Int J Life Cycle Assess (2016) 21:820–830
DOI 10.1007/s11367-016-1054-4

LCA FOR AGRICULTURE

Allocation of greenhouse gas production between wool and meat in the life cycle assessment of Australian sheep production

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Received: 4 November 2015 / Accepted: 25 January 2016 / Published online: 4 February 2016

Abstract
Purpose Australia is the largest supplier of high-quality wool in the world. The environmental burden of sheep production must be shared between wool and meat. We examine different methods to handle these co-products and focus on proportional protein content as a basis for allocation, that is, protein mass allocation (PMA). This is the first comprehensive investigation applying PMA for calculating greenhouse gas (GHG) emissions for Australian sheep production, evaluating the variation in PMA across a large number of farms and locations over 20 years.
Materials and methods Inventory data for two superfine wool Merino farms were obtained from farmer records, interviews and site visits in study 1. Livestock GHG emissions were modelled using Australian National GHG Inventory methods. A comparison was made of mass, protein mass and economic allocation and system expansion methods for handling co-production of wool and sheep meat. In study 2, typical crossbred ewe, Merino ewe and Merino wether flocks in each of the 28 locations in eight climate zones were modelled using the GrassGro/GRAZPLAN simulation model and historical climatic data to examine the variation in PMA values for different enterprise types.
Results and discussion Different methods for handling co-products in study 1 changed allocated GHG emissions more than fourfold, highlighting the sensitivity to method choice. In study 2, enterprise, climate zone and year and their interactions had significant effects on PMA between wool and liveweight (LW) sold. The wool PMA (wool protein as proportion of total protein sold) least square means (LSM) were 0.61 ± 0.003 for wethers, 0.43 ± 0.003 for Merino ewes and 0.27 ± 0.003 for crossbred ewe enterprises. The wool PMA LSM for the main effect of Köppen climate zone varied from 0.39 to 0.46. Two zones (no dry season/warm summer and distinctively dry and hot) had significantly lower wool PMA LSM, of 0.39 and 0.41, respectively, than the four other climate zones.
Conclusions Effects of superfine wool production on GHG emissions differed between regions in response to differences in climate and productivity. Regarding methods for handling co-production, system expansion showed the greatest contrast between the two studied flocks and highlighted the importance of meat from wool production systems. However, we also propose PMA as a simple, easily applied allocation approach for use when attributional life cycle assessment (LCA) is undertaken.

Keywords Allocation · Carbon footprint · Co-production · GHG · LCA · Sheep

Responsible editor: Niels Jungbluth

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1 Introduction

The Australian wool industry is a significant component of Australia's agricultural sector, contributing some Australian $2.3 billion to the economy, from a flock of 68.1 million wool sheep (AWI 2011). The sheep industry has historically played a very important role in Australia's development and prosperity, and continues to be an important industry in many regions of the country. Sheep producers are significant managers of Australia's land assets. In 1999, they managed over 85 M ha of land, or about 11 % of Australia's total land mass (ANRA 2007), though this percentage has reduced with the decline in the national flock since 2000. Australian wool production is based on the Merino sheep breed, which produce very high-quality wool for garment manufacture. Merino sheep also produce meat, which is an important and high-value system output. Australia's Merino wool flock underpins production of lamb and mutton by Merino crossbreds, making Australia one of the largest sheep meat exporters in the world. Wool and lamb production generates greenhouse gas (GHG) emissions and the carbon footprint of each of these products has been studied. However, few studies have investigated emissions from the high-value wool production systems typical in Australia.

The impacts of the production of agricultural products are best assessed by accounting for environmental emissions throughout the full life cycle of a product, and life cycle assessment (LCA) is an important methodology for this (e.g. ISO 2006). However, application of LCA to livestock production systems is a relatively new area of research. While studies applying LCA to dairy (Thomassen et al. 2009; van der Werf et al. 2009; Flysjö et al. 2011) and beef production (Williams et al. 2006; Lieffering et al. 2010; Peters et al. 2010; Nguyen et al. 2012; Wiedemann et al. 2015b) have been published for several major production regions of the world, there are fewer published LCAs on sheep and most of these have focussed on lamb production. Lamb LCA studies cover production in a range of regions, notably the Mediterranean (Ripoll-Bosch et al. 2013), New Zealand (Ledgard et al. 2011; Gac et al. 2012), the UK (Williams et al. 2006; Edwards-Jones et al. 2009) and Australia (Peters et al. 2010; Wiedemann et al. 2015c). Only three published studies have specifically investigated the LCA of wool, with two examining meat and wool production from single-case study farms in Australia (Eady et al. 2012; Brock et al. 2013) and the most recent studying four case studies across three countries (Wiedemann et al. 2015a). A common feature of most sheep farms that adds a degree of complexity to LCA studies is the co-production of meat and wool. The relative proportion and quality of wool and meat varies depending on the breed of sheep and the production system. In some cases, sheep systems exclusively produce meat from wool-shedding sheep such as the Dorper breed, while other meat sheep produce low-value wool as a by-product of meat production. In many cases, the system is 'dual purpose' producing both wool and meat for economic returns. In these systems, differences in the breed of sheep and production objectives result in variation in the relative quantity of meat production and in the quality and end-use of wool. Where there is co-production, LCA studies must apportion environmental impact between products, and the results vary significantly depending on the methods used (Ayer et al. 2007; Reap et al. 2008). As interest in the environmental impacts of livestock increases (Gerber et al. 2013), results for sheep meat and wool production are needed.

