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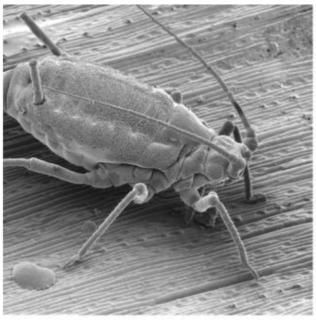
Pasture renewal activity data and factors for New Zealand

Steve Thomas, Dirk Wallace, Mike Beare

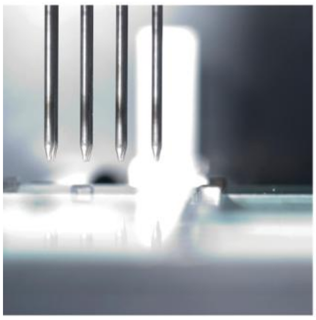
July 2014





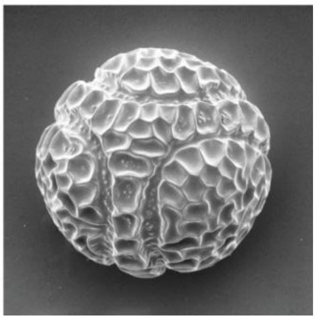










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Pasture renewal was identified as an unaccounted source of nitrous oxide (N_2O) emissions in the Intergovernmental Panel on Climate Change (IPCC) 2006 guidelines that was ignored in the earlier IPCC 1996 guidelines. As part of reporting commitments under the United Nations Framework Convention on Climate Change (UNFCCC), all Parties, including New Zealand, are now required to account for N_2O emissions due to perennial forage renewal following the IPCC 2006 guidelines.

This report provides a review of available information for relevant factors and activity data for estimating New Zealand N_2O emissions from pasture renewal following IPCC 2006 guidelines. The activity data and factors include: (i) the total area of grass-clover and lucerne (nitrogen fixing perennial forage), (ii) average annual yield information, (iii) above- and below-ground residues (amounts or factors) required to estimate the additional amount of nitrogen (N) released through renewal practices. We have reviewed and recommended activity data from 1990 to 2013, required for UNFCCC reporting. These and recommended factors can be applied in a spreadsheet that is consistent with IPCC 2006 guidelines.

A key finding is that there is very limited information for the amount of N contained in above- and below-ground residues. There are large differences in the N contained in grass-clover above- and below-ground residues depending on soil fertility and seasonality. Least is known about the amount of N contained in below-ground residue and how much of this residue will contribute to additional N_2O emissions due to renewal, i.e. above normal turnover rates. This is important because most of the N contributing to emission from renewal is below ground in the roots. These estimates of below ground residues are highly uncertain due to large variability in pasture root biomass and the low number of relevant studies representing the range of management and environments.

Based on the review of the available literature and expert advice, we have made recommendations for: crop (T) and yield ($Crop_{(T)}$) information, above-ground ($AG_{DM(T)}$) and below-ground residue ($BG_{DM(T)}$) dry matter, the ratio of below-ground dry matter to annual above-ground production ($R_{BG(T)}$) and above-ground and below-ground nitrogen contents ($N_{AG(T)}$ and $N_{BG(T)}$).

We recommend that MPI:

- Report activity data and factors for:
  - Grass-clover for low-fertility (sheep and beef) and high-fertility (dairy) farming systems separately.
  - Nitrogen-fixing perennial forage (lucerne)
- Use factors in the summary table below

Recommended annual yield, above- and below-ground residue dry matter and nitrogen contents for grass-clover and nitrogen fixing crops.

Pasture/Forage (T)	Crop Yield ($Crop$) (kg DM/ha/yr)	Above-ground residue ($AG_{DM(T)}$) (Mg DM/ha/yr)	Above-ground residue N content (N_{AG}) (g/kg DM)	Below-ground residue ($BG_{DM(T)}$) (Mg DM/ha/yr)	Ratio of ($BG_{(DM(T))}$ to ($Crop$/1000+$AG_{DM(T)}$) (R_{BG}) (kg DM/kg DM)	Below-ground residue N content (N_{BG}) (g/kg DM)
Grass-clover - sheep & beef	9,000	0.75	0.02	-	0.8 (± 50%)	0.012
Grass-clover - dairy	14,000	1.4	0.02	-	0.2	0.016
Lucerne - all	12,000	0.9	0.019	3.9	-	0.014

For Crop Area activity we recommend MPI:

- Use Agricultural Production Statistics (Statistics New Zealand) data for estimating grass-clover area.
- Report pasture renewal area for sheep and beef and dairy systems at a national scale based on the current availability of data.
- Use a 1990 value of 84,000 ha for lucerne.
- Use estimates of lucerne area based on seed import and New Zealand seed certification data available from 1990, assumed sowing rates of 8 kg seed/ha and renewal rate of 10% per annum. Based on these estimates the area of lucerne has increased to about 130,000 ha in 2013.

For estimating the amount of renewal activity data we recommend MPI:

- Use Plant & Food Research survey results from 1990 to 2008
- Use Statistics New Zealand data from 2009 to 2013, assuming it can be disaggregated into sheep, beef, deer and dairy, otherwise use recommended Plant & Food Research survey data. Pasture renewal rates between 2009 and 2013 are similar for the two surveys, indicating that this combined approach is appropriate for estimating pasture renewal across the time sequence from 1990.

This report includes tables with activity data and factors for estimating the amount of N_2O produced from pasture renewal for grass-clover pastures and nitrogen-fixing perennial forage (lucerne) from 1990 to 2013.

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1 Introduction

New Zealand is required to report and improve the inventory of annual greenhouse gas (GHG) emissions to the United Nations Framework Convention on Climate Change (UNFCCC). Renewal of perennial forages (pasture renewal) was identified as an unaccounted source of N_2O emissions in the Intergovernmental Panel on Climate Change (IPCC) 2006 guidelines that was ignored in the earlier IPCC 1996 guidelines (IPCC 2006). Consequently, as part of New Zealand's UNFCCC reporting commitment, New Zealand (as are other Parties) is now required to account for N_2O emissions due to perennial forage renewal following the IPCC 2006 guidelines.

While, the earlier IPCC 1996 guidelines accounted for the mineralisation of above- and below-ground residues from annual crops, including from annual forage crops, the effects of mineralisation of above- and below-ground residues during the periodic renewal of perennial forage crops and pasture residues was not included. This omission as a potential important source of N_2O emissions was acknowledged with its inclusion in the IPCC 2006 Guidelines. The values for annual forage crop activity data were proposed in the earlier report by Curtin et al (2011).

In their review of the changes introduced in the IPCC 2006 guidelines, van der Weerden et al (2009) observed that there is a lack of readily available activity data for estimating N_2O emissions resulting from pastoral renewal.

MPI contracted Plant & Food Research to collate and review available activity data required to estimate N_2O emissions associated with perennial forage crops and pastoral renewal in New Zealand for the period 1990 – 2013 following the IPCC 2006 guidelines (IPCC 2006).

This report provides the collation of the activity data and recommendations for appropriate factors and activity data to enable MPI to report N_2O emissions associated with renewal of perennial forage crops and pasture following the IPCC 2006 Tier 1 methodology. These can be applied in a spreadsheet consistent with IPCC 2006 guidelines. Specifically, using the IPCC terminology, these data are required to estimate the amount of N in N-fixing and non-N-fixing forage crop residues, above-and below-ground, returned to soils annually, mineralised during forage or pasture renewal (F_{CR}) (IPCC 2006).

In New Zealand, pasture renewal may be defined as the complete destruction of low quality pasture followed by the sowing of improved pasture species/varieties. It is promoted as a simple method to increase farm gate profits in both dairy and dry stock (e.g. sheep, deer and non-dairy cattle) farming. A recent report has found that increasing annual pasture renewal from 2% to 8% of pastoral land on dry stock farms and from 6% to 12% on dairy units can increase farm gate profits by 18% and 16% respectively (Sanderson & Dustow 2011).

Although there is evidence that the method of renewal affects N_2O emissions (Thomas et al. 2008; Thomas et al. 2013), the IPCC 2006 default methodology does estimate the impact of the method of renewal on emissions; and is therefore beyond the scope of this report. The effect of different renewal practices on N mineralisation and N_2O emissions was considered in the earlier report by Beare et al. (2012). For completeness, we have included a summary of how renewal practice can impact N_2O emissions in Appendix 1.

2 IPCC 2006 methodology

2.1 Background

The IPCC 2006 guidelines cite two key studies that found significant increases in N_2O emissions following pasture renewal (IPCC 2006). This includes one New Zealand study by van der Weerden et al (1999) for the cultivation of a legume pasture. Including N_2O emissions from pasture renewal acknowledges the likelihood of increased emissions due to mineralisation of above- and below-ground pasture and perennial forage crop residues, and is consistent with the treatment of residues as a source of N_2O emissions from annual crops. However, there is a lack of data where N_2O emissions have been measured from pasture renewal events.

2.2 Relevant factors and activity data

The IPCC 2006 guidelines provides two equations for calculating the annual amount of N (kg N/yr) in above- and below-ground crop residues (F_{CR}) returned to soils annually and mineralised. The equations are 11.6 and 11.7A (IPCC 2006) and they are used for all crop residues including N fixing crops and from forage/pasture renewal. The original equations have been corrected in the 6th and 8th Corrigenda for IPCC 2006 Guidelines found on the IPCC website (http://www.ipcc-nggip.iges.or.jp). Both equations provide a Tier 1 approach for estimating N from crop residues and forage/pasture renewal.

Nitrous oxide emissions from F_{CR} are estimated by multiplying with EF_1, the emission factor for N_2O emissions from N inputs (kg N_2O-N/kg N input), i.e. the same factor for N additions from mineral fertilisers, organic amendments and crop residues, and N mineralised from mineral soil as a result of loss of soil carbon [kg N_2O–N/ kg N](IPCC 2006). The IPCC default value is 0.01 kg N_2O–N/ kg N.

IPCC equation 11.6:

$$F_{CR} = \sum \{Crop_{(T)} \times FracRenew_{(T)} \times \left[\left(Area_{(T)} - Areaburnt_{(T)} \times CF\right) \times R_{AG(T)} \times N_{AG(T)} \times \left(1 - Frac_{Remove(T)}\right) + Area_{(T)} \times R_{BG(T)} \times N_{BG(T)}\right]\}$$

Where, T is the crop or forage type,

$Crop_{(T)}$ is the average <u>annual</u> above-ground dry matter (DM) produced by the perennial forage crop or pasture, *T* (kg DM/ha). The IPCC 2006 guidelines lists four types of perennial forage or pasture types (*T*) to consider: (i) N fixing and (ii) non-N fixing forages, (iii) perennial grasses and (iv) grass-clover mixture.

$FracRenew_{(T)}$ is the fraction of total area under crop *T* that is renewed annually, where pastures are renewed on average every X years, *FracRenew* = 1/X,

$Area_{(T)}$ is the total annual area harvested of crop *T* (ha/yr),

As there is no data to suggest that forage crops or pasture are burnt as part of pasture renewal in New Zealand the *$Areaburnt_{(T)}$* and combustion factor (*CF*) are ignored.

$R_{AG(T)}$ = Ratio of above-ground residue dry matter to harvested yield for crop *T* (kg DM/ kg DM)

$N_{AG(T)}$ = N content of above-ground residues for crop *T (kg N/kg DM)*,

$Frac_{Remove(T)}$ = fraction of above-ground residues of crop *T* removed annually for feed, bedding and construction. It is used for calculating the above-ground residue of the forage crop and pasture. We propose a more direct method of estimating this residue so this factor can be ignored.

$R_{BG(T)}$ = Ratio of below-ground residues to harvested yield for crop *T* (kg DM/ kg DM),

$N_{BG(T)}$ = N content of below-ground residues for crop *T (kg N/kg DM)*,

2.3 Recommended modified equation for New Zealand

Our recommended, simplified and more robust approach for pasture renewal in New Zealand is:

$$F_{CR} = \sum_{T} \{FracRenew_{(T)} \times Area_{(T)} \times [(AG_{DM(T)} \times N_{AG(T)}) + (BG_{DM(T)} \times N_{BG(T)})]\}$$

Where, $AG_{DM(T)}$ is the above-ground dry matter residue and $BG_{DM(T)}$ is the below-ground dry matter residue. The key difference between this simplified equation and the IPCC 2006 methodology is the way that the above- and below-ground dry matter residue is estimated when pastures and crops are grazed or mown pre-renewal.

3 Review of activity data and relevant factors for pasture renewal practices in New Zealand

3.1 Perennial forage crop systems (*T*) to include in the inventory

Four species account for 98% of herbage seeds grown in New Zealand: perennial ryegrass (*Lolium perenne*), Italian ryegrass (*Lolium multiflorum*), tall fescue (*Festuca arundinacea*) and white clover (*Trifolium repens*), of which 70 to 80 % is perennial ryegrass (Pyke et al. 2004). Almost all pastures renewed in New Zealand are sown with some clover species (usually this is white clover) and most have a component of ryegrass; exceptions include Northland where sub-tropical C4 Kikuyu grass is sometimes sown.

Exceptions where single grass (or clover) crops are sown include herbage seed crops. Crop residue from these grass and clover seed crops (typically grown in Canterbury as part of a mixed-cropping rotation) is covered in the inventory calculations for annual crops. It is unclear whether these crops should now be accounted for as part of pasture renewal since they are often grazed and grown for more than one year. In this report we assume the former, i.e. that they are accounted for as annual crops.

Based on these data, we recommend that (i) grass-clover data is reported and (ii) that perennial grasses are not reported as a separate crop category.

