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Greenhouse gas emissions profile for 1 kg of wool produced in the Yass Region, New South Wales: A Life Cycle Assessment approach

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Abstract. The use of Life Cycle Assessment (LCA) to determine environmental impacts of agricultural production, as well as production by other industry sectors has increased. LCA provides an internationally accepted method to underpin labelling and marketing of agricultural products, a valuable tool to compare emissions reduction strategies and a means to identify perverse policy outcomes. A single-issue LCA focussing on greenhouse gas emissions was conducted to determine the emissions profile and carbon footprint of 19-micron wool produced in the Yass Region on the Southern Tablelands of New South Wales. Greenhouse gas emissions (in carbon dioxide equivalents; CO_2-e) from the production of all enterprise inputs and from the production of wool on-farm were included. Total emissions were found to be 24.9 kg CO_2-e per kg of greasy wool at the farm gate, based on a 4941 breeding ewe enterprise on 1000 ha, with a total greasy wool yield of 65.32 t per annum. The co-products included 174 t sheep meat as liveweight from wethers and cull ewes plus 978 maiden ewes sold off-farm as replacement stock. Total emissions from all products grown on 1000 ha were 2899 t CO_2-e per annum.

The relative contribution of greenhouse gas emissions from different components of the production system was determined. Direct emission of methane on-farm (86% of total) was the dominant emission, followed by nitrous oxide emitted from animal wastes directly (5%) and indirectly (5%), and decomposition of pasture residue (1%). Only 2% of total emissions were embodied in farm inputs, including fertiliser.

The emissions profile varied according to calculation method and assumptions. Enteric methane production was calculated using five recognised methods and results were found to vary by 27%. This study also showed that calculated emissions for wool production changed substantially, under an economic allocation method, by changing the enterprise emphasis from wool to meat production (41% decrease) and by changing wool price (29% variability), fibre diameter (23% variability) and fleece weight (11% variability). This paper provides data specific to the Yass Region and addresses broader methodological issues, to ensure that future livestock emissions calculations are robust.

Additional keywords: carbon footprint, methane, nitrous oxide, wool production.

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Introduction

An inventory of global anthropogenic greenhouse gas (GHG) emissions, prepared in 2005, indicates that agriculture accounted for ~60% of nitrous oxide (N_2O) emissions and 50% of methane (CH_4) emissions (Smith *et al*. 2007). Within Australia, agriculture directly accounts for 14.6% of GHG emissions (Australian Government 2012), of which enteric CH_4 accounts for ~65%. However, after accounting for end-use emissions, such as from electricity and fuel used in this sector, the contribution of agriculture to Australian GHG emissions increases to ~23% (Hatfield-Dodds *et al*. 2007).

Life Cycle Assessment (LCA) has become an increasingly common approach for environmental assessment, particularly in relation to GHG emissions (Horne *et al*. 2009). LCA was developed for the manufacturing sector and has since been applied to the agricultural sector (e.g. Narayanaswamy *et al*. 2004; Biswas *et al*. 2008; Weidemann *et al*. 2010). LCA provides an internationally accepted method to underpin labelling and marketing of products and can support industry to identify ways to simultaneously improve profitability and reduce emissions. Clarity about the method by which emissions from wool production might be calculated and assumptions which underpin the calculations, is important in the context of trial eco-labelling legislation in France (Ministry of Ecology, Sustainable Development, Transport and Housing 2010) and emerging labelling work for other Australian commodities, such as cotton (ALCAS NSW Chapter 2012). In light of the Australian Government commitments to reduce GHG emissions and the advent of the Carbon Farming Initiative (Australian Government 2011), there is also a need for more thorough analysis of the impacts of different Australian agricultural enterprises on emissions and how management practices affect those emissions. As some potential emissions reduction strategies will affect minor emissions and because these strategies could be applied over many enterprises, we also identify methodological issues associated with these minor emissions. The purpose of this study is to enable the Australian wool industry to respond to an array of emerging emissions-related issues, by providing objective information and broad methodological development.

In this study, LCA was used to determine the GHG emissions associated with the production of wool in the Yass Region, on the Southern Tablelands of New South Wales (NSW). We provide a single-issue LCA focussed on GHG emissions (in kg CO_2-equivalents; kg CO_2-e), in contrast to some LCA, which explore all environmental impacts of production. Wool was chosen for this study because of the substantial value of production and the large number of sheep in Australia. ABARE (2010) report that despite declining sheep numbers, the value of greasy wool exported from Australia for the 5 years to 2009–10 was \$1960 million per annum, with total wool and sheep skin products valued at \$2144 million per annum. During the same period, in addition to Australian local consumption, mutton and lamb exports have a reported collective value of \$1281 million per annum. NSW remains a substantial wool producing State, with 34 million sheep shorn per annum in NSW for the 5 years to 2008–09, compared with 100 million across Australia over the same period (ABARE 2010).

Although some LCA assess the full life of a product, including emissions from its use and disposal, the system boundary for this LCA is limited to pre-farm (input) and on-farm emissions. By excluding emissions from post-farm transport and processing and those from eventual decomposition of products, the data are relevant to a wide array of supply chains. We report emissions per unit of product (kg CO_2-e per kg greasy wool), as is common practice in LCA (Horne *et al*. 2009), rather than by area (ha) of land in production. This functional unit enables the data to support labelling of single products, requires us to confront problems arising from allocation between co-products and allows potential perverse outcomes, such as impacts on production security from different policy signals, to be identified. As we also compare calculation methods, this work is not constrained to the current policy environment in Australia, for which emissions trading is to occur on a net-basis. A lack of constraint is important in the context of the approach proposed for New Zealand, involving an output intensity-basis (Ministry of Primary Industries NZ 2011) for emissions trading. However, to increase the short-term relevance of this LCA, we also report emissions for the full enterprise.

Materials and methods

Modelled wool production system

The foreground inventory data for the primary LCA (i.e. data specific to the on-farm production system and not held in international databases) were obtained through simulation modelling conducted in GrassGro version 3.2.5 (Moore *et al*. 1997; Simpson *et al*. 2006). The input data to GrassGro, from which the inventory data were derived, comprise historical soil and pasture data from a DPI NSW trial site at 'Kia Ora' Bookham, near Yass (Fig. 1; Graham 2010), along with Yass weather data from the Specialised Information for Land Owners (SILO) (Department of Environment and Heritage Protection 2012) climate database and regionally-representative livestock enterprise attributes (Table 1).

The modelling was conducted on a daily basis for a 51-year period from 15 November 1960 to 14 December 2010, with fixed pasture utilisation. Livestock numbers (Table 2), livestock attributes (Table 3) and pasture production parameters (Table 4) were generated, along with values for enteric CH_4 emissions. These values are specific to the enterprise and are presented in detail because they differ from National Inventory Report (NIR; Australian Government 2012) default values, which underpin emissions calculation at a National scale. Then, the median year for enteric CH_4 production (1985) was chosen from the long-term simulation. Data for this year provided inputs to the FarmGAS Calculator (Australian Farm Institute 2009) and SimaPro (2011), from which other emissions were calculated, using the method explained in the Emissions calculation section below.

