Towards a more accurate assessment of the vegetation carbon stocks in New Zealand grasslands

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Abstract

Carbon (C) markets are well established for aboveground woody vegetation domestically, and for soil organic C overseas. By reviewing published literature, this project aims to provide a scientifically defensible framework and dataset for estimating the vegetation C stocks in New Zealand grassland ecosystems. New Zealand currently uses IPCC Tier 1 values for biomass and root-to-shoot ratios derived from global vegetation types that do not align well with our intensively managed grassland systems. Shifting the High and Low producing grassland types used in the Land Cover Database to a Tier 2 approach requires inclusion of New Zealand-specific values of aboveground and belowground biomass. From the literature search of field measurements, the overall mean root-to-shoot ratio was 1.35 ± 1.86 and 3.64 ± 2.91 for High and Low producing grassland, respectively. These differ substantially from those root-to-shoot ratios (4.0 and 2.8) currently used in National Inventory calculations. There is good reason to challenge the Tier 1 assumptions, as a higher proportion of the C fixed by the plant is allocated belowground in environments where nutrients are scarce, such as in Low producing grassland, compared with High producing grassland. The review also identified an overall lower C concentration in plant tissue than that used in the inventory. This might be contributing to an overestimation of vegetation C stocks in grassland. We suggest the replacement of Tier 1 with Tier 2 values. Doing so provides a more accurate assessment of the C stocks in New Zealand grassland for the purpose of inventory reporting.

Keywords: aboveground biomass, belowground biomass, climate policy, national inventory, root-to-shoot ratio

Introduction

Sequestered carbon (C) in long-lived organic stocks is emerging as an important product of rural enterprises in New Zealand (NZ). Carbon markets are well established for aboveground woody vegetation domestically (Ministry for Primary Industries 2025) and for soil organic C overseas (Barbato and Strong 2023). There are continued expectations of substantive potential for the inclusion of C sequestered in grassland and stored in soil organic matter to be added to our inventories. Despite an increasing interest in C stocks and stock changes beyond forestry, estimates of vegetation C stock values of grassland (i.e., the living aboveground and belowground biomass) are scarce in NZ. Addressing this information gap is important for GHG accounting and reporting to the Intergovernmental Panel on Climate Change (IPCC), while also supporting recognition and potential rewards for C sequestered in vegetation beyond ETS eligibility.

Carbon stocks in NZ's grassland are affected by both natural drivers (i.e., climate, soil and vegetation) and human activities (e.g., fertilisers, cultivation, pasture species, livestock type, and grazing practices and fencing designs). Grasslands vary in their intensity of use, from extensively managed tussock rangelands to intensively managed sown pastures. At large, rainfall, soil characteristics and topography, over which farming operations impose local modifiers, determine the spatial distribution of grassland biomass across the country (Tran et al. 2025). Improving estimates of grassland vegetation C stocks therefore requires locally representative parameters that account for both environmental conditions and the way grasslands are managed and used by farmers throughout NZ.

In the Land Use, Land-Use Change and Forestry (LULUCF) sector, the current approach for the assessment of biomass C stock estimates of NZ grassland comprises a combination of Tier 1 IPCC default values and Tier 2 methodologies (Ministry for the Environment 2025). By reviewing published literature, this project aimed to provide a scientifically defensible framework and dataset for estimating the C stocks in NZ grassland ecosystems, that recognises spatiotemporal variability that would meet the criteria set out in the IPCC Tier 2 guidelines. A combination of literature, databases and modelling were used to assemble NZ-specific values of aboveground (AGB) and belowground biomass (BGB) to make the case for a shift from a Tier 1 to

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a Tier 2 approach to improve the quantification of the vegetation C stocks of grasslands. This will provide a more accurate assessment of the C stocks in grasslands without woody biomass and increase the granularity of data available for assessing the impact of land use change within the grassland biome on C stocks for the purpose of inventory reporting.

Materials and Methods

How are vegetation carbon stocks currently calculated in the National Inventory?

