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Resource use and greenhouse gas emissions from three wool production regions in Australia

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A B S T R A C T

Australia is the largest supplier of fine apparel wool in the world, produced from diverse sheep production systems. To date, broad scale analyses of the environmental credentials of Australian wool have not used detailed farm-scale data, resulting in a knowledge gap regarding the performance of this product. This study is the first multiple impact life cycle assessment (LCA) investigation of three wool types, produced in three geographically defined regions of Australia: the high rainfall zone located in New South Wales (NSW HRZ) producing super-fine Merino wool, the Western Australian wheat-sheep zone (WA WSZ) producing fine Merino wool, and the southern pastoral zone (SA SPZ) of central South Australia, producing medium Merino wool. Inventory data were collected from both case study farms and regional datasets. Life cycle inventory and impact assessment methods were applied to determine resource use (energy and water use, and land occupation) and GHG emissions, including emissions and removal associated with land use (LU) and direct land use change (dLUC). Land occupation was divided into use of arable and non-arable land resources. A comparison of biophysical allocation and system expansion methods for handling co-production of greasy wool and live weight (for meat) was included.

Based on the regional analysis results, GHG emissions (excluding LU and dLUC) were 20.1 ± 3.1 (WA WSZ, mean ± 2 S.D) to 21.3 ± 3.4 kg CO_2-e/kg wool in the NSW HRZ, with no significant difference between regions or wool type. Accounting for LU and dLUC emissions and removals resulted in either very modest increases in emissions (0.3%) or reduced net emissions by 0–11% depending on pasture management and revegetation activities, though a higher degree of uncertainty was observed in these results. Fossil fuel energy demand ranged from 12.5 ± 4.1 in the SA SPZ to 22.5 ± 6.2 MJ/kg wool (WA WSZ) in response to differences in grazing intensity. Fresh water consumption ranged from 204.3 ± 59.1 in the NSW HRZ to 393.7 ± 123.8 L/kg wool in the WA WSZ, with differences primarily relating to climate. Stress-weighted water use ranged from 11.0 ± 3.0 (SA SPZ) to 74.6 ± 119.5 L H_2O-e/kg wool (NSW HRZ) and followed an opposite trend to water consumption in response to the different levels of water stress across the regions. Non-arable grazing land was found to range from 55% to almost 100% of total land occupation. Different methods for handling co-production of greasy wool and live weight changed estimated total GHG emissions by a factor of three, highlighting the sensitivity to this methodological choice and the significance of meat production in the wool supply chain. The results presented improve the understanding of environmental impacts and resource use in these wool production regions as a basis for more detailed full supply chain analysis.

1. Introduction

Australia is the largest exporter of greasy wool in the world, trading over 289 thousand tonnes in 2011 (FAO, 2011), from a flock of 68.1 million wool sheep (AWI, 2011), though production has declined in the past two decades (Curtis, 2009). Australian wool production is based on the Merino sheep breed, which produces highly sought-after wool for garment manufacture. Meat

Abbreviations: ABARES, Australian Bureau of Agricultural and Resource Economics and Sciences; CSF, case study farm; dLUC, direct land use change; GHG, greenhouse gas; GWP, global warming potential; NSW HRZ, high rainfall zone; LCA, life cycle assessment; LU, land use; LW, live weight; NSW, New South Wales; RAF, regional average farm; SA, South Australia; SE, system expansion; SA SPZ, Southern Pastoral Zone; WA, Western Australia; WA WSZ, Wheat Sheep Zone; WSI, water stress index.

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production from lambs and cull-for-age (CFA) breeding animals also represents a valuable co-product.

With increased demand for information regarding the environmental credentials of fibre products from garment manufacturers, retailers and consumers (Kviseth and Tobiasson, 2011; BSI, 2014; Karim et al., 2014), the need for scientifically-sound whole of supply chain research addressing key environmental impacts and resource use issues is acute. Addressing this need for wool production is more complex than is generally the case for man-made fibres as the latter have relatively consistent and regulated systems for the raw material phase of the supply chain compared to wool.

Life cycle assessment (LCA) is the most widely used tool for reporting the environmental impacts and resource use of products (ISO 2006) and ideally assessment should report on all major environmental impact and resource use categories affected by a product across the full supply chain. A number of sheep studies have focussed on lamb production (Ledgard et al., 2011; Peters et al., 2010a, 2010b; Ripoll-Bosch et al., 2012; Wiedemann et al., 2015c; Williams et al., 2006) though few of these reported impacts for wool. A review by Henry (2011) demonstrated the limitations in data and methodology in past LCA studies, and, to date, only two detailed LCA studies have been published for wool produced in Australia and these reported only the single impact of greenhouse gas (GHG) emissions, excluding land use (LU) and direct land use change (dLUC), for cradle to farm-gate wool production, each from a single case study farm (Brock et al., 2013; Eady et al., 2012).

In the absence of detailed studies based on Australian production practices and performance data, the environmental credentials of wool have been modelled using inventory data (i.e. Made-by, 2011) that do not accurately reflect Australian production methods. Given this, and the narrow focus of the case studies to date, the present study aimed to produce a benchmark analysis of water, energy, land and greenhouse gas emissions for three types of Australian Merino wool, produced in three different production systems across the country using a broader farm dataset. Detailed aims are provided in the following section.

2. Materials and methods

2.1. Goal and scope

The study investigated impacts from major Australian wool production regions to provide information to the wool industry, wool fabric users and the general public. The study specifically aimed to i) quantify resource use for energy, water and land, ii) to estimate GHG emissions and removal associated with land use and direct land use change (LU and dLUC) from wool production, and iii) to identify impact hotspots in the production system. The system boundary included all supply chain processes associated with the primary production of wool to the farm-gate (Fig. 1). The functional unit was ‘1 kg of greasy wool at the farm gate’.

Impact assessment included global warming using Global Warming Potentials (GWPs) based on the IPCC (Solomon et al., 2007). Fossil fuel energy demand was assessed from an inventory of energy demand throughout the system, and was reported in mega-joules (MJ) with lower heating values (LHV). Stress-weighted water use was assessed using the water stress index (WSI) of Pfister et al. (2009) and reported in water equivalents (H_2O-e) after Ridoutt and Pfister (2010). Inventory results were also presented for fresh water consumption and land occupation with methods described in the following sections.

2.1.1. Regions and farming systems

Wool is produced in three broadly defined Australian agro-climatic zones; the high rainfall zone (>600 mm average annual rainfall or a.a.r), the wheat-sheep zone (300–600 mm a.a.r) and the pastoral zone (<300 mm a.a.r) (Hassall & Associates Pty Ltd, 2006). The largest numbers are located in the wheat-sheep and high rainfall zones (~53% and 39%) with smaller numbers in the pastoral zone (Hassall & Associates Pty Ltd, 2006). This study selected farms from geo-spatially defined regions within each zone (see Supplementary material). The defined regions were located in the western wheat-sheep zone (WA WSZ), the eastern high-rainfall zone (northern NSW HRZ) and the southern pastoral zone (central SA SPZ).