The choice of static, attributional LCA analyses versus dynamic, consequential LCA analyses (Brandão et al. 2014) is not the focus of this study. Wiedemann et al. (2015a) recommended that allocation based on protein partitioning between wool and liveweight (LW) was best for attributional studies, proposing the protein mass allocation (PMA) method as an easily applied biophysical allocation method. Protein mass allocation is superior to simple mass allocation as it relates directly to the digestible protein leaving the stomach in individual animals, which is the major biophysical driver of wool and LW growth (Cronje 2012). Sensitivity analysis using system expansion was recommended by Wiedemann et al. (2015c) to investigate the implications of a change in production, the implications of choosing alternative products or systems, and to evaluate system change strategies, in which case consequential modelling is appropriate. To avoid risks of burden shifting when economic allocation methods are applied, Wiedemann et al. (2015a) suggested that emissions intensity (EI) results should be presented for both wool and meat. PMA is likely to vary between sheep production systems as the proportion of wool and LW (or meat) sold varies.

The aims of this research are to (1) study the implications of allocation methods when modelling sheep production; (2) generate PMA values for handling the co-production of meat and wool in sheep production systems based on running either Merino ewes, Merino wethers or crossbred ewes; and (3) quantify the impacts of location and year to year variation and their interactions on the PMA values. In study 1, actual production from two farms running superfine Merinos in different climate zones, northern New South Wales (NSW) in eastern Australia, and Western Australia (WA) was compared. In study 2, output from a simulation model Grazfeed/Grassgro (Freer et al. 1997) was used to predict production and PMA values at typical farms at 28 locations across Australia using historical climate data.

2 Materials and methods

2.1 LCA study 1

This study is the second published multi-impact analysis of GHG emissions from Australian Merino sheep production systems, the first being Wiedemann et al. (2015a). This study investigates production from two farms in different regions, northern New South Wales in eastern Australia and Western Australia. The NSW property (CS4 in Wiedemann et al. 2015a) was located in the Armidale district (800 mm average annual rainfall). The WA farm was located in the Kojonup region (528 mm average annual rainfall). The aim was to further explore methods for handling co-production between wool and meat.

The system boundary comprised all on-farm and upstream processes associated with the primary production of wool to the farm gate, including all husbandry activities associated with pasture-fed sheep and inputs such as fuel, electricity, fertiliser, veterinary chemicals, pasture seed and supplementary feed. The functional unit was 1 kg of greasy wool at the farm gate. Total GHG emissions are assessed using the Intergovernmental Panel on Climate Change global warming potentials (Forster et al. 2007) as modified by Boucher et al. (2009).

2.2 Inventory data

Detailed production data, livestock inventories and input data were collected from farm financial records, interviews and a site visit. Flock production data are presented in Table 1.

Transport records for livestock, purchased inputs and staff were incorporated into the modelling. Services (financial, communications, repairs) were modelled based on expenditure, using economic input–output data (Rebitzer et al. 2002). Capital infrastructure (buildings, fences) and machinery were excluded. Energy demand was determined from purchased energy (electricity, diesel, petrol) and purchased inputs used by the farm. Background data were sourced from the Australian Life Cycle Inventory database (Life Cycle Strategies 2007) where available, or the European Ecoinvent (2.0) database (Frischknecht et al. 2005).

Production data were used as a basis for modelling GHG emissions. Feed intake and livestock GHG emissions (enteric and manure emissions) were modelled using the Australian National Greenhouse Gas Inventory methods (DCCEE 2014). A summary of emission sources and factors is provided in Table 2. The DCCEE (2014) methods do not explicitly provide a method for handling uncertainty, so uncertainty was estimated following the methods of Dong et al. (2006). There is also substantial uncertainty related to the prediction of feed intake for grazing ruminants (Poppi 1996), which is a critical input for predicting both enteric methane and manure emissions. To account for this, we used an uncertainty range of ±20 % for predicted dry matter intake, based on the review by Poppi (1996). Nitrous oxide emissions from pasture litter decomposition were included for the legume pastures on both farms. Emission rates were based on Australian nitrous oxide measurement data from Galbally et al. (2010).

2.3 Handling co-production

Both farms produced products other than wool. The NSW farm grazed steers in addition to the sheep flock and the WA farm produced cereal grain. On both farms, the sheep production system produced three products: wool, lamb and mutton. Multiple products present a challenge for assessing the inputs and impacts of the product in question.

The options for handling co-production according to ISO 14044 (ISO 2006) in order of preference are:

- Clear subdivision of the system.
- System expansion (expanding the product system to include the additional functions related to the co-products to avoid allocation).
- Allocation on the basis of physical or biological relationship (mass, protein or energy for example).
- Allocation on some other basis; most commonly economic (market) value.