Carbon stocks from grassland are currently estimated for individual grassland types in the National Inventory as follows:

C stock (t C) = Area (ha) × [peak AGB + peak BGB] (t DM) × Conc (t C/t DM) [Equation 1]

where C stock is the total C stock in vegetation for a given grassland type, Area is the total mapped area of a given grassland type (ha), peak AGB and peak BGB are the maximum aboveground biomass and maximum belowground biomass of a given annual growth cycle (on a dry matter basis), and Conc is the concentration of C in biomass (Tier 1 value = 47%). These grassland C stocks are then converted to CO_2 equivalents (CO_2-e) according to atomic mass (1 kg C = 3.67 kg CO_2) and are expressed as kt CO_2-e (Ministry for the Environment 2025).

The areas in each grassland type are derived from the most recent land-use map in the Land Use and Carbon Assessment System (LUCAS), which is based on the Land Cover Database (LCDB) and is generally updated every four years (Ministry for the Environment 2024). This change in area (or 'activity data') is one mechanism by which the total C stock for a grassland type may change over time.

Land classes and grassland vegetation

The relevant grassland types within the Grassland land class category include the subcategories 'High producing grassland' and 'Low producing grassland', and 'Grassland with woody biomass'.

- *High producing grassland* is defined as intensively managed pastureland with high quality pasture species.
- *Low producing grassland* is defined as hill country pastures with low fertility grasses and areas with native tussock and shrubby vegetation.
- *Grassland with woody biomass* is defined as areas with woody species in <30% of the area and/or do not meet the definition of a forest due to management regime or vegetation and/or environmental constraints (Ministry for the Environment 2024).

Because the calculation of C stocks in Grassland with woody biomass already follows a Tier 2 approach (Wakelin and Beets 2013), this study focused on the High and Low producing grassland subcategories.

High producing grasslands are managed sown grasslands that receive regular inputs such as P and N fertilizers, are cultivated and sown with new plant germplasm and are intensively grazed by livestock throughout the year. These are typically located on flat and rolling landscapes, under dairying and intensive sheep and beef operations.

Low producing grasslands are also managed grasslands, but with low P and minimal N fertilizer inputs, rarely cultivated and/or over sown with new germplasm, and are often grazed at lower stocking rates by sheep and cattle than high producing grasslands. These are located in predominantly hill and steep land in both Islands and in the high country of the South Island. These areas tend to experience climatic (rainfall and temperature) extremes, often on soils that are poorly developed, shallow and with limited natural capital.

From Tier 1 to Tier 2

Region-or country-specific data on AGB and BGB are needed for a Tier 2 approach (IPCC 2006). New Zealand uses a combination of Tier 1 and Tier 2 for estimating C emissions and removals of Grassland in the LULUCF sector. The High and Low producing grassland C stock values are currently obtained following a Tier 1 approach from IPCC guidelines (IPCC 2006) and are based on the Warm Temperate-Wet biomass biome (AGB + BGB = 13,500 kg DM/ha) and Warm Temperate-Dry biomass biome (AGB + BGB = 6,100 kg DM/ha) (Table 1). A C concentration of 47% in plant tissue is assumed for both AGB and BGB (DM basis). These mean values can be considered Tier 1 emission factors and have been obtained from the Oak Ridge National Laboratory Distributed Active Archive Centre net primary production data collection (IPCC 2006). This dataset is derived from about 100 study sites worldwide, including 37 datasets for Grassland. In translating these data for a NZ context it is important to note that they are typically not derived from grazed grasslands.

Estimating BGB is a critical part of grassland biomass assessments (e.g., IPCC 2006), but direct field measurements are often laborious and difficult, and so data are often limited. As a result, 'expansion factors' are commonly used to estimate BGB from AGB. Under the IPCC Tier 1 and 2 methodology, default root-to-shoot ratios are used as expansion factors to estimate BGB (IPCC 2006). Root-to-shoot ratios of 4.0 and 2.8 are assumed for Warm Temperate-Wet and Warm Temperate-Dry grassland, respectively (IPCC 2006) and thus for NZ High and Low producing grassland subcategories (Table 1). Therefore, moving the High and Low producing grassland type calculations to a Tier 2 approach, consistent with the current approach to Grassland with Woody Biomass, requires provision of NZ-specific values for the following:

- Peak AGB,
- Peak BGB or an AGB:BGB expansion factor, and
- Concentration of C in AGB and BGB.