The western wheat-sheep region is classified as temperate, with a winter dominant rainfall pattern of 400–550 mm a.a.r. Within this region, the case study farms were located at an elevation of ~250–300 m above sea level in flat to undulating terrain, near the town of Darken. Temperatures range from an average minimum monthly average of ~6 °C in winter, to a maximum monthly average of ~30 °C in summer. Farms produced wheat and other grains on arable land, and typically grazed sheep on non-arable land, or land being used for pasture leys within the cropping cycle. Grazing is supported by native pastures with introduced clover, predominantly *Trifolium subterraneum*, and supplied with annual or bi-annual applications of super-phosphate and lime as required. Supplementary feeding and forage crops are used to manage annual feed deficiencies in summer. Wool is produced from large-bodied Merino sheep, producing fine wool (20 μm) and lambs for meat production.

The eastern high rainfall region is a cool temperate environment with a summer dominant rainfall pattern of 700–900 mm a.a.r. Temperatures range from an average minimum monthly average of ~0 °C in winter, to a maximum average of ~27 °C in summer. Within this region, the case study farms were located at an elevation of ~950–1000 m above sea level in undulating to hilly terrain, near the town of Armidale. Farms are typically mixed grazing enterprises, producing wool, lamb and beef with only small areas of crop land used for forage. Grazing is supported by native pastures with introduced clover, or sown pastures, and is typically supplied with applications of superphosphate every 2–3 years. Small amounts of supplementary feed are used in lower rainfall years and annually during winter. Wool is typically produced from smaller bodied Merino sheep, producing super-fine wool (17 μm) and smaller lambs for meat production.

The southern pastoral region contains large sections of arid (<250 mm) desert lands, with smaller areas of semi-arid (>250 mm, winter dominant) native grasslands or savannas, which support low densities of sheep and cattle, with no cropping and few alternative farming systems available. Supplementary feed is not typically used. Temperatures range from an average minimum monthly average of ~4 °C in winter, to a maximum average of ~34 °C in summer. Within this region, the case study farms were located at an elevation of ~300–350 m in flat to to hilly terrain, near the town of Hawker. Because of the low grazing density, the farms studied from this region were very large (>15,000 ha) and management inputs were low. Sheep on the farms studied were typically set-stocked in large paddocks (>2000 ha) and were handled infrequently. Wool is produced from large-bodied Merino sheep, producing medium micron wool (21–22 μm) and lambs for meat production.

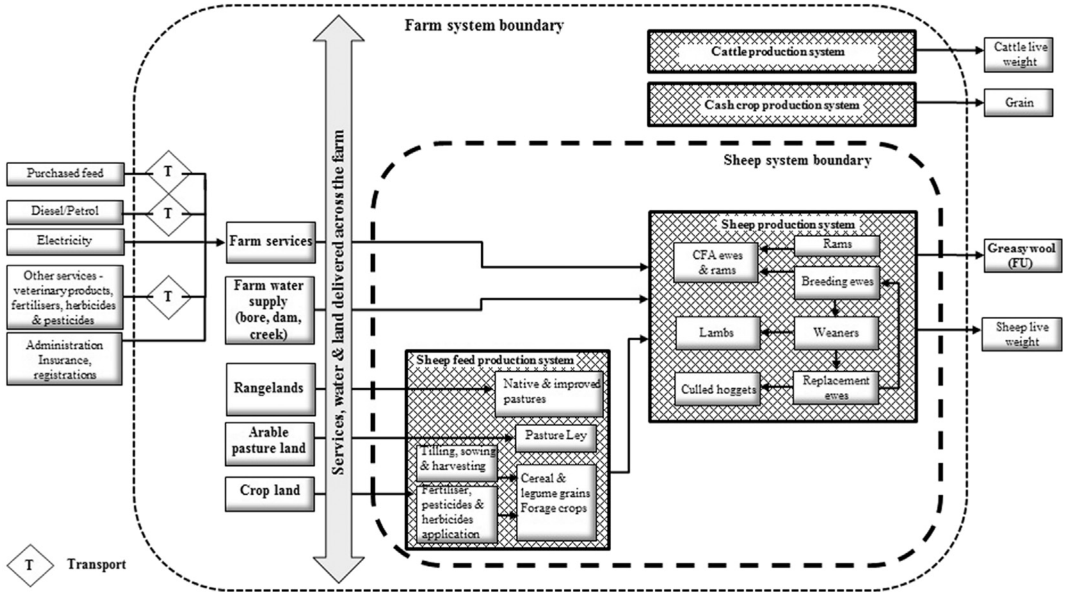

Fig. 1. Farm system boundary and sheep sub-system boundary (dashed line). System separation process used to divide inputs associated with separate farm sub-systems. Only inputs crossing the sheep system boundary were allocated to sheep and wool production.

2.2. Inventory data

2.2.1. Datasets

Data were collected from 10 case study farms (CSFs) via site visits, interviews and a survey of each farm in 2012–13. An analysis of regional average farms (RAFs) was performed using farm survey data collected from specialist sheep farms as part of the Australian Agricultural and Grazing Industries Survey performed annually by the Australian Bureau of Agricultural and Resource Economics and Sciences. Research methods for this survey are outlined in ABARES (2011). The specialist sheep farm dataset included 34 farms (NSW HRZ, ABARES region 131), 18 farms (WA WSZ, ABARES region 521) and 19 farms (SA SPZ, ABARES region 411) covering five years from 2006 to 2010 (ABARES, 2013). Five years of data were used to account for inter-annual variation as a result of seasonal variation, following recommendations from LEAP (2014).

Land and water resources, and sheep flock characteristics of CSFs and RAFs are presented in Tables 1–4. Sheep numbers, live weights and growth rates were used to model feed intake, manure production and drinking water consumption, and to verify the output of wool and live weight reported. The RAF analysis required additional information to determine the sale weight and age of lambs and sheep leaving the flock. These were determined from reported sale prices ($/lamb) and market average sale prices ($/kg). Replacement ewe numbers were determined from the replacement requirements to maintain flock numbers (i.e. equivalent to annual mortalities and sales of cull breeding sheep) and replacement ewes were assumed to be mated for the first time at 18 months of age. The flocks sold lambs, breeding sheep and older sheep and total live weight sold was an aggregate of all sheep sales. Growth rates were determined from lower-bound estimates of lamb age from the corresponding CSF dataset, resulting in growth rates that were intermediate between the CSFs and values reported by the Commonwealth of Australia (2015).

The inventory of major purchased inputs and land use, along with the major outputs (greasy wool and sheep sales) for the sheep sub-systems are presented in Tables 5 and 6. Transport of livestock and purchased inputs were included. Purchased goods and services (e.g. administration, veterinary services) were modelled based on expenditure, using economic input–output data (Rebitzer et al., 2002). Inventory data were reported in mass units for the CSF dataset. However, the RAF dataset was reported as expenditure and mass of purchased inputs were determined using product prices and disaggregation data supplied in the Supplementary material.

Modelling of energy demand was based on the inventory of purchased goods, services and transport distances (Tables 5 and 6). Capital infrastructure (buildings, fences) and machinery were excluded based on their minor contribution (<1% of impacts) assessed during the scoping phase. Impacts generated off-farm via the use of purchased inputs were modelled using background data were sourced from the Australian life cycle inventory database (Life Cycle Strategies, 2007) where available, or the European Ecoinvent (2.2) database (Swiss Centre for Life Cycle Inventories, 2010). Impacts associated with the use of purchased grains were modelled using feed grain inventories described by the authors (Wiedemann et al., 2010a, 2010b; Wiedemann and McGahan, 2011).