We considered whether there is any merit in further disaggregating grass-clover systems for the estimation of F_{CR} based on species composition. While most pastures are ryegrass based, the proportion of clover varies widely, and other grasses may also compete with ryegrass. Caradus et al. (1996) estimated the proportion of clover in permanent grass-clover sown pastures to range between 2-20 % clover. Clover amounts are affected by livestock grazing, other management (e.g. fertiliser, grazing timing) and pest pressure (e.g. clover root weevil, clover flea, porina etc.). In high N inputs systems ryegrass can out compete clover, while preferential grazing of clover by sheep may lower clover production (Sharp 2007). A recent botanical survey of dairy pastures in New Zealand's three highest producing dairy areas reported clover and ryegrass percentages of grass-clover swards of 11% and 85% respectively for Canterbury (13 farms), 8% and 75% respectively for Taranaki (13 farms) and 11% and 59% respectively for the Waikato-Bay of Plenty area (14 farms) (Tozer et al. 2014).

An option we considered to estimate grass-clover composition is to use seed sale data and assumed sowing rates. However, this is likely to problematic. In particular, it assumes that sowing rates and resulting species composition in the field are the same. As the study by Caradus et al. (1996) and others indicates, actual species persistence and pasture composition varies greatly. Given the large effects of a range of factors on pasture composition, including grazing and fertiliser management, weed competition, pest pressure and soil and climate factors, we do not recommend using seed sale or sowing data. The second factor we considered on the merits of disaggregating grass-clover systems based on species composition was whether there would be sufficient information about the effect of composition on the amounts of residue N. We have concluded from our review of available information that there is insufficient residue N data from pastures of different compositions to support disaggregation.

The second type of perennial forage crop we recommend reporting is N-fixing perennial forage, i.e. lucerne. Lucerne has been grown as perennial forage in New Zealand for many years. Planting area peaked at about 220,000 ha in the 1970s but had declined to about 84,000 ha in the late 1980s (Purves & Wynn-Williams 1989). In the last decade or more there has been a resurgence in the use of lucerne forage with over 10,000 ha sown a year, based on seed sale information (Derrick Moot pers. comm. 2014).

There is some use of non-N fixing perennial forages such as plantain and chicory sown as individual forage crops in dairy systems to provide summer feed. These are considered "specialist" crops. They require different grazing management to grass-clover pasture. Due to declining productivity, chicory crops are normally grown in the North Island dairy farms for 2-years only (John de Ruiter pers. comm. 2014). The area of planting is presumed to be small and there are no current data available on the areas sown as either single crops or as part of pasture mixes dominated by ryegrass and clover. According to Moloney and Milne (1993), between 8,000 and 10,000 ha of chicory was reportedly sown with clover or mixed with grass-clover (i.e. not as a single crop) for sheep grazing in 1993, although they provided no evidence to support this. Currently (and since 1990), due to the small size of these plantings, we do not believe that there is justification for including non-N fixing forages as a separate forage crop type. This could be considered in the future if there is evidence of more widespread use.

Of the four categories of perennial forage that the IPCC 2006 guidelines list for pasture renewal, we believe only two categories are appropriate for New Zealand. These are the grass-clover systems that dominate New Zealand pastoral farming systems and lucerne (N-fixing perennial forage).

4 Crop production (*Crop*$_{(T)}$)

4.1 Grass-clover

Annual grass-clover pasture production is highly variable and is affected by management (e.g. nutrient inputs, stocking, grazing rotation, irrigation, pasture mixes) and environmental (e.g. climate, slope, soil) conditions. These vary between and within farming system types. We propose that high-fertility (i.e. dairy) and low-fertility (sheep and beef) farming systems are reported separately. Key differences between these systems are highlighted in the following sections.

While maximum production levels of 26.6 Mg DM/ha/yr may be attainable, the actual "yield limitation" for ryegrass-white clover pastures is closer to 15 Mg DM/ha/yr (Clark et al. 2001). Improved conventional breeding may increase potential yield gains but these are likely to be small; <1% DM/yr when pastures are managed well (Clark et al. 2001).

4.1.1 Availability of DM yield data and changes since 1990.

Pasture yield data is not routinely collected or reported in national statistics. We have sought advice from pastoral experts from DairyNZ (Dawn Dalley and Kim Mashlan pers. comm. 2014.) and Beef & Lamb (Rob Gibson pers. comm. 2014) to determine whether there is any evidence of changes in pasture dry matter production since 1990. The expert comments were that while there is good annual data available for pastoral area, animal numbers, milk and meat production collected by Statistics New Zealand, DairyNZ and Beef and Lamb, there is a lack of similar annual pasture dry matter production information.

4.1.2 Dry matter production for dairy farms systems.

Useful datasets are held by DairyNZ and much of this is published online (Kim Mashlan pers. comm. 2014). For example, many of these data are reported in their Facts and Figures publication for New Zealand Dairy Farmers (http://www.dairynz.co.nz). There is a range of annual data that have been collected over different time periods, across a range of regions and sites within regions where dry matter production has been measured or estimated from this data (Table 1). Based on an analysis of these data, only including sites that were measured between 1990 and 2013, the annual average dairy pasture production across regions is 14.0 Mg DM/ha/yr with a range of 9.1 – 20.0 Mg DM/ha/yr.

However, because of the lack of long-term datasets that span the period from 1990 to 2013 we are unable to adequately assess whether there have been any changing trends in annual dry matter production (Mg DM/ha). Temporal changes in annual pasture production will however have been largely affected by regional climate variability over this period and in particular the effect of rainfall variability on regional soil moisture deficits limiting pasture growth. For example, extreme affects on pasture growth in the recent 2012-2013 drought affected a number of regions (including Northland, Waikato, Bay of Plenty and the West Coast of the South Island), while most of the South Island was unaffected (Porteous & Mullen 2013). In a 9-year farmlet study at DairyNZ's Scott Farm in the Waikato, the average DM production was 18.7 Mg DM/ha/yr when N fertiliser was applied at an average rate of 181 kg N/ha/yr; annual DM production in the 9-year study varied from about 15 to 22 Mg DM ha/yr with no obvious trend (Glassey et al. 2013).

Table 1 Regional dairy grass-clover pasture annual production data from DairyNZ Facts and Figures for New Zealand dairy farmers (http://www.dairynz.co.nz).

	Annual dry matter production (Mg DM/ha)					
Region	Average	Range between sites	Sites	Earliest year	Latest year	Average number of years data collected
Northland	14.5	9.6 to 19.6	16	1992	2001	5.6
Waikato	14.3	11.6 to 16.6	16	1992	2002	2.4
Bay of Plenty	14.8	11.2 to 17.6	11	1990	2000	4.8
Taranaki	14.5	12.9 to 15.4	3	1990	2001	5.0
Lower North Island	11.8	9.1 to 13.3	12	1991	2003	2.6
Tasman/Marlborough	12.9	9.9 to14.2	6	1990	2000	4.2
Canterbury	17.3	14.2 to 20.0	3	2001	2010	2.7
West coast	13.3	9.7 to 16.3	10	1994	1997	2.1
Southland	12.9	11.6 to 14.4	11	1996	2004	3.5

There is scope to improve the certainty of these estimates in the future. For example, we are aware of unpublished datasets that may be useful. The Lincoln University Dairy Farm estimates and records annual dry matter production. However, the dairy farm was converted from sheep grazing in 2001 so does not cover the period from 1990. The early data may also be skewed in the early conversion period from sheep pasture when new pastures were established. Another option for estimating trends in pasture production would be to use milk production data and modelling the pasture consumed based on feed quality, utilisation, area grazed and feed imported. Industry databases (e.g. DairyNZ Dairybase) might be available to provide the necessary data to do this. However, because Dairybase is relatively new (records go back to 2000) it has limited ability to address 1990 to 2013 trends. These modelling approaches are beyond the scope of this report.

4.1.1 Dry matter production for sheep and beef pastures.

Pasture production on sheep and beef pasture systems varies greatly. Key determinants of sheep and beef pasture production and in particular hill county pasture are climate and site characteristics. On hill country, physical aspects such as slope and aspect influence moisture and fertility that in turn affects production (Dodd et al. 2004). Lower fertility pastures are also likely to have greater responses to nitrogen fertiliser. At the Ballantrae research farm in the Wairarapa high nitrogen rates of up to 400 kg N/ha/yr increased annual production of 9.2 Mg DM/ha/yr from the non-fertiliser control to more than 17.1 Mg DM/ha/yr (Lambert et al. 2003). Similarly, higher production is achieved through irrigation in areas where seasonally low rainfall amounts limit growth (Smith et al. 2012). Although field trials demonstrate production may be increased through greater use of fertiliser, irrigation or pasture renewal, the costs of these measures and the need to farm profitably may not justify this intensification (White et al. 2010). Changes in economic drivers since 1990 may be as important as other environmental or management factors affecting annual pasture DM production.

There are a limited number of reported long-term records of annual dry matter production data for sheep and beef farms. The longest continuous records for pasture production in New Zealand are from the long-term Winchmore irrigation and fertiliser trials in Canterbury. There are over 60 years of records for the fertiliser study at Winchmore. An analysis of annual dry matter production data between 1990 to 2007 found that pasture production remained static at 12 Mg DM/ha/yr (Smith et al. 2012). This result, from a relatively high fertility site, suggests that there is no basis for varying the annual dry matter production values between these years. Reduced annual production between 2007 and 2009 illustrates the effect that management (irrigation) had on production (Smith et al. 2012).

From the review of the literature there are a number of published studies that report annual dry matter production across a range of sites, treatments and years (Barker et al. 1988b; MacKay et al. 1991; Saggar et al. 1997; Lambert et al. 2003; Dodd et al. 2004; Allard et al. 2005; Gray et al. 2005; Mills et al. 2008; Scott et al. 2012; Smith et al. 2012). However, because of the range of different experimental and seasonal conditions it is difficult to assess how well they represent a particular farm system, region or year. There does not appear to be any published, comprehensive review of pasture production for sheep and beef farms across New Zealand that accounts for the range of management and environmental conditions. To partly address this we have sought expert advice on typical annual dry matter production values from sheep and beef systems across New Zealand (Table 2) (David Stevens, pers. comm. 2014).

Table 2 Annual pasture production estimates for Sheep and Beef farm classes for 2012. Data provided by David Stevens (pers. comm. 2014). Farm classes are defined by Beef + Lamb New Zealand (www.beeflambnz.com).

	Annual DM pasture production estimates and area for Sheep & Beef farm classes							
Class	**1 SI High Country**	**2 SI Hill**	**3 NI Hard Hill**	**4 NI Hill**	**5 NI Finishing**	**6 SI Finishing Breeding**	**7 SI Intensive Finishing**	**8 SI Mixed Finishing**
Annual DM production (Mg DM/ha/yr)	1.7	6.9	7.5	7.9	12	8.1	11	13.2
Area (000's ha)	1707	1213	977	1741	439	1305	330	239

SI - South Island

NI - North Island

A range of data is collected by Beef + Lamb New Zealand through national surveys including these farm classes (defined by Beef + Lamb New Zealand, www.beeflambnz.com). However the surveys do not collect pasture production or the pasture renewal data. MPI could investigate whether annual DM production data can be collected through these surveys or collected by Statistics New Zealand for the APS.

To estimate an appropriate annual DM production value for New Zealand sheep and beef farms that undergo pasture renewal, we have used the farm classes to provide a weighted average value. We believe this national weighted average approach for sheep and beef farms is necessary as we do not have pasture renewal data at the more detailed farm class level. We have assumed that pasture renewal of low fertility and productivity class 1 (SI high country) is negligible and that hill country farms (classes 2 to 4) can be grouped similarly based on annual production values (i.e. 6.9 to 7.9 Mg DM/ha/yr, Table 2). The weighted average (sum of the total production for each class/sum of the total area for the 3 classes) for classes 2 to 4 is 7.5 Mg DM/ha/yr. We have also assumed that the finishing farms (classes 5 to 8) can also be grouped similarly (i.e. 8.1 to 13.2 Mg DM/ha/yr, Table 2). The weighted average of this group is 9.8 Mg DM/ha/yr. Overall the weighted average for farm classes 2 to 8 is 9.0 Mg DM/ha/yr.

This approach can be refined in the future when more detailed information for pasture renewal becomes available.

4.2 N-fixing forage (lucerne)

Lucerne yields are also highly variable and are affected by similar management and environmental factors to grass-clover forages. Lucerne is grown in both the North and South Islands, but most is grown in the South Island. Most of the recent yield data available is based on research conducted in Canterbury. A report prepared by (Ward & Moot 2009) provides an excellent review of measured lucerne yields across New Zealand.

Although lucerne is well suited to dryland conditions with better drought tolerance than ryegrass, a key factor achieving potential yield is water availability, i.e. influenced by soil water storage and irrigation. Typically, irrigated crops are high producing. In dry years, irrigation has the potential to double yields. In a trial at Lincoln 28 Mg DM/ha/yr was produced in the first re-growth year and an average of 21 Mg DM/ha/yr over 6 years (range from 16 to 28 Mg DM/ha/yr), whereas dryland stands produced between 17.5 and 21 Mg DM/ha/yr under (Brown & Moot 2004; Brown et al. 2005). Rotations tend to be shorter in irrigated stands and on soils with high water availability due to disease and weed competition. Similar production (13.1 to 18.5 Mg DM/ha/yr) was measured for dryland conditions on the same deep soil type at Lincoln (Mills et al. 2008). On hill country in the Upper Waitaki, average dryland yields were 8.8 Mg DM/ha/yr (Anderson et al. 2014). On very stony Lismore soils in Canterbury, average yields were 6.5 Mg DM/ha/yr (Hayman 1985). Over 7 to 8 years, yields ranged from 8 to 11 Mg DM/ha/yr on shallow stony soils at Lincoln University's Ashley Dene research farm (Derrick Moot pers. comm. 2014). In the North Island near Hamilton, average annual yields were 10.8 Mg DM/ha/yr in the first year and 8.2 to 13.6 Mg DM/ha/yr in the following 4 years, and similar and higher yields have been recorded in the Waikato, Central Plateau region and Manawatu (Ward & Moot 2009).