Here we explore the literature, firstly in terms of AGB and BGB (2nd predictor in Equation 1), with an emphasis on root-to-shoot ratios, followed by C concentration in grassland biomass (3rd predictor in Equation 1).

Aboveground biomass for Tier 2

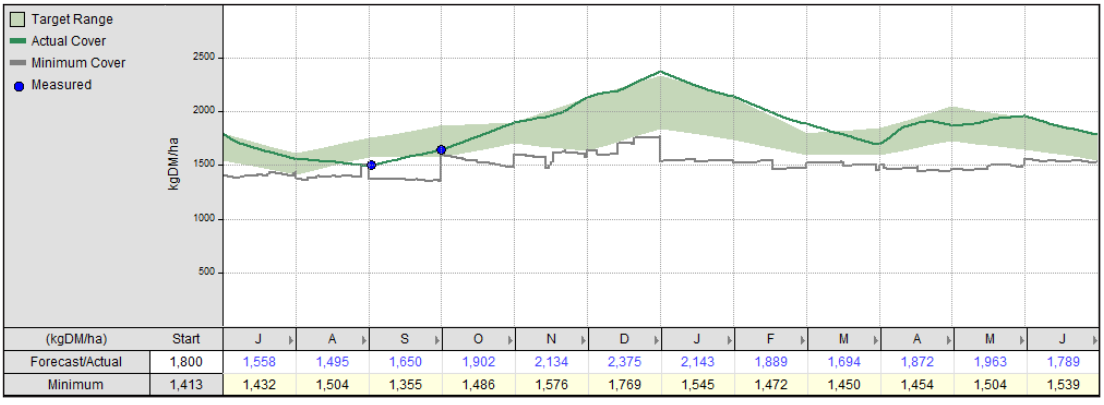
The simplest Tier 2 approach for deriving AGB C stocks in grasslands involves replacing the internationally derived Tier 1 values (IPCC 2006) with values estimated from NZ national data. However, at present there is no national survey of grassland AGB (equivalent to pasture cover).

A broad-scale national source of AGB data are on-farm pasture cover measures and estimates extracted from the FARMAX database (https://www.farmax.co.nz). FARMAX is a farm system modelling and management tool that is widely used in feed budgeting in the pastoral sector. As of 2024, the cloud-based FARMAX dataset includes records of approx. 260 individual farms across New Zealand. The FARMAX database contains records of seasonal pasture cover for a range of farm systems across New Zealand. Pasture cover data are derived from a combination of actual measurements and modelling, whereby farm managers record pasture areas under grazing, livestock numbers, performance and requirements, supplementary feed used and (in some cases) measure actual pasture cover and/or pasture growth rates. These data are generally recorded in monthly time steps. Built-in feeding tables can determine the quantity of feed intake to reach the given performance observations (DM intake). The combination of animal demand, supplementary feed quantities, pasture growth rates and block areas provide a realistic estimate of average pasture cover (AGB) on a monthly basis across the farm. In the FARMAX model user interface, data are presented in a table and a seasonal chart, with maximum farm-scale average pasture cover extracted (Figure 1). In the example in Figure 1, maximum average cover occurs at the end of December (c. 2400 kg DM/ha).

A critical feature of the AGB data is that they represent a spatial area-weighted average of AGB at any given time of the year. Thus, this feature explicitly recognises that at any time within a farm, all paddocks can have different levels of pasture mass as a result of staggered rotational grazing. A single point in time snapshot of this is known as a "feed wedge" (Figure 2). While some paddocks will have a biomass greater than the spatial average, just prior to being grazed or the making of supplementary feeds (i.e., hay or silage), at no time does the entire area reach this 'peak biomass' cited in IPCC tables. For the purposes of an all-of NZ inventory, the spatial average biomass at its annual

Table 1 Carbon (C) biomass emission factors of New Zealand's Grassland land use category with aboveground (AGB) and belowground (BGB) biomass used in the National Inventory (Ministry for the Environment 2025). [1]Living biomass. [2]Carbon gain through plant growth is balanced by plant loss (steady state; for comparison with Tier 1 IPCC default values).