2.2.2. Feed intake and greenhouse gas emissions

In each region, sheep were grazed in open pasture lands year round, with short periods of supplementary feeding in two regions only. Feed intake was modelled using the AFRC (1990) method applied by the Australian National Greenhouse Gas Inventory (NGGI) (Commonwealth of Australia, 2015). The mass and characteristics of supplementary feed (Tables 5 and 6) were collected from farm records, and deducted from modelled feed intake to determine the mass of pasture consumed. Pasture type and pasture characteristics such as crude protein levels were assessed visually during site visits to the CSF. Uncertainty related to the prediction of feed intake for grazing ruminants may be substantial (Poppi, 1996), and was accounted for using a range of ±20% for predicted dry matter intake based on the review by Poppi (1996).

Livestock greenhouse gas emissions were determined by applying methods outlined in the Australian NGGI (Commonwealth of Australia (2015) where specific tier two methods were available, or from the IPCC (De Klein et al., 2006). Key factors are provided in the Supplementary material. Uncertainty associated with emission factors was determined from the corresponding IPCC inventory methods (De Klein et al., 2006; Dong et al., 2006).

Table 1
Farm and flock characteristics for the case study farms (CSF) based on primary data in the eastern High Rainfall Zone (NSW HRZ), the western Wheat Sheep Zone (WA WSZ) and the Southern Pastoral Zone (SA SPZ).

Parameter	NSW HRZ CSF ($n = 3$)	WA WSZ CSF ($n = 4$)	SA SPZ CSF ($n = 3$)	Description
Climate				
Annual rainfall (mm)	767	550	264	100 year average from nearest town[a] – SILO climate database (Queensland Government, 2015)
Average annual evaporation (mm)	1278	1461	2236	101 year average from nearest town[a] – SILO climate database (Queensland Government, 2015)
Water Stress Index (WSI)	0.011	0.012	0.017	Determined from GIS overlay of Pfister et al. (2009)
Land resources for the whole farm				
Total utilised land area (ha)	878	2820	19,000	Farm data
Crop land (ha)	0	1294	500	Farm data
Arable land for pasture (ha)	41	405	0	Farm data
Non arable land (ha)	837	1121	18,500	Farm data
Sheep flock				
Breeding ewes (no. joined)	2715	5917	2733	Farm data
Ewe standard reference weight (SRW) (kg/head)	45	55	60	Farm data
Breeding ewe replacement rate	26	31	33	Farm data
Breeding ewe mortality rate (%)	2.3	4.3	4.0	Farm data
Fibre diameter (μm)	17	20	21	Farm data
Clean wool yield (% greasy)	67	60.8	63	Farm data
Lambing (% at marking)	86.4	86.5	90	Farm data
Annual wool clip (total kg greasy)	16,905	45,975	28,277	Farm data
Annual sheep sales (total kg LW)	97,206	239,899	126,144	Farm data

[a] NSW HRZ nearest towns include Kentucky, Kentucky South & Dangarsleigh. WA WSZ nearest towns include Darkan, Bokal and Quindanning. SA SPZ nearest towns include Carrieton, Quorn and Hawker.

Table 2
Modelled outputs for the case study farms (CSF) in the eastern High Rainfall Zone (NSW HRZ), the western Wheat Sheep Zone (WA WSZ) and the southern Pastoral Zone (SA SPZ).

Modelled outputs	NSW HRZ CSF ($n = 3$)	WA WSZ CSF ($n = 4$)	SA SPZ CSF ($n = 3$)	Description
Wool sold per breeding ewe (kg greasy/head)	6.2	7.8	10.3	Modelled using annual wool clip and breeding ewe number (Table 1)
Live weight (LW) sold per breeding ewe (kg LW/head)	35.8	40.5	46.2	Modelled using annual sheep sales and breeding ewe number (Table 1)
Total flock dry matter intake (t DMI)	1976	4227	2506	Modelled feed intake based on livestock numbers, live weight and metabolizability of the diet using Commonwealth of Australia (2015) method
Pasture land used for sheep (%)	73.7	100	93.1	Determined from total livestock numbers and modelled feed intake
Biophysical allocation to wool (%)	35.4	37.8	39.7	Modelled using method outlined in Wiedemann et al. (2015a)
Farm water model				
Farm dam water supply (%)	77.7	76.0	26.7	Derived from farm water supply system model
Bore water supply (%)	15.6	10.3	73.3	Derived from farm water supply system model
Creek water supply (%)	6.7	13.8	0	Derived from farm water supply system model
Dam density (ML per km^2)	8.2	3.3	0.3	Derived from farm water supply system model
Dam efficiency factor	0.175	0.1	0.075	Derived from farm water supply system model

Methods and inventory data relating to emissions and removals from LU and dLUC were assessed in a parallel study (Henry et al., 2015) which included the impacts of soil carbon change under pastures, and the impact of deforestation and reforestation. Soil carbon and deforestation associated with regional cropping was included using methods outlined in Wiedemann et al. (2015c).

2.2.3. Fresh water consumption

Fresh water consumption refers to evaporative losses, or uses that incorporate water into a product that is subsequently not released back into the same river catchment (ISO, 2014). The impact of a change in water yield as a result of dLUC, as recommended by ISO (2014), was assessed using a baseline period of 1990 to make the comparison, and changes were assumed to be negligible. The focus on fresh water consumption reflects the intent of LCA to investigate the impacts of resource use, either on human health, natural ecosystems or competitive water users (Bayart et al., 2010). The water use inventory covering all sources and losses associated with wool production both in foreground and background systems. Livestock drinking water included assessment of all livestock including cattle (where present) to ensure comprehensive data on water extraction. Sheep drinking water was estimated using the equation determined by Luke, cited in CSIRO (2007):

$$I_w = 0.1911 \times t - 2.882$$

where I_w = water intake (L/45 kg LW sheep per day); t = maximum daily air temperature (°C).

The equation is zero when $t \leq 15$, when sheep are able to meet their water requirements from pasture intake alone. R^2 for the equation = 0.84.

Drinking water per sheep accounted for differences in live weight and reproductive status using the method outlined by Luke (1987). Drinking water for cattle was predicted using equations from Ridoutt et al. (2012). All drinking water was modelled as fresh water consumption, because water is lost to the atmosphere via respiration and perspiration, integrated into the product and released outside the river catchment or excreted as urine, which is analogous to irrigation of pasture. Proportions of drinking water supplied from bores, creeks and rivers or farm dams (Table 2) were

Table 3
Farm and flock characteristics for the regional average farms (RAF) based on primary and modelled data in the eastern High Rainfall Zone (NSW HRZ), the western Wheat Sheep Zone (WA WSZ) and the Southern Pastoral Zone (SA SPZ).