Breeding ewes were present for the whole year, with numbers varying during the year due to stock deaths and replacement by maiden ewes. Lambing occurs in early September, with some lambs becoming the maiden ewes and yearling wethers in the subsequent year (Table 2). While ram numbers are presented, their emissions are not included since these emissions are not calculated in GrassGro and in a preliminary assessment, they were found to contribute less than 0.5% of annual enteric CH_4 emissions. Other classes, namely wethers and unjoined maiden ewes also vary in number, due to death, sale and replacement, as is typical of enterprises in the Yass Region (Table 2).

The 1985 shearing year (15 November 1984–14 November 1985) was modelled to represent the full 12-month period over which the product was grown. However, since most of the wool was grown in 1985, we refer to the year as 1985 and present the flock structure on that basis (Table 2). We chose to analyse the median year (1985) because using 51-year averages for the range of variables tended to obfuscate the physical relationship between them. Long-term average enteric CH_4 emissions only differed from 1985 median emissions by 0.9% and emissions from the 25th and 75th percentile CH_4 years each varied 8.5% from those for the median year, indicating that minor variation in the choice of year would not have a marked effect on results.

The functional unit for the study is 1 kg of greasy 19-micron merino wool, modelled for the soil type at Bookham and weather conditions at Yass, from a self-replacing flock of 53 kg mature weight, at a stocking rate of 13.2 dry sheep equivalents (DSE)/ha (Table 1). The wool is produced on a pasture with a mix of native and naturalised annual grasses and a legume component (*Trifolium subterraneum*), typical of that in the region (Graham 2010). Wool cut was modelled as kg of clean wool, as this is a more comparable unit of measurement between farms than greasy wool. Wool cuts and associated emissions were then converted to a greasy wool basis by applying a clean wool yield of 68% sourced from regional statistics (Martin *et al*. 2010). This approach not

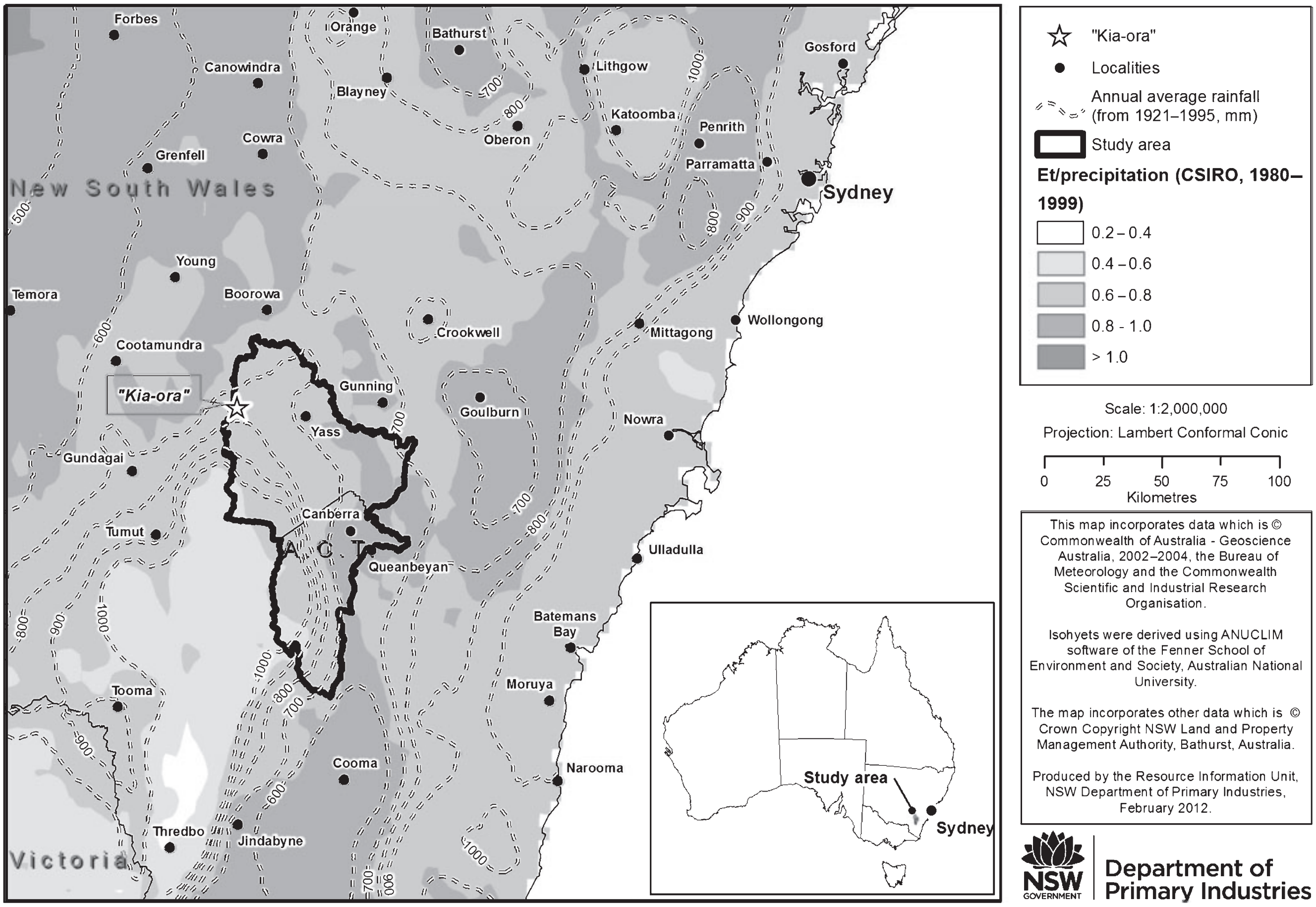

Fig. 1. Map of the region to which this Life Cycle Assessment applies, in New South Wales, the distance from Yass (as the regional centre) to Sydney and the evapotranspiration divided by precipitation (Et/P) 0.8 to 1 zone in which runoff and leaching of fertiliser is deemed not to occur.

only enables reporting of emissions per kg of greasy wool, which is the relevant functional unit at the farm gate, it also allows individual producers to revise the results by substituting wool yields for their own enterprises. The total annual co-products over 1000 ha are 174 t of liveweight from wethers (hoggets) and cull ewes plus 978 maiden ewes sold off-farm as replacement stock.

Current enterprise costs and prices were chosen for the economic analysis, rather than 1985 values, as 1985 represents a biophysical state and is not the median gross margin year. For the period for the week ending 4 March 2011 wool and co-products were valued at \$16.46/kg clean wool (Australian Wool Exchange 2011), \$4.00/kg for sheep meat at a dressing percentage of 44% and \$140/head for surplus hogget ewes (MLA 2011), yielding a gross margin of \$720/ha.

Emissions calculation

For the primary LCA, the daily time step data obtained from GrassGro were used as inputs to the FarmGAS Calculator, from which seasonal indirect CH_4 emissions (from animal wastes) and N_2O emissions were calculated. These data were then entered into SimaPro (2011) software to conduct the LCA and draw background data from both the Australasian LCA Database (RMIT 2005) and the Swiss Ecoinvent Database (Hischier *et al.* 2009). Calculation of most emissions on a seasonal basis is consistent with the NIR (Australian Government 2012) methodology, with enteric CH_4 modelled on a daily basis for the primary LCA because biophysical modelling of this dominant emission is possible.

