeness - estimates are currently not reported for some land uses or are based on limited information. Secondly, there is interest from the agricultural sector in being recognised and rewarded for the carbon sequestration in vegetation on their land, whether or not it meets the thresholds for forest land eligible for rewards through the Emissions Trading Scheme.

The aims of this project were:
1. To develop an initial approach to on-farm non-forest woody vegetation carbon estimation based on a virtual plot network.
2. To provide a preliminary assessment of options to quantify non-forest farm sequestration.

Estimation of forest carbon takes advantage of decades of research on the application of mensuration methods and its translation into carbon and relevant models for forests. Extending this to non-forest vegetation presents some difficulties due to the lack of this research base. We propose five principles that should apply to the development of a carbon accounting approach for woody biomass in non-forest lands in New Zealand:

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

These principles apply to the research phase and ideally also to the implementation phase, (although implementation of re-measurements for inventory reporting could be initially be replaced with tier 2 emission factors derived from the research phase). This will enable the unbiased and accurate estimation of carbon stocks and stock changes on a national and individual farm level, consistent with current national and international accounting methods.

The key findings of this report are:

- The virtual plot network established on a 4km grid is a useful basis for improving current estimates of carbon stocks and stock changes used in New Zealand's greenhouse gas inventory reporting.
- An IPCC Tier 2 approach could be used to estimate carbon stock changes in farm vegetation, based on existing models and emission factors, but this is likely to introduce bias because of a lack of representative sampling. It would still improve existing estimates by improving estimates of the extent of vegetation.
- An IPCC Tier 3 approach would require representative sample to develop relationships across the full range of vegetation present to develop the underlying research base.
- There are costs and benefits to the Crown in improving the emissions factors used for greenhouse gas inventory reporting, and costs and benefits to both the Crown and participants in a scheme to reward sequestration in non-forest vegetation. Because carbon storage in vegetation is not permanent, ongoing monitoring costs are unavoidable.
- The Crown benefits from incentivising sequestration that contributes to New Zealand's net position. Incentives that promote sequestration that does not contribute to the net position (e.g. trees and shrubs outside forests are not part of the net position) has the opposite effect, reducing the incentive to lower emissions. Capturing additional sequestration within the net position that is not already part of New Zealand's Nationally Determined Contribution (NDC) would require an adjustment of targets to maintain the same level of

ambition, so does not necessarily provide a direct benefit to the Crown. However, expansion of NDC accounting does provide the Crown with greater policy flexibility and provides a reputational benefit through increased inventory coverage.
- Net benefits to participants are most likely if large areas are eligible to be included, the relevant vegetation types show high sequestration rates, carbon prices are high, discount rates are low, establishment and land costs are not accounted for and any costs to participate are low (e.g. through the use of lookup tables rather than costly field measurements).

Quantifying sequestration in farm vegetation

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Glossary

FAO – Food and Agriculture Organisation of the United Nations

Forest land – the definition adopted by New Zealand for international carbon reporting and accounting is “land with potential for a tree canopy cover of at least 30% and tree height of 5m when mature. Smallest size is 1 ha and 30 m in width”

GHG – greenhouse gas

GWB – grassland with woody biomass, a sub-category of Grassland used in greenhouse gas inventory reporting

IPCC – Intergovernmental Panel on Climate Change

LUCAS – Land Use Carbon Analysis System, Ministry for the Environment-managed system for reporting carbon stocks and stock changes for greenhouse gas inventory reporting.

LULUCF – Land Use, Land Use Change and Forestry, the UNFCCC greenhouse gas inventory sector within which carbon stock changes in land uses are reported.

LUM – Land Use Map, LUCAS map of land use classes used in greenhouse gas inventory reporting

NFI – National Forest Inventory

TOF – Trees Outside Forest land (where forest land is defined as above).

TSOF – Trees and shrubs outside forest land. Trees and shrubs that do not meet the definition of forests.

UNFCCC – United Nations Framework Convention on Climate Change

Introduction

Trees in the landscape and their contribution to climate change mitigation

International context

The role of woody biomass outside forests as a terrestrial carbon pool globally has been receiving attention (Thomas *et al.*, 2021). However, appropriate methods to monitor and assess this resource are undeveloped in comparison to forests and our knowledge about trees and shrubs outside forests (TSOFs)[1] is still rather limited (Shvidenko *et al.*, 2005; Smeets and Faaij, 2007). Some studies do exist that show the importance of this woody biomass resource (Zomer *et al.*, 2014; Schnell *et al.*, 2015a). While the relevance of TSOFs has been recognised by the FAO (2001), the monitoring of TSOF is still highly variable across different countries and systems that routinely monitor TSOF are often missing or incomplete.

In recent years several national forest inventories (NFIs) have extended their scope to include non-forest trees. The NFIs of Switzerland, Sweden and India include trees outside forests (TOFs) as part of the assessment. A driver for the inclusion of TOFs for some of these countries has been reporting obligations under the land use, land use change and forestry sector of the Kyoto Protocol. Interestingly none of these countries has established a carbon market based on the carbon stock changes in TOFs. In each case the data acquired on TOFs is not analysed using methods specific to TOFs and the results are mostly not publicly available yet. Comparability of results is a concern. Existing systems for monitoring TOFs are still in their infancy and require further improvements (Schnell *et al.*, 2015b).

The role of TOFs as a terrestrial carbon pool at a national scale is of particular interest for countries with large areas of sparse tree cover (e.g. savannas). For example, in India 25.6% of the national woody biomass stock was found outside of forests. In contrast, in Switzerland and Sweden TSOFs covered 4.1% of non-forest area and represented 0.7% of the growing stock respectively (Schnell *et al.*, 2015a). The small contribution from TOFs for a highly forested country such as Sweden is not unexpected.

New Zealand

In New Zealand there has been relatively little focus on TSOFs as a terrestrial carbon pool until recently. Natural and planted forests are well monitored for their carbon stock changes (Paul et al 2021; Beets et al 2012) and mapped reasonably well according to the forest definition across the extent of New Zealand (MFE 2021).

Under the United Nations Convention on Climate Change, New Zealand prepares an annual greenhouse gas inventory which includes the contribution to net emissions from the Land Use, Land Use Change and Forestry (LULUCF) sector. As part of the inventory, reporting of carbon stocks and stock changes in vegetation is required for six land uses: forest land, grassland, cropland, wetlands, settlements and other land (IPCC 2006, MFE 2020).

A subset of these stock changes contributes to New Zealand's net position under the Kyoto Protocol and are likely to form the basis of Paris Agreement reporting. This includes carbon losses due to deforestation, stock changes in lands converted to forest land since 1989 (afforestation), and gains in stocks above a business-as-usual baseline on lands that were already forested by 1990 (IPCC 2014). New Zealand has therefore prioritised data collection on forest land, where vegetation carbon stocks and stock changes are greatest and accounting under the Kyoto Protocol was mandatory. Other reasons for the focus on forest carbon stocks include the fact that data and models were available for the economically important and intensively managed plantations even before the NFI was established, and there is interest in the status of natural forests given the wide range of ecosystem services they provide. Reporting of carbon stocks and stock changes in the other land use categories of New Zealand's greenhouse gas inventory is less well developed, while

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[1] We extended the commonly internationally used term Trees Outside Forests (TOFs) to include shrublands that are part of our national vegetation classification.

the New Zealand Emissions Trading Scheme (ETS) is only open to post-1989 forest lands as defined using the same criteria used for greenhouse gas inventory reporting.

More recently a number of studies have been conducted to determine the extent of forests and TSOFs specifically on private land such as farms (Norton and Pannell 2018). This is motivated in part by a desire for farmers to receive greater recognition for the role they play as land stewards in protecting natural heritage values. TSOFs are also promoted to play a potential part in sequestering carbon on farms and therefore offsetting farm greenhouse gas emissions, should farm emissions enter a pricing scheme such as the ETS, as intended by government.

The recent studies (Case and Ryan 2020; Norton and Pannell 2018) have used satellite imagery-based maps with a higher number of land-cover classes than those used to stratify land into land-use types for international greenhouse gas inventory reporting. The disaggregation into additional land-cover classes is intended to provide a better breakdown of land on a farm-level and allow identification of TSOFs on farms. Furthermore, attempts were made to estimate the associated carbon stocks for detailed classes (Case and Ryan 2020) including carbon stock and stock change estimates for natural and planted forests based on information derived from the national LUCAS National Forest Inventories for planted and natural forests (Paul et al 2021). Carbon stock change estimates for other non-forest land (TSOF) were assigned based on a literature review. An earlier report also reviewed the literature to determine the likely range of annual sequestration in farm vegetation (Burrows et al 2018), while in a review of the Case and Ryan report, MFE estimated sequestration based only on the information used in the annual greenhouse gas inventory (MFE 2021).

There are two main drivers for the current interest in TSOFs. Firstly, the process of continuous improvement in international reporting requires progress on inventory completeness and accuracy. Currently carbon stocks and stock changes in vegetation in wetlands and settlements are not reported by New Zealand, and IPCC default values are used for annual cropland as well as high and low-producing grassland. These default emission factors do not take into account woody non-forest vegetation associated with these land uses, such as shelterbelts.

Secondly, there has been a suggestion that New Zealand sheep and beef farms are already almost carbon neutral due to the claimed large woody vegetation sink present (Case and Ryan 2020). While much of this sink was believed to be in forests and the degree of carbon neutrality has been challenged (MFE 2021), there remains uncertainty about the role of TSOFs because systematic sampling has not been undertaken. The size of the sink on farmland is of particular interest in light of the intention for agriculture to enter the ETS (or an equivalent scheme) by 2025.