Parameter	NSW HRZ RAF ($n = 34$)	WA WSZ RAF ($n = 18$)	SA SPZ RAF ($n = 19$)	Description
Climate				
Annual rainfall (mm)	751	461	243	Long term average from representative towns[a] – Australian Rainman climate database (Clewett et al., 2003)
Average annual evaporation (mm)	1451	1832	2504	Long term average from representative towns[a] – Australian Rainman climate database (Clewett et al., 2003)
Water Stress Index (WSI)	0.214[b]	0.012	0.017	Determined from GIS overlay of Pfister et al. (2009)
Land resources for the whole farm				
Total land area (ha)	929	1804	58,878	Farm data[c]
Crop land (ha)	0	251	119	Farm data[c]
Arable land for pasture (ha)	43.4	412	0	Derived from farm data[d]
Non arable land (ha)	885.6	1141	58,761	Derived from farm data[d]
Sheep flock				
Breeding ewes (no. joined)	1516	2179	2885	Farm data[c]
Ewe standard reference weight (SRW) (kg/head)	50	60	60	Regional average from Commonwealth of Australia (2015)
Breeding ewe mortality rate (%)	4.0	7.4	8.2	Farm data[c]
Number of prime lambs sold	339	463	72	Farm data[c]
Value of prime lambs ($/head)	96	74	62	Farm data[c]
Total number of lambs sold	618	775	513	Farm data[c]
Total number of adult sheep	3074	3837	5226	Farm data[c]
Clean wool yield (% greasy)	63.8	61.1	61.6	Regional wool sales records – AWTA Reports (AWTA, 2006–2010)
Lambing (% at marking)	84.6	76.2	69.2	Farm data[c]
Annual wool clip (total kg greasy)	12,454	18,106	28,950	Farm data[c]

[a] NSW HRZ towns include Bungadore, Orange, Bathurst, Goulburn & Armidale. WA WSZ towns include Geraldton, Northam, Narrogin, Ravensthorpe & Katanning. SA SPZ towns include Whyalla, Port Augusta, Roxby Downs, Coober Pedy and Woomera.
[b] This region had significant areas of high water stress. Therefore, the WSI was calculated from a weighted mean based on the land area in each water stress category within the ABARES region. 25% of the region had a WSI of 0.815, 10% of 0.032 and 65% at 0.011, giving a regional average of 0.214.
[c] Data collected in annual survey, averaged over the years 2006–2010. Average annual number of farms surveyed is 34, 18 and 19 for NSW HRZ, WA WSZ and SA SPZ respectively.
[d] Area of arable and non-arable pasture land determined from proportions on CSF farms in each region.

Table 4
Modelled outputs for the regional average farms (RAF) in the eastern High Rainfall Zone (NSW HRZ), the western Wheat Sheep Zone (WA WSZ) and the Southern Pastoral Zone (SA SPZ).

Modelled outputs	NSW HRZ RAF ($n = 34$)	WA WSZ RAF ($n = 18$)	SA SPZ RAF ($n = 19$)	Description
Wool sold per breeding ewe (kg greasy/head)	8.2	8.3	10	Based on annual wool clip and breeding ewe number (Table 3).
Live weight (LW) sold per breeding ewe (kg LW/head)	34.4	30.1	32.3	Modelled from annual sheep sales and breeding ewe number (Table 3).
Breeding ewe replacement rate	22	26	28	Replacement rate determined from flock model from adult sheep numbers sold, assuming a static number of breeding ewes maintained in the flock equivalent to the five year flock size average in the dataset
Annual sheep sales (total kg LW)	52,173	65,677	93,279	Determined from reported number of sheep and lambs sold, sale price of animals (Table 3) and regional sale values to determine mass at sale
Total flock dry matter intake (t DMI)	1049.4	1264.6	2078.5	Modelled feed intake based on livestock numbers, live weight and metabolizability of the diet using Commonwealth of Australia (2015) method
Pasture land used for sheep (%)	69.7	88.4	94.4	Determined from total livestock numbers and modelled feed intake
Biophysical allocation to wool (%)	41.7	46.7	47.2	Modelled using method outlined in Wiedemann et al. (2015a)

determined from the survey and site visits for the CSF and verified by an analysis of water supply points using satellite imagery.

Losses from the water supply system and dam supply efficiency were modelled using methods outlined in Wiedemann et al. (2015b) which are described briefly here. Where losses associated with the supply of water were caused by the production system, they were attributed to livestock production. Losses from farm reticulation systems were determined from sources of leakage and evaporation from open tanks and troughs. Evaporation losses from creeks and rivers were endemic to the natural system and were not attributed to livestock. Farm dam water balances were constructed from the inflow, extraction rates, predicted evaporation and seepage using a daily time-step water balance over a 70 year period, using long term rainfall and evaporation data (Jeffrey et al., 2001; Queensland Government, 2015). Catchment runoff (dam inflow) was modelled using USDA-SCS KII curve numbers (USDA NRCS, 2007) with appropriate values determined from site observations of soil type, farming practices and farmer knowledge of the frequency of runoff events. Dam supply efficiency is reported in Table 2, and represents the volume of water extracted as drinking water divided by the total water extraction, with the remaining proportion being losses.

2.2.4. Stress weighted water use

Stress weighted water use was determined by multiplying fresh water consumption by the appropriate water stress index (WSI)

Table 5
Major inputs and outputs for the sheep sub-system on case study farms (CSF) in the eastern High Rainfall Zone (NSW HRZ), the western Wheat Sheep Zone (WA WSZ) and the Southern Pastoral Zone (SA SPZ).

Parameter	NSW HRZ CSF ($n = 3$)	WA WSZ CSF ($n = 4$)	SA SPZ CSF ($n = 3$)	Description
Inputs				
Land				
On-farm crop land (ha)	0	241	0	Farm data
Arable land for pasture (ha)	31	405	0	Farm data
Non arable land (ha)	624	1121	17,223	Farm data
Energy				
Electricity (kWh)	5657	6706	8202	Farm data
Diesel (L)	2434	9330	6131	Farm data
Petrol (L)	1866	2655	1750	Farm data
Fertiliser				
Superphosphate (t)	24	107	0	Farm data
Lime (t)	69	175	0	Farm data
Purchased feed				
Protein grains (t)	30	205	0	Farm data
Overheads				
Administration ($)	8192	20,850	6964	Farm data[a]
Veterinary products ($)	15,478	28,156	7620	Farm data[a]
Herbicides ($)	807	0	0	Farm data
Transport (t km)	4901	39,308	16,039	Transport distance and total mass of inputs and outputs reported from farm data
Outputs				
Greasy wool (kg)	16,905	45,975	28,277	Farm data
Sheep sales (kg LW)	97,206	239,899	126,144	Farm data

[a] Farm data reported expenditure. Mass of purchased inputs for the sheep sub-system determined using methods outlined in the Supplementary material.

Table 6
Major inputs and outputs for the sheep sub-system on regional average farms (RAF) in the eastern High Rainfall Zone (NSW HRZ), the Western Wheat Sheep Zone (WA WSZ) and the southern Pastoral Zone (SA SPZ).