Based on the available data (Table 3) and expert opinion of Derrick Moot (pers. comm. 2014), we propose that an average value of 12 Mg DM/ha/yr for lucerne is applied to lucerne crops between 1990 and 2013. This expert judgement considered the likely relative contribution of irrigated and dryland lucerne crops (Derrick Moot pers. comm. 2014)

Table 3 Summary of annual lucerne dry matter production

Site	Average annual production (Mg DM /ha	Range of annual production (Mg DM/ha)	Years	Soil type	Irrigated	source
Lincoln	22.0	16 to 28	6	Wakanui deep silt loam	yes	(Brown & Moot 2004; Brown et al. 2005)
Lincoln	19.3	17.5 to 21	6	Wakanui deep silt loam	no	(Brown & Moot 2004; Brown et al. 2005)
Lincoln	15.8	13.1 to 18.5	6	Wakanui deep silt loam	no	Mills et al. (2008)
Lincoln	9.5	8 to 11	8	Balmoral stony silt loam	no	(Derrick Moot pers. comm. 2014)
Central Otago	8.8		3	Unknown - loess origin, pallic soil	no	Anderson et al. (2014)
Central Otago	10.5		3	Unknown - loess origin, pallic soil	yes	Anderson et al. (2014)
Canterbury	6.5		5	Lismore stony silt loam	no	Hayman (1985)
Canterbury	12.0		5	Wakanui deep silt loam	no	Hayman (1985)
Canterbury	10.3	8.5 to 12	3	Lismore stony silt loam	no	Hunter et al. (1994)
Waikato	10.9	8.2 to 13.6	5	Dunmore silt loam - free draining	no	In Ward and Moot (2009)
Taupo	9.6	7.6 to 11.5	2	Oruanui free-draining sand	no	Betteridge et al. (2007)
Manawatu	20.7	18.4 to 23.	6	Fine sandy loam	no	In Ward and Moot (2009)
Marlborough	7.8	6 to 9.5	3	Dashwood shallow silt loam	no	Hunter et al. (1994)
Marlborough	4.3	2.5 to 6.5	3	Dashwood stony loam	no	Hunter et al. (1994)
Average	12					
Standard deviation	5.4					

4.3 Recommendations for crop types *(T)*

We recommend reporting only two perennial forage types, these are: grass-clover pastures and nitrogen fixing forages.

4.3.1 Grass-clover

We recommend:

- Separating grass-clover forage into two farm system types:
  - High fertility, dairy, and
  - Low fertility, sheep and beef (this includes other grazing livestock such as deer and goats)
- Reporting average annual DM yield for:
  - 14.0 Mg DM/ha/yr for dairy farm systems, and
  - 9.0 Mg DM/ha/yr for sheep and beef
- Report the same average annual DM yield for all grass-clover forage between 1990 and 2013.

4.3.2 Nitrogen fixing forage (lucerne)

We recommend:

- Including lucerne as it represents a significantly large perennial forage crop area and this may continue to increase,
- An average yield for lucerne of 12 Mg DM/ha/yr. This is based on the available data and expert judgement that takes into account the likely contribution between irrigated and dryland crops from Derrick Moot (Lincoln University).
- Report the same average annual DM yield for all years from 1990 to 2013.

4.4 Gaps and uncertainty for *Crop(T)*

4.4.1 Grass-clover

- The range of annual dry matter production across New Zealand pastoral farming systems varies widely and is largely controlled by environmental conditions (soils and climate) and management decisions.
- There is a lack of annual pasture growth monitoring and reporting performed for either sheep and beef or dairy. It is therefore difficult to assess whether there have been increases or reductions in annual dry matter production since 1990. Hence, we have proposed that the same average annual dry matter production estimates are used for the period 1990-2013.
- We have been unable to assess whether the benefits of genetic improvements in grass and clover species are being realised on farm. Similarly, whether there have been changes in production due to increased or decreased fertiliser use over time or better management practices.

4.4.2 Nitrogen fixing forage (Lucerne)

- Recommendations are based on expert judgement.

- Although most lucerne is grown in dryland conditions, there is a lack of certainty about the proportion of dryland and irrigated crops.
- Similar to grass-clover pastures, yield is highly variable (range of 6.5 to 28 Mg DM/ha/yr) and will depend on environmental conditions (e.g. rainfall and soils) and management decisions.

5 Crop areas (Area)

5.1 Grass-clover

Statistics New Zealand collects agricultural production statistics (APS) including the area of grassland and a range of annual crops. Data are collated from surveys and censuses, and can be provided for all years from 1990. The agricultural production survey and census is distributed to all farms that are identified on Statistics New Zealand's Business Frame or the Inland Revenue Department's Client Register as being engaged in agricultural activity (www.stats.govt.nz). Data are collected for livestock farming, fruit, vegetables, wine grapes, forestry and farm practices. Agricultural production censuses have been conducted in 1990, 1994, 2000, 2002, 2007 and 2012 and annual surveys since 2003.

The areas of each perennial forage crop grown between 1990 and 2013 are summarised in Table 4.

Table 4 Change in New Zealand pasture area since 1990 for sheep and beef and dairy farms. Data source – Statistics New Zealand, supplied by Beef + Lamb New Zealand (Rob Gibson, pers. comm. 2014). Lucerne data based on expert opinion (Derrick Moot pers. comm. 2014).

	Land area (000's of ha)		
	Grass-clover		Lucerne
Year	Sheep/Beef/Deer/Goat	Dairy	All livestock
1990	12465	1349	84
1991	12375	1340	88
1992	12481	1360	98
1993	12545	1400	103
1994	12014	1521	106
1995	11900	1620	107
1996	11631	1635	115
1997	11347	1702	114
1998	11091	1742	112
1999	10873	1743	111
2000	10583	1816	113
2001	10311	1872	113
2002	10060	1907	120
2003	9965	1880	121
2004	9825	1896	123
2005	9731	1868	123
2006	9587	1890	118
2007	9439	1915	117
2008	9335	2019	117
2009	9302	2111	124
2010	9180	2122	119
2011	9077	2213	122
2012	8842	2255	129
2013	8685	2289	132

5.2 Nitrogen-fixing forage (lucerne)

Total lucerne area, either grazed or cut, has not been collected through the production surveys and censuses since the 1980s. There is a question included in the supplementary feed section in the survey and census questionnaire (Statistics New Zealand Code 6410, http://datainfoplus.stats.govt.nz): “what was the area of forage, fodder or green feed crops grown on farm” with one of the options being lucerne. However, because lucerne is also a main feed source in some farm systems (i.e. not a supplementary feed), this under-reports the total lucerne area. Without specific survey information it is also uncertain what the proportion of grazed to cut and carried is. While lucerne supplementary feed area represents a proportion of lucerne, the increase in harvested area between 2009 (20,284 ha) and 2013 (39,897 ha) suggests that there is a trend of increased lucerne forage (from the APS, Statistics New Zealand 2014, data provided by Simon Wear, pers. comm.). This trend and increases in seed sales supports expert opinion (Derrick Moot pers. comm. 2014) that the area of lucerne planted was increasing over this period.

In the absence of national statistics for the area of lucerne planted, we sought expert opinion for estimates of the changes in lucerne planted area since 1990. Since the 2000s there has been a resurgence of lucerne grown and currently there could be about 150,000 ha grown (Derrick Moot pers. comm. 2014). This resurgence is largely a response to the demonstration of the economic benefits of lucerne as a forage source compared to pastures in some farm systems and environments. The planted area grown in 1990 would have been low and probably similar to the 84,000 ha reported by Purves & Wynn-Williams (1989) after the decline from the mid-1970s (Derrick Moot pers. comm. 2014).

In addition to this opinion, we have made estimates of the area planted based on annual seed import and New Zealand seed certification data using assumed sowing and renewal rates. Much of the lucerne seed is imported and this data is collected by Statistics New Zealand (kg imported). This information has been provided by MPI (Peter Ettema pers. comm. 2014). We have estimated the amount of New Zealand grown seed from seed certification information (data provided by AsureQuality – David Geary pers. comm. 2014) which provides the area of seed crops sown each year. This assumes that most of the seed grown in New Zealand is certified. Based on expert opinion, it is believed that about 90% of seed is certified (Phil Rolston pers. comm. 2014).

Since 1990, the area of lucerne seed crops has ranged between 34 and 316 ha. We have limited information available for the seed yield from these crops. Although the area of certified lucerne seed crop is available, we have been unable to find data for seed yield from this crop area except for a period between 2005 and 2009 (Anon 2009). It is unclear whether other yield information is available beyond this period, however it is likely that the data between 2005 and 2009 provide a reasonable indication of lucerne seed yield. The median seed yield was 139 kg seed/ha/yr with a range of 58 to 159 kg seed/ha/yr. These yields are low by international standards. Under good growing conditions and a well-managed crop, yields in Canterbury and Marlborough may be expected to be in the range of 300 to 500 kg/ha (Dunbier et al. 1983). Poor pollination is the main factor limiting yields. The small area and low yields of lucerne seed crops indicate that the contribution of New Zealand grown seed is small relative to imported seed (Table 5, Figure 1).

We have estimated the area of lucerne grown between 1990 and 2013, based on the seed data, sowing rates and pasture renewal rates (Table 5). There are a number of key assumptions made: (i) we have assumed that the area growing lucerne was the same as that reported by Purves & Wynn-Williams (1989); (ii) that the seed yield from New Zealand seed crops was the median rate (139 kg seed/ha) for certified seed crops between 2005 and 2009 (Anon 2009); (iii) seed is sown at a rate of 8 kg/ha, recommended rates for uncoated seed are 6 to 10 kg/ha; (iv) that lucerne is renewed at a rate of 10 % (Derrick

Moot, pers. comm. 2014); and (v) all seed is sown for lucerne forage. Some of the seed is likely to be used for alfalfa sprouts for human consumption.

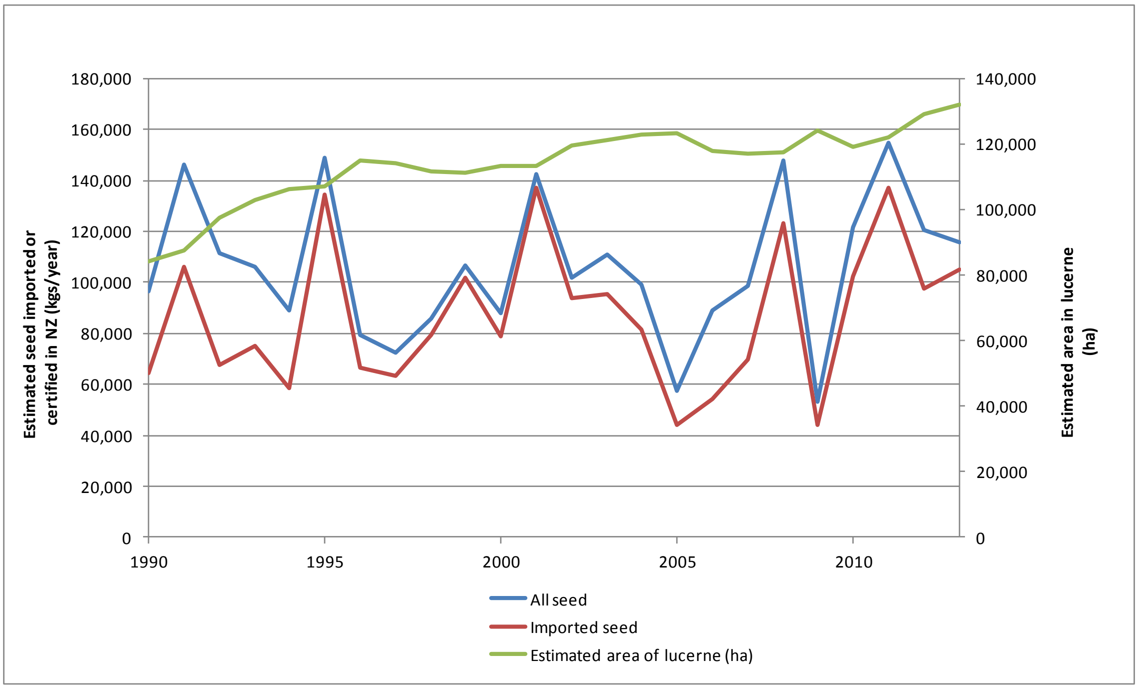

Figure 1 Estimate of area planted in lucerne based on imported and domestically grown lucerne seed

This approach has large uncertainties due to the number of assumptions required, including the accuracy of the area of seed production in New Zealand, the estimate of average annual lucerne seed yield, typical seed sowing rates and renewal rates, amount of seed used for human consumption. For example, if seed was sown at a rate of 6 kg/ha rather than 8 kg/ha the estimated area of lucerne grown increases by more than 30%, and if the rate was increase to 10 kg seed/ha the rate would be 20% less. Given that there are potentially large errors in this estimate, an area of 130,000 ha is not unrealistic compared to the expert estimate of 150,000 ha provided by Derrick Moot (pers. comm. 2014).

Table 5 Estimate of lucerne cropping area and area renewed from 1990.