Co-production of beef and cereal grain on the two farms was handled by dividing the sub-systems and accounting for each separately. In most cases, inputs could be divided because they were specific to one system only. On the NSW farm, overheads (such as electricity use) were divided based on the total predicted feed consumption by cattle (25 %) compared to sheep (75 %). At the WA farm, records were kept separately for most inputs relating to either the sheep or the grain production system. However, there are interactions between the sheep and grain systems that required further exploration. Firstly, some overheads (i.e., farm electricity use, administration overheads) could not be easily divided between the sheep and cropping systems. Secondly, sheep are grazed

Table 1 Flock parameters for the two case study farms

Parameter	Units	NSW	WA
Breeding ewes	No. joined	1500	1394
Annual greasy wool production—ewes	kg/hd	4.1	5.0
Annual greasy wool production—hoggets	kg/hd	3	3.5
Fibre diameter	µm	17	18
Lambing % (at marking)	3 year av.%	80.0	89.3
Ewe replacement rate	%/year	13	26
Annual wool clip	total kg greasy	9995	9252
Annual sheep sales	total kg LW	56,178	55,674

Table 2 Greenhouse gas emission sources, equations and uncertainty

Emission source	Key parameters/model	Assumed uncertainty
Enteric methane	*M* (kg/hd) = *I* (kg DM/hd) × 0.0188 + 0.00158	DM/hd prediction ± 20 %
Manure methane	5.4 × 10–5 kg CH_4/kg DM manure	±20 %
Manure nitrous oxide	Urinary N—0.004 kg N_2O–N/kg N in urine Faecal N—0.005 kg N_2O–N/kg N in faeces	±50 %
Manure ammonia	0.2 kg NH_3–N/kg N of excreted in manure	±20 %
Indirect nitrous oxide from ammonia losses	0.01 kg N_2O–N/kg NH_3–N volatilised	±50 %
Legume pasture emission from residue N	0.35 kg N_2O–N/ha year	±50 %

over summer on crop stubbles, deriving some benefit from the crop growing process. There are reciprocal benefits to the crop system from sheep grazing, such as weed control and nutrient cycling. Sheep on the case study farm were grazed on stubble to a limited extent. The primary benefit from stubble grazing in WA is from consuming spilled grain and weeds after harvest rather than the stubble per se (Butler and Croker 2006). Considering that spilled grain is essentially a waste product from the cropping cycle and grazing weeds is mutually beneficial to both systems, the net contribution of cropping to the sheep system from stubble grazing was assumed to be negligible and was therefore excluded. While this decision was appropriate for the case study farm, this may change on other farms where stubble grazing is a more significant input to the sheep production system. Inputs from farm overheads were apportioned based on the total income received from the sheep production system (85 % of income) compared to the grain system (15 %).

Handling co-production of wool and meat is more complex, because the system cannot be divided. Wool and meat are jointly produced from the sheep flock and are both significant sources of income. There is no clear primary product and by-product. At the farm level, meat is produced from both lambs and cull-for-age breeding animals. These were not differentiated because both meat products were considered to be functionally comparable (i.e., provision of a high-quality protein food source for human consumption) despite being sold to different markets. A comparison of four possible methods for handling co-production was included, these being: mass allocation, PMA, economic allocation and system expansion. The mass allocation process used the combined mass of products at the farm gate: greasy wool and live weight (lamb and mutton combined). The PMA method followed the approach of Wiedemann et al. (2015a): the protein content of greasy wool was estimated from the protein content of clean wool on a dry matter basis (i.e. 100 %) adjusted for the dry matter content of clean wool (84 %) and ratio of clean wool to greasy wool (0.70). The protein content of live weight was assumed to be 18 % based on Sanson et al. (1993) using a fixed assumption applied to all case studies in the absence of specific data regarding sheep condition scores. Wool PMA values were calculated as the protein content of greasy wool as a proportion of total protein (wool plus LW) sold. Economic allocation was based on the total value of products at the farm gate. The system expansion approach used three different substitution products to replace sheep meat: sheep meat from an alternative sheep meat production system where wool is considered a low-value by-product; replacement with beef production or replacement with three meat products in ratios that approximate market share in the Australian domestic retail meat market: beef (40 %), pork (20 %) and chicken (40 %). The alternative sheep meat production system was based on meat breed sheep (purpose grown meat sheep) grown in a similar farming system. Live weight (LW) from Merinos was substituted for purpose grown meat sheep taking into account the lower carcase yield that would be expected by using an equivalence factor of 0.95 (100 kg of Merino LW was considered equivalent to 95 kg of LW from the avoided product systems, see MLA 2003; Wiedemann et al. 2015a, c). System expansion with other meat products was based on data for Australian chicken (Wiedemann et al. 2012), pork (Wiedemann et al. 2010) and beef (Wiedemann et al. 2015b) (Table 3).

2.4 Impact assessment

SimaPro™ 7.3 software (SimaPro 2012) was used for the impact assessment. This included an uncertainty analysis which accounted for inter-annual variation in inputs, and uncertainty related to assumptions made during the modelling process. Uncertainty was assessed using a Monte Carlo analysis in SimaPro 7.3. One thousand iterations provided a 95 % confidence interval for results.