Parameter	NSW HRZ RAF ($n = 34$)	WA WSZ RAF ($n = 18$)	SA SPZ RAF ($n = 19$)	Description
Inputs				
Land				
On-farm crop land (ha)	0	74	7	Farm data
Arable land for pasture (ha)	30	363	0	Farm data
Non arable land (ha)	617	1004	55,234	Farm data
Energy				
Electricity (kWh)	7162	3769	6998	Farm data
Diesel (L)	2747	5714	10,753	Farm data
Petrol (L)	2106	2218	3069	Farm data
Fertiliser				
Superphosphate (t)	19	62	0	Farm data
Lime (t)	3	44	0	Farm data
Purchased feed				
Protein grains (t)	36	54	5	Farm data
Overheads				
Administration ($)	4579	6238	6699	Farm data[a]
Veterinary products ($)	8651	8424	6822	Farm data[a]
Herbicides ($)	391	2926	0	Farm data
Transport (t km)	2649	12,543	7616	Transport distance and total mass of inputs and outputs reported from farm data
Outputs				
Greasy wool (kg)	12,454	18,106	28,950	Farm data (see description under Table 3)
Sheep sales (kg LW)	52,173	65,677	93,279	Determined from reported number of sheep and lambs sold, sale price of animals (Table 3) and regional sale values to determine mass at sale

[a] Farm data reported expenditure. Mass of purchased inputs for the sheep sub-system determined using methods outlined in the Supplementary material.

values from Pfister et al. (2009) (Tables 1 and 3). The WSI indicates the portion of fresh water consumption that deprives other users of fresh water, and is thus a measure of scarcity of fresh water. For fresh water consumption in upstream processes of unknown origin, we applied the global average WSI of 0.602 (Ridoutt and Pfister, 2010).

2.2.5. Land occupation

Land occupation was determined using a disaggregated land inventory accounting for differences in land type using three categories (measured in m^2/yr): i) occupation of non-arable (rangelands) for pasture, ii) occupation of crop land – cultivated for grain or forage crop production, and iii) occupation of arable land for pasture. The proportion of land in each category was determined from information provided by the farmers, field observations and analysis of satellite imagery for the CSF. Total land occupation and crop land occupation was reported in the ABARES dataset and was used for the RAF analysis. Non-crop land was determined from the difference between total land area and reported crop land. In this remaining area, we determined the relative proportions of non-farming land, arable pasture and rangeland from equivalent proportions in the CSF dataset for each region.

2.3. Handling co-production

A number of co-products were produced from the farm systems. Sheep farms typically also produced other livestock and grain, which was handled by dividing the sub-systems and accounting for each separately (see Fig. 1).

In most cases, inputs could be divided because they were specific to one system only. Livestock systems were divided based on relative feed requirements, which was causally related to land occupation and to stocking density. The proportion of grazing land used for sheep is reported in Tables 2 and 4. On the case study farms, inputs associated with the cropping system were separated by the farmers. Further detail of the methods applied to separate cropping systems in the RAF dataset is provided in the Supplementary material. Whole farm inputs (overheads, such as electricity use) remaining after the system separation processes were a minor contribution to total impacts, and were divided on the basis of land occupation which aligned to the biological separation process applied for grazing livestock. Interactions between sheep and grain production included the grazing of residuals after crop harvest, benefiting the sheep system, and weed control which benefited the crop system. The primary benefit from the crop system to sheep was from the consumption of grain spilled on the ground after harvest, and weeds growing in the stubble, rather than crop residues *per se* (Butler and Croker, 2006). Considering that spilled grain is 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 considered negligible and no impacts from the cropping cycle were attributed to sheep or vice versa.

Handling co-production of wool and live weight (for meat) was modelled following Wiedemann et al. (2015a) using the protein mass allocation (PMA) method, with a system expansion process used for comparison. The protein mass of greasy wool was estimated by multiplying greasy wool mass by clean wool content (Tables 1 and 3) and assuming a dry matter content of clean wool of 84% and a 100% protein content for dry, clean wool. The protein content of live weight was assumed to be 18% (Wiedemann and Yan, 2014) based on body composition. As a comparison, a system expansion (SE) approach was applied using two scenarios where live weight from the Merino sheep system resulted in avoided live weight production from either an alternative meat sheep flock or from beef cattle production, after Wiedemann et al. (2015a). To account for the lower carcase yield of Merinos compared with meat sheep, a factor of 0.95 was used so that 100 kg of Merino LW was considered equivalent to 95 kg of LW from the avoided meat sheep flock, based on MLA (2003). Two combinations of alternative meat sheep breeds were explored. A composite, crossbreeding system based on Border Leicester crossbred ewes and Poll Dorset rams was chosen for NSW HRZ and WA WSZ systems, while Dorper breed sheep that are well suited to pastoral zone conditions was chosen for SA SPZ system. Dorper sheep produce a very small amount of wool and shed their fleece naturally each year, thereby producing no saleable wool. The Border Leicester crossbreeding system produces wool for interior textiles rather than garment manufacture. In order to use the crossbreeding system to substitute for meat from Merinos, a second substitution process was required to take into account the change in production of interior textiles wool, where the change in this wool product was substituted for nylon at a 1:1 ratio, using nylon processes from EcoInvent. Inventory data for modelling the alternative beef production systems were collected from the farms that also produced beef, and were augmented with regional data from the ABARES survey to ensure productivity levels were typical of the regions. When substituting beef with sheep meat from the Merino flocks, an equivalence factor of 0.85 was applied to account for differences in carcase yield (Wiedemann and Yan, 2014). The final results of system expansion were averaged across the two live weight substitution scenarios.

2.4. Analysis

Modelling was conducted using SimaPro 8.0 (Pré-Consultants, 2014). Two types of uncertainties in the input variables were considered: alpha and beta uncertainties, after Leinonen et al. (2012). Alpha uncertainty describes the variations among farms reflecting the primary datasets. Beta uncertainty describes the uncertainties in the model and took into account uncertainty in the prediction of feed intake, application of GHG emission factors (see Supplementary material) and uncertainty in background processes based on the applied datasets (see Supplementary material). Alpha and Beta uncertainty was assessed using a Monte Carlo analysis in SimaPro 8.0 (Pré-Consultants, 2014), using one thousand iterations to provide a 95% confidence interval for results. Results were presented using the mean ± 2S.D, and both alpha and beta uncertainties were used to calculate the S.D. As beta uncertainty was shared by all systems, comparison of the mean results between regions was based on alpha uncertainties only, and significant differences were determined using the following equation of Wiltshire et al. (2009):

$$z = \frac{100 * |A - B|}{\sqrt{CV_A^2 * A^2 + CV_B^2 * B^2}}$$

where A, B are the mean values and CV_A and CV_B are coefficients of variance of the two systems compared. In addition, multiple linear regression (MLR) was conducted in R (R Development Core Team, 2014) to determine the factors that most influenced GHG emissions.

3. Results

Excluding LU and dLUC, GHG emissions from wool production varied from 19.5 ± 4.1 kg CO_2-e/kg wool (mean ± 2S.D) in the SA SPZ CSF, to 25.1 ± 4.8 kg CO_2-e/kg wool in the NSW HRZ CSF. GHG emissions were dominated by enteric methane, which contributed from 79 to 86% in the RAF dataset, and up to and 89% in the CSF dataset. Nitrous oxide emissions, mainly from animal manure, ranged from 10 to 11% in the RAF dataset and from 9% (SA SPZ and NSW HRZ) to 11% (WA WSZ) in the case study dataset. Carbon dioxide emissions contributed between 4% (SA SPZ) and 9% (WA WSZ) in the RAF dataset and from 3% (SA SPZ) to 7% (WA WSZ) in CSF dataset. These emissions were primarily associated with fossil energy demand, though in the WA WSZ the elevated CO_2 emissions were also partially in response to lime application. Linear regression of wool production per breeding ewe and GHG emissions showed this indicator explained 0.79 of variability (see Fig. 3):

$$Y = 30.23 - 1.04X \quad \left(R^2 = 0.79\right)$$

where X is flock wool production per breeding ewe (total flock wool production divided by ewes joined); Y is GHG emissions (kg CO_2-e/kg greasy wool).

