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Life cycle assessment modelling of complex agricultural systems with multiple food and fibre co-products

Sandra Eady[a,*], Andrew Carre[b], Tim Grant[c]

[a] CSIRO Livestock Industries, Locked Bag 1, Armidale NSW 2350, Australia
[b] Centre for Design, RMIT, Swanston Street, Melbourne Vic 3000, Australia
[c] Life Cycle Strategies Pty Ltd, 125 Swanston Street, Melbourne Vic 3000, Australia

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ABSTRACT

Most agricultural products are produced on farms where there is a mix of activities, resulting in a range of co-products. This raises the issue of how best to model these complex production systems for Life Cycle Assessment, especially where there are benefits imparted by one activity in the mixed farming system to another. On the mixed farm studied, there were significant two-way reference flows (representing 288 t CO_2-*e*/year or 10% of the total farm emissions) between activities producing distinct products (wool, meat, grain) and these were modelled using system expansion. Cropping and sheep activities were modelled as separate sub-processes in the farming system, with unique inputs and outputs identified for each. Co-production from the sheep activity was modelling using allocation, comparing biophysical and economic relationships. Using an economic allocation resulted in different estimates of global warming impact for sheep co-products, with figures varying by 7–52%. When compared to biophysical allocation, economic allocation shifted the environmental burden to the higher value co-products and away from the high resource use products. Using economic allocation, for every kilogram of wool produced there was an estimated 28.7 kg of CO_2-*e* emitted. Amongst the live animal products, the stud rams had the highest estimated carbon footprint (719 kg CO_2-e/ram). Amongst the crops, estimates of emissions for the cereal grains averaged 202 kg CO_2-*e*/tonne grain, canola 222 kg CO_2-*e*/tonne and lupins 510 kg CO_2-*e*/tonne, when modelled to include the benefits of the mixed farming system.

1. Introduction

Many agricultural products are produced on farms where there is a mix of activities, resulting in a range of distinct farm outputs. Only on specialised farms can the environmental impacts of the farming system be allocated to one product. In addition, a mixed farming system captures additional benefits, such as legume fixed soil nitrogen (*N*), weed and disease control, and utilisation of low value crop residues by livestock (Fels and Young, 1989). This raises the issue of how best to model more complex production systems for Life Cycle Assessment (LCA), especially where production of one product imparts a benefit to another in the system. For some farming activities, especially those involving livestock, there a number of inter-related products produced and the paper also explores different approaches to modelling this co-production so that the environmental impact is shared across the products.

Using the impact category of global warming, the study had two objectives: to compare the carbon footprint of products with and without quantifying the benefits imparted by the mixed farming system; and to compare different methods of modelling co-products for a livestock farming activity.

2. Materials and methods

Case study farm: The case study farm produces Merino sheep and crops in the south western region of Western Australia, a region which experiences a 'Mediterranean' climate of wet winters and dry summers. The farmer swaps between activities depending on the relative profitability of each. Crops grown are wheat, barely, oats, canola, and lupins. The Merino sheep activity produces wool, surplus sheep and stud rams. Arable land is cropped in rotations of cereal, canola, legumes, and sown pasture. Non-arable land is largely improved pasture based on annual legumes

* Corresponding author. Tel.: +61 267761394.
E-mail address: sandra.eady@csiro.au (S. Eady).

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and grasses. While the majority of the grain is sold as a cash crop, significant proportions of cereal and lupins are retained to feed sheep over the dry summer period, when pastures are not adequate to support grazing. Crop stubble is extensively utilised during this period as a source of dry feed and there is no burning of crop stubble. Approximately 20% of the crop stubble (Roberts, 2006) forms a component of feed for livestock and the remainder is retained to enhance soil organic matter or is removed from the farm by wind or water.

The area of the farm is approximately 3,000 ha: 1,800 ha of arable land of which approximately 830 is planted to grain crops annually; 970 ha sown to pasture in rotation with the crops; 600 ha of predominantly annual legume pasture; and 600 ha of natural vegetation not used for farming activities. No-till systems are used for cropping. Cereal crops receive approximately 43 kg ha^{-1} of fertiliser N and canola 36 kg ha^{-1} of N. Mature weight of the ewe flock is approximately 55 kg and the weaning rate is close to 95%. Dry matter availability, crude protein content and dry matter digestibility of the feed are assumed to be similar to the NGGI (2006) estimates used for national greenhouse gas accounts.

The sheep activity offers benefits to crop production in terms of weed control during the intercropping period and return of *N* to the soil via dung and urine deposition. The legume crops in the cropping rotation (lupins and sown pasture) also offer soil N benefits to the following crop. Cereal production is the major cropping activity in the region and cereal crops are rotated with ‘break crops’, such as lupins and canola, and sown annual pastures to provide pest/disease control benefits to the cereal system (Fels and Young, 1989). The ‘break crop’ benefits were modelled as the difference in cereal yield resulting from the rotation (excluding the additional N effect from a legume phase). These interdependencies were explicitly modelled in the LCA.