To determine the sensitivity of calculated enteric CH_4 emissions to different calculation methods, five different approaches were compared. This was important given the dominance of enteric CH_4 emissions in livestock enterprises (Browne *et al.* 2011). The result from daily time step modelling in GrassGro for the median year (1985) forms Method 1 and was used to generate the primary LCA. Other methods were tested to inform discussion about sensitivity and are additional to the method by which the primary LCA was developed. Method 2 uses the results from long-term average modelling (over 51 years) from GrassGro. Method 3 uses seasonal average modelling in FarmGAS and Method 4 uses annual average modelling in FarmGAS, with both of these methods using livestock and pasture data from GrassGro. Method 5 uses seasonal modelling in FarmGAS, applying the NIR default values. The formulae for annual average modelling (Method 4) were built into SimaPro, to support future mixed farm modelling and cross checked with results from FarmGAS. Data

Table 1. Enterprise inputs for modelling in GrassGro at the commencement of the first year of modelling

Characteristic	Attribute	Value
Soil characteristics	Soil type	A sandy loam over heavy clay
	Depth of top soil	460 mm
	Fertility of top soil	0.7
	Field capacity	0.24 m^3/m^3
	Wilting point	0.06 m^3/m^3
	Bulk density	1.36 Mg/m^3
	Saturated conductivity	62.31 mm/h
	Soil evaporation	3.5 mm/day
Climatic conditions (BoM 2012)	Annual average rainfall	650 mm
	Annual average monthly maximum temperature	20.7°C
	Annual average monthly minimum temperature	7.2°C
Pasture characteristics – annual ryegrass	Standing dead DM at the start of modelling	3000 kg/ha
	Litter DM	500 kg/ha
	Maximum rooting depth	600 mm
	Seed DM	100 kg/ha
Pasture characteristics – Seaton Park subterranean clover	Standing dead DM	1000 kg/ha
	Litter DM	336 kg/ha
	Maximum rooting depth	600 mm
	Seed DM	300 kg/ha
Livestock characteristics – 19 micron merino	Standard reference weight	53 kg
	Greasy fleece weight	5.6 kg
	Fleece yield	68%
	Death rate	4% per year for adults and 7% for weaners
	Stocking rate	13.2 dry sheep equivalents/ha
	Cast for age stock	Sold at 6–7 years on 31 December
	Lamb age at sale	Lambs sold in August
	Hogget age at sale	Yearling wethers sold at 14 months of age
	Initial joining	At 1 year of age (April) and at one ram per 100 ewes
	Weaning percentage	91%
	Percentage of year when ewes are lactating	25%

Table 2. Numbers of sheep within animal classes on hand as model outputs from GrassGro for 1985

Class	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Breeding ewes	3996	3978	3965	3948	3932	3918	3904	4941	4941	4922	4901	4860
Rams	50	50	50	50	50	50	50	50	50	50	50	50
Maiden ewes	1054	1050	1049	1047	1044	1041	1039	0	2108	2103	2098	1114
Wethers	0	0	0	0	0	0	0	0	2094	2090	2088	0
Lambs	4385	4359	4332	4310	4286	4265	4239	4200	4229	4213	4192	4168

Table 3. Livestock attributes of sheep within animal classes, as model outputs from GrassGro for 1985

n.a., not applicable

Attribute	Wool yield (kg)	Number sold	Liveweight of sold stock	Dressed weights	Annual average liveweight	Standard reference weights
Breeding ewes	4.5	845	60	25.8	58	53
Rams[A]	6.4	16	83	38.2	83	80
Maiden ewes	4.1	978	50	live	53	53
Wethers	4.8	2088	60	26.4	60	58
Lambs	2.2	n.a.	n.a.	n.a.	30	53

[A]Ram numbers are assumed to remain static at 50, with the 16 reported here just to describe the enterprise.

Table 4. Pasture attributes, as model outputs from GrassGro for 15 November 1984 to 15 November 1985 and feed intake values calculated in FarmGAS for the same period
n.a., not applicable

Pasture attributes and feed intake values	Spring	Summer	Autumn	Winter
DM digestibility of pasture intake	77%	67%	63%	78%
Seasonal average total available DM kg/ha[A] (and green available DM kg/ha)	2995 (2444)	3367 (75)	1573 (209)	1481 (931)
Total NPP[B] for the year to 14 November 1985	7838 kg/ha.year			
Seasonal average total available DM of subterranean clover kg/ha[C,D] (and green available DM of subterranean clover kg/ha)	48 (33)	586 (0)	133 (1.8)	42 (12)
Total NPP[B] for subterranean clover for the year to 14 November 1985	336 kg/ha.year			
Average crude protein of pasture	14.2%	8.5%	7.2%	16.0%
Feed intake (DM kg/head.day)				
Breeding ewes	1.82	1.32	1.11	1.48
Other ewes	1.26	1.21	1.03	1.38
Lambs	0.42	0.68	0.66	1.05
Rams	2.05	1.82	1.72	2.05
Wethers	1.48	n.a.	n.a.	n.a.

[A]As DM availability of pasture is not a limiting factor, intra-seasonal data are not presented.
[B]Net Primary Production.
[C]The total annual weight of the sub-clover component was used to calculate emissions from a single theoretical decomposition process.
[D]Seasonal average values differ from NPP, as they include feed carried over between seasons and are calculated for a different reporting period. NPP is included as a description of the pasture and is not used for modelling in FarmGAS.

about seasonal pasture characteristics (Table 4) were averaged to provide annual values for Method 4 calculations.

Where field data, biophysical model-derived data or Australian-specific data from the NIR were not available, NIR and IPCC (2006) emissions factors and calculation methods were used, with the more recently updated IPCC factors taking precedence. The use of detailed local data is acceptable under the NIR. We also wished to test the effect of applying NIR default values to the calculation of enteric CH_4 (Method 5), in which case NIR default values were deliberately applied. The NIR is consistent with the earlier methodological document, the Australian Methodology for the Estimation of Greenhouse Gas Emissions and Sinks 2006, Agriculture, National Greenhouse Gas Inventory (Australian Government 2007).

Impact assessment

Analysis was conducted in SimaPro using the Australian Indicator Set version 2.01 (RMIT 2005), which assumes a global warming potential of 298 CO_2-e for N_2O and 25 CO_2-e for CH_4. These potentials are consistent with IPCC (Forster *et al.* 2007).

The total enterprise emissions were apportioned to wool and co-products on the basis of their gross economic value. LCA theory requires practitioners to first consider avoiding allocation by expanding the system or second consider product substitution (Horne *et al.* 2009). However, due to uncertainty about likely substitution in the market place, in practice, economic allocation is commonly used in LCA. Economic allocation also simplifies comparison of the effect of regional variability in genetic traits on the emissions profile. Total enterprise emissions, from the 1000 ha are also reported. Fifty-six percent was allocated to the production of wool, 32% to the production of meat from cull stock and 12% to the surplus young ewes sold off-farm. Gross value was calculated as the product of the market price and the enterprise output for each commodity. These proportions are typical of wool-focussed enterprises in the study region under the market conditions described. The effect of this allocation method is discussed.

Scope and assumptions

To describe the system boundary for the primary LCA, it was important to identify all pre-farm and on-farm assumptions underpinning emissions calculation.