2.5 Study 2 enterprises, location and years

To capture the highly diverse nature of broadacre livestock farming enterprises across southern Australia the GRAZPLAN/GrassGro simulation models (Cottle et al. 2016; Freer et al. 1997; Ghahramani and Moore 2013; Moore and Ghahramani 2013a, b) were used to predict production of three representative sheep enterprises operating at 28 sites across southern Australia, where sites were classified according to their rainfall and

Table 3 Assumptions used for the alternative methods of handling co-production

Products	Mass allocation factors (%)	Protein mass allocation factors (%)	Economic allocation factors (%)	System expansion substitution products
Wool (greasy wool) kg	14–15	35–37	55–65	Purpose grown sheep meat, beef or mixed meat (beef, pork and chicken meat).
Sheep sales (lamb + mutton − liveweight) kg	85–86	63–65	35–45	

dominant livestock enterprise. GRAZPLAN/GrassGro is a complex, biophysical model that simulates livestock production based on climate and soil data and simulated pasture production. The livestock production equations are described in detail in Freer et al. (1997).

The three enterprise types modelled at all locations were (1) Merino ewe production for both fine wool and lambs for meat, (2) Merino × Border Leicester cross ewes with an emphasis on lamb production and (3) Merino wethers for fine wool production. In an attempt to encompass the diversity in soil types, climates and typical forage species found in the 1×10^6 m^2 study area across southern Australia, statistical areas level 2 within the study area (SA2s; Australian Bureau of Statistics) were classified into a set of 28 sites with approximately equal gross value of agricultural production (GVAP, see Moore and Ghahramani 2013a). The SA2s were grouped according to their average annual rainfall and land use (i.e. the proportions of GVAP attributable to cropping, sheep and cattle production), producing a final set of 28 sites (Table 4).

A single Australian Bureau of Meteorology (BoM) weather station was selected to represent each site on the basis of weather and management data availability; all simulations were conducted using historical climates measured between 1980 and 1999. Climates and soil types across the study areas varied widely, with ranges in annual rainfall and temperature at the locations modelled of 299–1091 mm and 11.6–19.1 °C, respectively, and with soil types ranging from deep sands to red-brown earths to sandy-clay loams. Pasture composition and average above-ground primary production (ANPP) also varied substantially across the study area (Table 4) but in general pastures consisted of an annual or perennial grass combined with a perennial legume. To enable assessment of the consistency of PMA values across Australian environments, we sub-classified each site in Table 4 into similar climatic zones following a Köppen classification system and long-term average climatology records (BoM 2015). Further information on site characteristics, climate, pasture and soil data is given in Table 1 of Moore and Ghahramani (2013a) and Table 3 of Ghahramani and Moore (2013).

To facilitate comparisons between sites, identical livestock genotypes were modelled within each enterprise in all climate zones. Management policies (livestock replacement, the timing of the reproductive cycle, the sale of young stock and thresholds for supplementary feeding) were described separately for each of the 28 site ×3 enterprise combinations following Moore and Ghahramani (2013a). Information on typical management systems elicited by state agency officers in producer workshops was used where possible; otherwise, expert opinion, literature accounts and preliminary simulations were used to derive sensible values. The months when crossbred ewes and wethers were purchased and sold were simulated in line with the reproductive cycle of adult ewes in the Merino ewe enterprise. Stocks were sold at various ages at set market weights (Table 5). The approach to feed supplementation of sheep on stubble paddocks is described by Moore and Ghahramani (2013a).

2.6 Stocking rates and ground cover

Regional stocking rates were adopted from Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES 2014). A limitation of these data is that they do not distinguish between enterprise types within each region, so we computed a realistic stocking rate for each enterprise type in this study based on a minimum allowable ground cover threshold. These thresholds were determined by allowing a minimum cover in a minimum number of years in each 20-year simulation, resulting in different stocking rates for each enterprise at each location. These ratios were then applied to the overall ABARES stocking rate, resulting in individual enterprise stocking rates (Table 4).

2.7 Intervention to pasture management

Pasture options examined here for their impacts on GHG emission are those examined by Cottle et al. (2016) and Ghahramani and Moore (2013). Briefly, the strategies were:

- High and very high soil phosphorus fertility;
- Two levels of confinement feeding: placing all animals in a feedlot from summer to mid-winter in the following year when total above-ground biomass fell below 2000 (‘confinement 2000’) or 1000 kg/ha (‘confinement 1000’);
- Two levels of increased proportions of farm area sown to lucerne: either 20 or 40 %;

Table 4 Historical pasture and livestock production and stocking rates for three livestock enterprises. Source: Cottle et al. (2016)