System boundary: A LCA was undertaken from ‘cradle-to-farm gate’ for all farm products for the impact category of global warming. The system boundary for the LCA is shown in Fig. 1 and covers the on-farm production of sheep (including feed grown on the farm and imported to the farm), the production of a range of crops and stubble, and the interrelationships between the sheep and cropping activities. Where transport between processes was included, it is explicitly shown. Construction of infrastructure and farm establishment were not included in the system boundary. Biogenic carbon that is part of the annual carbon cycle was assumed to be in equilibrium so changes in soil and vegetation carbon, carbon respired by livestock and soil microbes, and carbon in farm products were not included in the system boundary.

Data inventories and environmental flows: Three years of written farm records and the business accounting system were used to collect data for number of sheep, fodder purchases, health treatments, shearing, area and yield of crops planted, machinery operation, use of fertiliser and pesticide, and general farm services. Estimates of parameters such as crop stubble and pasture dry matter were drawn from the literature and agricultural models such as APSIM (Keating et al. 2002).

Background data were sourced from LCI libraries incorporated into LCA software, SimaPro (PRé Consultants, Amersfoort, The Netherlands 2007), and included the Australian Unit Process LCI (Lifecycle Strategies, Melbourne, Australia 2010), Ecoinvent 2.0 unit processes (Swiss Centre for Life Cycle Inventories, St-Gallen,