Pre-farm emissions of all GHG are presented on the basis of kg CO_2-e for the full production year. In this study, emissions from all stages in the production of vaccine (13.4 kg, partly comprising the active ingredient), drench and fly strike treatment (27.7 kg of active ingredient), single superphosphate fertiliser (90 kg/ha) spread by truck, diesel and electricity (Table 5), are considered, using current values, as explained above. Some uncertainty exists over the relevance of international data on embodied emissions of inputs and how they should be applied when developing LCA in the Australian context. Even though data were chosen primarily on the basis of the descriptions provided in the databases, the impact of any error would not be substantial, as pre-farm emissions contribute less than 2.3% of total emissions.

Emissions from the delivery of inputs to regional store and transport to the farm were also included and presented as t km. The regional store was located at Yass, 280 km from Sydney and the trial site at Bookham, 34 km from Yass. The pre-farm component for the production and delivery of diesel fuel used during the application of fertiliser and use of the utility and motorbike (17%) was separated from the on-farm combustion component (83%) (Table 5). Data for the emissions from delivery of diesel to the regional store were also increased from a standard delivery distance of 60 km (RMIT 2005) to reflect the location of the enterprise. In this study, supplementary feeding (180 t wheat for the enterprise) was considered when calculating the effect on emissions from a change in enterprise emphasis to the production of first-cross lambs, in which case the results of a prior wheat study

Table 5. Greenhouse gas emissions from the production of 1 kg of greasy wool on-farm for 1985

Input type and stage of production	Inputs/kg greasy wool	Emissions (kg CO_2-e/kg greasy wool)	% contribution
Pre-farm			
Production of vaccine	0.000115 kg	0.007	0.03
Production of drench	0.000237 kg	0.002	0.01
Production of single superphosphate	0.772 kg	0.515	2.07
Transport of inputs, other than diesel	0.114 t.km	0.024	0.1
Production and transport of diesel[A]	–	0.012	0.05
Production of electricity	0.0123 MJ	0.003	0.01
Pre-farm subtotal		0.56	2.27
On-farm			
CH_4 emissions direct enteric	0.85 kg CH_4	21.4	86.12
CH_4 emissions indirect from manure	0.00014 kg CH_4	0.0035	0.01
N_2O emissions directly from manure and urine	0.00426 kg N_2O	1.28	5.15
N_2O emissions indirectly from manure and urine via volatilisation and re-emission	0.00199 kg N_2O	0.596	2.4
N_2O emissions indirectly from manure and urine via leaching and runoff	0.00224 kg N_2O	0.671	2.7
N_2O emissions directly from pasture residue	0.000927 kg N_2O	0.278	1.12
Combustion of diesel			
Spreading of fertiliser (at 1.2 L diesel/ha)	0.018 L	0.028	0.11
Utility	0.010 L	0.017	0.07
Motorbike	0.004 L	0.008	0.03
Vet services	USD $0.00857	0.005	0.02
On-farm subtotal		24.29	97.73
Total emissions		24.85	100

[A]Includes 17% of total emissions from the production and transport and use of diesel for fertiliser spreading, utility and motor bike that could be attributed to production and delivery to farm. As the emissions from diesel are a mixture of production and transport emissions, using different units, the quantity is not reported here.

(Brock *et al.* 2012*a*), with total emissions of 200 kg CO_2-e per t of wheat, were applied. However, feed supplementation was not required during the median emissions year (1985) on which the primary LCA is based, indicating that hand feeding is an irregular practice in this region.

Embodied emissions from the manufacture of farm machinery, are not included in this LCA, as this emission tends to be minor and excluded in other agricultural LCA (Narayanaswamy *et al.* 2004; Biswas *et al.* 2008; Weidemann *et al.* 2010), particularly those associated with livestock. Emissions from packaging, such as drench containers, which are sometimes considered in LCA are also excluded as minor, on the basis of sensitivity testing in the wheat LCA (Brock *et al.* 2012*a*), where emissions from packaging were less than 0.001% of total emissions. Emissions from the production of electricity are included (Table 5).

For the on-farm component of the primary LCA, in addition to including direct enteric CH_4 emissions and indirect CH_4 emissions from manure and urine, four different N_2O emissions were included. The direct emissions were N_2O from manure and urine plus N_2O from decomposition of the legume component of the pasture. The indirect emissions were N_2O from manure and urine through volatilisation, deposition and re-emission plus N_2O from leaching and runoff of deposited manure and urine. These minor emissions are discussed because of the need to establish and simplify a calculation method for future livestock emissions studies.

In this study, leaching and runoff of N_2O from deposited manure and urine are included, on the basis of the regional soil type and climatic conditions. Leaching and runoff in non-irrigated areas is deemed in the NIR to be included, except where the ratio of evapotranspiration to precipitation is between 0.8 and 1.0. A map of evaporation divided by precipitation (Et/P) zones was developed and combined at the same scale and projection with a map of the region under study (Fig. 1). The study region closely correlates with the zone in which leaching is deemed to occur (Fig. 1). In contrast, legume-fixed nitrogen (N) was not considered to be volatilised or lost through leaching and runoff, as much of this product is subsurface and reused by the non-legume component of the pasture, with a portion ultimately counted as a livestock emission, via feed intake values derived in GrassGro.

To calculate N_2O released indirectly from manure and urine through leaching and runoff, a factor of 0.0075 (IPCC 2006) was applied, rather than 0.0125 (Australian Government 2012), as this factor was updated more recently in the IPCC report. In contrast, the Australian value of 0.00014 (Australian Government 2012) was adopted for indirect CH_4 emissions from manure and urine through volatilisation and redeposition, rather than 0.28, which is used internationally (IPCC 2006). This indirect emission has been deemed minor in Australia's drier climatic conditions.

Nitrous oxide released directly from decomposition of the uneaten legume component of the pasture is included, calculated in SimaPro using the method from Unkovich *et al.* (2010), as recommended for this specific enterprise (D. F. Herridge, pers. comm., University of New England). The value of 20.2 kg of shoot N fixed per t of biomass was applied, plus a factor to convert shoot DM to both root and shoot DM (1.75) for subterranean clover (Unkovich *et al.* 2010), for 0.336 t of sub-clover DM/ha (Table 4) and a pasture utilisation of 42%. These results were compared with N_2O emissions calculated using the NIR method and default values. By including emissions released during legume residue breakdown and excluding potential N_2O emissions from legume-fixed N, we avoid double counting. Potential emissions from the non-legume component are excluded as inconsequential, an approach which is again consistent with the NIR.

In this study, no net sequestration of soil organic carbon (C) is assumed, with the production system having reached equilibrium with regard to soil C over time. Therefore, no attempt has been made to demonstrate possible sequestration and release flows between seasons and years.

The volume of diesel combusted on-farm during spreading of superphosphate by truck was assumed to be equivalent to the volume required to spread lime by truck in Central West NSW, at 1.2 L diesel/ha (Brock *et al*. 2012*a*), even though the weight of product would be smaller. This assumed volume of diesel is half of that calculated using the Western Australian Farm Fuel Calculator (Salam *et al*. 2010) for spreading by tractor and as this emission is minor, data were not refined further.