Research needs

The current state of monitoring of TOF and their contribution to carbon stock change research (Schnell *et al.*, 2015b; Beckschäfer *et al.*, 2018) highlights that standardised methods are needed to assess woody biomass in non-forest areas, and that representative data and models are lacking. This is the case for New Zealand, which has not attempted to quantify woody vegetation stocks in some land use categories and uses IPCC defaults for others. Where country-specific emission factors are used they are not based on representative data. The values for perennial cropland are based on a literature review and surveyed areas of the main crops (Davis and Wakelin 2010, MFE 2021), while the grassland with woody biomass category is split in two – emission factors for 'transitional' GWB are derived from modelling while for 'permanent' GWB (including subalpine shrublands), limited LUCAS plot data from shrublands has been combined with vegetation cover estimates from virtual photo plots (Wakelin and Beets 2013).

The range of sequestration rates and the impact of management on this for TSOFs across the landscape is poorly understood. For example, perennial cropland carbon stocks are strongly influenced by shelterbelt carbon storage, which is included in the national emission factors based on experts' assessment of the prevalence of shelterbelts in the main crops. There is a need to test assumptions made about the proportion of shelterbelt area, crop area and unplanted area (Davis & Wakelin 2010), including land with other woody vegetation.

Shelterbelts are also a feature of annual cropland and grassland. A monitoring design that allows the accurate and representative estimation of carbon stock and change in shelterbelts is required.

One case study in North Canterbury exists (Czerepowicz *et al.*, 2012), and there has been some work on estimating carbon stocks (Welsch et al 2016).

As in many counties with significant forested land, New Zealand has concentrated its reporting efforts on the planted and indigenous forests which are the biggest terrestrial pools of woody carbon. Carbon stocks and the related carbon stock change in New Zealand are estimated based on plot-based forest inventories designed to provide unbiased and precise national estimates. This is the most common approach used globally for estimating carbon stock changes in forests at a national level (Tomppo *et al.*, 2010). Estimates based instead on non-systematic case studies drawn from the literature may introduce bias. Greenhouse gas inventory reporting is required to meet the best practice standards laid out in the IPCC guidelines (IPCC 2006, 2014, 2020). This covers acceptable standards for transparency, accuracy, completeness, consistency and comparability.

Report Objectives

The objectives of this report are:

1. To develop an initial approach to on-farm non-forest woody vegetation carbon estimation based on the virtual plot network.

2. To provide a preliminary assessment of options to quantify non-forest farm sequestration.

We first establish the principles governing methods for assessing of non-forest woody vegetation for carbon reporting and accounting and then describe a virtual plot approach implemented to enable a nationally representative sample of vegetation cover to be made for non-forest land uses. The resulting variation of area for landscape components such as shelterbelts, riparians, individual trees, and small woodlots allows the estimation of the proportional presence of these components. We then propose options for using this information as the basis for improving estimates of non-forest vegetation carbon stocks and stock changes.

Assessment of non-forest woody vegetation for carbon reporting and accounting

The LUCAS sampling and modelling network for estimating national carbon stocks and carbon stock change

Carbon stocks and stock change in forested lands

Reporting of carbon stocks and stock changes in forest land in New Zealand's greenhouse gas inventory is based on MFE's LUCAS nationally representative network of plots established on a grid across mapped land use sub-categories (MFE 2021). The National Forest Inventory covers Pre-1990 Planted Forests, Post-1989 Planted forests, Pre-1990 Natural forests and Post-1989 Natural Forests. On established permanent plots, the volume growth of trees and shrubs is determined through the re-measurement of critical metrics such as stem numbers by species and their diameter and height. Through an established and proven modelling framework carbon stocks and their change are estimated, using relationships established from decades of biomass sampling research (Beets et al 1999).

The LUCAS 8km grid and 4km sub-grid cover the landmass of New Zealand and therefore span across all land uses, but grid points in non-forest areas have not yet been systematically sampled. The 2020 UNFCCC Expert Review of New Zealand's greenhouse gas inventory identified the need to report carbon stocks and stock changes in the non-forest land uses and the logical approach is to gather carbon stock intelligence on the established sampling grid. Direct recommendations were made for New Zealand to report biomass carbon stocks and stock changes in vegetated wetlands for the first time and to revise reporting for perennial croplands in accordance with IPCC guidance (UNFCCC 2020).

Scion has developed models to relate remote-sensed data with carbon stocks in planted forests (e.g. with metrics captured by LiDAR (Light Detection and Ranging)) (Beets *et al.*, 2011b). Approaches such as regression-based double-sampling allow us to infer carbon estimates on sites not covered by the ground inventory or increase our sampling (Beets *et al.*, 2012a).

As part of the modelling framework allometric equations are used to relate easily measured parameters to metrics of interest that are more difficult to measure directly. This is routinely applied in the forest industry, where the parameter of interest (e.g. volume of logs at the time of harvest) is estimated from measurements of stocking, diameter and tree height. Heights themselves are usually measured for a subset of trees in order to establish a height-diameter relationship that is used to estimate unmeasured heights.

Remote sensing (such as aerial photography, LiDAR and multi-spectral satellite imagery) allows some parameters such as canopy height to be derived from point clouds accurately while other point cloud-based metrics can be related to stand volume, biomass or carbon (Beets *et al.*, 2011b). Scion has been instrumental in making the use of satellite imagery and LiDAR routine in the New Zealand forest industry. However, the use of remote sensing still relies on the ability to establish relationships between carbon in vegetation components (based on biomass estimates and carbon fractions in stem, bark, branches, roots, litter and therefore the allometric relationships) and the metrics derived from remote sensing.

In the case of forests, existing relationships have been developed for both:

1. estimating carbon in vegetation components from easily measured stand parameters, based on decades of destructive sampling of biomass in trees at different ages;(Beets, 1980, 2006; Beets *et al.*, 2008; Beets *et al.*, 2012b; Mason *et al.*, 2014) and
2. estimating vegetation parameters, biomass or carbon directly from remote-sensed data (Boudreau *et al.*, 2008; Beets *et al.*, 2011b; González-Ferreiro *et al.*, 2012; Asner and Mascaro, 2014) based on previously developed relationships with actual measurements of biomass or Net Primary Production.

However, these relationships are derived for forest trees and may not be accurate when applied to non-forest vegetation as highlighted by Schnell *et al.* (2015a) and McHale *et al.* (2009).

Carbon stocks and stock change in unforested lands

Biomass carbon stock changes in forests are important components not just for international reporting but also within New Zealand's Emissions Trading Scheme (ETS) as they not only contribute towards the commitments under the Paris Agreements but also to New Zealand's 2030 and 2050 net emission targets. However, there is also increasing interest in the potential contribution of non-forest vegetation types, both at a national level and a property level. For example, farmers are interested in offsetting the emissions arising from livestock, fertilisation, soil disturbance and other factors with carbon uptake in the vegetation on their properties. The sequestration potential of non-forest farm vegetation types is an element of the He Waka Eke Noa joint action plan on primary sector emissions reductions.

Unforested lands are currently not monitored for their carbon stocks and carbon stock changes through a well-designed and proven monitoring system. Therefore, the basis and sources for biomass carbon estimates used in the greenhouse gas inventory for the non-forest land uses are multiple (Table 1).

Table 1. NZ GHG Inventory sub-categories and country specific IPCC defaults

Non-forested Land Use Sub-category	LUM area (2016 assessment, in ha)	Basis for current GHG inventory stock and stock change estimates	Seq. rate (G) T C ha-1 year-1	Max. stock tC ha-1	Maturity cycle	Reference
Grassland with Woody Biomass ("Permanent")	1,376,035	LUCAS shrubland plots + virtual plot woody cover estimates for unmeasured plots (double sampling)	0	60.57	-	Wakelin and Beets (2013)
Grassland with Woody Biomass ("Transitional")		From mean of ages 0-10 in yield table for post89 NF plots (Marlborough pilot)	0.48	13.05	20	Wakelin and Beets (2013)
Low-producing grassland	6,400,945	IPCC default	2.867	2.867	1	IPCC, 2006a, table 6.4
High-producing grassland	6,872,829	IPCC default	6.345	6.345	1	IPCC, 2006a, table 6.4
Annual Cropland	371,357	IPCC default	5	5	1	IPCC default (table 5.9, IPCC, 2006a)
Perennial Cropland	103,696	Literature review + crop area statistics	0.67	18.76	28	Davis and Wakelin (2010)
Vegetated Wetlands	226,933	Not reported				
Settlements	236,357	Not reported				
Other Land	896,164	Not reported				

The non-forest vegetation types or trees and shrubs outside forests on farms of interest include:

- shelterbelts
- woody riparian vegetation
- shrublands
- space-planted poplars and other single trees
- small woodlots (that do not meet the one ha size criteria to be a forest).

Recent non-national carbon stock and stock change approaches

Farm forest- and TSOF area, carbon stock and carbon stock changes have been the focus of recent reports in New Zealand (Burrows *et al.*, 2018; Norton and Pannell, 2018; Case and Ryan, 2020). These studies attempted to estimate carbon stocks and carbon stock changes based on existing datasets and synthesised data from either case studies with local focus or relate representative sample data from the forest inventories to the substrata of specific farm-types (e.g. sheep and beef farms).

The spatial extent of native vegetation on farms nationally has been estimated by (Norton and Pannell, 2018) based on native vegetation classes represented in the LCDB2 (version 4.1; based on 2012 satellite imagery) which were further condensed to estimate the spatial extent of potential natural forests (by combining the LCDB classes mānuka/kānuka + broadleaved indigenous hardwoods + indigenous forest). This provided an estimate of forest area when over-laid with farm properties to estimate forest area on farms.

Case and Ryan (2020) undertook a carbon stock assessment based in part on LCDB mapping, using for non-forested lands the carbon stocks and sequestration rates based on a literature review. In many cases case-study sequestration estimates reported in previous reviews (e.g. Burrows et al 2018) were selected.

Suggested approach: Integrating TSOFs into a national inventory to inform farm-level carbon stocks and change

The current research landscape highlights the lack of comparability between the range of studies and therefore the range of estimated carbon stocks and stock changes from TSOFs. The potential implications are far reaching as such differences can lead to misinterpretation, lack of consistency in results and biased policy decisions. As Schnell *et al.* (2015b) and Beckschäfer *et al.* (2018) state this is a global phenomenon since definitions of "forest" vary and therefore the definitions of TOFs also vary. This complicates area assessments and also the way the biomass and therefore carbon should be estimated via sampling and modelling. For example, New Zealand's definition is different to the FAOs definition used for global assessments in its required crown cover (30% in NZ vs 10% FAO) and smallest unit (1 ha vs 0.5 ha respectively) but matches in regard to maturity height of 5 m).