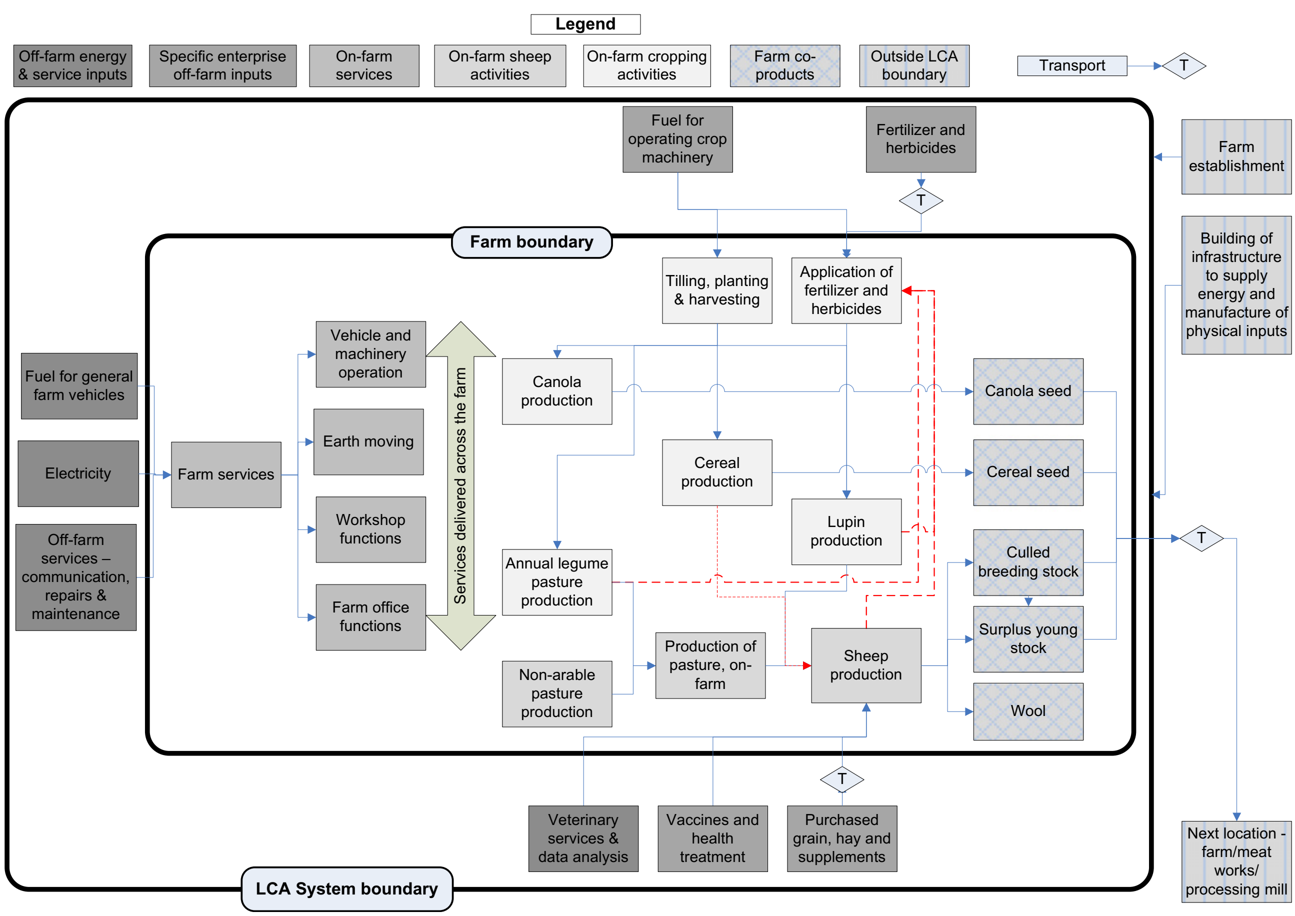

Fig. 1. System boundary for life cycle assessment of mixed farming crop and livestock co-products. Dashed arrow lines show flow of ‘benefits’ from avoided products.

Switzerland 2007), and LCA Food DK Library (Nielsen et al. 2003). These libraries were used for raw materials, their processing into components, transport, and energy inputs.

The GHG emissions associated with each input were drawn from a variety of sources. Sheep Greenhouse Accounting Framework V4 (Eckard, 2011) and FarmGAS (Australian Farm Institute, 2009) were used to estimate direct and indirect emissions from livestock, nitrogen fertiliser and legume pastures, as per the current carbon accounting methodology in Australia (NGGI, 2006). When estimating emissions from legumes in pastures, the calculation was based on the estimated proportion of the pasture dry matter yield contributed by legumes and the legume residue remaining after grazing, so that emissions from N-fixation were not double counted as both residue emissions and animal emissions. GHG emissions associated with background data were sourced from the respective published life cycle inventory that was used.

Functional unit: The functional unit (FU) chosen for each farm product was the most common unit used for trading the product and for market quotation of prices. For grain this was 1 tonne, for wool the FU was 1 kg of greasy wool and for sheep the FU was one animal.

Co-products: The issue of how to allocate inputs to outputs arises when a farm produces inter-related products. The ISO recommendation for addressing co-production (ISO 14044:2006) is to first avoid allocation altogether, if possible, by dividing the multi-function process into sub-processes or expanding the system so as to include functions related to all the products. The system expansion path is a ‘consequential’ modelling approach where the secondary co-products are modelled as an avoided substitute product. This allows 100% of the environmental impacts to be allocated to the primary product. Where allocation cannot be avoided, the next preference is to use an underlying physical cause-effect relationship to allocate inputs to products. The last resort is to use other relationships (such as economic returns) to allocate inputs. The modelling approach where allocation is used is referred to as ‘attributional’, where inputs are attributed to outputs based a defined relationship.

Amongst LCA practitioners (Finnveden et al. 2009) there is some consensus that an attributional modelling approach is appropriate when the goal of the LCA is to describe the product, whereas a consequential approach is more appropriate when the goal is to investigate a change in production. Because of the complexity of agricultural production, a physical cause-effect or economic allocation is often used (Kanyarushoki et al. 2008; Pelletier et al. 2010; Peters et al. 2010).

Following ISO recommendations, the farm was first divided into sub-processes for individual crops and the sheep flock, with specific inputs identified for each. If cropping and livestock processes (and their inputs) are not modelled separately, that is, all farm inputs are allocated to farm co-products based on the proportion of income earnt by each activity, results can be distorted. Kanyarushoki et al. (2008) conclude that the exclusion of cash crops from a mixed farming system changes the results for dairy production; when cash crops are included in the system, impacts per 1000 kg of milk increased with the % of milk sales in total sales, whereas this was not the case when cash crops were modelled as a separate process.

After dividing the farm activities into sub-processes, there are still two areas where allocation may be required. The first arises with the sheep activity which produces a number of inter-related products – wool, wethers, stud rams and cull livestock. The second case for allocation deals with the attribution of general farm services such as vehicle use, farm office, repairs and maintenance, inputs that cannot be specifically identified as applying to a particular crop or the livestock activity.

For the first instance, where the sheep activity produces a number of inter-related products, two approaches can be taken: an attributional approach based on a biophysical or economic relationship or a consequential approach based on system expansion. System expansion is where the secondary co-products are modelled as an avoided substitute product, allowing 100% of the environmental impacts to be allocated to the primary product, in this case wool. The wool is then credited with an avoided impact, equivalent to the impact of the co-product substitute. A LCA that uses a system expansion needs to model not just wool production but also the production of the substitute products, allowing the ‘consequence’ of a change in wool production to be assessed.