		Sheep/ha			ANPP (kgDM/ha)			Legume ANPP (kgDM/ha)			LW sold (kg/ha)			Clean wool sales (kg/ha)			Rainfall (mm)
Site	Zone code	CE	ME	W	CE	ME	W	CE	ME	W	CE	ME	W	CE	ME	W	CE/ME/W
Ararat	6	3.2	3.3	2.6	8683	8666	8650	3090	3215	2976	90.5	59.5	25.9	6.6	8.3	7.9	607
Armidale	6	2.1	2.3	2.3	7427	7452	7408	3621	3792	3562	56.7	37.0	18.7	5.2	7.0	6.9	759
Birchip	12	0.6	0.7	0.4	5059	5069	5104	2750	2713	2694	15.8	12.3	4.7	1.3	2.3	1.4	372
Colac	6	3.2	3.2	2.7	12,210	12,167	12,148	1328	1351	1338	93.4	60.3	27.1	6.4	7.2	7.4	689
Condobolin	12	1.2	1.2	1.1	4801	4785	4749	3160	3153	3000	36.2	22.8	10.3	3.0	3.9	3.7	468
Cootamundra	9	1.1	1.1	1.0	9491	9493	9488	791	802	835	34.1	20.1	8.8	1.7	2.4	3.1	671
Cummins	4	0.6	0.5	0.5	5798	5785	5759	3799	3772	3709	16.6	9.7	5.4	1.3	1.5	1.8	396
Cunderdin	14	1.5	1.2	1.1	3145	3057	3049	1462	1270	1124	43.8	23.8	11.6	3.4	4.3	4.1	375
Dalwallinu	14	0.5	0.5	0.4	4478	4468	4446	2373	2341	2345	15.3	9.2	3.7	1.1	1.5	1.6	377
Dookie	9	1.8	1.5	1.4	7959	7988	7983	1288	1242	1300	51.8	26.6	14.5	4.2	4.0	4.4	600
Ellinbank	6	3.1	3.1	2.7	14,892	14,866	14,835	3479	3497	3487	91.9	57.0	27.5	6.4	7.0	7.4	1110
Esperance	4	1.4	1.5	1.5	6857	6843	6813	1483	1412	1240	42.8	29.3	11.9	2.3	3.9	4.8	491
Goulburn	6	2.2	2.2	1.7	7677	7674	7686	598	603	606	55.4	33.9	15.6	4.7	6.4	4.7	652
Hamilton	6	3.4	3.2	2.5	10,418	10,348	10,326	627	631	696	94.6	56.1	41.7	7.1	7.5	6.9	643
Katanning	4	1.8	1.8	1.6	6468	6471	6468	1942	1875	1995	47.6	36.4	12.7	3.2	4.8	5.3	467
Lameroo	12	0.8	0.8	0.7	4265	4281	4237	1910	1944	1833	22.4	14.3	7.0	1.9	2.7	2.5	379
Launceston	3	2.7	2.6	2.0	8560	8572	8532	3023	2684	3194	59.5	47.3	22.5	4.9	5.5	6.4	607
Mansfield	6	3.5	3.3	2.7	9054	9006	9027	2329	1644	1700	98.6	59.6	26.1	6.7	8.6	7.6	760
Minnipa	11	0.5	0.5	0.4	4266	4261	4268	1870	1844	1870	13.8	9.0	4.3	1.2	1.5	1.5	316
Mt Barker	4	2.8	2.8	2.3	10,609	10,651	10,531	4437	4587	4360	85.7	54.5	20.8	5.3	7.0	7.2	653
Mullewa	14	0.3	0.6	0.3	2612	2987	2612	431	421	416	8.8	11.4	2.4	0.7	1.9	1.1	353
Naracoorte	4	2.7	2.5	2.1	7760	7759	7660	3571	3432	3094	77.0	45.6	20.5	5.2	7.1	6.2	557
Narrandera	12	1.2	1.2	0.9	7028	7058	7033	1476	1549	1625	33.6	23.9	7.9	2.6	2.5	3.2	453
Northam	7	1.6	1.8	1.2	7495	7500	7456	3374	3428	3221	47.9	37.3	13.0	3.3	5.5	4.2	423
Southern Cross	11	0.5	0.5	0.4	4618	4627	4614	2043	2059	2038	14.7	10.9	4.3	1.1	1.6	1.5	344
Swan Hill	12	0.5	0.5	0.5	3856	3861	3846	1206	1197	1151	16.2	9.1	5.0	1.3	1.8	1.7	347
Waikerie	12	0.7	0.7	0.6	3149	3136	3113	1143	1161	1148	20.5	13.0	6.2	1.8	2.3	2.2	270
Wellington	9	1.7	1.4	1.2	6188	6173	6221	1327	1343	1287	45.6	23.0	12.0	3.7	3.7	3.9	591

Crossbred ewes, Merino ewes and wethers at each of 28 locations under historical climate (1980–99). Stocking rates are calculated immediately after entry of replacement animals. Further details are provided in Ghahramani and Moore (2013)

Köppen zone code: 3 = No dry season (mild summer), 4 = Distinctively dry (and warm), 6 = No dry season (warm summer), 7 = Distinctively dry (and hot), 9 = No dry season (hot summer), 11 = warm (summer drought), 12 = Warm (persistently dry) and 14 = Hot (summer drought)

CE crossbred ewes, *ME* Merino ewes, *W* wethers, *ANPP* above-ground net primary productivity, *CFW* clean fleece weight, *DM* dry matter, *LW* liveweight

- Removing annual legumes from the modelled pasture mix.