For crop land, GHG emissions from LU and dLUC varied from 0.1 to 0.4 kg CO_2-e/kg greasy wool in the RAF across the three regions (Table 7). GHG removals (indicated by negative emission values) from LU from fertilised pastures varied from −0.8 to 0.0 kg CO_2-e/kg greasy wool for the RAF analysis between regions, depending on assumptions regarding soil carbon sequestration under pasture. Corresponding GHG removals from vegetation regrowth of planted trees and shrubs varied from −1.6 to 0.0 kg CO_2-e/kg greasy wool in the RAF dataset, depending on region (see Table 7). In the CSF dataset, removals associated with pasture ranged from −1.1 to 0.0 kg CO_2-e/kg greasy wool and removals associated with vegetation regrowth of planted trees and shrubs varied from −2.4 to −0.3 kg CO_2-e/kg greasy wool.

Fossil fuel energy demand ranged from 11.2 ± 7.4 (NSW HRZ CSF) to 22.5 ± 6.2 MJ/kg wool (WA WSZ) in the RAF dataset with impacts being significantly higher in the WA WSZ (Fig. 2). Farm energy demand (fuel and electricity) was the largest contributor (28–83%) across all regions. In the NSW HRZ and WA WSZ the next largest contributors were fertiliser/pesticides (12–36%) and animal health services (8–23%). Energy demand followed a similar trend in the CSF dataset for the NSW HRZ and WA WSZ, though results were significantly lower for the SA SPZ CSF when compared against the other states and compared to the SA SPZ RAF analysis.

Fresh water consumption ranged from 204.3 ± 59.1 in the NSW HRZ RAF to 393.8 ± 123.8 L/kg greasy wool in the WA WSZ RAF (Table 8). Fresh water consumption was dominated by losses from the farm water supply system across all regions (77–85%), followed by livestock drinking water (13–22%). Evaporative losses from farm dams were the largest contributor to farm water supply losses. Stress weighted water use was significantly lower than fresh water consumption for all regions, ranging from 6.2 ± 3.0 (NSW HRZ CSF) to 74.6 ± 119.5 L H_2O-e/kg greasy wool in the NSW HRZ RAF.

The land occupation assessment showed a distinct variation between regions in crop land occupation, ranging from 0.03 ± 0.02 in the SA SPZ CSF, to 52.9 ± 15.2 m^2/kg greasy wool in the WA WSZ (RAF) wheat sheep zone. Arable pasture land occupation ranged from negligible levels in the SA SPZ to 93.6 ± 22.3 m^2/kg greasy wool in the WA WSZ RAF, while non-arable pasture land occupation ranged from 92.1 ± 30.0 (WA WSZ CSF) to 9005.4 ± 3150.9 m^2/kg greasy wool in the SA SPZ RAF (Fig. 2). Pasture land occupation was lower in the CSF dataset for each region, as a result of higher stocking rates compared to the regional average.

4. Discussion

Australia has three major wool producing regions which vary substantially in terms of rainfall, land area and land type, management systems and sheep type. The study considered three representative areas within each region, using two datasets. Despite the very large differences in sheep type and biophysical resources, differences in impacts were relatively small for some impacts such as greenhouse gas emissions intensity. Application of two datasets improved the representativeness and specificity of results. We found the CSF dataset to provide highly detailed data regarding flock management and biophysical resources such as land and water, albeit for a limited number of farms in each region and for one or two years only. In contrast, the RAF dataset provided a larger number of farms in each region, and repeated measures over a longer time frame (five years), but contained less detail regarding some biophysical resources and flock management. This approach provided an internal comparison within each region and improved the overall representativeness of the regional results. To improve the transparency of the results, impacts for sheep meat determined using biophysical allocation are also presented in the Supplementary material.

4.1. Greenhouse gas emissions and removals

GHG emissions (excluding LU and dLUC) were not significantly different between regions. However, a regression analysis of individual farms in the CSF dataset revealed a trend towards higher impacts from systems where wool yield per sheep was lower (i.e. NSW HRZ CSF). Differences in wool and meat production per ewe were largely associated with the strain of Merino sheep bred in each region. Superfine Merinos (from the high rainfall zone in the present study) typically have lower body weights and produce less wool per head than fine and medium wool Merinos. In both the WA WSZ and SA SPZ sheep systems, there was a greater emphasis on breeding for lamb production than in the NSW HRZ farms analysed, which corresponded to a greater mass of live weight produced per breeding ewe in these regions. These sheep systems are also more common in the lower rainfall climates in these regions. Interestingly, the very large differences in production intensity and land resources did not correspond to major differences in emissions, because productivity per breeding ewe was maintained by using lower stocking rates and different strains of Merinos in the lower rainfall areas. Emissions intensity was similar to Eady et al. (2012) and Brock et al. (2013) when differences in allocation procedure and production intensity were taken into account (Fig. 3). The research farm system studied by Brock et al. (2013) had wool production of 13.2 kg greasy wool per ewe joined; significantly

Table 7
Greenhouse gas emissions and removals (negative values) from LU and dLUC.

Emissions and removals	NSW HRZ RAF	WA WSZ RAF	SA SPZ RAF	NSW HRZ CSF	WA WSZ CSF	SA SPZ CSF
	kg CO_2-e/kg greasy wool					
Soil carbon – crop land	0.4	0.3	0.1	0.2	0.2	0.0
Soil carbon – pasture						
Lower estimate	−0.8	0.0	0.0	−1.1	0.0	0.0
Upper estimate	0.0	0.0	0.0	0.0	0.0	0.0
Vegetation						
Lower estimate	−1.6	−0.4	0.0	−1.6	−0.4	−2.4[a]
Upper estimate	−1.1	−0.3	0.0	−1.1	−0.3	−2.4[a]
Total LU and dLUC emissions or removals						
Lower estimate	−1.9	−0.1	0.1	−2.5	−0.1	−2.4
Upper estimate	−0.7	0.0	0.1	−0.8	0.0	−2.4

[a] Only one estimate provided.