Year	Imported seed	NZ seed production cert.				All seed					
	A. Seed imported (kg)[1]	B. Area of seed crop (ha)[2]	C. kg seed[2]	D. Seed yield (kg seed/ha)[2]	E. Estimated seed production (kg)	F. Estimate of total seed sown (kg) A + E	G. Assumed sowing rate (kg/ha)	H. Estimated area sown (ha/yr) F / G	I. Area renewed per year (ha/yr)[3]	J. Net change (ha) H-I	K. Estimated total crop area (ha) $K_{(Year-1)} + J_{(Year-1)}$
1990	64,184	231	N/A	139	32109	96,293	8	12037	8400	3637	84000
1991	106,207	288	N/A	139	40032	146,239	8	18280	8400	9880	87637
1992	67,762	316	N/A	139	43924	111,686	8	13961	8764	5197	97517
1993	75,208	223	N/A	139	30997	106,205	8	13276	9752	3524	102714
1994	58,510	219	N/A	139	30441	88,951	8	11119	10271	848	106238
1995	134,197	107	N/A	139	14873	149,070	8	18634	10624	8010	107085
1996	66,650	90	N/A	139	12510	79,160	8	9895	10709	-814	115095
1997	63,250	67	N/A	139	9313	72,563	8	9070	11510	-2439	114282
1998	79,315	45	N/A	139	6255	85,570	8	10696	11428	-732	111842
1999	101,916	34	N/A	139	4726	106,642	8	13330	11184	2146	111111
2000	78,735	65	N/A	139	9035	87,770	8	10971	11111	-140	113257
2001	136,981	41	N/A	139	5699	142,680	8	17835	11326	6509	113117
2002	93,550	58	N/A	139	8062	101,612	8	12702	11312	1390	119626
2003	95,342	111	N/A	139	15429	110,771	8	13846	11963	1884	121016
2004	81,675	124	N/A	139	17236	98,911	8	12364	12102	262	122900
2005	44,161	213	13350	63	13350	57,511	8	7189	12290	-5101	123162
2006	54,002	252	34983	139	34983	88,985	8	11123	12316	-1193	118061
2007	69,749	193	28971	150	28971	98,720	8	12340	11806	534	116868

Year	Imported seed	NZ seed production cert.				All seed					
	A. Seed imported (kg)[1]	B. Area of seed crop (ha)[2]	C. kg seed[2]	D. Seed yield (kg seed/ha)[2]	E. Estimated seed production (kg)	F. Estimate of total seed sown (kg) A + E	G. Assumed sowing rate (kg/ha)	H. Estimated area sown (ha/yr) F / G	I. Area renewed per year (ha/yr)[3]	J. Net change (ha) H-I	K. Estimated total crop area (ha) $K_{(Year-1)} + J_{(Year-1)}$
2008	123,291	154	24470	159	24470	147,761	8	18470	11687	6783	117402
2009	43,800	163	9478	58	9478	53,278	8	6660	11740	-5080	124185
2010	102,347	139	N/A	139	19321	121,668	8	15209	12419	2790	119105
2011	136,984	127	N/A	139	17653	154,637	8	19330	11910	7419	121895
2012	97,430	166	N/A	139	23074	120,504	8	15063	12189	2874	129314
2013	104,808	77	N/A	139	10703	115,511	8	14439	12931	1507	132187

[1]Imported seed data collected by Statistics New Zealand provided by MPI (Peter Ettema pers. comm.. 2014)

[2]Certified seed area and seed yield information provided by AsureQuality (Anon 2009) and David Geary (pers. comm. 2014)

[3]Assumed renewal rate of 10 years (i.e. $Fracrenew_{(T)}$ = 1/10), Derrick Moot pers comm. (2014).

N/A - not available.

5.3 Recommendations for *Area* activity data

5.3.1 Grass-clover

We recommend:

- Using Statistics New Zealand data for estimating pastoral area.
- All pastoral area is considered to be predominantly grass-clover.
- Separating and reporting the area of dairy from other livestock (sheep and beef, deer etc.)(Table 4).
- Reporting pasture renewal area for sheep and beef and dairy systems at a national scale. Although the data are available at regional levels, we do not believe that there are sufficient or detailed and accurate activity data to justify reporting at this level.

5.3.2 Nitrogen-fixing forage (Lucerne)

We recommend:

- Use a 1990 value of 84,000 ha which was the last data reported in 1988.
- Use estimates of lucerne area based on seed import and New Zealand seed certification data available from 1990, assumed sowing rates of 8 kg seed/ha and renewal rate of 10% per annum. Based on these estimates the area of lucerne has increased to about 130,000 ha in 2013.
- MPI request Statistics New Zealand collect annual total lucerne area, not just the area used for supplementary feed, and the area of lucerne renewed per year.

5.3.3 Gaps and uncertainty for Area

- There is a lack of quantitative data for lucerne area.
- Our estimates of the total area of lucerne and the area renewed are highly uncertain as they rely on the accuracy of the cropped area in 1990, seed sowing rates for renewal, accurate capture of seed import and New Zealand grown seed area and yields, renewal rates and the amount of seed used from human consumption; all of which have their own uncertainty.
- Better information about seed yield information for New Zealand certified seeds since 1990. This may be available through AsureQuality.

6 *Area* and frequency of renewal *(FracRenew)*

6.1 Grass-clover

There are three key sources that are available to evaluate the area and frequency of renewal for grass-clover forage, these are: Statistics New Zealand Agricultural Production Survey (APS), The Pasture Renewal Charitable Trust (Bewsell et al. 2008), and a Plant & Food Research survey (Beare et al. 2012).

Survey definitions of pasture renewal practices differ between the surveys and over time in the case of the APS questions. Bewsell et al. (2008) distinguished renovation from renewal, where oversowing was considered to be a renovation practice. Whereas, in their definition of pasture renewal, Beare et al. (2012) included the practice of oversowing when herbicide was used to kill off pasture.

Statistics New Zealand have distinguished between pasture renewal and oversowing in their survey questions. Since 2009 they have included questions (Statistics New Zealand codes 5035 and 5040) about pasture renewal (http://datainfoplus.stats.govt.nz/). Pasture renewal is counted where the land has been cultivated or direct drilled. In both the 2009 and 2010 surveys there was an additional question to count for oversowing as a pasture renewal practice (Statistics New Zealand codes 5045, http://datainfoplus.stats.govt.nz).

For IPCC 2006 methodology reporting of pasture renewal, we believe that oversowing where the sward has been killed off using a herbicide should be included, since plant N from the dead material (i.e. both above and below-ground residue) will be mineralised and provide an additional source of N for N_2O emissions.

6.2 Statistics New Zealand

Data are collected for the area renewed by either conventional cultivation or direct drill. The current survey questions (http://datainfoplus.stats.govt.nz) are:

1. “Has pasture renewal been performed in the last 12 months?”
2. “If so, what was the renewal area?”

Data from these surveys have been provided by MPI (Simon Wear, pers. comm. 2014)

6.3 Pasture Renewal Charitable Trust

Data on the rate of pasture renewal were obtained from a report prepared by AgResearch Ltd. on behalf of the Pasture Renewal Charitable Trust (PRCT) entitled *Understanding pasture renewal in New Zealand: Report on market research for PRCT* (Bewsell et al., 2008). The PRCT represents 16 agri-business organisations with a common interest in communicating the benefits of pasture renewal to farmers (www.pasturerenewal.org.nz). The research was commissioned to obtain information from farmers on current pasture renewal practices and the perceived benefits and barriers to its adoption. Data for area of renewal were collected in 2007-8.

The research commissioned by PRCT (Bewsell et al. 2008) involved collecting data from a total of 1000 farmers representing the dairy (53%), sheep/beef/deer (41%) and cropping (6%) sectors. The survey collected activity data from all respondents for: region farmed, farm type, annual rainfall and irrigation, area under improved pasture, area renewed in last 12 months. Survey participants were also asked for a percentage of pasture renovation, where renovation was defined as oversowing. Bewsell et al. (2008) did not include responses from steep hill country farmers as pasture renewal is limited in these areas.

6.4 Plant & Food Research Report 2012

In their report, Beare et al. (2012) provided data for two periods, 1990 and 2008, to allow comparison with the above PRCT report. However, additional survey data for 5-year periods from 1990 to 2010 were collected but were not presented in the 2012 report. This additional information has been analysed and is presented in Table 6. A full description of the survey methodology is described in the report by Beare et al. (2012).

In brief, data were obtained via telephone interview with 31 pastoral sector experts in 2011. Experts were asked about current pasture renewal practices in 2011 and those practised between 1990-1995, 1995-2000, 2000 -2005 and 2005-2010. Survey respondents were asked to estimate: grassland under pasture renewal, the percentage of this performed as grass to grass, grass to summer crop to grass, grass to winter forage crop to grass and other. Respondents were also asked to provide these estimates for dairy, and sheep, beef and deer for 1990 to 1995, 1995 to 2000, 2000 to 2005, 2005 to 2010.

6.5 Comparison of results from the surveys:

The PRCT survey provides data for a single time point (2008), it excluded oversowing and did not include steep pastures. The Plant & Food Research survey was designed to identify trends in the type of renewal practices over time since 1990. The APS provides annual information since 2009.

Both the PRCT survey and the Plant & Food Research survey provide information about difference in renewal rates between sheep and beef and dairy farm systems across a range of regions. We believe that the APS data can be interrogated to assess differences between farming system and recommend this is investigated.

There are differences in the definitions of pasture renewal that will affect the data collected, in particular how oversowing is dealt with and the inclusion or exclusion of steep hill country. From the APS data collected in 2009 and 2010, approximately 15% of the total pasture renewal was due to oversowing. In the following years this question has not been asked. We suggest that it should be included or in a modified form in the future; specifically when herbicide is used to kill of the existing pasture.

Sample size is likely to affect the accuracy of the results. The PRCT survey included a large sample (1000 respondents). The Plant & Food Research survey focussed on expert opinions but was a relatively small sample (31 respondents). The APS provides the largest sample size and should be the best option for collecting these data in the future.

Since 2009 the data collected by Statistics New Zealand largely addresses the lack of quantitative information required for the inventory reporting.

We propose that data collected through the surveys by Plant & Food Research and the Pasture Renewal Charitable Trust are used to fill the gap between 1990 and 2008. Furthermore, on the basis of differences in renewal frequency and consideration of differences in farming systems (i.e. lower fertility and higher fertility systems), it is proposed that pasture renewal is reported separately for sheep and beef as opposed to dairy systems.

Table 6 Summary of pasture renewal frequency for grass-clover pastures from 1990. Data sources: Bewsell et al. (2008), Beare et al. (2012), Plant & Food Research unpublished survey (2012) and Agricultural Production Statistics (Statistic New Zealand).

	Annual pasture renewal rate (%)		
Year	Sheep/Beef/Deer	Dairy	All NZ pastures
1990-94	1.5[a]	5.6[a]	
1995-99	1.9[b]	6.1[b]	
2000-04	2.6[b]	7.0[b]	
2005	3[a]	7.5[a]	
2006	2[c]	6.1[c]	
2008	3[a] – 5[c]	7.4[a] – 10[c]	
2009	3[a]	7.4[a]	3.5[d]
2010	3[a]	7.4[a]	4.8[d]
2011	3[a]	7.4[a]	5.1[d]
2012	3[a]	7.4[a]	4.8 [d]
2013	3[a]	7.4[a]	5.3[d]

Source: a – Beare et al. (2012), b – from the Plant & Food Research survey 2012, data not previously reported, c – Bewsell et al. (2008), d – Agricultural production statistics collected by Statistics New Zealand.

6.6 Total grassland renewal – Statistics New Zealand data

Pasture renewal data reported in the APS by Statistics New Zealand provided to us by MPI (Simon Wear pers. comm.) are normally aggregated to the regional, district and national level. These data may be available by livestock farm type, though this will need to be confirmed by Statistics New Zealand.

Pasture renewal estimates from the Plant & Food Research survey (Beare et al. 2012) are similar to those collected by Statistics New Zealand between 2009 and 2013 (Table 7). We have made the comparison based on the total renewed area of grassland. Areas of pasture renewal for dairy and sheep and beef pastures have been estimated from the Plant & Food Research survey by weighting the renewal rates using the relative areas of these two types of farming systems (data from Table 4). This provides confidence that the estimates of pasture renewal from the Plant & Food Research survey are realistic.

Table 7 Comparison of pasture renewal rates from the Plant & Food Research survey (Beare et al. 2012) and Statistics New Zealand.

Year	Renewal rate (%) calculated from Beare et al. (2012)	Renewal rate (%) reported by APS
2009	3.8	2.9
2010	3.8	3.9
2011	3.9	3.6
2012	3.9	3.4
2013	3.9	3.8
Average	3.9	3.5

Notes: Renewal rates calculated using renewal rates from Beare et al. (2012) and renewal areas from the 2009 to 2013 Statistics New Zealand's Agricultural Production Statistics (Simon Wear, pers. comm.2014) and grassland areas in Table 4. Data include oversowed area collected in 2009 and 2010 by Statistics New Zealand.

6.7 Changes in sheep and beef pasture renewal since 1990.

According to the Plant & Food Research survey responses, the frequency of pasture renewal has doubled in the sheep and beef systems between 1990 (1.5%) and 2011 (3%) when averaged over all regions. In the North Island the predominant form of pasture renewal in sheep/beef/deer industries is grass to grass, whereas, in the South Island renewal is typically performed through either a winter forage or summer crop. More information about the regional differences in types of practices can be found in the reports by (Bewsell et al. 2008) and (Beare et al. 2012).

Bewsell et al. (2008) estimated a greater rate of renewal from their survey with 5% of sheep and beef pastures renewed in 2008 and a range of 3 – 7% , this survey did have a greater number of respondents, however, the data are only an estimate for one year.

6.8 Changes in dairy pasture renewal frequency since 1990

Bewsell et al. (2008) reported a pasture renewal frequency of 10% for 2008 and a range of 8 – 12%. (Beare et al. 2012) found that renewal frequency increased from 5.6% in 1990 to about 7.5% in 2011. This was attributed to an increased cropping to supply extra feed in both winter and summer. Across regions the range in renewal frequency was 1 – 15%.

6.9 Oversowing – a source of N_2O

As we have noted, oversowing information is not currently collected for the APS by Statistics New Zealand. However, when oversowing involves the spraying off of the old pasture it should be accounted for in the IPCC 2006 estimates of renewal. Therefore, we recommend that the area oversown using herbicide applications that kill of the sward should be collected for the APS.

6.10 Type and frequency of lucerne renewal

The longevity of a lucerne crop is affected by factors including grazing and harvest management, site fertility and climate, soil type, weed and disease pressures. More highly productive lucerne crops (e.g. on deep soils and/or irrigated) will last 5 to 7 years before they are renewed. Stands are renewed at this stage following a decline in productivity due to disease pressure and weed competition. In contrast, less productive crops on shallower, dryland soils may last up to 30 years (e.g. Central Otago; Ward and Moot (2009)).

In the absence of accurate quantitative national or regional information on average renewal rates for lucerne we propose that an annual renewal rate of 10% (i.e. once every 10 years) recommended by Professor Derrick Moot (pers. comm. 2014) is adopted. His assessment is based on his expert knowledge of lucerne renewal practices and the distribution of low and high production crops across New Zealand.