For New Zealand the different definitions will have a strong influence on the estimation of land that is covered by forests versus land with TSOFs. As land area is a critical multiplier, any differences will exacerbate potential differences in carbon stock and stock change estimates derived on a per hectare basis.

TSOF carbon stock and stock change estimates need to be robust and representative. Case and Ryan (2020) included estimates for the same vegetation type from different studies that varied nearly eight-fold in the case of exotic shrublands. These studies did not make a random or systematic selection of stands to sample. It is difficult to justify the use of studies that were not designed to produce results that are generalisable to the areas mapped. As Schnell *et al.* (2015b), Beckschäfer *et al.* (2018) and Thomas *et al.* (2021) highlighted, it is important to have representative sampling designs and suitable models that are applicable across a range of situations with sufficient underpinning data. Well-designed monitoring frameworks can provide this, which is often achieved by the extension of forest inventories into wooded land with modification to account for the different spatial distribution of TOF (Fattorini *et al.*, 2016; Price *et al.*, 2017).

There are two aspects of such an approach: the underpinning science that is developed to establish relationships between metrics and carbon, and the incorporation of that science within an inventory framework that can be implemented. For the ongoing monitoring of carbon stocks and their change, the relationships and interactions between the various research aspects shown in Figure 1 are therefore important.

Importantly Step A (field research, Figure 1) should be based on a representative sample achieved by a suitable sampling design, while Step B (remote-sensing research, Figure 1) can be achieved through double sampling to determine the relationship in an unbiased manner. This indirectly highlights the separation often encountered between the research developing correct approaches to account for carbon stock and their changes on the one hand, and its operationalisation at either the same or finer scale (e.g. farm-level).

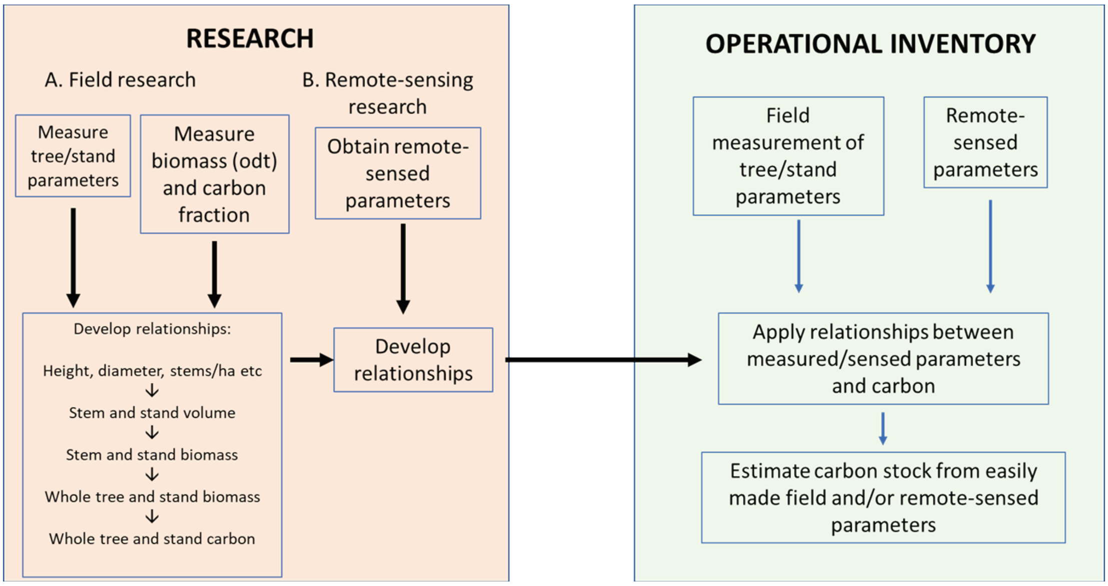


Figure 1. Research underpinning practical implementation for measurement and monitoring carbon stocks and changes on a per hectare basis.

We propose five principles that should apply to the development of a carbon accounting approach for woody biomass in non-forest lands in New Zealand to enable the estimation of carbon stocks and stock changes nationally and on individual farms, in a way that is consistent with current national and international accounting methods. This will ensure comparability and integration of local, national and international reporting and accounting. These principles are:

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

They apply to both the research phase and the implementation phase and are discussed in the following sections.

Five principles for non-forest woody vegetation carbon accounting

1. Accurate area estimation of the land on which woody carbon stocks are found and stock change occurs is essential for land-based accounting

At the national level land-use mapping has been conducted specifically for carbon accounting in New Zealand. The resulting LUM spatial database is the basis on which New Zealand reports internationally its carbon stocks and stock changes for different land-uses and for occurring land-use changes over time.

In parallel a different classification of land-uses exists (LCDB) and differences between these spatial databases exist (e.g. Figure 2). The discrepancy between the resulting maps for land with woody biomass has been a discussion point when calculating carbon stocks and carbon stock change for specific land-use areas. Inaccuracies and errors exist for both mapping exercises and should be incorporated in any estimates of carbon stocks per area. While error estimates exist for most mapping results these are often not included in the error associated with the estimation of carbon stocks and change per land-use area. Even when the error is reported at a national level, local mapping difficulties can increase mapping error in certain regions or landscapes (Manley *et al.*, 2020) and make direct comparison and decisions on which map to use difficult. However, for consistency on the national level, area estimates should be based on the spatial land-use database that is used for New Zealand carbon stock and stock change reporting internationally so inconsistencies between national and internationally reported carbon stocks and change can be avoided.

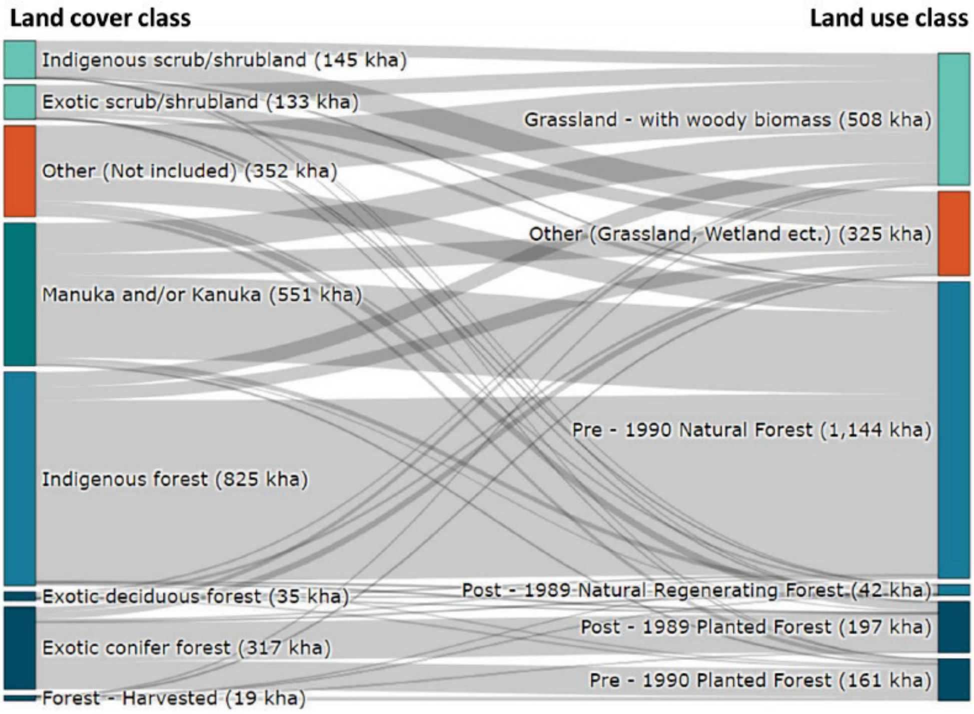


Figure 2. Area reconciliation between land cover (LCDB) and Land Use Class (National GHG inventory) on farmland. From MFE 2021.

The LUM classifies non-forest land-uses that have the potential of the presence of TSOFs, including the sub-category grasslands with woody biomass but also other pasture and croplands with woody biomass components. These woody components include those that do not meet the forest definition, such as shelterbelts and riparian vegetation less than 30 m wide, and woodlots smaller than 1 ha. While mapping out the specific areas of such woody biomass features via remote sensing has its own complications (and therefore they have not been mapped to date) the contribution of these TSOFs to carbon stock and stock change is of interest if a more detailed estimation of the contribution of these TSOFs is required.

A phase 1 sample exercise was performed in non-forest classes of the LUM in accordance with the sample design of New Zealand's Forest Inventories in natural and indigenous forests. This used the 4km grid sampling and 1ha virtual plots to estimate the relative presence of the following TSOF woody biomass features: shrublands, shelterbelts, single trees, riparian and woodlots. This is discussed later in this report.

2. Carbon stocks and stock change need to be estimated based on unbiased and representative sampling

While forests are sampled based on an inventory design that ensures spatial representation and is designed to be unbiased for the mapped area of forests in New Zealand on the national scale (Beets *et al.*, 2011a, 2012a; Paul *et al.*, 2021), carbon stocks and stock change estimates have not been derived with similar rigour for TSOFs. Instead results from case studies are collated as the basis for generalisation. However often such approaches violate the principles of objectiveness of data collection and consistent methodological approaches, and can lead to false results. To overcome such drawbacks specific methodological knowledge might enable the use of data from multiple case studies to analyse overall trends (e.g. meta-analysis) but often base data is confidential or not available.

A rigorous sampling approach can also avoid a potential bias through selective sampling. Again, case studies might have specific objectives and sampling approaches that might not allow the generalisation of the results e.g. if the objective is the sampling of examples of closed-canopy shrublands placing plots only in fully stocked areas but not capturing the full range of successional stages.