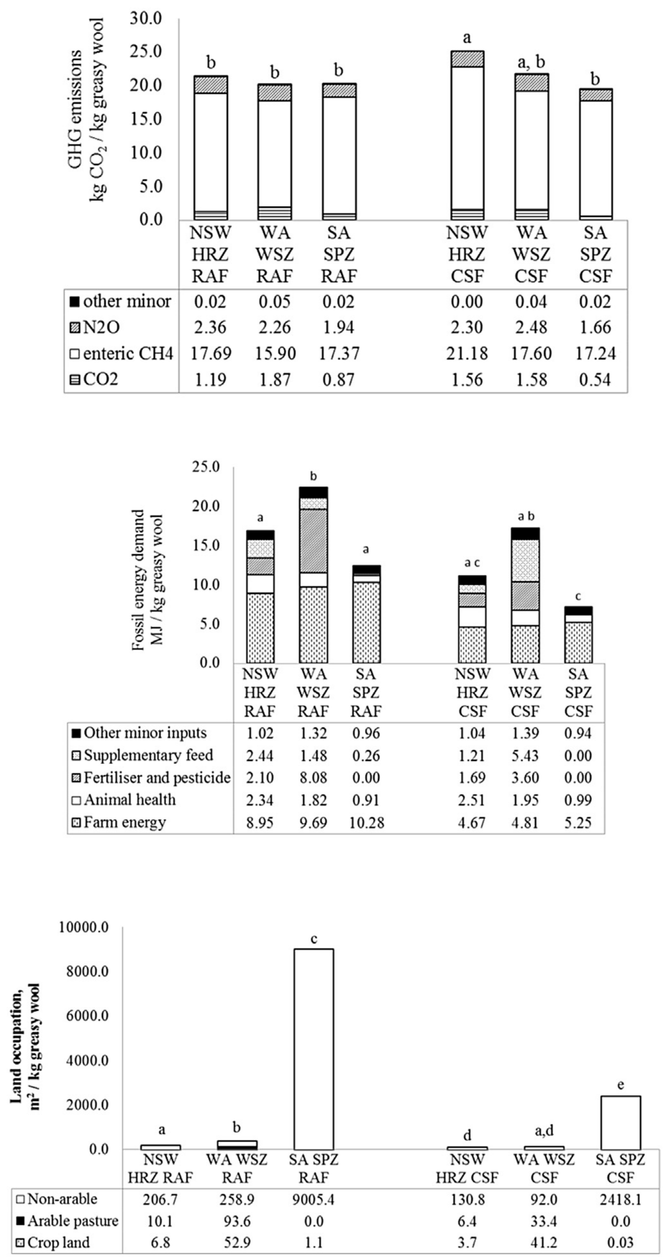

Fig. 2. GHG emissions, energy, and land occupation of 1 kg of greasy wool produced from case study farms (CSF) and regional average farms (RAF) in the eastern High Rainfall Zone (NSW HRZ), the Western Wheat Sheep Zone (WA WSZ) and the southern Pastoral Zone (SA SPZ). Different letters on bars indicate significant differences between total impacts assessed by Monte Carlo analysis based on the alpha uncertainty and Wiltshire et al. (2009).

higher than the NSW HRZ CSF (6.2 kg) and NSW HRZ RAF (8.2 kg) assessed here, suggesting that much higher wool production is possible in this region, potentially leading to lower GHG impacts. Emissions were also similar to the supplementary results presented for wool by Wiedemann et al. (2015d) who studied Australian cross-bred sheep systems focussed on lamb production.

Wool farms generate both emissions and removals of greenhouse gases, though the latter have not previously been considered in wool LCAs. While emissions from livestock and energy sources can be modelled using well-defined methods, the determination and attribution of emissions and removals from LU and dLUC sources is more complex and uncertain, particularly at the regional scale. In a parallel study by the authors, Henry et al. (2015) estimated CO_2 removals in planted exotic pines and mixed native species of 4.4 and 2.0 t CO_2 per ha per year, respectively for the same NSW HRZ and WA WSZ regions, and sequestration of 0.07 t CO_2 per ha per year over 100 years for chenopod shrub lands of the SA SPZ CSF. Sequestration of soil organic carbon in improved permanent pastures in the NSW HRZ was evaluated to be highly uncertain and small but potentially significant over large areas of pasture land (Henry et al., 2015).

4.2. Water use

This study presents the first wool specific analysis of water use with comprehensive LCA methods to the authors' knowledge. Water use was dominated by supply losses and to a lesser extent direct drinking water requirements, and no farms used irrigation water for pasture production. Water losses were highest where the reliance on water from small farm dams was high and evaporation losses were also high. For regions with very high annual evaporative losses such as the SA SPZ, even moderate reliance on dams (27% of supply) resulted in large losses. Dam efficiency was primarily influenced by net evaporation, dam density (total volume stored per km^2) and surface area to volume ratio. Dam densities were within the range reported by Nathan and Lowe (2012) but modelled extractions for livestock drinking water as a proportion of dam volume were much lower in the present study (see Table 2) than the assumptions made by these authors. Supplementary data from Wiedemann et al. (2015d) showed that water use from wool in cross-bred sheep systems focussed on lamb production could be higher (up to 741.4 L/kg greasy wool) where irrigation is used.

Stress weighted water use results showed much lower values than fresh water consumption. The exception was the NSW HRZ RAF, which had an average WSI of 0.214, driven mainly by an area of higher water stress located in the southern part of this region. This finding is important for a globally traded product such as wool; the impact of using water to produce wool in these Australian regions is comparatively low both in terms of competitive water uses (i.e. for human consumption or industry) or the environment.

4.3. Fossil energy demand

Fossil energy demand varied significantly in response to production intensity, with the highest values observed in the WA WSZ where fertiliser and pesticide inputs associated with pasture and forage were much higher. In contrast, fertiliser was lower in the extensive

Table 8
Fresh water consumption and stress weighted water use of 1 kg of greasy wool produced from case study farms (CSF) and regional average farms (RAF) in the eastern High Rainfall Zone (NSW HRZ), the western Wheat Sheep Zone (WA WSZ) and the Southern Pastoral Zone (SA SPZ) using biophysical allocation.

	NSW HRZ RAF	WA WSZ RAF	SA SPZ RAF	NSW HRZ CSF	WA WSZ CSF	SA SPZ CSF
Total fresh water consumption (L)	204.3 a	393.8 b	379.7 b	238.7 a	359.7 b	322.4 a b
Livestock drinking (L)	43.3	50.4	84.7	51.0	45.9	72.0
Drinking water supply losses (L)	156.9	335.0	294.5	184.9	304.9	250.3
Other minor inputs (L)	4.0	8.3	0.4	2.7	8.9	0.1
Stress weighted water use (L H_2O-e)	74.6 d	21.5 c	11 b	6.2 a	13.4 b	9.2 a b

Different letters indicate significant differences between cases based on alpha uncertainty.

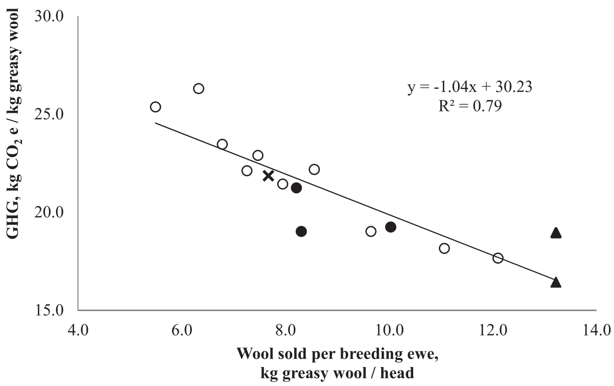

Fig. 3. Regression of wool production per breeding ewe and greenhouse gas emissions. results from individual farm of this study (○), RAF farm of this study (●), Brock et al. (2013) (▲), and Eady et al. (2012) (×) were plotted, with the same protein mass allocation between wool and live weight. Linear regression equation only applies to results from this study.

management systems used in the SA SPZ, resulting in lower energy demand. Few other studies were found reporting energy demand for wool, though the results presented here were of a similar order to the 13.4 MJ/kg greasy wool for one study in New Zealand (Barber and Pellow, 2006) and tended to be slightly higher than wool from cross-bred sheep systems (Wiedemann et al., 2015d).