Pasture establishment and renovation was not included in the LCA as it is an irregular practice in the region and on a long-term regional basis would not heavily influence the emissions profile. A preliminary calculation showed that if pasture is sown on ~20% of properties once every 10 years, the estimated increase in total emissions would be 0.01 kg CO_2-e/kg greasy wool or 0.04% of the emissions profile.

The volume of diesel combusted in the farm utility and motorbike on the farm was calculated from trial site data (B. Hazel, pers. comm. 'Kia Ora', Bookham), with 300 km travelled per week, of which 140 km was by utility (at 9.3 L/100 km) and 160 km by motorbike (at 3.2 L/100 km). This equates to 677 L diesel per annum for the utility and 266.2 L petrol per annum for the motorbike. As the international LCA databases do not contain more specific data, we assume a light commercial vehicle of less than 3.5 t for both calculations.

Electricity use was 400 kWh/year (B. Hazel, pers. comm. 'Kia Ora', Bookham), including electricity used for shearing, crutching, electric fence operation and pumping of stock water, of which 90 kWh/year was used for shearing.

Farm labour was not included directly in the emissions calculation because it was not expected to result in significant emissions but is included in overhead costs. However, veterinary fees have been included at $1000 USD, using 2004 USA input-output data, as they could be attributed specifically to the product. Debate continues in the LCA community about how farm labour should be addressed, with the PAS 2050 (PAS 2008) Standard excluding human labour and the draft ISO 14067 (ISO 2011) Standard requiring all significant impacts to be included. As only additional consumption brought about by labour to produce a specific product, beyond that required for sedentary activity, is reasonable to include, emissions from labour were excluded as minor in this LCA. Emissions from transport of shearers to farm are excluded, as per a LCA convention to only include travel where it occurs during employment or over very large distances, e.g. itinerant workers travelling between countries.

In addition to costs specified in the gross margin, overheads, including wages, were assumed to be $139/ha based on an average of $15.30/DSE for 1998–2010 (Holmes Sackett 2011), which is similar to the overheads for the top 20% of producers in 2010 ($15.99/DSE).

The economic allocation of emissions for the primary LCA relies on assumptions about market conditions and the relative wool and meat productivity of the enterprise. Therefore, we have explored the sensitivity of the LCA to variation in these factors and now outline the methods by which these factors were modified. We test each variable separately to show its specific effect on the calculated C footprint.

Sensitivity to change in enterprise dominance

To determine the effect of changes to the enterprise dominance, an alternate enterprise producing first-cross lambs was also modelled in GrassGro. The same genotype of merino ewes were mated to Poll Dorset rams instead of Merino rams leading to a greater relative emphasis on the production of meat rather than wool. In this enterprise, replacement ewes are purchased and all progeny are sold to slaughter at 44 kg liveweight. Grain is used to finish the lambs in years when the pasture is insufficient for stock to reach the target weights. Since replacement ewes are purchased, the number of ewes joined is higher than for the self-replacing merino enterprise in which ewe lambs are retained. The stocking rates for both enterprises are set to achieve similar pasture utilisation rates. The embodied emissions in purchased feed grain and purchased replacement ewes are included. The data from GrassGro were imported into SimaPro and the economic allocation changed, based on data from the price period used for the primary LCA, to reflect the progeny having a higher meat value.

Sensitivity to change in market price

Sensitivity of the emissions profile to market price was tested by comparing the primary LCA with assessments conducted using two alternate price periods (the weeks ending 13 August 2010 and 7 November 2008) for wool (Australian Wool Exchange 2011), mutton and lamb (MLA 2011). The results are presented as percentage contribution of the product to total income. In this instance, the change in calculated emissions is the result of a change in economic allocation in SimaPro, independent of GrassGro, as livestock characteristics are not directly altered by market price.

Sensitivity to change in fibre diameter

As fibre diameter is the wool trait that has the greatest influence on wool price, the effect of choosing genotypes that differ in fibre diameter from those in the primary LCA, was considered. To test the sensitivity of wool emissions intensity to change in fibre diameter, emissions from the production of wool at two additional fibre diameters (18 and 20 microns) were compared with those for production of 19-micron wool used in the primary LCA. Average fleece weight was held constant. In this case, enteric CH_4 emissions were remodelled in GrassGro and economic allocations changed in SimaPro. As change in enteric CH_4 emissions per ha were not substantial (in the order of 1.3%), other emissions were not remodelled in FarmGAS.

The primary influence on the results was from the change in economic allocation.

Sensitivity to change in fleece weight

Relative production levels of wool also vary due to the genetic merit of the sheep. So, the sensitivity of wool emissions intensity to fleece weight was tested, applying a similar method to that used to test the effect of a change in fibre diameter. Genotypes with average greasy fleece weights of 5.0 and 6.2 kg/head were compared with those in the primary LCA (5.6 kg/head). This range in fleece weight is typical of the variation in genotype found in the industry (Martin *et al*. 2010). Average fleece micron was held constant, to test each variable independently and indicate the effect of different flock genetics across the region. As per the approach taken for fibre diameter, enteric CH_4 emissions were remodelled in GrassGro and economic allocations changed in SimaPro. As change in enteric CH_4 emissions per ha were not substantial (in the order of 2.3%), other emissions were not remodelled in FarmGAS.

Results

Total emissions

The value of total emissions allocated to wool in the primary LCA were 24.9 kg CO_2-e/kg greasy wool, which forms the basis for comparison between components of the emissions profile. The total unallocated value of all emissions on an enterprise-basis (i.e. from production of wool and all co-products) from all inputs and processes were 2899 kg CO_2-e (Table 6).

Enteric CH_4

For the primary LCA, the direct enteric CH_4 emissions on-farm (at 21.4 kg CO_2-e/kg greasy wool) comprise 86% of the emissions profile (Table 5, Fig. 2). When different calculation methods were applied, the enteric CH_4 emissions were found to vary between 21.4 kg CO_2-e (99.1 kg CH_4) and 15.6 kg CO_2-e/kg greasy wool (72.42 kg CH_4) (Table 7). Enteric CH_4 emissions were similar for daily modelling in GrassGro for the median year (Method 1) and for 51 years of modelled data (Method 2). However, results achieved using seasonal (Method 3) and annual (Method 4) modelling in FarmGAS for 1985, differed by ~14% from the result of the primary LCA, despite pasture and livestock characteristics remaining unchanged between these approaches. A further decrease in calculated emissions was observed when NIR livestock and pasture data and default emissions factors were adopted (Method 5), to a total reduction of 27%, when compared with the daily modelled result for 1985 (Method 1) (Table 7).

Indirect CH_4

Estimates of indirect CH_4 emissions from manure and urine, calculated using FarmGAS on a seasonal basis (of 0.0035 kg CO_2-e/kg greasy wool), comprise ~0.01% of the emissions profile for the primary LCA (Table 5, Fig. 2) and changed slightly under different calculation methods (Fig. 3).