Lucerne renewal normally consists of either spraying out the lucerne and weeds, then cultivating in the residues or by cultivation only, followed by a crop or short-term grass (e.g. cereal or Italian ryegrass) for one or two years, sometimes then followed by a brassica crop. It is recommended that the next lucerne crop is sown in mid- spring. (guidelines for lucerne renewal provided by Lincoln University (http://www.lincoln.ac.nz).

6.11 Recommendations for *FracRenew*

6.11.1 Grass-clover

- Separate renewal areas into dairy, and sheep, beef and deer.
- Use Plant & Food Research survey results from 1990 to 2008.
- Use Statistics New Zealand data from 2009 to 2013, assuming it can be disaggregated into sheep, beef, deer and dairy, otherwise use recommended Plant & Food Research survey data. Pasture renewal rates between 2009 and 2013 are similar for the two surveys, indicating that this combined approach is appropriate for estimating pasture renewal across the time sequence from 1990.
- MPI request that Statistics New Zealand provide frequency of renewal data by farm system type (i.e. dairy, and sheep, beef and deer).

6.11.2 Lucerne

- An average value of 10% (once every 10 years) is applied to all years. This is based on the expert judgement of Professor Derrick Moot.

6.12 Gaps and uncertainty for *FracRenew*

6.12.1 Grass-clover

- Early data are based on the recent Pasture Renewal Trust and Plant & Food Research surveys.
- APS pasture renewal data may not differentiate between high-fertility and low-fertility systems.
- Comparison of APS data and survey responses, (i.e. weighting sheep and beef, and dairy survey responses with APS areas), gives a similar value for the total area of renewal.
- Oversowing is not currently recorded as pasture renewal in the APS

6.12.2 Lucerne

- There are no relevant, recent APS data for lucerne. The APS data collected relate only to lucerne as a supplementary feed.
- Frequency of renewal is based on expert judgement (Derrick Moot, pers. comm. 2014).

7 Dry matter and N concentration values for above-ground residues ($AG_{DM(T)}$ and N_{AG})

7.1 Above-ground dry matter residual ($AG_{DM(T)}$)

The default IPCC 2006 method for calculating the above-ground dry matter residue ($AG_{DM(T)}$) is to apply a ratio of above-ground residues dry matter (R_{AG}) to the harvested yield ($Crop_{(T)}$). However, we propose a simpler method using the grazed residuals immediately before renewal. We believe this approach is much more robust for grazed pastures in New Zealand when there is much greater certainty of the amount of pre-renewal residues than $Crop_{(T)}$ and R_{AG}.

7.1.1 Dairy $AG_{DM(T)}$

Above-ground dry matter residual in a dairy system pre-renewal is typically between 1.3 and 1.5 Mg DM/ha (Dawn Dalley pers. comm. 2014). Industry guidelines recommend residuals of 1.5 to 1.6 Mg DM/ha are maintained during the milking season. Dairy farmers will not tend to graze lactating cows below 1.5 Mg DM/ha as the lower quality of the residue below this value will not meet energy requirements of lactating cows unless supplements are added to the diet. Pre-renewal some farmers will graze lower than 1.5 Mg DM/ha but this is unlikely to be lower than 1.3 Mg DM/ha. In some cases sheep or cattle may be used to graze to lower residuals (see next section) but this is not expected to widespread due to the limited benefit to dairy farmers. There is a lack of quantitative information collected for the pre-renewal dry matter residues. Therefore we recommend that a $AG_{DM(T)}$ value of 1.4 Mg DM/ha is applied for dairy pastures.

7.1.2 Comparison of recommended Dairy $AG_{DM(T)}$ for New Zealand conditions and $AG_{DM(T)}$ estimated using the IPCC 2006 default values.

The IPCC 2006 equation for calculating above-ground residue, $AG_{DM(T)}$ (Mg/ha), is:

$$AG_{DM(T)} = \left(Crop_{(T)} \div 1000\right) \times slope_T + intercept_T.$$

This value is calculated using default values in the IPCC 2006 Table 11.2 (see values in Table 8 of this report) and is applied in IPCC 2006 Equation 11.7A.

We have compared our recommended approach with the IPCC 2006 method for estimating $AG_{DM(T)}$. For a grass-clover crop producing 14,000 kg DM/ha/yr ($Crop_{(T)}$) and the default IPCC value of 0.3 (slope) for grass-clover pastures, $AG_{DM(T)}$ is 4.2 Mg DM/ha. This is an overestimate of 2.8 Mg DM/ha compared to typical New Zealand practice. To achieve our recommended $AG_{DM(T)}$ value of 1.4 Mg DM/ha for dairy pastures, $Crop_{(T)}$ using the IPCC method would be very low at 4,700 kg DM/ha/yr.

7.1.3 Sheep and beef $AG_{DM(T)}$

We propose a similar approach for estimating $AG_{DM(T)}$ for sheep and beef pastures. Due to different grazing patterns and lower animal energy requirements compared to lactating cows, a lower pre-renewal residual is more appropriate.

The method for renewing hill country pasture is dependent on topography and accessibility, however, recommended practice involves the application of herbicide followed by hard grazing to reduce potential cover/competition (Wedderburn et al. 1996; PGG Wrightson 2008; Stevens & Thompson 2011). Hard grazing is difficult to define but has been estimated to be 0.75 Mg DM/ha and a height of approximately 2 cm by Morris and Kenyon (2004) and Moot (Derrick Moot pers. comm. 2014).

We recommend that the $AG_{DM(T)}$ for New Zealand sheep and beef grass-clover pastures is 0.75 Mg DM/ha.

We have compared our recommended $AG_{DM(T)}$ with the IPCC 2006 method. For a grass-clover crop producing 8,300 kg DM/ha/yr ($Crop_{(T)}$) and the default IPCC value of 0.3 (slope) for grass-clover pastures, $AG_{DM(T)}$ is 2.5 Mg DM/ha. This is an overestimate of 1.75 Mg DM/ha compared to typical New Zealand practice.

7.2 Lucerne $AG_{DM(T)}$

The amount of lucerne $AG_{DM(T)}$ depends on whether the crop has been grazed or cut. Typically about 0.8 Mg DM/ha stem material is left when the crop is cut, whereas about 1 Mg DM/ha would be left if the crop was grazed (Derrick Moot, pers. comm. 2014).

Table 8 Table IPCC 2006 default factors for estimating above-ground and below-ground residue dry matter and N contents using Equation 11.7A, Values are from Table 11.2 (IPCC 2006)

		Above-ground residue dry matter $AG_{DM(T)}$ (Mg/ha): $AG_{DM(T)} = (Crop_T/1000)*slope_T + intercept_T$				
Crop	Dry matter fraction of harvested product (DRY)	Slope	Intercept	N-content of above-ground residues (N_{AG})	Ratio of below-ground residues to above-ground biomass (R_{BG-BIO})	N content of below-ground residues (N_{BG})
N fixing forages	0.9	0.3 (± 50%)	0	0.027	0.4 (± 50%)	0.022
Non-N fixing forages	0.9	0.3 (± 50%)	0	0.015	0.54 (± 50%)	0.012
Grass-Clover Mixture	0.9	0.3 (± 50%)	0	0.025	0.8 (± 50%)	0.016
Perennial grasses	0.9	0.3 (± 50%)	0	0.015	0.8 (± 50%)	0.012

7.3 Pasture residue N concentration (N_{AG})

The IPCC 2006 default factor for above-ground grass-clover DM residue N concentration is 2.5%.

Our search of the literature has shown that there is a surprising lack of information on the N concentration of the pasture residue, i.e. the component of the sward that is left after grazing; most studies report the harvested component. In comparison to the residue component, there is reasonably good information on the N concentration in the harvested component of the sward from a range of sources for the range of pastoral systems and regions. These concentrations range between 2.6 and 5.4 % and are greater than the above-ground residue components.

The proportion of clover and grass, the amount of clover leaf and stem and the proportion of live to dead material are important determinants of the residue N concentration.

According to Haynes and Williams (1997) the N concentration of grass-clover residue is 2 to 3 %. In their ^{15}N fate and recovery experiment, the N concentration of the combined above-ground and below-ground, 70% ryegrass and 30% clover components was 2.2%. In another ^{15}N fate and recovery experiment study, where urine had been applied to field plots, the combined above-ground and below-ground residues N concentrations were higher at 3.4 to 3.8 % N (Williams & Haynes 1997).

In a recent study by Pal et al. (2012), the post-grazing residue dry matter and N concentration of ryegrass-clover pasture at the Lincoln University Dairy Farm was 1.2 Mg DM/ha and 2%, respectively. The pre-grazing N concentration of the pasture dry matter was 2.8%.

Moir et al. (2012) measured ryegrass stubble N concentrations of 1 to 1.2 % from ryegrass grown in the glasshouse; the shoot N concentrations ranged between 2.7 and 3.8 % depending on the rate of N addition.

7.4 Factors affecting pasture N residue concentrations and recommended N_{AG} value:

Harvested pasture N concentration is affected by farm system (i.e. sheep and beef, and dairy), slope, grass species and seasonality (Ledgard et al. 2002). The differences in N concentration on different slopes partly reflect the pasture species composition. Ledgard et al. (2002) thought it unlikely that it would be feasible to account for differences in species composition for the inventory calculations (for N excreta) although where there were large contrasts due to regional climatic differences, some exceptions might be appropriate.

Harvested pasture N concentration data are summarised in the Overseer Technical Manual (www.overseer.co.nz). These values are used to parameterise the OVERSEER model. This updates the analysis of more than 6,000 samples in a report to MPI by Ledgard et al. (2002). These values are used in the National Inventory to calculate N in excreta. Leaf N concentration in ryegrass-clover swards varies seasonally. Typically N concentrations are lower between October and March (late spring to early autumn) than in winter and early spring.

Residue N concentration may also be affected by the clover content of the sward as clover tends to have higher N concentrations than ryegrass, although the proportion of clover biomass in post-grazed residue is likely to be small (Derrick Moot pers. comm. 2014).

We recommend that N_{AG} grass-clover dry matter residue is 2 %. This is lower than the IPCC default value of 2.5%. Our reasoning is that the post-grazed, pre-renewal residues in New Zealand are small (i.e. < 1.4 Mg DM/ha, much lower those predicted using IPCC default factors), they include a high proportion of senesced material that has a much lower N concentration than the live residue or harvested component, small pre-renewal residuals consist of grass and clover stubble that have low N concentrations than the leaf, dairy pastures tend to have low clover contents, and grass stubble have low N concentrations.

7.5 Lucerne N concentration (N_{AG})

The IPCC 2006 default value for N fixing forages is 2.7 % N. This value is more than 40 % greater than measured values found in above-ground residues (1.9 % N) by Brown and Moot (2004).

7.6 Recommendations for calculating $AG_{DM(T)}$ and N_{AG}

7.6.1 Grass-clover

We recommend:

- A fixed value of $AG_{DM(T)}$ of
  - 0.75 Mg DM/ha for sheep and beef, and
  - 1.4 Mg DM/ha dairy systems. These values are based on current recommended practice (range of 1.3 to 1.5 Mg DM/ha/yr).
- Typically residues will have been grazed to low residuals pre-renewal (e.g. 0.75 Mg DM/ha for sheep grazed and 1.4 Mg DM for dairy grazed systems). This residual component will consist of the lower quality stem material containing lower concentrations of N.
- A value of 2 % N for N_{AG} for both sheep and beef and dairy systems. This value is lower than the IPCC 2006 default of 2.5 %.

7.6.2 Lucerne

We recommend:

- A fixed grazing or cut above-ground residual of 0.9 Mg DM/ha. This is based on expert judgement (Derrick Moot pers. comm. 2014).
- A value of 1.9% N for these residues based on New Zealand measured values.

7.7 Gaps and uncertainty for $AG_{DM(T)}$ and N_{AG}

7.7.1 Grass-clover

- There are limited number of reported data for the N concentration of the residual component of grass-clover systems for sheep and beef and dairy pastures,

7.7.2 Lucerne

- There is a lack of quantitative data on the area that would be cut or grazed before renewal. More data should be collected to provide an estimate of certainty for this value.
- There is a lack of reported data for the N concentration of the residual component of lucerne in either dryland or irrigated system.

8 Below-ground dry matter residue ($BG_{DM(T)}$ and N_{BG})

To estimate the contribution of below-ground residues ($BG_{DM(T)}$) to N_2O emissions during pasture renewal it is necessary to estimate the amount of N contained and released from the root biomass as a direct result of pasture renewal. This is the amount of root live material (and associated live rhizosphere material) that is killed by spraying or cultivation and that is above normal decomposition processes (root turnover).

To estimate $BG_{DM(T)}$, the IPCC 2006 default method applies a ratio ($R_{BG(T)}$) of below-ground residues to above-ground harvested biomass (the annual dry matter production for pastures) + above-ground residue:

$$BG_{DM(T)} = R_{BG(T)} \times \left(Crop_{(T)} + AG_{DM(T)}\right)$$

The $R_{BG(T)}$ default value for grass-clover systems is 0.8 (+/- 50 % standard deviation) and is based on the assumption that in natural grass systems below-ground biomass is approximately equal to twice (range of one to three times) the above-ground biomass and that root turnover in these systems averages about 40% per year (IPCC 2006). Root turnover is the inverse of root longevity and can be calculated as the annual amount of root production compared to an estimate of standing root biomass.

Using IPCC 2006 equation 11.7A and default values in Table 11.2 (IPCC 2006) (see Table 8) this would mean that a pasture producing 14 Mg DM/ha/yr (e.g. a dairy pasture) would have an above ground residue of 4.2 Mg DM/ha and a below-ground residue of 14.6 Mg DM/ha (i.e. 80% of the total annual above ground biomass (14 + 4.2 Mg DM/ha) produced including residue). This estimate of below-ground biomass is very high and unrealistic for dairy farm systems compared to most New Zealand data. Using the IPCC 2006 default value for N_{BG} for grass-clover pastures (1.6 %, Table 4) this would release 233 kg N/ha from the below-ground residues only, equivalent to 2.3 kg N_2O-N/ha based on the default EF_1 value (1 %).