2.8 Livestock breeding options

Animal options studied were also from Cottle et al. (2016) and Moore and Ghahramani (2013b) and were:

- Greater body size or LW;
- Animals with higher clean fleece weight (CFW) and the same mature LW as baseline animals;
- Higher conception rates;
- For the crossbred ewe enterprise, sires with higher LW.

2.9 Livestock greenhouse gas emissions and protein mass allocations

Greenhouse gas emissions were determined using equations for broadacre sheep grazing specified by the Australian Government Department of Climate Change and Energy Efficiency (Browne et al. 2011; DCCEE 2014). In contrast to previous work determining livestock emissions of prime lamb enterprises on a

Table 5 Attributes of livestock enterprises modelled at each of the 28 sites (see text for further details). Ranges indicate the minimum and maximum values across all sites. Source: Cottle et al. (2016)

	Merino ewes	Crossbred ewes	Wethers
Genotype of main flock	Merino	Border Leicester × Merino	Merino
Standard reference weight (kg)	50	60	50
Reference fleece weight (kg greasy wool)	5.0	5.0	5.0
Reference wool fibre diameter (μm)	19.0	23.0	19.0
Ram genotype	Merino	Border Leicester	NA
Standard reference weight of rams (kg)	70	84	NA
Adult mortality rate (% per year)	4	4	4
Source of replacement livestock	Self-replacing	Purchase	Purchase
Age at entry (months)	4–15	13–20	5–18
Age at sale (months)	63-78	73–82	54–77
Birth date of lambs	9 Apr.–1 Oct.	29 May–6 Sep.	23 Feb.–1 Sep.
Age at sale of lambs (months)	4–17	4–19	8–18

seasonal basis (Alcock et al. 2015), the present study computed emissions on a daily time-step aggregated into monthly data, which was considered more accurate given temporal variation in pasture quality and quantity, livestock number and LW. Greenhouse gas emissions were calculated on a carbon dioxide equivalent basis (CO_2-e) for methane from enteric fermentation and manure deposition, and nitrous oxide from leaching and surface water run-off (indirect) and livestock urine and faeces. All emissions and end products were aggregated into annual totals across all livestock classes where appropriate.

To calculate EI for wool and LW sold and to avoid double counting, emissions for each enterprise/location/enterprise/year combination were allocated to wool or LW sold using a PMA approach, as described for study 1. The mass of CFW or LW sold in each row of yearly data were multiplied by their protein contents to calculate the proportions of total protein produced, which was used as the basis of emissions' allocation to greasy wool or LW sold. The emission results are published in Cottle et al. (2016).

2.10 Statistical analysis

Least squares, linear models of main effects (management option, zone, enterprise and year) and significant two-way interactions were fit to the dependent variables using JMP statistical software (JMP 2015). Student *t* tests ($P < 0.05$) were used to determine the significance of differences between the least square means (LSM) of fixed main effects and their interactions.

3 Results

3.1 Study 1 total GHG

Total GHG emissions from wool production were similar for the two supply chains, ranging from 8.5 ± 0.6 to 8.7 ± 0.6 kg CO2-e/kg wool for the NSW and WA case study farms, respectively. Total GHG emissions were dominated (76–79 %) by livestock emissions (enteric methane and manure methane and nitrous oxide emissions) with emissions from purchased inputs, transport and services contributing 13–14 %. Pasture emissions from leguminous N residues contributed 11 and 7 % for the NSW and WA farms, respectively. Estimated GHG emissions per kilogram wool were highly sensitive to the method for handling co-production between wool and meat (Table 6). System expansion with sheep meat generated results that were closer to mass allocation than economic allocation results, while system expansion with alternative meats (beef, pork and chicken) generated results that were intermediate between the mass and economic values and were similar to protein mass allocation.

3.2 Study 2 protein mass allocations

All main (option, enterprise type, climate zone, year) effects and their two-way interaction effects were significant ($P < 0.0001$), other than option interactions, in the linear model for wool PMA. The goodness of fit was $R^2 = 0.87$ with RMSE = 0.053.

The LSM for wool PMA values for main effects of climate zone, year and options are shown in Tables 7, 8 and 9. The LSM for wool PMA values for the main effect of enterprise were 0.609 ± 0.003, 0.430 ± 0.003 and 0.273 ± 0.003 for Merino wether, Merino ewe and crossbred enterprises, respectively, and these were all significantly different ($P < 0.05$). The PMA values for LW sold (which multiplied by dressing percentage equals meat sold) are equal to one minus the wool PMA values. The lowest wool PMA value (0.394) was generally found in the no dry season (warm summer) zone. The lowest enterprise by zone wool PMA value was for crossbred ewes in the distinctly dry and hot zone (0.238), while the highest wool PMA value was found in wether enterprises

Table 6 Total GHG emissions using contrasting methods for handling co-production for the NSW farm. The total GHG (562, 537 kg CO_2-e) per kg of total product (9995 kg greasy wool + 56,178 kg LW sold) is 8.5 for the mass, protein and economic allocation methods