Land use	C pool[1]	Steady state C stock[2] (t C/ha)	Root-to-shoot C ratio	Reference
High producing grassland	AGB	1.269	4:1	IPCC (2006)
	BGB	5.076		
	Total	6.345		
Low producing grassland	AGB	0.752	2.8:1	
	BGB	2.115		
	Total	2.867		



(kgDM/ha)	Start	J	A	S	O	N	D	J	F	M	A	M	J
Forecast/Actual	1,800	1,558	1,495	1,650	1,902	2,134	2,375	2,143	1,889	1,694	1,872	1,963	1,789
Minimum	1,413	1,432	1,504	1,355	1,486	1,576	1,769	1,545	1,472	1,450	1,454	1,504	1,539

Figure 1 Example of a seasonal cover chart of a Gisborne mixed livestock farm in 2022-23 from the FARMAX model. It includes actual average pasture cover across the whole farm produced by monthly animal data and pasture measurements.

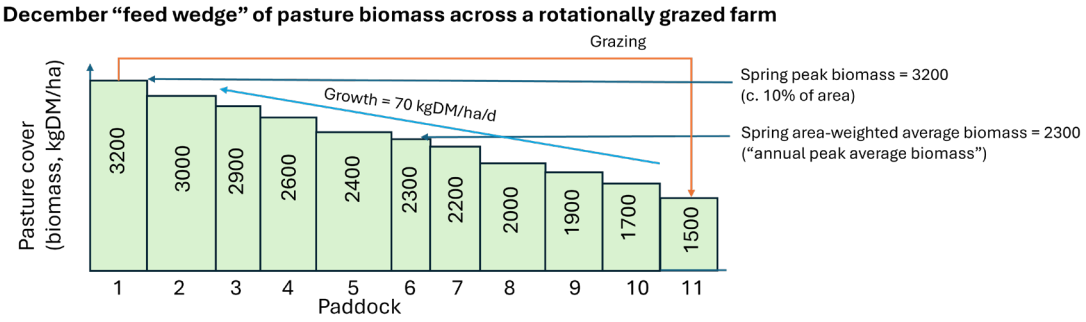


Figure 2 Simplified example of a "feed wedge" generated by rotational grazing of multiple paddocks within a typical New Zealand farm system, indicating peak biomass for individual paddocks compared with an area-weighted average biomass which reaches its maximum value, typically in December (see Figure 1).

peak value is the more relevant number than the peak biomass attainable for any given paddock.

On request, FARMAX extracted the data for the annual maximum average pasture cover on each farm in the database (at the end of December), starting in 2003 (when there were only 26 farms in the database) through to 2024 (256 farms). The geographic location of each farm was also supplied, to align them with the LUCAS grassland land class subcategories (Figure 3).

The current Tier 1 approach uses a fixed value for peak standing biomass, derived largely from extensive ungrazed grassland biomes with limited management inputs. New Zealand grasslands are far more dynamic (Figure 1), with cycles of regrowth after grazing (Figure 2) and the periodic renewal of pastures and nitrogen fertiliser input. Both are known to influence AGB and BGB in the short-term (within a growing season) and the long-term (over decadal scales). This has implications for both the need for disaggregation of land use types within the grassland category and the time at which stocks are estimated (i.e., on an annual basis, comparing the highly variable late spring peak vs. the more consistent mid-winter growth, Figure 1).

Belowground biomass for Tier 2

There are no systematic data collection and curation for BGB in NZ. The lack of monitoring is most likely due to a combination of factors, including limited interest by either pasture managers, researchers or policy agencies. The difficulty of obtaining root biomass data is no doubt one of the reasons for the limited interest. There have been a modest number of research studies that measured instantaneous root mass, and a smaller number of studies that followed root dynamics over time (e.g., Barker et al. 1988; Matthew 1992; Nie et al. 1997; Dodd et al. 2011). Therefore, the most appropriate approach was to derive NZ-based values for BGB:AGB (effectively root-to-shoot ratios) from such studies and apply them to the AGB vales derived from the FARMAX data.