This also limits the use of double sampling based on data obtained from plots outside forests that were measured previously as part of forest inventories, as they are likely to introduce a bias towards higher stocked areas with higher carbon stocks (since remote sensing metrics initially classified the area as forest land).

As recommended internationally, forest inventories could be expanded to include TSOFs and could be developed into national tree and shrub inventories (Schnell *et al.*, 2015b). In many instances tree and shrub measurements would be the same (e.g. for carbon stock and change estimation). The same underlying sampling design could be used but potentially with adjustment to the plot design to account for the size and dispersion of shrubs and trees in non-forested land-use classes (Fattorini *et al.*, 2016; Beckschäfer *et al.*, 2018).

3. Repeatable methods that provide precise and accurate estimates of carbon stocks and stock change are required

The estimation of carbon stock change in any woody biomass requires ongoing monitoring, ideally through re-measurement of a representative sample. A prerequisite of such an approach is that growth can be clearly detected (i.e. the signal is greater than then noise) and therefore the measurement interval and errors introduced by the method need to be considered. For example, if growth is slow the remeasurement period needs to be lengthened to avoid a situation where growth increment is less or equal to the expected measurement error. This is not only a problem for field methods but also need to be considered for remote sensing technologies such as LiDAR (White *et al.*, 2013). For example, there are technical limitations with LiDAR where shrubland heights are low.

Permanent plot-based methods allow for the accurate accounting of ingrowth and mortality of TSOFs if a suitable plot size has been chosen. Proven field measurement approaches exist that are routinely used in commercial operations where accuracy is important enough to be audited.

4. Models developed and applied need to be based on sufficient and representative data, and rely on the quality of input data

While the representative monitoring of TSOFs can be ensured nationally through a sampling design and measurement methods that are similar to the National Forest Inventories, the often unique form of open grown trees and shrubs might require the development of new allometric equations (McHale *et al.*, 2009). This would initially require the sampling of biomass and vegetation structure across the range of environments in land-use areas with TSOFs that can be related to simple metrics such as DBH and height. This is especially relevant for those vegetation types where form is highly modified, such as hedged or topped shelterbelts and browsed or clipped shrubs.

Ideally model development should be done with a representative sub-sample across the inventory (double sampling for model development). Non-destructive methods that allow the rapid characterisation and measurement of allometric components of trees and shrubs such as terrestrial LiDAR could be deployed in the future.

The development of remote sensing approach as part of a multisource inventory of TSOFs is a promising potential approach to monitor TSOFs (McHale *et al.*, 2009; Johnson *et al.*, 2015; Maack *et al.*, 2017). This does require that remote sensing technologies become cost efficient operationally at multiple scales (national to farm) and prove to be suitable, such as providing sufficient information density (e.g. for LiDAR, a high number of returns per m^2). Initial development of relationships between remotely-sensed data and carbon stocks (often estimated through field measurements and the application of allometric relationships) would be required and once such models have been developed with data from the sampling network, remote sensing-based monitoring could be deployed via initial double sampling and furthermore applied to individual farms, if cost effective for land-owners. This is a fast-moving research space and developments that could support the operational mapping of TSOFs and provide input into future carbon models is realistic in the mid-term (5 years). However, this does not remove the overall principle of developing models in a representative and generalisable way to ensure models can be used widely with high accuracy and precision.

5. The costs of carbon stock and stock change estimation should not exceed the expected benefits

Forests are the biggest terrestrial carbon sink in New Zealand and globally. During the period 2013-2020 it is estimated that 109.2 Mt CO_2 was offset from total emissions of 642 Mt CO_2-e. As part of the international community's climate change mitigation efforts, it is relatively easy to justify the costs of the forest inventories.

From a national perspective, a direct greenhouse gas benefit from estimating sequestration in on-farm non-forest vegetation is unlikely. Carbon stock changes in this vegetation does not currently contribute to New Zealand's Nationally Determined Contribution (NDC) under the Paris Agreement, and any change in accounting approach would require a re-calculation of the target to ensure that ambition is not reduced. However, expansion of NDC accounting does provide the Crown with greater policy flexibility and provides a reputational benefit through increased inventory coverage.

At a property level, a landowner may have large areas of non-ETS compliant vegetation that offers potential for offsetting farm emissions under a scheme that incentivises reductions in net emissions. The need to ensure the environmental integrity of offsets due to the impermanence of carbon sequestered by vegetation leads to costs in monitoring and verification. Determining whether the benefits from claiming credits under such a scheme outweigh the costs requires information that is currently highly uncertain. This is discussed below.

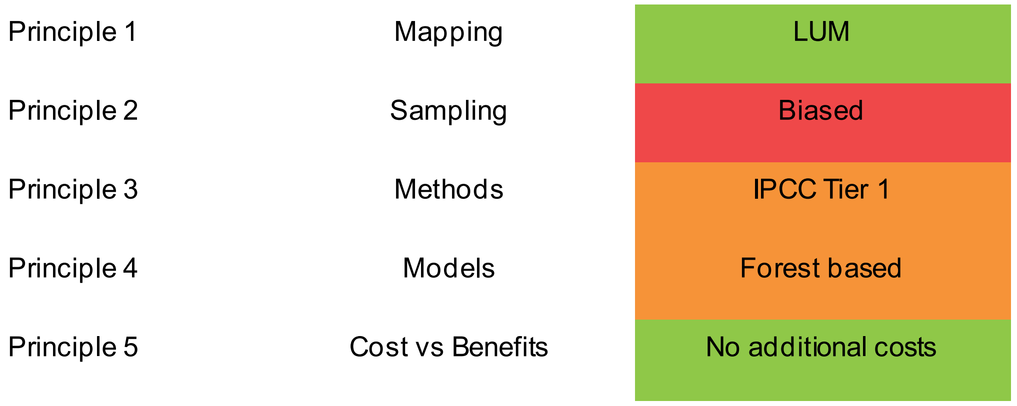
Application of principles – national and farm implementation for TSOFs

The IPCC guidelines for inventory reporting describe three reporting Tiers that increase in complexity. Tier 1 relies on simple models and default emission factors, which provides all reporting countries with a starting point for calculations once they have derived land use areas. Tier 2 replaces the default emissions factors with country specific factors while retaining the simple modelling approach. Tier 3 allows more sophisticated models and assumptions supported by country-specific data (IPCC 2006).

Two approaches to estimating TSOF stocks and stock changes are assessed here, based on a simple Tier2 approach using existing emission factors or the use of representative sampling to determine unbiased estimates.

Approach 1
The first approach to estimating TSOF stocks and stock changes is to follow IPCC Tier 1 or 2 guidelines. For Tier 2, New Zealand emission factors would be used (Table 1) with Tier 1 methods. For example, a farmer who converts low producing grassland to grassland with woody biomass could receive the difference between the maximum stocks of the two land uses (about 58 t C ha^{-1}), spread over 20 years. A transition from high-producing grassland to Grassland with Woody Biomass would result in lower reward as the initial carbon stock is higher. However, the IPCC defaults for low and high producing grassland do not include a contribution from woody biomass.

In terms of the five principles, mapping could be based on the LUM, but sampling would be biased, as the existing emissions factors are not derived from a nationally representative sample (Figure 3). Tier 1 methods would be followed which are simplistic but acceptable for an initial quantification, while allometric models that have been developed for forest land uses would need to be used. Finally, the cost:benefit ratio is likely to be favourable because no extra costs are incurred.



Principle 1	Mapping	LUM
Principle 2	Sampling	Biased
Principle 3	Methods	IPCC Tier 1
Principle 4	Models	Forest based
Principle 5	Cost vs Benefits	No additional costs

Figure 3. Assessment of Approach 1 (IPCC Tier 2) to carbon estimation for TSOF (national and farm-scale), against principles. Green indicates that the proposed method meets the relevant principle. Orange indicates that the method could be acceptable and red indicates that the principle is not met.

Approach 2
A second approach would develop the underpinning research required to develop relationships and New Zealand-specific emission factors.

Mapping would still be based on the LUM to maintain consistency. Forest areas are well mapped, sampled and modelled (meeting principles 1-4) so do not need further work if stocks and stock change values are to be applied as national values. However, for more accurate representation, detailed mapping within areas that contain TSOF is required. This could include mapping shrublands by cover and/or height.

A sampling approach can be used to estimate the prevalence of woody vegetation types. We used the 4km sample grid with 1ha virtual plots to estimate the relative presence of the following TSOF woody biomass features: shrublands, shelterbelts, single trees, riparian and woodlots.

In total 9315 virtual plots were assessed across 14.899 million hectares of grassland and annual cropland classes mapped by the LUM to record the presence of the above TSOF features. Initially simple presence or absence of a vegetation type was noted, designated as "Prevalence" in Table 2. Note that multiple vegetation types could be found within the same virtual plot. Subsequently vegetation cover in hectares was measured for a sub-sample of virtual plots. This allows the contribution of the vegetation type to the total grassland and annual cropland area to be estimated.

Table 2. Prevalence of vegetation types and their contribution to total grassland and annual cropland area[2]

	Prevalence encountered		**Cover within plots where found**	**Cover across all grassland and annual cropland**	
Vegetation	**% of virtual plots**	**Area (Mha)**	**Mean %**	**Mean %**	**Implied area (Mha)**
Without TSOF*	58	8.6 ±0.15	*NA*	*NA*	*NA*
Shrubland	25	3.6 ±0.13	28	7	1
Shelterbelts	7	1 ±0.08	6.4	0.5	0.07
Small woodlots	2	0.3 ±0.04	*NA*	*NA*	*NA*
Scattered trees	2	0.3 ±0.04	*NA*	*NA*	*NA*

* plots with less than 5% woody cover were accounted in this vegetation class

The analysis showed that in 58% of grassland and cropland, little (< 5%) or no TSOF features are present (8.6M ha ±0.15M ha). The most common TSOF features in grasslands and croplands were shrubs, which were present in close to 3.6M hectares (±0.130M), suggesting that about 25% of the total grassland and cropland area has shrubland present. The remaining TSOF features were present in 13% of the grassland and cropland area with shelterbelts present in 7% and small woodlots and single trees each present in 2% of the area.