Product	Mass	Protein	Economic	System expansion (purpose grown sheep meat)	System expansion (beef)	System expansion (beef, pork, chicken)
	Total GHG − kg CO_2–e/kg product at the farm gate					
Super fine wool (greasy)	8.5	20.7	35.8	9.0	−6.6	23.7
Sheep meat (lamb and mutton LW)	8.5	6.3	3.6	–	–	–

run in the hot summer drought zone (0.652). While there was a significant enterprise by zone interaction, crossbred ewes had lower wool PMA values than Merino ewes in all zones, which had lower wool PMA values than wether enterprises in all climate zones. The wool PMA values varied significantly between year main effects (Table 8) but the range in values was only small being 0.427 in 1991 to 0.444 in 1984. The management options wool PMA value main effects (Table 9) were significantly different but only varied from 0.427 (larger ram size) to 0.485 (higher fleece weight) with the baseline, conventional management having a wool PMA value of 0.436.

4 Discussion

4.1 Emissions

The two case studies in study 1 represent different climates and production systems with the WA farm having a greater use of forage crops and supplementary grain feeding compared to the NSW farm. Enteric methane emissions per breeding animal tended to be lower for the NSW farm, reflecting the lower body weight and average dry matter intake of sheep compared to the WA farm. However, the differences in daily emissions per breeding animal were offset by higher production (both wool and meat) per breeding animal for the WA flock, resulting in similar EI levels. In study 2, the relative percentages of 80.6, 0.02, 11.2 and 8.1 % for enteric methane, manure methane, indirect nitrous oxide and excreta nitrous oxide (tCO_2-e) components of GHG, respectively, were similar across options, enterprises or zones.

Compared to the few other Australian wool LCA studies, the GHG results are generally lower, though this relates more to differences in methodology rather than differences in the production systems studied. Biswas et al. (2010) investigated a mixed wheat, wool and meat production system from lambs in southern Australia. Their study excluded impacts associated with the breeding flock, however, and was not comparable to our results. Eady et al. (2012) reported an EI of 36.2 (biophysical allocation) and 28.7 kg CO2-e/kg greasy wool (economic allocation) for a mixed sheep and grain producing farm in WA. While the results of Eady et al. were considerably higher using biophysical allocation, they were lower than the economic allocation result in our study. The different approaches

Table 7 The least squares means (LSM) of wool protein mass allocation proportions for the main effect of climate zone from highest to lowest value

Climate	LSM
Warm (summer drought)	0.459a
Hot (summer drought)	0.457a
No dry season (mild summer)	0.449ab
Warm (persistently dry)	0.443b
Distinctively dry (and warm)	0.441b
No dry season (hot summer)	0.441b
Distinctively dry (and hot)	0.413c
No dry season (warm summer)	0.394c

Row means without common letters differ significantly ($P < 0.05$)

Table 8 The least squares means (LSM) of wool protein mass allocation proportions for the main effect of year from highest to lowest value

Year	LSM
1984	0.444a
1994	0.444ab
1987	0.442abc
1983	0.441abc
1995	0.439bcd
1982	0.438cde
1980	0.437cde
1981	0.436def
1998	0.433efg
1996	0.432fgh
1993	0.432fgh
1989	0.431fgh
1986	0.431fgh
1999	0.430fgh
1985	0.429gh
1992	0.429gh
1997	0.428gh
1988	0.427h
1990	0.427h
1991	0.427h

Row means without common letters differ significantly ($P < 0.05$)

Table 9 The least squares means (LSM) of wool protein mass allocation proportions for the main effect of management option from highest to lowest value

Option	LSM
Higher fleece weight	0.485a
Zero annual legume	0.437b
Confinement 1000	0.436bc
Baseline	0.436bc
Higher conception rate	0.435bcd
Larger body size	0.434cd
Lucerne 40 %	0.433cde
Lucerne 20 %	0.433cde
High soil P fertility	0.432de
Confinement 2000	0.430ef
Very high soil P fertility	0.429f
Larger ram size	0.427f

Row means without common letters differ significantly ($P < 0.05$)

used to handle co-products are discussed further in the following section.

4.2 Approaches used for handling co-production

This study highlights the sensitivity of methodological choices related to co-production in high-value wool production systems. A similar (though lesser) degree of sensitivity has been shown when comparing methods for handling the co-production of milk and meat in dairy systems (Cederberg and Stadig 2003; Casey and Holden 2005; Flysjö et al. 2011). These studies showed that system expansion resulted in considerably lower emissions for milk compared with economic allocation calculations. In the Cederberg and Casey studies, the dairy system was expanded to account for avoided meat production from purpose grown beef cattle systems. Flysjö et al. (2011) also showed that using a different avoided meat product (chicken instead of beef) resulted in a lower offset to the milk product.

Choice of allocation method must also be taken into account when considering GHG mitigation approaches. Zehetmeier et al. (2012) showed that practices aimed at reducing the EI of milk (which result in a reduction in overall beef production from the dairy herd) could be entirely offset by increases in emissions from the beef production sector in order to maintain beef production in line with demand. A similar situation exists for Merino sheep production in Australia. If efforts to reduce the EI of wool led to lower sheep meat output per unit wool produced, there could be increased emissions from increased sheep meat production elsewhere.