Direct and indirect N_2O

Estimates of direct N_2O emissions from manure and urine (of 1.28 kg CO_2-e/kg greasy wool) provided the second most substantial contribution to the emissions profile, comprising 5.2% of the profile. Indirect N_2O emissions from manure and urine through volatilisation, deposition and re-emission comprise 2.4% of the emissions profile and those from leaching and runoff 2.7% (Table 5, Figs 2, 3). Direct N_2O emissions from decomposition of the legume component of pasture residue (of 0.278 kg CO_2-e/kg greasy wool) comprise 1.1% of the emissions profile (Table 5, Fig. 2), when the method of Unkovich *et al.* (2010) was used (i.e. Methods 3 and 4 in Fig. 3). However, when NIR formulae and emission factors were applied for the same volume of legume component and percentage utilisation, N_2O emissions from decomposition of pasture residue (at 0.219 kg CO_2-e/kg greasy wool) comprise 0.88% of a slightly reduced emissions profile (i.e. Method 5 in Fig. 3). As this discrepancy only applies to a small component of the emissions profile and there is greater effect from inter-annual variation in pasture growth, further refinement was not conducted. In Fig. 3, minor emissions are not reported for Methods 1 and 2 as GrassGro only calculates enteric CH_4 emissions. When calculating the total C footprint for the primary LCA, Method 3 data were used for minor emissions.

Emissions from production of inputs and minor contributions on-farm

Estimates of all emissions associated with production and transport of farm inputs (of 0.56 kg CO_2-e/kg greasy wool) comprise 2.3% of the emissions profile. The production and delivery to the regional store of animal health products (0.04%) and fertiliser (2.07%) comprise 2.11% of the emissions profile (Table 5, Fig. 3). In addition, emissions from the transport of inputs from the regional store to the farm comprise 0.10%, emissions from pre-farm production and transport of fuel used during fertiliser spreading and by the utility and farm motorbike comprise 0.05%, and emissions from electricity used on-farm comprise ~0.01% of the emissions profile. Veterinary services, recorded as an on-farm emission, comprise 0.02% of the emissions profile (Table 5, Fig. 2).

Table 6. Greenhouse gas emissions from the entire enterprise, including co-products, for 1985

Input type and stage of production	Emissions (t CO_2-e/65.32 t greasy wool)	Emissions (t CO_2-e/174 to sheep meat liveweight)	Emissions (t CO_2-e/978 maiden ewes)	Emissions (t CO_2-e/enterprise)
Pre-farm subtotal	36.58	20.90	7.84	65.32
On-farm subtotal	1586.62	906.64	339.99	2833.26
Total emissions	1623.20	927.54	347.84	2898.58

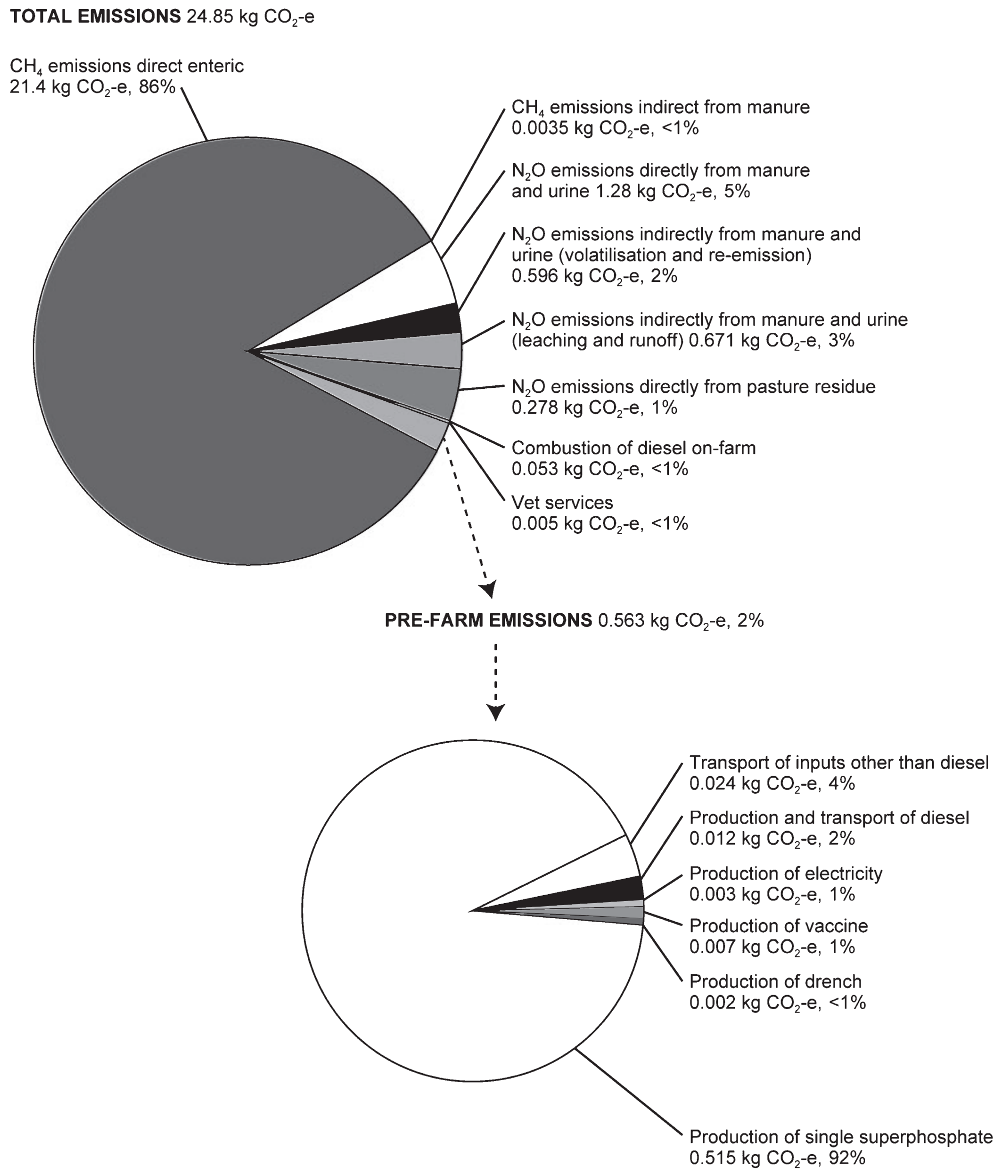

Fig. 2. Greenhouse gas emissions (kg CO_2-e) from the production of 1 kg of greasy wool at the farm gate in the Yass Region.

Table 7. Comparison of the direct enteric methane emissions from wool production using different calculation methods

Method	Calculation method	Methane (kg/ha)	Methane (kg CO_2-e/kg greasy wool)	% of 1985 daily modelling
Method 1	Daily modelling in GrassGro for the median year of 1985	99.10	21.4	100
Method 2	Daily modelling in GrassGro for the 51-year long-term average period	98.28	21.2	99.1
Method 3	Seasonal modelling in FarmGAS using livestock and pasture data from GrassGro for 1985	86.02	18.5	86.4
Method 4	Annual average modelling in FarmGAS or SimaPro using livestock and pasture data from GrassGro for 1985	85.11	18.3	85.5
Method 5	Seasonal modelling in FarmGAS using only livestock and pasture emissions factors and defaults from the National Inventory Report	72.42	15.6	72.9