The results of this exercise indicate that TSOF are represented on less than half of the mapped LUM area of grasslands and croplands. However, TSOFs are still found in significant areas across more than 5.5M hectares, an area three times greater than the current estimated area of planted forests in New Zealand. This is a significant area, although the vegetation cover within this area is lower. Emission factors for broad land use categories used for national reporting (e.g. "high producing grassland") should be derived taking into account areas with and without woody vegetation, whereas emission factors for specific vegetation types (e.g. shrublands) need to be based on the mapped boundaries of that vegetation.

Therefore, at the farm level it is of interest to account for the variability of the area actually occupied by TSOFs and not just their presence. On a national scale the estimation of area of occupancy on a per hectare basis is of interest as this variability can influence the estimation of carbon stocks per hectare. For shrubs and small trees in grasslands where shrubs were present, the average estimated relative cover in 1 ha virtual plots was 28% (or an area of occupancy of 2800m^2 per hectare). Figure 4 shows a histogram of the distribution of relative cover in grassland with shrub. Shrub cover varies widely, but about half of the plots with shrubs present have a shrub cover of 15% or less.

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[2] Woody Cover assessments for classes – not carried out for 'no woody vegetation', woodlots and scattered trees.

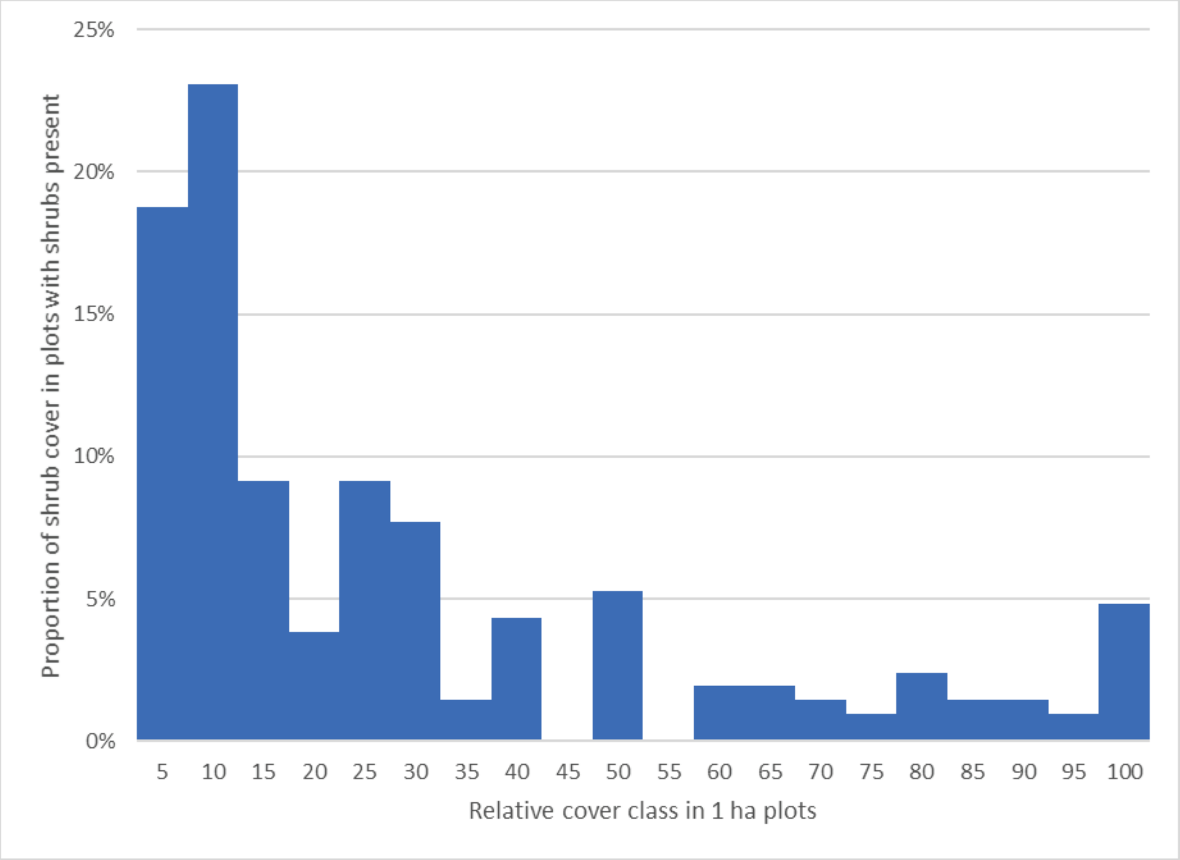


Figure 4: Histogram of relative cover classes (5%) of shrubs in virtual plots with shrub presence.

Shelterbelts are the next most prevalent TSOF feature in grasslands. Plots with shelterbelts present had an average shelterbelt length of 90 metres. Shelterbelts vary widely in form, function and management, with 54% classed as the hedged type and 46% free growing shelterbelts. Conifer tree species formed 56% of the shelterbelts and hardwoods 44%.

A previous study in a North Canterbury area where shelterbelts are a prominent landscape feature found that they comprised 2.5% of the land area (Czerepowicz et al 2012). At a national level, the virtual plot analysis suggests that shelterbelts would make up less than 0.5% of grassland and annual cropland area.

Shelterbelts are also a feature of some - but not all - perennial croplands. Perennial croplands include all fruit and nut orchards, berries, vineyards and associated shelterbelts. The current perennial cropland emissions factors used for New Zealand’s Tier 1 reporting are based on the areas of the main crops derived from the Agricultural Production Survey, estimates of carbon stocks and stock changes (excluding impermanent seasonal growth e.g. pruned shoots) for kiwifruit, grapes and apples from a literature review, and expert estimates of the prevalence of shelterbelts (Davis and Wakelin 2010). These assumptions are currently under review by Plant and Food in a report for HortNZ, but the virtual plot network was used to test the assumptions.

Perennial cropland was not included in the analysis presented in Table 2, but a separate summary of the 62 plots in perennial cropland is given in Table 3. Almost half of the plots had no woody biomass other than the crop itself, while 42% had shelterbelts (with or without other woody biomass) and 10% had no shelterbelts but other woody vegetation present. These proportions include the eight plots that did not contain crops.

The trend of increasing area of grapes observed in Davis and Wakelin (2010) has continued. In the 2020 Agricultural Production Survey grapes made up 47% of crop area, while the equivalent estimate from the virtual plots was 40%. This compares with a 1990-2007 mean of 24% used to weight the emission factor estimated in Wakelin and Davis (2010).

Table 3. Number of plots in perennial cropland with non-crop woody biomass

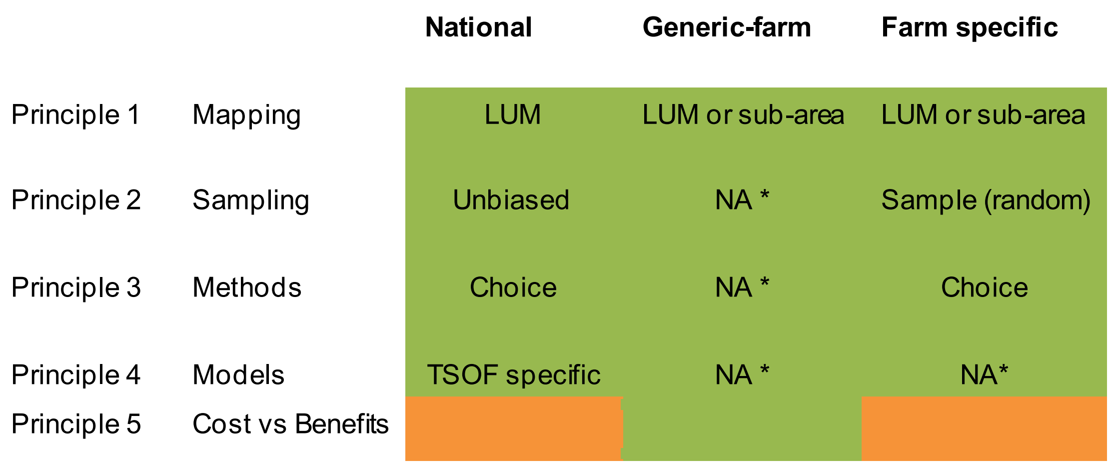
	Without other woody biomass	**With shelterbelts**	**With other woody biomass**	**Total**
Vineyard	17	3	0	
Vineyard + other LU	2	1	2	
All vineyard	**19**	**4**	**2**	**25**
Orchard	7	5	0	
Orchard + other LU	2	4	3	
All Orchard	**9**	**9**	**3**	**21**
Kiwifruit	0	4	0	
Kiwifruit + Other LU	0	2	0	
All kiwifruit	**0**	**6**	**0**	**6**
Other perennial	0	2	0	
Other perennial + other LU	0	0	0	
All other	**0**	**2**	**0**	**2**
Non-perennial	2	4	0	
Non-perennial + other LU	0	1	1	
All non-perennial	**2**	**5**	**1**	**8**
TOTAL	**30**	**26**	**6**	**62**

An assessment was also made of the extent of shelterbelts in perennial cropland and compared with assumptions made for the current emission factor (Table 4).

Table 4. Prevalence of shelter in perennial croplands

	Metres per hectare			
	Grapes	Orchard	Kiwifruit	Other
Virtual plots	**17**	**117**	**159**	**32**
Wakelin and Davis (2010)	**0**	**200**	**400**	**200**

An assessment of Approach 2 against the principles is given in Figure 5. Nationally derived emission factors can be applied at a generic farm level as lookup tables, as long as the national estimates are fully representative of the range of situations present on farms. This ensures that while some farms will have the sequestration over-estimated and others under-estimated, the national mean will be correct. Farm-specific estimates require sampling of the population of interest at the farm level.