A literature search was conducted using published and unpublished articles, reports, masters/doctoral dissertations and datasets that reported field measurements of AGB and BGB in NZ grasslands. In a first attempt, 25 NZ sources were identified. Of these 25 sources, only six studies provided sufficient data to estimate root-to-shoot ratios from High producing grasslands (Matthew 1992; Saggar and Hedley 2001; Black et al. 2006; Dodd et al. 2011; McNally et al. 2017; Garbuz et al. 2021) and five studies from Low producing grasslands (Barker et al. 1988; Nie et al. 1997; Barker et al. 1998; Saggar et al. 1999; Garbuz et al. 2021). The dataset compiled from this search includes experimental details such as location, soil type, plant species, topographic features, treatments, and research objectives.

Statistical analysis

A simple unbalanced ANOVA was conducted to determine whether the interannual differences and regional differences in annual maximum pasture covers (kg DM/ha) for FARMAX registered farms located within LUCAS High Producing and Low Producing grassland cover types across New Zealand, over four selected years were significant for the two grassland productivity types.

Results and Discussion

Peak aboveground biomass

The number of data-contributing farms has increased over time to provide a more robust sample of national average in more recent years (Table 2). For the purpose of this analysis, data for 2012, 2016 and 2020 were selected, coinciding with the years for which LUCAS provides land class data, as well as the most recent year (2024). The data also emphasise the interannual variability of annual maximum average pasture cover, which will be mainly a function of the variation in seasonal pasture supply (driven by climate) and feed demand (driven by management decisions).

A simple unbalanced ANOVA was conducted to determine whether the interannual differences and

Table 2 Annual maximum average pasture cover (kg DM/ha) for FARMAX registered farms located within LUCAS High producing and Low producing grassland cover types across New Zealand, over four selected years.

Grassland type		2012	2016	2020	2024
High producing	Annual maximum average pasture cover (kg DM/ha)	2,385	2,375	2,439	2,534
	Farm numbers	23	49	73	209
Low producing	Annual maximum average pasture cover (kg DM/ha)	2,490	2,639	2,530	2,355
	Farm numbers	3	10	10	22

regional differences were significant for the two grassland types. The effect of region was significant ($p<0.05$) with a range of 234 kg DM/ha (c. ±5%), but there was no significant year effect. Therefore, it is reasonable to infer that a single multi-year national mean value can be used for each grassland type. The mean values over time from Table 2 are 2,490 kg DM/ha for High producing grassland and 2,414 kg DM/ha for Low producing grassland. These values differ from those currently used in the NZ National Inventory (2,700 and 1,600 kg DM/ha, respectively).

A key weakness of the use of FARMAX-derived data for estimating peak AGB is the unbalanced spatial coverage of the data across the two main grassland subcategories (Figure 3). Developments in commercial remote sensing services probably represent the best and most cost-effective opportunity into the future to provide representative data at a national scale (Anderson et al. 2020).

Aboveground and belowground grassland biomass

Grassland root-to-shoot ratios are effective parameters to describe the allocation between AGB and BGB, and thus provide a practical tool to estimate BGB by a relatively easier to obtain estimate of AGB, and can show a wide range in values. Single- and multiple-year NZ studies that have reported both AGB and BGB values of High producing grasslands have allowed for the estimation of root-to-shoot ratios across different seasons (Saggar and Hedley 2001; Dodd et al. 2011), re-grassing management (McNally et al. 2017), sowing dates and seed rates (Black et al. 2006), and different defoliation regimes (Matthew 1992). Similarly, studies that have reported AGB and BGB values of Low producing grasslands provide estimates from farmlets with contrasting fertiliser input and livestock carrying capacity (Barker et al. 1988; Barker et al. 1998) and slope classes (Saggar et al. 1999), as well as seasonal effects (Dodd et al. 2011). The effect of a pastoral fallow (Nie et al. 1997) and biochar addition