4.4. Land occupation

Land occupation for wool production varied more than any other factor in the present study, in response to differences in the underlying land resources available for sheep production across the regions and to differences in the level of supplementary feed used. Crop land occupation was low in the NSW HRZ and the SA SPZ because farms in these regions had less land available for grain and forage cropping compared to the WA WSZ, and utilised only small amounts of purchased supplementary feed. Arable land resources represent only ~4% of national land mass (Lesslie and Mewett, 2013) making this the most constrained land resource in Australia. In contrast, occupation of non-arable land may not result in as high a degree of modification to the natural ecosystem and such land is less suitable for alternative agricultural production, being generally limited to grazing by ruminants. In contrast, crop production results in a higher degree of disturbance of soil and vegetation than grazing. Considering the importance of land type for understanding competitive resource use and environmental impact, we consider a simple analysis of ‘total land occupation’ for animal production (i.e. de Vries and de Boer, 2010) to be of limited value in the Australian context. Arable land was used for pasture on some farms because the land areas were small and discontinuous, or because soils and landscape conditions made cropping marginal. As crop production is typically more profitable per unit area of land in Australia (NSW DPI, 2012a,b) an economic incentive exists to use such land for cropping provided other technical or management barriers are not present. This being the case, we found arable pasture land to more strongly resemble non-arable land with respect to land capability in the present study. Further research and metrics are required to quantify the impacts of land occupation on biodiversity across different land types and management systems in Australia.

4.5. Sensitivity analysis

Allocating impacts on the basis of protein mass resulted in a high allocation of impacts to wool compared to live weight (impacts presented in the Supplementary material) because of the high protein density of wool. Protein mass was determined from product mass and estimated protein content of greasy wool and the live weight of animals sold. To test the sensitivity of the model to assumptions relating to protein content, we varied the wool yield factor within the highest known monthly yield variance measured by the Australian Wool Testing Authority (AWTA, 2015), which was 5.5 percentage points for the WA WSZ region. Variance in this factor resulted in a maximum 5% change in impacts between the highest and lowest values. Similarly, a change in live weight protein yield of one percentage point (from 18% to 19%) reduced impacts by 3%.

In the present study we also applied a system expansion approach for comparison to the selected allocation method (Wiedemann et al., 2015a). System expansion results (see Fig. 4) are presented as a proportion of the biophysical results to demonstrate the effect of changing methods. On average, impacts were 70% lower for GHG, while stress weighted water use was much lower and was negative. These lower impacts resulted from the relatively lower efficiency of the expanded sheep and beef systems. Using these assumptions, we found that changes in wool production may have significantly less impact on total GHG and water use than would be suggested from the benchmarking results because of changes in the meat supply system. Energy demand was 65% higher using SE, due to the energy requirements for alternative fabric (nylon) production to replace wool in the avoided meat sheep scenario. Sensitivity to changes in the co-product system has also resulted in substantially different results between allocation and system expansion in the dairy sector (Cederberg and Stadig, 2003; Flysjö et al., 2011; Zehetmeier et al., 2012). Considering the sensitivity of the results to this methodological aspect, further analysis using consequential modelling is expected to be important for understanding impacts from changing wool supply and demand or investigating mitigations that result in changed production. Further to this, benchmarking results determined using allocation may not provide an accurate picture of the change in environmental impact resulting from a change in supply and demand, because the induced change in the co-product system has not been taken into account.

We also tested the model to sensitivity in assumptions regarding lamb sale age in the RAF model, which was a variable

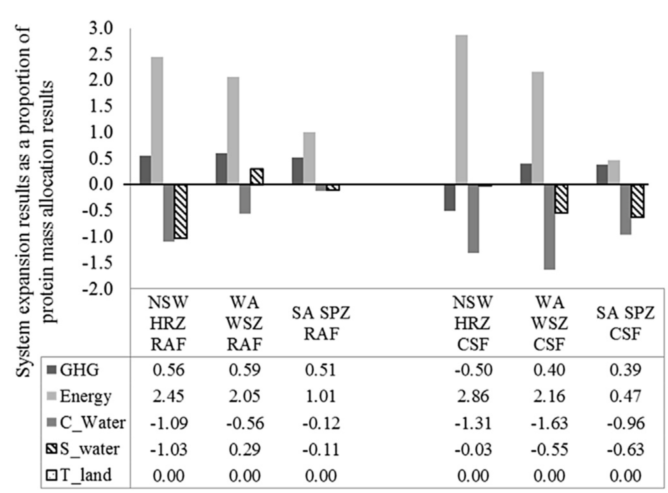

Fig. 4. Results of impacts per kilogram of greasy wool produced from case study farms (CSF) or regional average farms (RAF) calculated using system expansion (SE) divided by results using protein mass allocation. Results above one indicate that the system expansion results are higher than allocation, results below one indicate system expansion results are lower than allocation results. C_water = fresh water consumption, S_water = stress weighted water, T_land = total land occupation.

determined from sale values and typical sale age for the markets available in each region. We modelled scenarios where the sale age of lambs was reduced by 3 months (i.e. from 12 months to 9 months) at a fixed sale weight by increasing growth rate. This was found to result in modest changes (~3%) to impacts for wool. Regarding GHG modelling assumptions, we found a modest reduction (~4%) in GHG emissions when IPCC (Dong et al., 2006) enteric methane assumptions were applied. While not tested here, the sensitivity of impacts to alternative feed intake prediction methods has been highlighted by Brock et al. (2013) and may result in up to 20% difference in GHG impacts for wool depending on what method is applied. The method used here is applied in the Australian GHG inventory and is considered appropriate for the scale of the assessment. In the RAF model, water supply ratios at the regional level were assumed to follow the ratios determined from the smaller CSF dataset. We found that a 10% increase in the water supplied from farm dams rather than bores or rivers increased fresh water consumption by up to 30% for the SA SPZ, where water supply efficiency from dams was lowest compared to other water sources. Changes were less pronounced (10%) in the NSW HRZ because of the comparatively better dam supply efficiency. The sensitivity of the regional model to this factor suggests further research is warranted to improve the regional assessment of farm water supply. Within the fossil fuel energy assessment, the system separation method was also a sensitive assumption because energy was influenced to a greater extent by farm overheads than other impact categories.

5. Conclusions

This study addresses the lack of farm-level production information regarding the environmental impacts and resource use associated with producing Australian wool by presenting results for three significant regional production zones. While not representative of the whole country, the study significantly expands the knowledge base regarding Australian wool production to the farm gate. The study showed significant differences in some impacts from region to region, influenced by production intensity, the level of inputs and climate. Arable land occupation and energy demand was highest in the mixed grazing and cropping regions where larger amounts of supplementary feed grown on arable land was used for sheep production. The results also showed that non-arable land comprises the largest proportion of total land occupation, which indicated low resource use for crop land that can be used for other fibre and food production systems. Water resource use was highest in production regions with low annual rainfall and high evaporation. Applying the appropriate WSI showed wool to have a relatively low impact on constrained water resources in the three regions, with an exception made for the NSW HRZ RAF. Wool production per breeding ewe explained a high proportion of the variability in GHG emissions intensity (excl. LU and dLUC), highlighting the importance of production efficiency as a means to reduce emissions. Though more uncertain, inclusion of LU and dLUC resulted in lower net emissions, or very modest increases in emissions, than if these emissions were excluded. Application of an alternative system expansion method for handling co-production substantially changed results, highlighting the sensitivity of these results to changes in the co-product system. Thus, further research is required using consequential analysis methods to more accurately determine the environmental impacts from a change in wool production.

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Appendix A. Supplementary material

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2016.02.025.

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