		National	Generic-farm	Farm specific
Principle 1	Mapping	LUM	LUM or sub-area	LUM or sub-area
Principle 2	Sampling	Unbiased	NA *	Sample (random)
Principle 3	Methods	Choice	NA *	Choice
Principle 4	Models	TSOF specific	NA *	NA*
Principle 5	Cost vs Benefits	🟧	🟩	🟧

* Not required if national sampling occurs, methods and models properly developed (representing the range of situations on farms)

Figure 5. Assessment of Approach 2 (IPCC Tier 2 or 3) to carbon estimation for TSOF (national and farm-scale), against principles. Green indicates that the proposed method meets the relevant principle. Orange indicates that the method could be acceptable and red indicates that the principle is not met.

Preliminary Assessment of Costs and Benefits

The costs of carbon stock and stock change estimation should not exceed the expected benefits. The IPCC Tier 1 approach is simple to apply and incurs no additional costs but suffers from bias as the existing emission factors are not based on a representative sample. At a farm level, the use of lookup tables reduces the cost for participants but relies on there being adequate research to determine appropriate values. This transfers cost to the Crown or other research funding bodies.

Assessment of costs and benefits is difficult to determine without knowledge of potential sequestration rates in the relevant vegetation types, their variability, and the performance of allometric models that have yet to be developed.

As already indicated, direct accounting benefits to New Zealand are unlikely as targets would be recalculated to reflect any additional vegetation sinks, maintaining a constant level of ambition. Social benefits may accrue due to the off-farm benefits of increased planting of vegetation (e.g. riparian planting impacts on water quality), and there are potential benefits from consistent environmental monitoring and greater flexibility in policy levers.

In the case of a farm level sequestration scheme, costs and benefits depend on several factors. A key point is that because vegetation does not lock-up carbon permanently, in order to meet the basic standards of environmental integrity some level of ongoing monitoring cost is unavoidable.

Annual benefits
Estimation of the gross annual revenue (GAR) benefit is based on the following formula:

$$GAR = A\ x\ C_{seq} x\ \$CO_{2eq}$$

With A being the area of the relevant vegetation; C_{seq} the estimated annual carbon sequestration rate per hectare and $\$CO_{2eq}$ the price for one tonne of CO_2-equivalent.

Annual costs
Annual costs to the landowner include the costs of registering in a scheme, initial mapping and eligibility survey work, professional advice (e.g. regarding legal, financial, taxation, and farm planning matters related to the scheme), administration, any measurement required, preparing emission returns, and ongoing monitoring. If a scheme generates units that can be sold, there may be commissions on those sales as in the ETS. Alternatively, the estimated sequestration may be credited to the farm emission account with no trading allowed, in which case it would be priced at the cost of emissions.

There may also be costs associated with net emissions from temporary or permanent clearance of vegetation, depending on the accounting rules employed, and costs associated with determining the level of these liabilities.

If the vegetation has been established specifically for participation in the scheme with no other co-benefits, then the full cost of establishment and ongoing maintenance is also relevant. However, if the vegetation is giving other net benefits then costs and benefits may be limited to those directly associated with participation in the reward scheme, such as costs of mapping, measurement and administration.

Other costs to the landowner potentially include the loss of land use flexibility or the opportunity cost of foregoing alternative uses of the land (unless a liability is paid).

The Crown may incur significant costs if it has responsibility for administering the scheme. ETS costs include not only the direct costs estimated at $2700 per transaction, but also $80 million spent over four years on a new IT system, and salaries for 14 ETS team members to manage the 350,000 ha in the scheme. There may also be research costs including data collection for quantification of sequestration and model development. Given that the land area including shrubs is ten-times greater, the number of participants and transactions may also be an order of magnitude greater for a scheme rewarding sequestration in non-forest vegetation.

Ensuring the environmental integrity of the scheme (such as avoiding double counting) introduces a requirement for auditing, verification, monitoring, and maintaining a registry. An alternative approach to the issue of the impermanence of vegetation carbon is to only reward a fraction of the carbon sequestered each year. For example, in year one if sequestration is *x* t CO_2 ha^{-1} $year^{-1}$, then the reward is x/100; in year two with sequestration of *y* t CO_2 ha^{-1} $year^{-1}$, the reward is x/100 + y/100. Any vegetation cleared before 100 years simply stops earning rewards, while vegetation cleared after 100 years does not attack a liability. While this simplifies the monitoring requirements and therefore costs (e.g. where land is changing ownership), it also reduces the rewards.

Net Present Value
Since costs and revenues may be unevenly distributed over time, participation in the scheme can be treated as an investment, where the initial investment made to meet the requirements for registration is offset over time by ongoing carbon revenues. The discount rate is a key driver for measures of the profitability of the scheme, such as Net Present Value.

Accounting method
For vegetation that undergoes cycles of harvesting, the averaging accounting method developed for commercial forests under the ETS is likely to be appropriate. This affects both the length of time over which revenue is earned and the costs of participation.

Estimating likely benefits

The average sequestration rate expected in non-forest farm vegetation and the range is not well understood as there is a lack of representative sampling and allometry. Scenarios of sequestration rate (modelled as a simple constant value, Table 4) and carbon price were used instead to assess the present value of a constant stream of revenues over three different time periods.

Table 4. Sequestration rate scenarios

Sequestration Scenario ($t\ CO_2\ ha^{-1}\ yr^{-1}$)	**Basis/Examples** ($t\ CO_2\ ha^{-1}\ yr^{-1}$)	**Source**
1	1.22 shelterbelts per ha of cropland	Kort and Turnock (1998)
2	2.0 (Space-planted poplars 37 stems/ha) 2.3 (regenerating pre-1990 natural forest) 2.5 (current NZ perennial cropland)	Guevara-Escobar et al. (2002) Paul et al (2021) Davis and Wakelin (2010)
4	3.3 (gain from deer control in pre-1990 forest) 3.7 (ETS FMA and Ebex post-1989 indigenous forest)	Tanentzap and Coomes (2012) MWLCR
6.5	6.5 = ETS Indigenous average over 50 years 6.6 (Space-planted poplars modelled) 5.9 (Kanuka/manuka)	ETS Scion modelled Paul et al (2021)
8	10.0 (Poplars at 200 stems/ha)	Scion modelled
16	17 (TTT planted indigenous shrubs)	Tanes Tree Trust
28	Average ETS radiata lookup table over 28 years.	ETS

Carbon prices assumed were \$20, \$35, \$50, \$70, \$100 and \$150 per t CO_2.

Net revenues were assessed over 15, 50 and 100 years. Fifteen years was used as an estimate of the age at which the long-term average stock is reached for cyclical plantings such as woodlots and shelterbelts.

Discount rates of 2, 4, 6 and 8% were used. The rate assumed affects profitability metrics. Table 5 shows the impact of discount rate on the future value of money. At a rate of 8% (typical for forestry investment analysis), revenues beyond year 50 contribute less than about 2% of their nominal value to Net Present Value. This means that afforestation decisions based on NPV analysis can be made with some confidence despite the ETS lookup table for indigenous forest ending at age 50. In contrast, at a discount rate of 2% these post-year 50 revenues still contribute up to 37% of their nominal value. The current ETS lookup table does not provide sufficient information for investors with lower discount rates.

Table 5 Discount factors – present value of $1 in future years

Year	2%	4%	6%	8%	10%
0	1.0000	1.0000	1.0000	1.0000	1.0000
10	0.8203	0.6756	0.5584	0.4632	0.3855
20	0.6730	0.4564	0.3118	0.2145	0.1486
30	0.5521	0.3083	0.1741	0.0994	0.0573
40	0.4529	0.2083	0.0972	0.0460	0.0221
50	0.3715	0.1407	0.0543	0.0213	0.0085
60	0.3048	0.0951	0.0303	0.0099	0.0033
70	0.2500	0.0642	0.0169	0.0046	0.0013
80	0.2051	0.0434	0.0095	0.0021	0.0005
90	0.1683	0.0293	0.0053	0.0010	0.0002
100	0.1380	0.0198	0.0029	0.0005	0.0001

The present value of 50 years' worth of revenue at example discount rates of 2% and 8% are given in Tables 6 and 7 respectively. These values are for 1 ha but are scalable – e.g. the present value for 10 ha is ten times higher, because constant annual sequestration and constant carbon prices are assumed. The tables provide thresholds for the present value of costs, which must be lower to give a positive net present value. For example, for a 1 ha stand growing at the mean rate assumed in the ETS Indigenous forest lookup table (6.5 t CO_2 ha^{-1} yr^{-1}), the present value of participation costs must be less than $4215, or less than $42,150 for a 10 ha block, if a CO_2-equivalent is worth $20.

Table 6. Present value of revenue stream – 1 ha, 50 years; 2%

	Sequestration rate (t CO_2 ha^{-1} yr^{-1})						
Price $	**1**	**2**	**4**	**6.5**	**8**	**16**	**28**
20	648	1297	2594	4215	5188	10376	18157
35	663	2270	4539	7376	9079	18157	31775
50	1621	3242	6485	10538	12969	25939	45393
70	2270	4539	9079	14753	18157	36314	63550
100	3242	6485	12969	21075	25939	51878	90786
150	4864	9727	19454	31613	38908	77817	136179

Table 7. Present value of revenue stream – 1 ha, 50 years; 8%

	Sequestration rate (t CO_2 ha^{-1} yr^{-1})						
Price $	**1**	**2**	**4**	**6.5**	**8**	**16**	**28**
20	265	529	1059	1720	2117	4235	7411
35	463	926	1853	3011	3705	7411	12969
50	662	1323	2647	4301	5293	10587	18527
70	926	1853	3705	6021	7411	14822	25938
100	1323	2647	5293	8602	10587	21174	37054
150	1985	3970	7940	12903	15880	31760	55581

Shaded cells are those combinations of carbon price and sequestration rate for which the present value of returns is greater than the estimated $22,000 ha^{-1} cost of successfully establishing native forest through planting and weed control, while ignoring any costs of participation in the scheme. These results also assume an annual revenue stream – in practice, emission returns may only be required periodically, such as the mandatory reporting required every fifth year in the ETS.