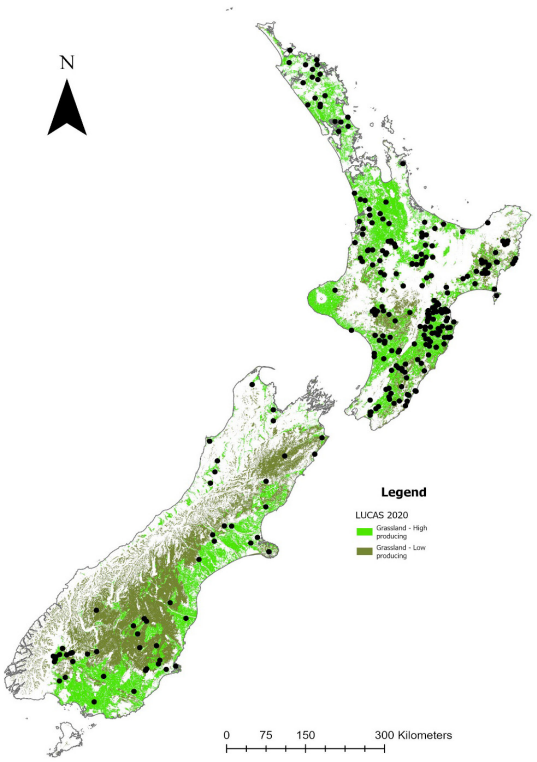


Figure 3 Black dots indicate location of individual farms (as at 2024) against the LUCAS vegetation cover classes (2020 layer).

on root growth (Garbuz et al. 2021) have also been reported. These studies suggest that factors such as season, pasture renewal, defoliation, soil fertility, and topographic features such as slope and aspect, influence root-to-shoot ratios, and are all important in deriving representative root-to-shoot values that can be used across the grassland types found in NZ.

Collectively, the ten studies presented here reported 72 root-to-shoot ratio treatment means, ranging from 0.23 (High producing grassland; Matthew 1992) to 7.04 (Low producing grassland; Garbuz et al. 2021). Aboveground biomass values >4,500 kg DM/ha (and their pairing BGB value and root-to-shoot ratio) were removed from the dataset as these are not representative of managed grazing systems. For this reason, 27 treatment means were removed from the High producing grassland dataset and two treatment means were removed from the Low producing grassland dataset. The remaining treatment means were used to obtain the recommended root-to-shoot ratios.

For High producing grassland, AGB values ranged from 1,009 to 4,460 kg DM/ha, and BGB values ranged from 906 to 9,742 kg DM/ha. The overall mean root-to-shoot ratio, obtained from the sum of selected AGB and BGB treatment means was 1.35 (n = 33 treatment