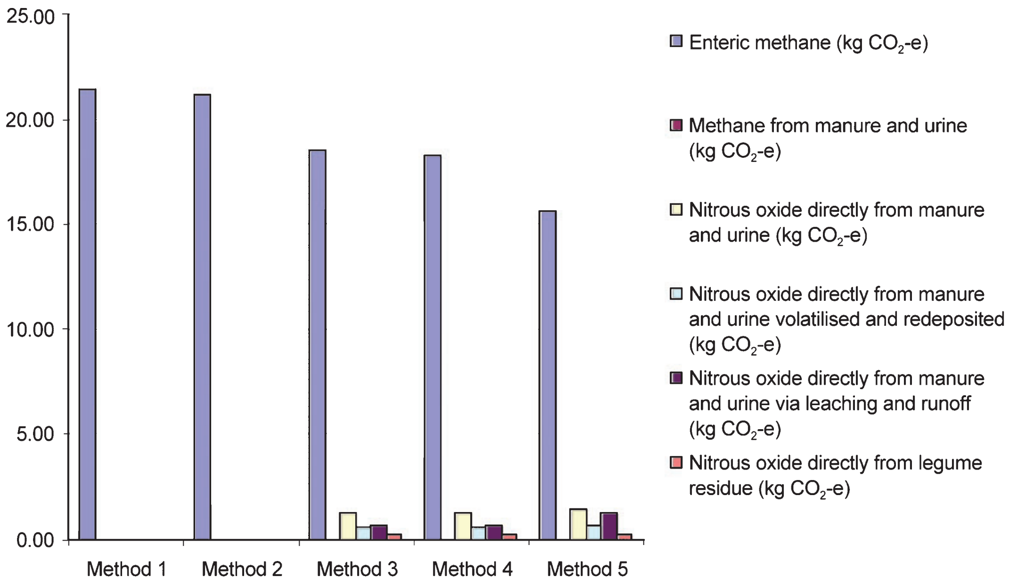

Fig. 3. Livestock and pasture emissions from production of 1 kg of greasy wool, excluding other emissions.

Economic basis

Total profit was \$200/t CO_2-e, based on a 100% allocation across all co-products on 1000 ha, with the entire enterprise producing 2899 t of CO_2-e, a gross margin value of \$720/ha and overhead costs of \$139/ha.

Sensitivity of allocated emissions to change in variables

Substantial differences in wool emissions intensity occurred when enterprise and product variables were modified. When the enterprise focus changes from wool to meat production, the allocation of emissions on the basis of relative economic value changes the allocation to wool from 58 to 27%. This results in a 41% reduction in calculated wool emissions intensity (Table 8). Emissions from additional inputs to the production system (180 t of feed wheat and 1670 replacement ewes) were not substantial (0.16 and 2.29 kg CO_2-e/ha, respectively). The emissions from the enterprises were found to be almost identical on a per-head basis, until the different economic allocation was applied.

When market prices vary, the allocation of emissions to wool varies, altering the calculated emissions intensity. In this case, the altered market conditions changed the allocation of emissions to wool from 56% to 50 and 66% resulting in greasy wool emissions intensities of 22.1 and 29.4 kg CO_2-e, respectively, showing 29% variability when compared with the primary LCA (Table 9). The studied change in fibre diameter changed the allocation of emissions to wool from 56% to 63 and 51%, resulting in calculated greasy wool emissions intensities of 28.4 and 22.6 kg CO_2-e, respectively, showing 23% variability when compared with the primary LCA (Table 10). The studied change in potential fleece weight changed the allocation of emissions to wool from 56% to 53 and 59%, resulting in calculated greasy wool emissions intensities of 23.8 and 26.5 kg CO_2-e, respectively, showing 11% variability when compared with the primary LCA (Table 11).

Discussion

For wool marketing to be underpinned by robust data, national policies to be regionally applicable and for landholders to identify opportunities for practice change, it is essential that inter- and intra-regional differences in emissions from wool production be better understood. Many LCA are conducted at a case-study scale and consider ~3–5 years of data. However, we have shown that by accommodating variability and testing the sensitivity of

Table 8. Comparison of calculated wool emissions intensity between a wool-dominant enterprise and an enterprise focussed on the production of first-cross lambs

Enterprise type	Percentage of total income contributed by each enterprise product			Enteric methane (kg/ha)	Total emissions (kg CO_2-e/kg greasy wool)
	Wool (%)	Mutton (%)	Lamb/live animal (%)		
19-micron wool production	56	32	12	99.1[A]	24.9
19-micron ewes joined to Dorset rams for meat production	31	11	58	94.0 + emissions from production of feed and replacement ewes	14.8[B]

[A]Based on the Method 2 calculations.
[B]Includes emissions from the production of wheat (0.157 kg CO_2-e) and replacement ewes (2.29 kg CO_2-e).

Table 9. Comparison of calculated wool emissions intensity for different market prices for wool, mutton and lamb

Price period (date)	Percentage of total income contributed by each enterprise product			Enteric methane (kg/ha)	Total emissions (kg CO_2-e/kg greasy wool)
	Wool (%)	Meat (%)	Live animals (%)		
13 Aug. 2011	50	42	8	99.1	22.1
4 Mar. 2011	56	32	12	99.1	24.9
7 Nov. 2008	66	27	7	99.1	29.4

Table 10. Comparison of calculated wool emissions intensity for different fibre diameters

Fibre diameter (um)	Percentage of total income contributed by each enterprise product			Enteric methane (kg/ha)	Total emissions per kg greasy wool (kg CO_2-e)
	Wool (%)	Meat (%)	Live animals (%)		
18 um	63	27	10	100.4	28.4
19 um	56	32	12	99.1	24.9
20 um	51	36	13	99.5	22.6

Table 11. Comparison of calculated wool emissions intensity for different fleece weights

Greasy fleece weight (kg/head)	Percentage of total income contributed by each enterprise product			Enteric methane (kg/ha)	Total emissions per kg greasy wool (kg CO_2-e)
	Wool (%)	Meat (%)	Live animals (%)		
5.0 kg	53	34	13	101.4	23.8
5.6 kg	56	32	12	99.1	24.9
6.2 kg	59	29	12	100.2	26.5

calculation methods, especially by applying biophysical modelling over a long time horizon, a highly robust LCA can be produced for the wool industry that is applicable at a regional-scale. This broader approach (Brock *et al.* 2012*b*) will not only improve our understanding about the representativeness of existing case-studies but also, to some extent, overcome the problem faced by individual producers in obtaining enterprise-level seasonally-specific data. We have also considered methodological issues which will inform future LCA development. By comparing five recognised methods for calculating enteric CH_4 and exploring the effects of different market and enterprise assumptions, during economic allocation, we provide a robust basis for future work. We focus on differences in enterprise emphasis on wool production and genetic traits, across a regionally-representative range, in the context of maintaining or improving yield.

Findings relevant to enterprise management

By using a LCA approach, it is possible to observe the full suite of consequences from practice change and understand the relative importance of specific emissions. Wool production is a function of pasture growth and animal genetics, so measures to optimise pasture production and wool yield or select low CH_4 emitters (Alford *et al*. 2006) will reduce emissions per unit of product, provided that there is not an increase in other components of the emissions profile. Best management practices adopted by industry over recent years, such as improved grazing management and genetic improvements in wool yield, may have already reduced emissions intensity (Alcock and Hegarty 2006).

We have shown that enteric CH_4, which is closely tied to sheep numbers, dominates the emissions profile (at 86% in this LCA). So, where producers are able to reduce average stock numbers while maintaining production, emissions intensity and total emissions will be reduced. This could be achieved through lamb versus yearling joining in self-replacing flocks, improved reproductive genetics and increasing ewe longevity (Cruickshank *et al*. 2008; Hegarty *et al*. 2010). Reduced sheep numbers across Australia (ABARE 2010) have clearly reduced total national agricultural emissions.