8.1.1 Availability of relevant grass-clover pasture below-ground dry matter ($BG_{DM(T)}$) data

Compared to above-ground residue information, there is much less relevant below-ground data for the wide range of perennial forage species, pastoral management systems, regional and seasonal variability of climate and soils. As Scott (2000) summed up – root biomass and nutrient content are rarely sampled. A primary reason is that research involving the measurement of roots is expensive and time consuming (Reid & Crush 2013). We have summarised the range of relevant New Zealand literature for grass-based pastures in **Error! Reference source not found.**.

Because of the range of factors that affect root production, it is somewhat difficult to compare the various studies and extrapolate experiments to the wide range of New Zealand management and environmental conditions. Ideally, relevant data for pasture renewal residues are collected for more than one year and preferably from established pastures. Unfortunately, the number of studies of roots that fit these criteria in pasture is small. Not surprisingly given their wide distribution in New Zealand, most of the studies of root mass in New Zealand have been conducted on ryegrass-clover pastures, although pasture species and mixtures can affect both the below-ground biomass and distribution of roots with depth (Crush et al. 2005; Reid & Crush 2013; McNally et al. 2014).

Most pasture roots are found within the top 20 to 30 cm (Wedderburn et al. 2010), reporting work by Jacques (1943) and Gibbs (1986) in the Manawatu and Canterbury regions. Saggar and Hedley (2001) found that 92% of ryegrass-clover root biomass was in top 10 cm of soil.

8.1.2 Availability of relevant lucerne below-ground dry matter ($BG_{DM(T)}$).

Unlike most of the species in grass-clover pastures, most below-ground dry matter of a lucerne plant is contained in a large crown and taproot. A comprehensive study of seasonal and management (defoliation) on below-ground dry matter was conducted in Canterbury by Teixeira et al. (2007). There is a strong seasonal effect on below-ground dry matter. Generally there is a preferential allocation of dry matter to the crown and taproot from mid-summer to a maximum in autumn. This then declines over winter to spring (Teixeira et al. 2007). Below-ground matter is also affected by the productivity of the stands. Standing biomass ranged from 2.2 Mg DM/ha to 5.5 Mg DM/ha for high-producing stands (Teixeira et al. 2007).

Based on the seasonal variation and effects of productivity on the tap and crown root, we recommend using the mid-point in this range, i.e. $BG_{DM(T)}$ for lucerne is 3.9 Mg DM/ha. Recently completed studies at Lincoln may provide better quantification of this value and its uncertainty in the future (Edmar Teixeira, pers. comm. 2014). Turnover of the crown and tap roots is ignored. These are live storage organs and not subject to seasonal turnover as fine roots.

8.1.3 Pasture root biomass and turnover

Seasonal changes in root biomass occur due to relative differences in the production and disappearance of roots. The size and distribution of root biomass is dependent on a wide range of plant and environmental factors, for example fertility, aeration and water availability.

Large seasonal changes in root growth and biomass have been observed in a number of studies (Caradus & Evans 1977; Matthew 1992; Stewart & Metherell 1999; Saggar & Hedley 2001; Wedderburn et al. 2010; Dodd & Mackay 2011). In most New Zealand studies the least ryegrass-clover pasture root biomass and growth is observed in the winter (Allard et al. 2005; Dodd & Mackay 2011). Allard et al. (2005) found winter root biomass to be half of that measured between spring and autumn. The seasonality of maximum root growth rates varies. Reid and Crush (2013) showed that an increase in ryegrass root production in autumn measured using minirhizotrons was responsible for the increase in root biomass over the season using data from Wedderburn et al. (2010). Similarly autumn root production was shown to be significant in a ryegrass-clover sward using ^{13}C labelling (Stewart & Metherell 1999). Dodd and Mackay (2011) observed root growth maximum in spring and summer declining to a minimum in winter. Low biomass and growth rates have also been observed in summer due to drought stress (Wedderburn et al. 2010).

Consequently timing of pasture renewal in either spring or autumn is likely to affect the below-ground residue contribution to pasture renewal emissions. However, given the paucity of data, there is no justification for separating these periods.

Grazing management including the frequency and severity of defoliation (Matthew et al. 1991; Matthew 1992; Nie et al. 1997; Wedderburn et al. 2010) influences the amount of root biomass with less root biomass found with greater defoliation, although fluctuations in root mass and root growth can be smaller than those caused by seasonal root growth patterns (Matthew et al. 1991). Fertiliser and irrigation management can also have large effects on root biomass and production (Stewart & Metherell 1999; Scott 2000; Dodd & Mackay 2011; Reid & Crush 2013).

Low-fertility pasture systems have proportionally larger root biomasses compared to their above-ground productivity. In his high-country study of tussock-dominated pasture, Scott (2000) measured a range of roots and plant organic matter (>1.3 mm) between 6.5 and 58.5 Mg DM/ha. He was not able to separate living roots from coarse organic matter, but suggested that the amount of live roots would be less than one-third of the biomass. This would still mean a considerable pool of live roots. However no evidence was provided to support this.

Ideally, because of fertility effects and pasture species composition, it would be best to separate high-fertility and productivity farm systems (e.g. dairy) from lower fertility and productivity farm systems (e.g. sheep and beef).

The IPCC 2006 default value ($R_{BG\text{-}Bio}$) to estimate below-ground biomass assumes root biomass turnover is 40% per year with a range of 30 to 50 % (IPCC 2006). In other words the root biomass turns over once every 2 to 3.33 years.

Reid and Crush (2013) using minirhizotron data, estimated very high root turnover rates of 8 times per year for perennial ryegrass over a 2-year period, corresponding to an average root longevity of 44 days. These turnover rates are similar to those reported for a newly established pasture in Canterbury (Gibbs & Reid 1992). A recent analysis of minirhizotron measurements from an earlier 2.5 year study of ryegrass, clover, lucerne and chicory roots provided an estimated turnover rate of 3.4 times per year (submitted for publication, Jeff Reid pers. comm. 2014).

Median root longevity of pasture plant species tends to be in the range of 14 to 131 days, although earlier work by Troughton in the UK on the turnover of root axes suggested this might be longer, but this is probably attributable to differences between root axes that are relatively large in diameter and tend to have greater longevity, and the bulk of the root biomass of fine roots (submitted for publication, Jeff Reid pers. comm. 2014).

Analysis of ^{13}C data by Scott et al. (2012) suggested root turnover rates of an average of 1.3 years (0.77 times per year) with the longest turnover rates in low-fertility and low-productivity pasture treatments (up to 2 years). Scott et al (2012) suggest that this might be an overestimate of turnover; ^{13}C deposited from dead roots could also be taken up live roots (Reid & Crush 2013). Minirhizotrons are also prone to errors (Gibbs & Reid 1992). The minirhizotron technique is best suited to measuring the number of roots turning over and root length, they may underestimate root mass turnover (Reid & Crush 2013).

In summary, based on most of New Zealand studies, root turnover rates would appear to be much faster than the IPCC 2006 defaults. Turnover rates are fastest in high-fertility pastures, where root turnover rates are typically much less than 1 year. Only in low-fertility systems is turnover likely to slow towards the IPCC 2006 default value.

8.1.4 Comparison of R_{BG} estimated from New Zealand studies and using IPCC 2006 default calculations for fertilised grass-clover pasture systems:

Standing biomass estimates for a range of lower fertility systems vary greatly from <1 Mg DM/ha to greater than 20 Mg DM/ha, and in tussock grassland biomass may even be greater (Barker et al. 1988b; MacKay et al. 1991; Saggar et al. 1997; Scott 2000; Allard et al. 2005).

We have compared the four New Zealand sheep grazed studies (seven treatments) where we have been able to relate above-ground production with below ground root biomass measurements or estimates. We have plotted these data against the IPCC default relationship between above-ground production and below-ground biomass where it is assumed that below-ground root biomass is approximately twice the annual above-ground production (Figure 2). Although a small sample number, there is reasonable agreement between these studies and the IPCC 2006 value.

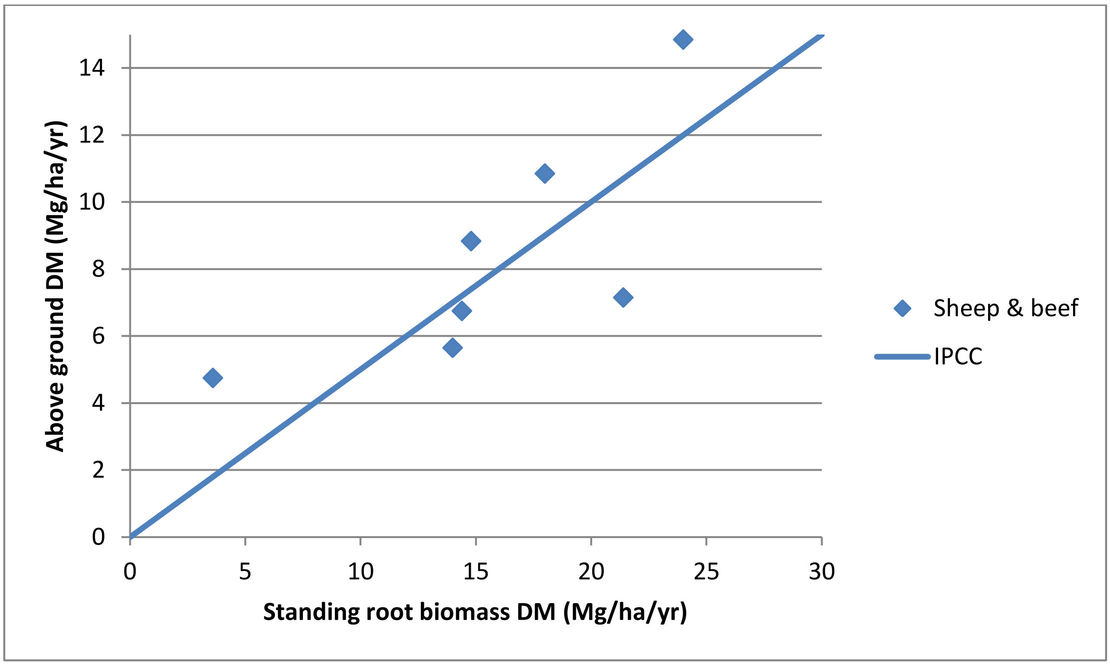

Figure 2 Comparison of New Zealand studies where annual above-ground dry matter production (plus above-ground residue of 0.75 Mg DM/ha) and standing root biomass have been measured or estimated (Barker et al. 1988a; Saggar et al. 1997; Allard et al. 2005; Scott et al. 2012). The solid line is the IPCC 2000 default relationship that assumes that root biomass (dead and alive) is twice that of annual above-ground production. Studies are summarised in Error! Reference source not found.**. In the study by (Scott et al. 2012) we have used a root turnover rate of 1.65 years.**

There is a dearth of studies where both annual above-ground production and standing root biomass were measured in New Zealand high fertility (e.g. dairy) pastures. In their study, Dodd and Mackay (Dodd & Mackay 2011, 2013) measured above-ground production approximately 10 times more than root growth (i.e. R_{BG} <0.1). They measured total above-ground pasture production of 17.8 to 23.2 Mg DM/ha/y and total standing root dry matter between 1 and 2.8 Mg DM/ha at nine times through the year. Their total root biomass was approximately a magnitude lower than calculated using the IPCC 2006 estimate (17 Mg DM/ha, IPCC 2006 equation 11.7A and Table 11.2; IPCC 2006), not accounting for any senesced roots that are included in the biomass measurements. The authors did recognise that methodology issues may have led to a three-fold underestimate of autumn root production, but even accounting for this, the IPCC 2006 calculation would greatly overestimate live roots.

It would appear from this study, another by Matthew et al. (1991) and expert opinion by Corey Matthew (pers. comm. 2014) that in these high-fertility systems the IPCC 2006 method appears to grossly overestimate below-ground root biomass and annual below-ground production would be expected to be less than 20% of total production. Furthermore, root turnover rates are likely to be high in these more fertile pastures; a value of 20% is still probably conservative. The R_{BG} value used by OVERSEER for clover and grass seed crops is of 0.1. Curtin et al. (2011) recommended that since there was a lack of other data for these seed crops that the OVERSEER value should be used in the inventory to estimate the below-ground residue component of these seed crops (i.e. temporary grass and clover).

8.2 Pasture root N concentration

8.2.1 Grass-clover pasture

The IPCC 2006 default N concentration value for grass-clover mixed pasture is 1.6%, and 1.2 % of perennial grasses; it is unclear what studies have been used to select these values.

Although there is limited New Zealand data for grass-clover root N concentrations, the value of 1.6% may be too high for the lower fertility pastures.

A range of pasture N concentrations has been measured for New Zealand pastures from less than 0.7 to 1.9%. Pastures with higher leaf N concentrations tend to have higher N root concentrations (Craine & Lee 2003). In their study Craine and Lee (2003) collected root and shoot samples from native and introduced pasture grasses across a range of altitudes in the South Island. The mean root N concentration for introduced pasture was 0.84 %; the mean shoot N concentration across the same samples was 1.6%. Based on the shoot N concentration, these pastures, on average, were probably of low pasture productivity. The mean root N concentration for native grasses (e.g. tussocks) was 0.7%. Average root N concentrations measured on sheep grazed hill pasture at Ballantrae ranged between 0.95, 1.2 and 1.5% for low-, medium- and high-fertility pastures, respectively, measured in spring (Saggar et al. 1997). In comparison, root N concentration in a high-fertility dairy pasture has been measured between 1.5 and 1.9 % (Saggar & Hedley 2001; Dodd & Mackay 2011).

Perennial ryegrass N root concentrations measured in four New Zealand studies range from 0.65 to 1.7 with a median of 1.25% (Crush et al. 2005; Popay & Crush 2009; Moir et al. 2012; Pal et al. 2013). These values are based on experiments with repacked soil column in glasshouse conditions, and include one study with two fertility treatments (Moir et al. 2012). Crush et al. (2005) measured N root concentrations for nine other grass species; these concentrations ranged between 1 to 1.8%. Curtin et al. (2011) proposed using the same N root concentration of 1% for ryegrass and clover seed crops; these are values used by the OVERSEER model.