Estimating likely costs

The costs incurred by a landowner will be a mixture of fixed costs and costs that vary with scale. They also depend on the participation requirements in terms of the information that must be provided, such as field measurements of key variables.

The accounting approach is also critical. Under averaging accounting, costs and revenues would only be incurred until the long-term average stock is reached. This approach simplifies the ETS for participants and removes the risk posed by the liabilities at harvest under stock change or “sawtooth” accounting. The advantages of this approach will apply even more to a scheme that recognises non-forest sequestration, because the rewards are likely to be lower due to lower sequestration rates.

The ETS provides for two basic approaches to estimating sequestration: ETS Lookup tables for owners with less than 100 ha, and a Field Measurement Approach requiring field plots to be installed and measured to provide the basis for a participant-specific carbon table.

In order to achieve environmental integrity, there are costs to ensure the land is eligible to participate, the information provided is accurate and complete, and carbon stocks are monitored over time, including after land changes ownership. Costs can be minimised by registering less than 100 ha in the ETS so that field plots are not required, and by limiting emission returns to the mandatory five-yearly return. Unlike revenues, the cost of installing plots is not a linear relationship with area, because fewer plots per hectare are required as the area increases. The area thresholds may be different for TSOF, depending on sequestration rates and therefore risks to the Crown and the costs of participation and administration in the scheme.

For this exercise it was assumed that averaging would be applied, and the long-term average would be reached after 15 years i.e. three mandatory reporting periods. It was then assumed that a simple verification process would be required in future to confirm re-establishment. Costs used in the analysis are given in Table 8.

Table 8. Example costs (based on ETS)

		Simple, averaging	**Field Measurement ~ 100-150 ha**
Year	**Activity**	**Cost**	**Cost**
0	Professional advice, mapping, registration	$3500	$3500
5	Emissions return, admin	500	$12000
10	“	500	$12000
15	“	500	$12000
35	Verification, monitoring	100	100
50	“	100	100
65	“	100	100
80	“	100	100
95	“	100	100

Table 9 shows net present value for an example of a 1 ha block and a 2% discount rate. With a sequestration rate of 6.5 t CO_2 /ha/year, a carbon price of over $50 is needed for profitability. Larger areas, higher carbon prices and low discount rates are beneficial. If vegetation establishment costs are included (e.g. $22,000/ha for planting native forest and controlling weed competition), then even with this low discount it will be difficult to break-even without a high sequestration rate and very high carbon price (shaded cells in Table 9). Permanent vegetation that gives a carbon return well beyond the 15-year period assumed here would improve these results, though as Table 5 shows the improvement is much greater at lower discount rates.

Table 9. Net Present Value at 2% discount rate for 1 ha; no field measurements.

	Sequestration rate (tCO2/ha/year)						
Price $	**1**	**2**	**4**	**6.5**	**8**	**16**	**28**
20	-4,608	-4,331	-3,777	-3,085	-2,669	-453	2,871
35	-4,593	-3,916	-2,946	-1,734	-1,007	2,871	8,687
50	-4,193	-3,500	-2,115	-384	655	6,194	14,504
70	-3,916	-2,946	-1,007	1,416	2,871	10,626	22,259
100	-3,500	-2,115	655	4,117	6,194	17,274	33,893
150	-2,808	-730	3,424	8,618	11,734	28,353	53,282

Figure 6 shows an example of the threshold sequestration rate required for a positive NPV for three stand sizes at a $35 carbon price and 6% discount rate. In this case a 2 hectare block requires a sequestration rate of 5 tCO$_2$ ha^{-1} yr^{-1} to be viable, while a 5 ha block will be viable with a sequestration rate of just 2 tCO$_2$ ha^{-1} yr^{-1}. Note that this includes only the direct costs of participation – costs for establishing and maintaining the vegetation and land rental or opportunity costs are not included.

Figure 6. NPV at $35 price by sequestration rate for three block sizes.

In summary, the Crown benefits from incentivising sequestration that contributes to New Zealand's net position. Incentives that promote sequestration that does not contribute to the net position has the opposite effect, by reducing the incentive to lower emissions. Capturing additional sequestration within the net position that is not already part of New Zealand's Nationally Determined Contribution (NDC) would require an adjustment of targets to maintain the same level of ambition, so does not provide a direct benefit to the Crown in terms of meeting the NDC target, although greater policy flexibility from expanding the NDC is helpful.

Costs are unavoidable due to the impermanence of carbon stored in vegetation and the need to ensure environmental integrity. The ETS demonstrates that even with the use of pre-defined sequestration rate values, administration costs can be high.

Participants facing fixed costs need to maximise their returns by registering larger areas that sequester carbon at higher rates. Net Present Value is one measure of the profitability of participation but cashflow is likely to be just as important. Participation is most likely for vegetation that is serving multiple purposes, such that the cost of establishment can already be justified.

Discussion

Non-forest woody vegetation (Trees and Shrubs Outside Forests, TSOF) may often be characterised by low sequestration rates per hectare, making it hard to detect real stock changes over short time periods. The heterogeneity of vegetation, including direct and indirect impacts of management, make the vegetation harder to map and monitor, and results in a potentially high degree of variation around a mean emission factor.

The virtual plot network established can be used to improve current emission factors – for example, based on shelterbelt prevalence. It also provides a better understanding of the extent and variation in woody vegetation cover on grassland and cropland, and potentially wetlands and settlements. It allows for further stratification, such as by farm type or eco-region and can serve as the framework for a national inventory of TSOF, aligned with greenhouse gas inventory approaches, while also providing evidence to support decisions around pursuing this goal.

Reassessment of virtual plots based on new photography offers the opportunity to track vegetation cover over time. Establishing baseline vegetation stocks as at 1990 or 2005 will required suitable imagery with national coverage to estimate cover change at that time as shrub removal and unaided and aided establishment of shrub cover will have occurred since then. A possible avenue would be the use of high spatial and temporal resolution satellite imagery and its timeseries analysis e.g. LandTrendR (Hudak, 2020; Kennedy, 2015), but such an approach would require further research to use it confidently.

Currently there is a lack of representative biomass and carbon estimates, including TSOF-specific allometry. This is required because while measurement can use ground-based methods, remote-sensing or a combination, it is generally not possible to directly measure the variables of interest. Instead, easily measured variables are used to infer information about carbon stocks, carbon sequestration, or intermediate variables that can be related to these metrics. These relationships need to be determined from representative sampling across the range of vegetation of interest.

To estimate stock change (sequestration rate), it is necessary to either:

a) Repeat measurements after enough time has elapsed that we can identify a real change through the noise in the data. This is easiest if the rate of change is high relative to the size of the stock and there is good precision in our stock estimates. The ETS Field Measurement Approach used for forests and the LUCAS National forest Inventory follow this approach.

b) Use an existing relationship between stock and sequestration rate for the type of vegetation in question, through a model or lookup table. This is feasible in the case of radiata pine woodlots, because knowing the stock or the underlying metrics used to derive it (or even just the age, with or without an estimate of stocking and an indication of site productivity) is sufficient to estimate likely sequestration rate with a reasonable level of accuracy at a national level. The ETS lookup table approach, based on region, species and age alone, applies this approach. This is not necessarily immediately achievable in other vegetation types that do not have the same research base.

LiDAR and to some extent Radar as active sensors and aerial photography and satellite imagery provide data to calculate spectral or energy return-based metrics that can be correlated to carbon stocks via new or previously developed relationships. However, if there have not been biomass studies undertaken in that vegetation type, the causal correlation or link between remotely sensed metrics and biomass are unlikely to produce accurate or precise estimates of carbon. For example if shrub species cannot be accurately identified via remote sensing, carbon stocks can vary through the species-specific wood density.

The LUCAS NFI approach is able to take simple measures such as tree diameters, heights and wood density and convert them into stem volume and biomass, which is expanded to biomass and carbon in other stand components. LiDAR has been used successfully through double sampling to improve the national carbon stock estimation in our relatively uniform plantation forests (Beets et al 2012a). However, LiDAR has not been deployed as the single measurement approach to estimate carbon nationally due to hard to determine variables such as stem density and age, essential for carbon stock and carbon stock change estimation.

Conclusions

We have proposed five principles that should apply to the development of a carbon accounting approach for woody biomass in non-forest lands in New Zealand to enable the estimation of carbon stocks and stock changes nationally and on individual farms, in a way that is consistent with current national and international accounting methods, ensuring comparability and integration of local, national and international reporting and accounting. These principles apply to both the research phase and the implementation phase:

1. Accurate area estimation of the land on which woody carbon stocks are found and stock change occurs is essential for land-based accounting
2. Carbon stocks and stock change need to be estimated based on unbiased and representative sampling
3. Repeatable methods that provide precise and accurate estimates of carbon stocks and stock change are required
4. Models developed and applied need to be based on sufficient and representative data, and rely on the quality of input data
5. The costs of carbon stock and stock change estimation should not exceed the expected benefits (bearing in mind that cost and benefits may be non-monetary).

The key findings of this report are:

- The virtual plot network established on a 4km grid is a useful basis for improving current estimates of carbon stocks and stock changes used in New Zealand's greenhouse gas inventory reporting.
- An IPCC Tier 2 approach could be used to estimate carbon stock changes in farm vegetation, based on existing models and emission factors, but this is likely to introduce bias because of a lack of representative sampling. It would still improve existing estimates by improving estimates of the extent of vegetation.
- An IPCC Tier 3 approach would require representative sample to develop relationships across the full range of vegetation present to develop the underlying research base.
- There are costs and benefits to the Crown in improving the emissions factors used for greenhouse gas inventory reporting, and costs and benefits to both the Crown and participants in a scheme to reward sequestration in non-forest vegetation. Because carbon storage in vegetation is not permanent, ongoing monitoring costs are unavoidable.
- The Crown benefits from incentivising sequestration that contributes to New Zealand's net position. Incentives that promote sequestration that does not contribute to the net position (e.g. TOFs are not part of net position) has the opposite effect, reducing the incentive to lower emissions. Capturing additional sequestration within the net position that is not already part of New Zealand's Nationally Determined Contribution (NDC) would require an adjustment of targets to maintain the same level of ambition, so does not necessarily provide a benefit to the Crown in enabling achievement of the NDC.
- Net benefits to participants are most likely if large areas are eligible to be included, the relevant vegetation types show high sequestration rates, carbon prices are high, discount rates are low, establishment and land costs are not accounted for and any costs to participate are low (e.g. through the use of lookup tables rather than costly field measurements).