For this study, it was evident that minor feed supplementation did not have a substantial impact on the emissions profile through embodied emissions in the grain and transport emissions, nor did inclusion of replacement ewes in the first-cross lamb enterprise. This LCA provides a basis to test whether this is the case where more substantial quantities of grain are required, for example to achieve earlier finishing of meat co-products or increase lamb growth rate in preparation for joining. From a supplementary feeding perspective, it is evident that producers need to consider at least medium-term seasonal variability (for emissions reduction and reporting purposes), with stock losing weight and reducing emissions during drought years but having high intakes and emissions when seasonal conditions improve. Supplementary feed with a high protein content will also increase levels of excreted N_2O (Freer *et al*. 1997). Also, from a pasture perspective, if long-term pasture utilisation is increased, the potential increase in livestock numbers needs to be considered in a full LCA context, including the effect of reducing N_2O emissions from pasture.

This study provides a regionally-relevant emissions profile to promote discussion among producers about opportunities to modify the emissions profile for their own production systems. However, this would be best done in conjunction with modelling in a package, such as GrassGro, which is specifically designed for use by producers and advisors. Modelling in GrassGro allows a far more rigorous understanding of the dominant enteric CH_4 emission but does not enable calculation of N_2O emissions.

Findings relevant to policy formulation

This paper has shown intra-regional variability by changing enterprise characteristics across a regionally-typical range and shown variability in estimated emissions using different calculation methods, with different data requirements. It is important for policies supporting emissions trading, such as those aligned with the Carbon Farming Initiative (Australian Government 2011; Department of Climate Change and Energy Efficiency 2012), to take into account variability associated with different calculation methods and livestock and pasture characteristics, both temporally and spatially. Also, it is important that policies do not drive practice change that might have undesired outcomes, such as reducing production volumes, increasing emissions in other components of the emissions profile or in related enterprises, or driving soil erosion or acidification. This LCA provides a basis for testing specific emissions reduction strategies and testing other scenarios, such as increases in the cost of inputs, such as diesel or grain.

Even though there was some variability in emissions on a per-head basis, the greatest variability in this study was in allocated emissions. However, allocated emissions will be important in a product marketing and labelling context and to assess production security, given the need to increase net production (at lower emissions intensity). Emerging eco-labelling policy in other countries may also drive a focus on allocated emissions, with methodological development associated with allocation discussed further below.

Findings relevant to future emissions calculation methodology

One of the key findings from this study was the substantial variation in calculated CH_4 emissions between the biophysical model GrassGro, and the reporting model FarmGAS (of 27%). FarmGAS, which is based on the NIR, uses the formulae from Howden *et al*. (1994). GrassGro, on the other hand, is based on formulae from Blaxter and Clapperton (1965). While the former has been tested against National data, primarily from the Australian Bureau of Statistics, the latter has been tested, from a feed intake perspective, against specific field trials. As our study is regionally applicable, either field- or national-scale approaches may be relevant. However, as GrassGro has been tested specifically within the region of study (Simpson *et al*. 2006) and we were able to conduct biophysical daily modelling, we are more confident that this approach accurately represents the status. The scope of this paper is to highlight these differences, rather than establish a mechanism for their resolution.

Our analysis shows that assumptions about genetic traits and market conditions have a marked effect on calculated emissions under economic allocation, and that fibre diameter and fleece weight also have a small impact on the emissions modelled in GrassGro (Tables 9, 10 and 11). It is important to test whether the impact is also small in other production systems and regions. The standard reference weight of each class of sheep is also likely to vary substantially, especially between regions. Changing the flock genotype to sheep with a higher micron, fleece weight and maintenance energy requirement will affect the emissions intensity.

It is important for international comparisons about the environmental credentials of products to be supported by a full understanding of underlying assumptions. Emissions for wool production in the USA reported in the Ecoinvent database (Hischier *et al*. 2009) are lower (19.2 kg CO_2-e/kg wool) than in our study (24.9 kg CO_2-e/kg greasy wool) (Table 5), due to a 22.8% allocation to wool (T. Nemecek, Agroscope Reckenholz-Taenikon Research Station ART, Zurich, Switzerland, pers. comm.), compared with a 56% allocation to our high quality product. In contrast, emissions reported for the USA are higher than in meat-dominant enterprise in our study (14.8 kg CO_2-e/kg greasy wool) at 31% allocation to wool. However, calculated emissions on a per-head basis for both Yass examples are lower than for wool production in the USA. Values for production in the USA are generalised and based on USDA (2011) and USEPA (2008).

While it would be beneficial to test a biophysical allocation, a similar situation would arise with genetic propensity for meat production reducing wool quality and yield. While allocation on a physiological basis might be desirable and may be possible for the specified co-products, the problem of allocating flock maintenance emissions remains. We highlight this problem for ongoing methodological development and stress the importance of clearly documenting assumptions in a product marketing context.

Default values and calculation methods for minor emissions also require clarification during methodological development. The NIR method applies an emission factor of 0.0125 for N_2O leaching and runoff from manure and urine, rather than the more recent factor of 0.0075 (IPCC 2006), effectively doubling these emissions from 2.7 to 5.1% of an increased emissions profile. This highlights the importance of updating methods to latest applicable research. The presence and extent of leaching and runoff, both from a fertiliser and livestock emissions perspective is important to resolve, especially in the context of interest in eutrophication attributes in LCA. We also found that minor attribute changes, such as setting DM digestibility at 71% and applying a more regionally-relevant approach to calculating N_2O emissions from decomposition of legume residues had an effect on the primary LCA. From a calculation perspective, the quantities of pasture available (feed on hand) modelled in GrassGro are outside some of the thresholds of the NIR formulae on which FarmGAS is based. Additionally, far more substantial field research may be required to build understanding of each of the CH_4 and N_2O emissions discussed here. The benefits of a field-based approach are already evident in cropping research, with regionally-specific N_2O emission factors generated (Schwenke *et al*. 2010).

Conclusions

This LCA provides information about potential median emissions from wool production in the Yass Region, from which extension information can be developed for wool growers in southern NSW. It also provides upstream data, along with detailed documentation of assumptions, to support development of full supply chain and whole farming systems LCA.

By discussing methodological issues, especially comparing five recognised calculation methods, this LCA provides findings relevant to policy development. It also provides a robust basis for investigating emissions reduction options and identifying unintended consequences of proposed economic and policy instruments. It enables assessment of new technologies and innovative practices in an emissions context and for impacts of projected climate change on the emissions profile to be considered, through changes in pasture availability.

This paper shows that it is possible to build a robust LCA for wool production that is applicable at a regional scale, provided that enterprise and wool parameters are clearly specified, methods defined, genetic and market variability tested and where possible emissions factors specific to NSW are applied. As it will not be possible to build LCA for all producers in NSW, assessments at this scale may fill a niche in supporting development of regionally-applicable policies and supporting landholders to identify emissions reduction strategies. However, it would be prudent to support further work at this scale with additional field-based research and ongoing refinement and regionalisation of pasture and livestock data and emission factors.

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