Regardless of intent or appropriateness, LCA results are used for comparative purposes and choices between alternative fibre products (Kviseth and Tobiasson 2011). Where such comparisons result in market decisions that affect the demand and therefore production of wool, it would be prudent to fully account for changes that may subsequently occur in both wool and sheep meat supply. While at the retail level sheep meat may be substituted by chicken or pork, this is infeasible at the production level for the vast majority of the wool industry, because of the difference in land capability. Consequently, such a change may inadvertently result in greater competition for cultivated land resources and potentially lower net food production. We suggest that choices relating to avoided products should take into account substitution both at the production level (considering availability of arable and grazing land) and the retail level. Taking this into account, purpose grown sheep meat or beef represent the most likely substitution products for meat from Australian wool production systems.

While system expansion is the preferred approach in the LCA standards (ISO 2006), and is important for research and policy development purposes (Brandão et al. 2014), we found that a simple mass allocation approach in study 1 generated similar results to system expansion (Table 6) with the preferred substitution process (purpose grown sheep meat) and is more easily explained to industry members, such as farmers. PMA gave similar results to system expansion with three meat products in their domestic retail market share ratio. Economic allocation resulted in a much higher proportion of the burden being allocated to the wool product than either the mass allocation, PMA or system expansion approaches. System expansion to beef resulted in −6.6 kg CO_2–e/kg wool (at the farm gate) as beef generally has a higher carbon footprint (10–12 kg CO_2-e/kg LW) than lamb/mutton. Thus when beef was substituted, this difference was enough to offset total emissions from LW and wool, leaving an apparent negative emission.

Eady et al. (2012) found a smaller difference between economic allocation and their biophysical allocation method applied. This was largely because the biophysical allocation approach taken by Eady et al. (2012) assumed that the nutrients (and therefore emissions) required to maintain adult breeding animals should be attributed to the wool product, which was deemed the primary product from the system. This sensitive decision is based on the view that wool is the primary product, which drives production, so should bear the full burden. Considering meat from Merino systems (particularly lambs) is a high-quality, highly sought after product, we feel this perspective is debateable in regard to the Australian sheep industry.

4.3 Study 2 PMA values

As noted by Wiedemann et al. (2015a), the PMA method can provide a suitable and simplified biophysical allocation approach *in lieu* of more detailed modelling needed for system expansion. Digestible protein leaving the stomach in individual animals is the major biophysical driver of wool and LW growth (Cronje 2012). The wool PMA values for enterprises varied significantly across zones and years but the size of the interactions were relatively small. Thus the enterprise main effects for wool PMA of 0.273 ± 0.003, 0.430 ± 0.003 and 0.609 ± 0.003, for crossbred ewes, Merino ewes and Merino wether enterprises, respectively, can be recommended for general use in future Australian sheep LCA studies when allocating GHG between wool and meat. PMA estimates across a wide range of locations and enterprises are not available from previous literature. The wool PMA value for Merino ewes in study 1 was slightly lower (Table 3) than the Merino ewe value in study 2. The wool PMA values, and hence LW sold PMA values, were relatively consistent across climate zones, years and management options (Tables 7, 8 and 9). Despite the two-way interactions between these effects also being significant (due mainly to the large dataset analysed) the relatively small sizes of the PMA differences suggests that the enterprise main effect PMA values are robust and could be used with confidence in other studies where PMA has not been calculated.

5 Conclusions

Agricultural LCA research is an evolving science, with a proliferation of studies appearing for a number of different livestock species in the past 10 years. This study highlights that the approach used for handling co-production is a highly sensitive aspect, resulting in large differences between the method favoured in LCA theory (system expansion) and the method most commonly applied in practice (economic allocation). System expansion using purpose grown sheep meat was most representative because it provided a substitution for meat out of the wool system at both the production level (farm) and the market level (meat). Two important outcomes from the investigation of co-production are evident: (i) where wool LCA research is used as a basis for investigating mitigation strategies, changed meat production levels must be taken into account, and this is most readily and accurately done using system expansion and (ii) where wool LCA is used to compare fabrics (taking into account the manufacturing processes post farm), this also should take into account changes in meat production that may arise from changing from one fabric to another. As few other mass produced fabrics (i.e. polyester or cotton) generate a similar, high-value co-product this may be a significant factor when assessing wool-based fabrics. However, we found PMA could be a simple, consistent biophysical factor that could be applied in situations where allocation is used to handle co-production of meat and wool, as did Wiedemann et al. (2015a). We provide suggested PMA values that could be used for LCA studies of Australian sheep enterprises in a variety of locations and years with varying sheep and pasture management strategies.

Acknowledgments The authors thank Steven Wiedemann, FSA, for his analyses of study 1 data and the two farm managers who supplied data to him. We also thank Dr. Afshin Ghahramani, CSIRO, for providing data generated from Grazfeed/GrassGro model runs used to calculate the PMA values in study 2 and the emission results reported in Cottle et al. (2016).

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