8.3 Lucerne root N concentration

The IPCC 2006 value for root N concentration for nitrogen-fixing forages is 2.2 %.

Root N concentration of lucerne plants varies seasonally but is also affected by management, i.e. grazing or cutting intensity (Teixeira et al. 2007). Average N concentration pooled over season and management was 1.4 % N with a range of 1.0 to 1.8% for a field trial conducted in Canterbury (Teixeira et al. 2007).

8.4 Recommendations for calculating $BG_{DM(T)}$, $R_{BG(T)}$ and $N_{BG(T)}$

8.4.1 Grass-clover

- For grass-clover systems BG_{DM} is calculated using R_{BG}. However, different values of R_{BG} need to applied to high fertility and low fertility pastures (i.e. different values for dairy and sheep and beef systems).

Sheep & beef R_{BG}

- The IPCC 2006 default value of 80% of annual above-ground production is used, based on standing root biomass twice the annual above-ground production and a root turnover rate of 40%. The IPCC range for this value is ± 50% (IPCC 2006).
- Applying this to our recommended yield and above-ground residue values, $BG_{DM(T)}$ will be 7.2 Mg DM/ha.

Dairy R_{BG}

- Based on measurements of root biomass in New Zealand dairy systems, the default method for estimating below-ground residues is not appropriate for high-fertility dairy pastures.

- Instead, we recommend that a root biomass is estimated as 20% of the total above-ground production. This is based on comparing root:shoot ratios for New Zealand dairy studies, high root turnover rates in higher fertility systems and expert opinion.
- Applying this to our recommended yield and above-ground residue values, $BG_{DM(T)}$ will be 2.8 Mg DM/ha.

N_{BG}

- Based on the range of values and potential differences between low- and high-fertility pasture systems, we propose using two values of N concentrations of:
    - 1.2 % for low-fertility pasture (sheep and beef), and
    - 1.6 % for high-fertility pasture (dairy); i.e. the IPCC 2006 default value.

8.4.2 Lucerne

- Because of lucerne physiology and relative insensitivity to above-ground production, a root:shoot ratio approach is not appropriate, instead a fixed value for $BG_{DM(T)}$ should be used,
- New Zealand measured value for $BG_{DM(T)}$ of 3.9 Mg DM/ha should be used.
- New Zealand measured value of root N concentration of 1.4% is used.

8.5 Gaps and uncertainty for R_{BG} and N_{BG}

The number of studies of below-ground root biomass, turnover, root nitrogen concentrations in pastoral systems is small.

9 Appropriateness of EF_1 for pasture residues.

Recent studies by Pal et al. (2012) conducted at Lincoln University have indicated that emissions from residues from perennial ryegrass and clover plants applied on or incorporated in soil are very similar to the EF_1 value of 1% for crop residues.

10 Summary of recommendations for activity data and relevant factors for calculating NZ N_2O emissions from pasture renewal from 1990 to present.

10.1 Crop and yield information, residue dry matter and nitrogen contents.

- Report activity data and factors for
  - Grass-clover for low-fertility (sheep and beef) and high-fertility (dairy) farming systems.
  - Nitrogen-fixing perennial forage (lucerne)
- Use factors in Table 9.

Table 9 Recommended annual yield, residue dry matter and nitrogen contents for grass-clover and nitrogen fixing crops.

Pasture/Forage (*T*)	Crop Yield (*Crop*) (kg DM/ha/yr)	Above-ground residue ($AG_{DM(T)}$) (Mg DM/ha/yr)	Above-ground residue N content (N_{AG}) (g/kg DM)	Below-ground residue ($BG_{DM(T)}$) (Mg DM/ha/yr)	Ratio of ($BG_{DM(T)}$) to ($Crop$/1000+$AG_{DM(T)}$) (R_{BG}) (kg DM/kg DM)	Below-ground residue N content (N_{BG}) (g/kg DM)
Grass-clover - sheep & beef	9,000	0.75	0.02	-	0.8 (± 50%)	0.012
Grass-clover - dairy	14,000	1.4	0.02	-	0.2	0.016
Lucerne - all	12,000	0.9	0.019	3.9	-	0.014

10.2 Crop *Area*

- Use Statistics New Zealand data for estimating grass-clover area.
- Report pasture renewal area for sheep and beef and dairy systems at a national scale based on the current availability of data.
- Use a 1990 value of 84,000 ha which was the last data reported in 1988.
- Use estimates of lucerne area based on seed import and New Zealand seed certification data available from 1990, assumed sowing rates of 8 kg seed/ha and renewal rate of 10% per annum. Based on these estimates the area of lucerne has increased to about 130,000 ha in 2013.

10.3 FracRenew

- Use Plant & Food Research survey results from 1990 to 2008.

- Use Statistics New Zealand data from 2009 to 2013, assuming it can be disaggregated into sheep, beef, deer and dairy, otherwise use recommended Plant & Food Research survey data.

10.4 Summaries of activity data and factors for grass-clover pastures and nitrogen fixing perennial forage (lucerne)

The recommended activity data and factors for calculating F_{CR} for sheep and beef (low-fertility) grass-clover pastures is provided in Table 10, for dairy (high-fertility) grass-clover pastures in Table 11 and for lucerne in Table 12.

Table 10 Summary of pasture renewal activity data and factors for Sheep and Beef (low-fertility) grass-clover pasture.

Year	Area (ha) A	Frequency of renewal (%) B	Total annual above-ground DM (kg DM/ha/yr) C	Above-ground residue DM pre- renewal (Mg DM/ha/yr) D	Below-ground DM (Mg DM/ha/yr) E	AG N (%) F	BG N (%) G	F_{CR} (Mg N) A*B/100*((D*F/100)+(E*G/100))
1990	12,464,774	1.5	9,000	0.75	7.2	2	1.2	18,960
1991	12,375,199	1.5	9,000	0.75	7.2	2	1.2	18,824
1992	12,481,023	1.5	9,000	0.75	7.2	2	1.2	18,985
1993	12,544,768	1.5	9,000	0.75	7.2	2	1.2	19,082
1994	12,014,309	1.5	9,000	0.75	7.2	2	1.2	18,275
1995	11,899,584	1.9	9,000	0.75	7.2	2	1.2	22,927
1996	11,630,514	1.9	9,000	0.75	7.2	2	1.2	22,409
1997	11,346,725	1.9	9,000	0.75	7.2	2	1.2	21,862
1998	11,090,807	1.9	9,000	0.75	7.2	2	1.2	21,369
1999	10,872,953	1.9	9,000	0.75	7.2	2	1.2	20,949
2000	10,583,428	2.6	9,000	0.75	7.2	2	1.2	27,904
2001	10,310,998	2.6	9,000	0.75	7.2	2	1.2	27,186
2002	10,060,296	2.6	9,000	0.75	7.2	2	1.2	26,525
2003	9,964,856	2.6	9,000	0.75	7.2	2	1.2	26,273
2004	9,825,489	2.6	9,000	0.75	7.2	2	1.2	25,906
2005	9,730,753	3.0	9,000	0.75	7.2	2	1.2	29,603
2006	9,586,894	3.0	9,000	0.75	7.2	2	1.2	29,165
2007	9,439,214	3.0	9,000	0.75	7.2	2	1.2	28,716
2008	9,335,328	3.0	9,000	0.75	7.2	2	1.2	28,400
2009	9,302,090	3.0	9,000	0.75	7.2	2	1.2	28,299

Year	Area (ha) A	Frequency of renewal (%) B	Total annual above-ground DM (kg DM/ha/yr) C	Above-ground residue DM pre- renewal (Mg DM/ha/yr) D	Below-ground DM (Mg DM/ha/yr) E	AG N (%) F	BG N (%) G	F_{CR} (Mg N) A*B/100*((D*F/100)+(E*G/100))
2010	9,180,291	3.0	9,000	0.75	7.2	2	1.2	27,928
2011	9,076,514	3.0	9,000	0.75	7.2	2	1.2	27,613
2012	8,841,788	3.0	9,000	0.75	7.2	2	1.2	26,899
2013	8,684,944	3.0	9,000	0.75	7.2	2	1.2	26,421

Table 11 Summary of pasture renewal activity data and factors for Dairy (high-fertility) grass-clover pasture.

Year	Area (ha) A	Frequency of renewal (%) B	Total annual above-ground DM (kg DM/ha/yr) C	Above-ground residue DM pre- renewal (Mg DM/ha/yr) D	Below-ground DM (Mg DM/ha/yr) E	AG N (%) F	BG N (%) G	F_{CR} (Mg N) A*B/100*((D*F/100)+(E*G/100))
1990	1,348,773	5.6	14,000	1.4	2.8	2	1.6	5499
1991	1,340,139	5.6	14,000	1.4	2.8	2	1.6	5464
1992	1,359,654	5.6	14,000	1.4	2.8	2	1.6	5543
1993	1,400,408	5.6	14,000	1.4	2.8	2	1.6	5710
1994	1,521,398	5.6	14,000	1.4	2.8	2	1.6	6203
1995	1,620,211	6.1	14,000	1.4	2.8	2	1.6	7195
1996	1,634,912	6.1	14,000	1.4	2.8	2	1.6	7261
1997	1,702,290	6.1	14,000	1.4	2.8	2	1.6	7560
1998	1,741,797	6.1	14,000	1.4	2.8	2	1.6	7735
1999	1,743,240	6.1	14,000	1.4	2.8	2	1.6	7742
2000	1,816,354	7.0	14,000	1.4	2.8	2	1.6	9310
2001	1,872,373	7.0	14,000	1.4	2.8	2	1.6	9597
2002	1,906,658	7.0	14,000	1.4	2.8	2	1.6	9772
2003	1,879,512	7.0	14,000	1.4	2.8	2	1.6	9633
2004	1,896,293	7.0	14,000	1.4	2.8	2	1.6	9719
2005	1,868,443	7.4	14,000	1.4	2.8	2	1.6	9998
2006	1,889,716	7.4	14,000	1.4	2.8	2	1.6	10112
2007	1,914,814	7.4	14,000	1.4	2.8	2	1.6	10246
2008	2,018,700	7.4	14,000	1.4	2.8	2	1.6	10802

Year	Area (ha) A	Frequency of renewal (%) B	Total annual above-ground DM (kg DM/ha/yr) C	Above-ground residue DM pre- renewal (Mg DM/ha/yr) D	Below-ground DM (Mg DM/ha/yr) E	AG N (%) F	BG N (%) G	F_{CR} (Mg N) A*B/100*((D*F/100)+(E*G/100))
2009	2,110,918	7.4	14,000	1.4	2.8	2	1.6	11296
2010	2,122,181	7.4	14,000	1.4	2.8	2	1.6	11356
2011	2,213,448	7.4	14,000	1.4	2.8	2	1.6	11844
2012	2,255,360	7.4	14,000	1.4	2.8	2	1.6	12069
2013	2,289,094	7.4	14,000	1.4	2.8	2	1.6	12249

Table 12 Summary of pasture renewal activity data and factors for nitrogen-fixing perennial forage - lucerne.

Year	Area (ha) A	Frequency of renewal (%) B	Total annual above-ground DM (kg DM/ha/yr) C	Above G-ground residue DM pre- renewal (Mg DM/ha/yr) D	Below-ground DM (Mg DM/ha/yr) E	AG N (%) F	BG N (%) G	FCR (Mg N) A*B/100*((D*F/100)+(E*G/100))
1990	84,000	10 %	12,000	0.9	3.9	1.9	1.4	602
1991	87,637	10 %	12,000	0.9	3.9	1.9	1.4	628
1992	97,517	10 %	12,000	0.9	3.9	1.9	1.4	699
1993	102,714	10 %	12,000	0.9	3.9	1.9	1.4	736
1994	106,238	10 %	12,000	0.9	3.9	1.9	1.4	762
1995	107,085	10 %	12,000	0.9	3.9	1.9	1.4	768
1996	115,095	10 %	12,000	0.9	3.9	1.9	1.4	825
1997	114,282	10 %	12,000	0.9	3.9	1.9	1.4	819
1998	111,842	10 %	12,000	0.9	3.9	1.9	1.4	802
1999	111,111	10 %	12,000	0.9	3.9	1.9	1.4	797
2000	113,257	10 %	12,000	0.9	3.9	1.9	1.4	812
2001	113,117	10 %	12,000	0.9	3.9	1.9	1.4	811
2002	119,626	10 %	12,000	0.9	3.9	1.9	1.4	858
2003	121,016	10 %	12,000	0.9	3.9	1.9	1.4	868
2004	122,900	10 %	12,000	0.9	3.9	1.9	1.4	881
2005	123,162	10 %	12,000	0.9	3.9	1.9	1.4	883
2006	118,061	10 %	12,000	0.9	3.9	1.9	1.4	846
2007	116,868	10 %	12,000	0.9	3.9	1.9	1.4	838
2008	117,402	10 %	12,000	0.9	3.9	1.9	1.4	842

Year	Area (ha) A	Frequency of renewal (%) B	Total annual above-ground DM (kg DM/ha/yr) C	Above G-ground residue DM pre- renewal (Mg DM/ha/yr) D	Below-ground DM (Mg DM/ha/yr) E	AG N (%) F	BG N (%) G	FCR (Mg N) A*B/100*((D*F/100)+(E*G/100))
2009	124,185	10 %	12,000	0.9	3.9	1.9	1.4	890
2010	119,105	10 %	12,000	0.9	3.9	1.9	1.4	854
2011	121,895	10 %	12,000	0.9	3.9	1.9	1.4	874
2012	129,314	10 %	12,000	0.9	3.9	1.9	1.4	927
2013	132,187	10 %	12,000	0.9	3.9	1.9	1.4	948

A: Based on expert opinion – Derrick Moot 2014.

B: Based on expert opinion – Derrick Moot 2014.

C: Based on expert opinion – Derrick Moot 2014 Not used in other calculations

D: Based on expert opinion – Derrick Moot 2014.