Next steps:

Cover assessment were not carried out for small woodlots and scattered trees as they were less extensive. This could be completed on a sample of virtual plots and an assessment of the woody cover on virtual plots with little or no woody vegetation would also be useful given the high proportion of plots in this category.

An assessment of the vegetation type cover against the land use sub-categories used in greenhouse gas inventory reporting could be used in the development of country-specific emission factors to replace the IPCC default values for high and low-producing grassland and annual cropland. An improvement of the perennial cropland emission factor is possible given new information on shelterbelt frequency, although a higher sampling intensity may be desirable. There is also scope to extend the virtual plot analysis to the Settlements land use category.

Virtual plots need to be assessed over a time series to establish a baseline at 1990 and change over time. Artificial intelligence approaches to vegetation classification should be applied where successful accuracy can be achieved, with the current assessment available as training data,

Carbon stock estimates are also required. While vegetation area cover estimates will improve emission estimates when coupled with existing carbon stock estimates, the existing stock estimates vary in quality and are not based on representative sampling. Ideally emission factors would be developed for vegetation classes based on a research programme including repeated field measurement of sample plots over time. Priority would be given to vegetation classes that are extensive, have high potential stocks and dynamic changes in area, noting however that national priorities may differ from farm-level or even regional priorities.

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References

Asner, G.P., Mascaro, J., 2014. Mapping tropical forest carbon: calibrating plot estimates to a simple LiDAR metric. Remote Sens Environ 140.

Beckschäfer, P., Schnell, S., Kleinn, C., 2018. Monitoring and assessment of trees outside forests (TOF). In, Agroforestry: Anecdotal to Modern Science, pp. 137-161.

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

Beets, P.N., 2006. Description of C_Change. In, 39979. Scion, Rotorua, New Zealand, p. 32 pp.

Beets, P.N., Brandon, A.M., Goulding, C.J., Kimberley, M.O., Paul, T.S.H., Searles, N., 2011a. The inventory of carbon stock in New Zealand's post-1989 planted forest for reporting under the Kyoto protocol. Forest Ecology and Management 262, 1119-1130.

Beets, P.N., Brandon, A.M., Goulding, C.J., Kimberley, M.O., Paul, T.S.H., Searles, N., 2012a. The national inventory of carbon stock in New Zealand’s pre-1990 planted forest using a LiDAR incomplete-transect approach. Forest Ecology and Management 280, 187-197.

Beets, P.N., Kimberley, M.O., Oliver, G.R., Pearce, S.H., Graham, J.D., Brandon, A., 2012b. Allometric Equations for Estimating Carbon Stocks in Natural Forest in New Zealand. Forests 3, 818-839.

Beets, P.N., Oliver, G.R., Kimberley, M.O., Pearce, S.H., 2008. Allometric functions for estimating above ground carbon in native forest trees, shrubs and tree ferns. In, 42088. Ensis/Scion, Rotorua, New Zealand, p. 63.

Beets, P.N., Reutebuch, S., Kimberley, M.O., Oliver, G.R., Pearce, S.H., McGaughey, R.J., 2011b. Leaf Area Index, Biomass Carbon and Growth Rate of Radiata Pine Genetic Types and Relationships with LiDAR. Forests 2, 637-659.

Boudreau, J., Nelson, R.F., Margolis, H.A., 2008. Regional aboveground forest biomass using airborne and spaceborne LiDAR in Quebec. Remote Sensing of the Environment 112, 3876-3890.

Burrows, L., Easdale, T.A., Wakelin, S., Quinn, J., Mackay, A.C., 2018. Carbon sequestration potential of non-ETS land on farms. In. Manaaki Whenua, Scion, Agresearch.

Case, B., Ryan, C., 2020. An analysis of carbon stocks and net carbon position for New Zealand sheep and beef farmland. In. Beef and Lamb, p. 29.

Czerepowicz, L., Case, B.S., Doscher, C., 2012. Using satellite image data to estimate aboveground shelterbelt carbon stocks across an agricultural landscape. Agriculture, Ecosystems & Environment 156, 142-150.

Davis MR, Wakelin SJ. 2010. Perennial Cropland Biomass: Sampling Requirements. Report prepared for the Ministry for the Environment by New Zealand Forest Research Institute Limited (trading as Scion). Contract report 11407

Fattorini, L., Puletti, N., Chirici, G., Corona, P., Gazzarri, C., Mura, M., Marchetti, M., 2016. Checking the performance of point and plot sampling on aerial photoimagery of a large-scale population of trees outside forests. Canadian Journal of Forest Research 46, 1264-1274.

González-Ferreiro, E., Diéguez-Aranda, U., Miranda, D., 2012. Estimation of stand variables in Pinus radiata D. Don plantations using different LiDAR pulse densities. Forestry 85, 281-292.

IPCC 2006, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan

IPCC 2014. 2013 revised supplementary methods and good practice guidance arising from the Kyoto protocol. In: Hiraishi T, Krug T, Tanabe K, Srivastava N, Baasansuren J, Fukuda M, Troxler TG, editors. Geneva: IPCC; 2014.

IPCC 2019, 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

Johnson, K.D., Birdsey, R., Cole, J., Swatantran, A., O'Neil-Dunne, J., Dubayah, R., Lister, A., 2015. Integrating LIDAR and forest inventories to fill the trees outside forests data gap. Environmental Monitoring and Assessment 187.

Maack, J., Lingenfelder, M., Eilers, C., Smaltschinski, T., Weinacker, H., Jaeger, D., Koch, B., 2017. Estimating the spatial distribution, extent and potential lignocellulosic biomass supply of Trees Outside Forests in Baden-Wuerttemberg using airborne LiDAR and OpenStreetMap data. International Journal of Applied Earth Observation and Geoinformation 58, 118-125.

Manley, B.R., Morgenroth, J., Xu, C., 2020. Quantifying the area of the small-scale owners' forest estate in the East Coast, Hawke's Bay and Southern North Island. New Zealand Journal of Forestry 64, 18-26.

Mason, N., Beets, P., Payton, I., Burrows, L., Holdaway, R., Carswell, F., 2014. Individual-Based Allometric Equations Accurately Measure Carbon Storage and Sequestration in Shrublands. Forests 5, 309.

McHale, M.R., Burke, I.C., Lefsky, M.A., Peper, P.J., McPherson, E.G., 2009. Urban forest biomass estimates: is it important to use allometric relationships developed specifically for urban trees? Urban Ecosystems 12, 95-113.

Ministry for the Environment. 2020. New Zealand's Greenhouse Gas Inventory 1990-2018. Wellington: Ministry for the Environment. Retrieved from https://www.mfe.govt.nz/publications/climate-change/new-zealands-greenhouse-gas-inventory-1990-2018 (15 May 2020).

Norton, D., Pannell, J.L., 2018. Desk-top assessment of native vegetation on New Zealand sheep and beef farms In. School of Forestry, University of Canterbury and Institute of Applied Ecology, Auckland University of Technology, p. 32.

Paul, T., Kimberley, M.O., Beets, P.N., 2021. Natural forests in New Zealand – a large terrestrial carbon pool in a national state of equilibrium. Forest Ecosystems 8, 34.

Price, B., Gomez, A., Mathys, L., Gardi, O., Schellenberger, A., Ginzler, C., Thürig, E., 2017. Tree biomass in the Swiss landscape: nationwide modelling for improved accounting for forest and non-forest trees. Environmental Monitoring and Assessment 189.

Schnell, S., Altrell, D., Ståhl, G., Kleinn, C., 2015a. The contribution of trees outside forests to national tree biomass and carbon stocks—a comparative study across three continents. Environmental Monitoring and Assessment 187.

Schnell, S., Kleinn, C., Ståhl, G., 2015b. Monitoring trees outside forests: a review. Environmental Monitoring and Assessment 187.

Shvidenko, A., Barber, C.V., Persson, R., 2005. Forest and woodland systems. In: Hassan, R., Scholes, R., Ash, N. (Eds.), Ecosystems and Human Wellbeing: Current State and Trends.

Smeets, E.M.W., Faaij, A.P.C., 2007. Bioenergy potentials from forestry in 2050. Climatic Change 81, 353-390.
Tanentzap AJ, Coomes DA 2012. Carbon storage in terrestrial ecosystems: do browsing and grazing herbivores matter? Biological Reviews 87: 72–94.
Thomas, N., Baltezar, P., Lagomasino, D., Stovall, A., Iqbal, Z., Fatoyinbo, L., 2021. Trees outside forests are an underestimated resource in a country with low forest cover. Scientific Reports 11.
Tomppo, E., Gschwantner, T., Lawrence, M., McRoberts, R.E. (Eds.), 2010. National Forest Inventories - Pathways for common reporting. Springer, New York.
Welsch, J., Hale, R. J., Buckley, H. L., & Case, B. S. 2016. Quantification and comparison of shelterbelt carbon stocks within and between an organic mixed-cropping farm and a conventional dairy farm. New Zealand Natural Sciences, 41.
White, J.C., Wulder, M.A., Varhola, A., Vastaranta, M., Coops, N.C., Cook, B.D., Pitt, D., Woods, M., 2013. A best practice guide for generating forest inventory attributes from airborne laser scanning data using area based approach (Version 2.0). In. Natural Resources Canada, p. 50.
Zomer, R.J., Trabucco, A., Coe, R., Place, F., Noordwijk van, M., Xu, J., 2014. Trees on farms: an update and re-analysis of agroforestry's global extent and socio-ecological characteristics. In. World Agroforestry Centre (ICRAF), Bogor, Indonesia.