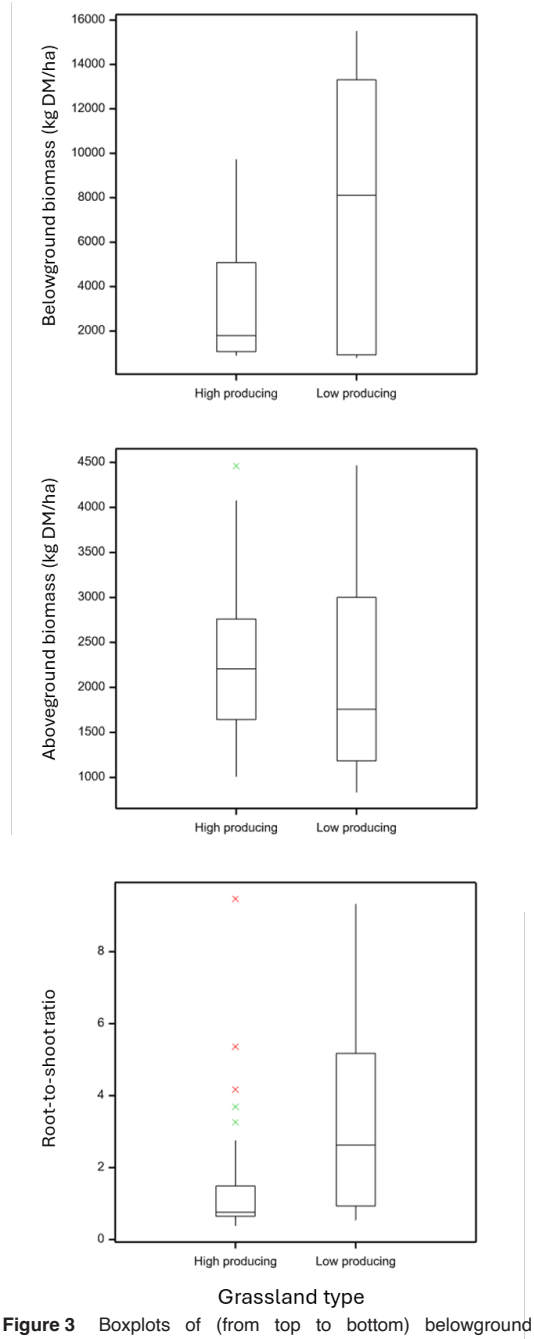


Figure 3 Boxplots of (from top to bottom) belowground biomass (kg DM/ha), aboveground biomass (kg DM/ha), and root-to-shoot ratios of High and Low producing grassland (n = 33 and 10 treatment means, respectively).

means; SD = 1.86). For Low producing grassland, AGB values ranged from 837 to 4,470 kg DM/ha, and BGB values ranged from 793 to 15,517 kg DM/ha. The corresponding overall mean root-to-shoot ratio value for the Low producing grassland was 3.64 (n = 10 treatment means; SD = 2.91) (Figure 3).

The root-to-shoot ratios of High and Low producing grassland (1.35 and 3.64, respectively) differ substantially from those currently used in National Inventory calculations (4.0 and 2.8;). There is good reason to challenge the latter value in particular, as a higher proportion of C fixed by the plant is allocated belowground (BGB) in environments where nutrients are scarce (e.g., Wang et al. 2014), such as in low producing grasslands, compared with high producing grasslands. Conversely, under high fertility and often non-limiting moisture conditions, a higher proportion of C remains aboveground (Saggar and Hedley 2001).

Carbon concentration in grassland biomass

There is no systematic data collection and dataset for the concentration of C in grassland biomass in NZ largely due to the minimal value placed on C concentration in pastures relative to essential nutrient concentrations (e.g., N, P, K, S). Even amongst the research literature, there are very few reported values. Jordan (2015) cites a generic value of 40% C concentration of mixed species root biomass obtained from the data of McNally et al. (2015), who presented C concentrations that ranged from 36.3 to 44.2% depending on species. These results are similar to those obtained from the NZ Free Air Cabon dioxide Enrichment (FACE) experiment (S. Brock, unpublished data) and those obtained from Massey University Dairy Farm, Unit I (Saggar and Hedley 2001). There appears to be good evidence that the current inventory value of 47% is not appropriate for NZ grasslands and as such merits further scrutiny.

Practical implications

Tier 1 values currently used for estimating AGB, BGB and grassland biomass C concentration in High and Low producing grassland types should be replaced with New Zealand-specific Tier 2 values. The FARMAX-derived dataset of annual maximum average pasture covers, combined with the root-to-shoot ratios derived from NZ-based studies and an improved estimate of plant tissue C concentration, could be used to replace the Tier 1 values for aboveground biomass C stocks in grassland with single AGB and BGB Tier 2 values for each grassland type. This would bring the inventory approach into alignment with the Tier 2 approach used for the Grassland with woody biomass vegetation type. Further research is needed to derive a national database of aboveground and belowground biomass values for High producing and Low producing grassland types, utilising an approach based on ground-calibrated remote sensing data. Collectively, these recommendations will provide a more accurate assessment of the C stocks in New Zealand grasslands and increase the granularity of data available for assessing the impact of land use change within the grassland biome on C stocks for the purpose of inventory monitoring.

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