E: BG DM (Mg DM/ha/yr) - 2.2 to 5 (Mg DM/ha/year) - (Teixeira et al. 2007)

F: AG_N (%) –post grazing residue N concentration (Brown & Moot 2004)

G: BG_N (%) average N concentration from (Teixeira et al. 2007) with a range of 1 to 1.8

11 Expert judgement and consultation

11.1 Pasture production and residuals:

Dr Dawn Dalley (DairyNZ) for information on best practice for renewal of dairy pasture, annual DM production and pre-renewal grazing residual amounts.

Kim Mashlan Senior Developer, Feed and Farm systems (DairyNZ) for annual pasture production data

Rob Gibson, Agricultural Analyst, Economic Service Team (Beef + Lamb New Zealand) for sheep and beef pasture production.

Dr David Stevens (Senior Scientist, AgResearch) for pasture production data for sheep and beef farms.

11.2 Pasture nitrogen values

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11.3 Lucerne

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Appendix 1

1 Summary of key International and New Zealand studies that quantify N_2O emissions associated with practices involved in pasture renewal

In their report, Beare et al. (2012) reviewed and summarised the national and international literature to describe the best available data on rates on N mineralisation from soil under pasture renewal practices and their contributions to N_2O emissions. They identified key components of pasture renewal systems that may contribute to enhanced emissions, including:

- the spraying-off and decomposition of pasture or crop biomass,
- the disturbance associated with tillage practices used to prepare the soil for sowing new grass or forage crops,
- the use of nitrogen fertilisers to establish new grass or forage crops,
- the deposition of livestock excreta (urine and dung) during the grazing of forage crops,
- the soil compaction that can result from stock treading during forage crop grazing.

Their key findings:

There are very few studies of pasture renewal systems that have quantified annual rates of N mineralisation or estimated rates of N mineralisation from measured C losses, as per the IPCC 2006 Tier 1 and 2 methodologies.

Cultivation of pasture soils to establish crops or new grass can increase annual rates of N mineralisation by between 10 and 400 kg N/ha compared to continuous pasture. There is a lack of relevant New Zealand studies; these data come from overseas sources.

In grazed forage crop systems, compaction from stock treading tends to increase with increases in the intensity of tillage used to establish crops and with increases in the soil moisture content at the time of grazing. Compaction from livestock treading has been shown to result in 2 to 6 fold higher rates of N_2O production compared to untreaded plots.

1.1 Summary of relevant New Zealand and overseas studies of N2O emissions from pasture renewal

Key relevant studies have been reported by Beare et al. (2012)¸

1.1.1 Tillage effects and N_2O emissions:

The effects of different types of tillage (Ploughing, Minimum tillage, No-tillage) on N_2O emissions during pasture or crop establishment have been the focus of other research. The results of these comparisons have sometimes produced contrasting findings. For example, some studies have reported higher N_2O emissions from no-tillage than from ploughed soils (Ball et al. 1999) that have been attributed to increased soil moisture, improved water conservation and lower soil gas diffusivity, whereas others report no significant effects of tillage on N_2O emissions (Yamulki & Jarvis, 2002).

In contrast to those studies, other researchers (Baggs et al., 2000; Estavillo et al., 2002; Do Carmo et al., 2005) have reported increased rates of N_2O production where tillage was used for pasture renewal under a variety of soil drainage and climatic conditions. Estavillo et al. (2002) attributed their observed increase in N_2O emission to increased mineralisation of soil organic N as a result of tillage-induced disturbance and plant residue decomposition. Pinto et al. (2004) also reported increased rates of N_2O emissions following cultivation of pasture soils that they attributed to both increased rates of organic matter mineralisation and more waterlogged, anoxic conditions in the cultivated soil. On the basis of this observation, they recommended avoiding N fertiliser additions immediately after tillage. operations in the early stages of pasture establishment.

Davies et al. (2001) also reported increased rates of N_2O emissions following pasture renewal with tillage, which were 4 to 5 times greater than those under permanent pasture and corresponded with increased levels of C and N availability in tilled soils.

Similarly, Mori and Hojito (2007) reported that grass-to-grass pasture renewal with tillage (volcanic soil, Japan) resulted in a doubling of N_2O emissions relative to permanent pasture, so pasture renewal increased N_2O emissions. This study determined the increase in N_2O emission was due to increased N mineralisation due to decomposition of incorporated plant residues.

Passianoto et al. (2003) investigated N_2O emissions from pasture renewal in Rondonia, Brazil. Cumulative N_2O emissions over six months were 2.23 kg N/ha, 1.62 kg N/ha and 0.07 kg N/ha from the tillage, no-till and control (no renewal) where both tillage treatments received the same rate of fertiliser N (40 kg N/ha).

MacDonald et al. (2011) showed that inversion tillage (e.g. ploughing) reduced N_2O emissions relative to the use of herbicides and direct reseeding to renew pastures in Western Canada. They attributed these effects to the high levels of total N present in their soils leading to increased soil NO_3^- levels and to relatively high soil moisture conditions during the measurement period.

1.1.2 Effect of spraying on N_2O emissions

The use of herbicides to kill off existing pasture is a common first step in any pasture renewal system. Spraying off of long-term pasture prior to sowing a winter forage crop released 2.2 kg N_2O-N over a 40-day period (MacDonald et al. 2011). These high losses were attributed to warm soil conditions promoting mineralisation and high soil water contents due to the lack of crop to extract soil water. Similarly, MacDonald et al. (2011) concluded that during a wet year, undisturbed soil with herbicide application produced greater N_2O emissions than full inversion tillage.

This finding is supported by earlier work which measured denitrification following herbicide application to grassland (Tenuta & Beauchamp 1996) whereby the application of glyphosate herbicide to grassland resulted in a 20 to 30 fold increase in denitrification rate 14 and 49 days after application, this increase in denitirification may also drive increases in N_2O emissions.

1.1.3 Tillage and pasture type

In their New Zealand study, Van der Weerden et al (1999) measured N_2O-N losses of 4 kg N/ha over a 48 -day period following the ploughing of a of 4-year-old clover sward. These were much greater than emissions from ploughing and rotavating a mixed ley sward (0.17 and 0.26 kg N_2O-N/ha).

1.1.4 Renewal timing

The timing of ploughing of a long-term pasture strongly affected the amount of N mineralisation (Francis et al. 1992). Velthof et al. (2010) compared spring (April) v. early autumn (September) renewal using herbicide followed by tillage in pastures in Netherlands. They reported that pasture renewal in grass-to-grass systems resulted in a 2 to 3 fold increase N_2O emissions relative to continuous pasture. They also reported 40% higher N_2O emissions during the establishment of the pasture when comparing spring v. late summer renewal.

1.1.5 Effects of grazing new pasture and forage crops on N_2O emissions following cultivation

The use of cultivation to establish forage crops or new grass pasture can also result in soil conditions (e.g. low bulk density, low soil strength) that increase their susceptibility to compaction during livestock grazing. Compaction can influence a wide range of soil physical properties, including soil bulk density, porosity, water-holding capacity, diffusivity and tortuosity, which are important to maintaining plant growth but also affect processes (e.g. organic matter solubility, nitrification, denitrification) that are important to determining rates of N_2O production (Abbasi and Adams 1998; Ball et al. 1999; Menneera et al. 2005; Lipiec and Hatano 2003).

Soil compaction is potentially a very important factor affecting rates on N mineralisation and N_2O emissions during pasture renewal, particularly following periods of livestock grazing. Livestock treading under wet conditions and the deposition of urine and dung can create conditions conducive to high rates of N_2O emissions and an increased risk of NO_3^- leaching (Thomas et al. 2008, Thomas et al. 2013, Beare et al. 2010, Monaghan et al. 2005; Simek et al. 2006, Smith et al. 2008).

Appendix 2

2 Summary of key New Zealand studies reporting pasture root measurements.

Main root measure	Pasture	Site	Experimental Treatment	Year/ Season	Depth (mm)	Annual above-ground DM production	BG DM Mg DM/ha, % of AG annual production, or root turnover	Source
Standing root biomass	Browntop and sweet vernal (low fertility tolerant grasses). Sheep grazed.	Ballantrae. Slope = 5 to 25°	Fallow and sheep grazed swards	1994 – Winter	0-600	N/A	Approx. 3.3 to 5.1 Mg DM/ha	(Nie et al. 1997)
Standing root biomass	Ryegrass – clover. Sheep grazed.	Winchmore, Canterbury. Flat.	13C labelling experiment. Superphosphate and irrigation rates.	Spring, summer, autumn 1995-1996	0-200	N/A	4.7 to 7 Mg DM/ha Fertility & irrigation reduced masses.	(Stewart & Metherell 1999)
Standing root biomass	Tussock and inter-tussock. Sheep.	Tara Hills Steep (22 to 33°).	13C labelling experiment. Stocking rates and grazing management (continuous and alternating)	Spring 1996	0-200	N/A	2.7 to 6.8 Mg DM/ha Higher DM in inter-tussock areas. Lowest with high stocking and alternating grazing managements	(Stewart & Metherell 1999)
Standing root biomass	Sheep grazed mixed pasture, hill country.	Ballantrae	14C pulse labelling. Low, medium and high fertility	Spring 1994	0-100	Low – 4.9 Medium – 10.1	Low – 14 Mg DM/ha Medium - 18 Mg DM/ha High – 24 Mg DM/ha	(Saggar et al. 1997)

Main root measure	Pasture	Site	Experimental Treatment	Year/ Season	Depth (mm)	Annual above-ground DM production	BG DM Mg DM/ha, % of AG annual production, or root turnover	Source
						High – 14.1		
Standing root biomass	Sheep and cattle grazed mixed pasture, hill country.	Ballantrae	Fertiliser/fallowing/grazing	Roots sampled in Autumn1990	0-220	>11 Mg DM/ha	13.8 Mg DM/ha (fertiliser and grazed) and 21.9 Mg DM/ha (fertiliser and fallow)	(MacKay et al. 1991)
Standing root biomass	Sheep grazed low fertility pasture, hill country	Ballantrae	Sunny and shady aspects	Summer 1986	0-800	6 to 6.4 t/ DM/ha	14.4 Mg DM/ha and 21.4 Mg DM/ha, shady and sunny aspects respectively.	(Barker et al. 1988b)
Root turnover	Ryegrass – clover. Sheep grazed.	Winchmore, Canterbury. Flat.	13C labelling experiment. Superphosphate and irrigation rates.	Spring, summer, autumn 1995-1996	0-200	14.8 t/DM ha (fertilised treatment)	Annual root production of 4.9 Mg DM/ha Root production to above ground production = 0.33 Root turnover time of between 1.3 and 2 yr.	(Scott et al. 2012)
Root turnover	Ryegrass (autumn establishment after tillage)	Lincoln, Canterbury.	Rhizotron root measurement	Spring to Autumn 1984-85	0-800	N/A	Root longevity of 46 days.	(Gibbs & Reid 1992)
Root production	Perennial ryegrass	Ruakura, Waikato	Minirhizotron of root growth of 5 ryegrasses	3-year study	Spring 1992 to Spring 1995	N/A	Growth and depth responses of root growth to soil water conditions.	(Wedderburn et al. 2010)
Root turnover	Perennial ryegrass	Ruakura, Waikato	Minirhizotron. Reanalysed data form study of	3-year study	Spring 1992 to	N/A	Turnover rate of approx 8 times per year.	(Reid & Crush 2013)

Main root measure	Pasture	Site	Experimental Treatment	Year/ Season	Depth (mm)	Annual above-ground DM production	BG DM Mg DM/ha, % of AG annual production, or root turnover	Source
			Wedderburn et al. (2010).		Spring 1995			
Root DM production	Perennial ryegrass-clover. Dairy	Massey University Dairy Farm, Manawatu	^{14}C pulse labelling	6 times from Sep 1998 to July 2000	0 -100	16 Mg DM/ha	Annual BG production = 16.7 Mg DM/ha, Does not provide standing biomass. Root half-lives ranged between 64 d in spring to 111 d in autumn.	(Saggar & Hedley 2001)
Root DM production & biomass & turnover	Perennial ryegrass-clover. Sheep grazed.	FACE study	Ambient CO_2 Ingrowth cores	Two periods in 2000 and 2001 Spring-Autumn Winter-Spring	0-200	4 Mg DM/ha	Root standing biomass of 0.5 (winter) to 1.2 Mg DM/ha (spring-autumn) Root biomass: above-ground production: 12.5 to 30%. Estimated root growth of >2.7Mg DM/ha over 9 months. Root longevity estimate of 40 to 174 d, winter-spring and spring-autumn, respectively.	(Allard et al. 2005)
Root DM production & biomass	Perennial ryegrass-clover. Dairy	Bunnythorpe, Manawatu. Dairy farm.	N and P fertility treatments. Ingrowth cores.	9 times from Spring 2008 to Spring	0 -160 and 0 - 120	Shoot growth > 10 times root growth. 17.8 to 23.2	Root N concentration of 1.5%. 1.0 to 2.75 Mg DM/ha (authors suggest these values could be up to may	(Dodd & Mackay 2011) (Dodd & MacKay

Main root measure	Pasture	Site	Experimental Treatment	Year/ Season	Depth (mm)	Annual above-ground DM production	BG DM Mg DM/ha, % of AG annual production, or root turnover	Source
				2009		Mg DM/ha/y.	be 3 x underestimated) Estimated annual root production = 0.31 and 0.33 Mg DM /ha, or 14 and 11% of medium and high fertility treatments, respectively	2013)
Root DM production & biomass	80% ryegrass – clover sprayed out. Sheep grazed.	Massey University, Manawatu	Lax versus hard grazing. Ingrowth cores.	1986-87	0-600	N/A	3.5 to 3.9 Mg DM/ha (0-250mm depth).	(Matthew et al. 1991)
Root DM production & biomass	80% ryegrass – clover sprayed out. Sheep grazed.	Massey University, Manawatu	N added as clover fixation replacement. Ingrowth cores.	1987-88	0-700	N/A	10 to 20% of modelled AG DM production	(Matthew 1992)

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