With this approach, the co-products (young wethers, stud rams and cull ewes) would be modelled in terms of avoided products that would substitute for these co-products. To do this requires a comprehensive understanding of supply and demand for a range of possible substitutes. For instance, cull ewes would most likely go to the lower-value processed meat sector and substitutes could be culled cattle or pigs. However, culled cattle and pigs are going to be secondary products in their own production system and would also be modelled as an avoided product. To use system expansion it is necessary to substitute a ‘primary’ product from the other system and this becomes more complex, for instance, what would be the avoided product for stud rams?

In this instance, there was no clear way forward to resolving the complexities of substitution for most of the sheep co-products, a point that might be argued amongst LCA practioners, but in practice the tools/resources needed to model substitution within an agricultural system (with any certainty) are not readily available. There are good tools to model pig or beef production that could substitute for cull sheep but little reliable data on how the markets (which have both national and international drivers) for the three products interact.

The choice of an avoided product for cull sheep (i.e. cull pigs or cattle) can have a large effect on results for impact categories such as global warming (Weidermann et al. 2010) or eutrophication, where the flows to the environment are vastly different for different species and production systems. And if the substitute is a low value meat animal, it will be a secondary product in its own system, so the question then becomes what underpinning low value protein source (that is a primary product in its system) would be considered to be an appropriate substitute? Extending the model in such a manner introduces a high level of uncertainty and still does not address the issue of what the substitute product is for stud rams! Therefore, for wool and sheep co-products an attributional approach was taken and inputs were allocated to outputs.

For the sheep co-products (wool, rams, cull sheep), a comparison was made between economic allocation and allocation based on resource use, to allocate greenhouse gas (GHG) emissions to each co-product (Table 1). Relative resource use is based on the nutrient requirement of each class of stock, the additional nutrients required to rear surplus stock and the relative nutrient requirement for wool versus body maintenance and live weight gain (Liu et al. 2003, NSW I&I 2005).

To explain in more detail, the nutrient requirement of each class of sheep was estimated based on maintenance, growth and reproductive requirements. The primary product was assumed to be wool therefore the nutrients required to maintain adult breeding animals in the flock were allocated to wool. The nutrients required to produce replacement sheep to maintain the flock's size were allocated to wool. The nutrients required to produce surplus young stock (including an amount for pregnancy and lactation) were allocated to the wethers, hogget ewes and stud rams that were sold. The nutrients required to produce cull ewes were those required to maintain the ewe for a period of six months between the time of

Table 1
Functional unit for enterprise products, level of production and allocation (based on proportion of farm income and biophysical resource use) of reference flows to sheep co-products.

Farm enterprise	Co-products and functional unit	Quantity produced	% of sheep income	% of resources	% of total farm income	% of area
Sheep activity						
6300 breeding ewes plus followers; flock dry sheep equivalents (DSE) of 9503.	Merino wool 19.5 μm (kg greasy)	48,315	53.6	67.6	55	65
	Wethers, 40 kg live weight, 12 months (number)	1903	19.7	11.6		
	Cast for age ewes (number)	1765	10.4	11.1		
	Stud rams (number)	515	14.3	6.9		
	Surplus hoggets, 18 months (number)	207	2.0	2.8		
Cropping activity						
Wheat	Grain (tonne)	545			13.0	8.7
Canola	Grain (tonne)	486			19.9	12.9
Barley	Grain (tonne)	402			9.8	5.8
Oats	Grain (tonne)	283			2.2	4.4
Lupins	Grain (tonne)	77			0.1	3.2

weaning her last lamb (when her contribution to the wool producing flock ceased) and the date she was sold.

The second case for allocation deals with the attribution of general farm services (such as vehicle use, farm office, repairs and maintenance), inputs that cannot be specifically identified as applying to a particular crop or the livestock activity. These inputs can be allocated on an economic basis in proportion to the farm income earned by each product or on a more direct resource use basis, such as farm area utilised, and both were investigated.

Mixed farming system benefits: A comparison was made of the carbon footprint of all farm products with and without inclusion of the benefits imparted by their combination in the mixed farming system. This was done by taking a consequential approach to modelling the synergies between farm activities and translating the benefits into avoided products.

Table 2 summarises the benefits imparted by each farming activity. These benefits are modelled as an equivalent avoided product credited to the activity providing the benefit. For example, the residual N left from dung and urine as sheep graze crop stubble is modelled as avoided *N* fertiliser which is credited to the sheep activity. In this instance, the benefit of *N* from sheep grazing is only applicable to non-legume crops as the legume crops do not require *N* fertiliser, as they fix *N* from the atmosphere.

Where a credit of avoided *N* fertiliser is given to a product the associated N_2O emissions are also credited as an avoided emission for the product; likewise, where a *N* fertiliser benefit is given to a product the associated N_2O emissions are also added to the product's GHG emissions. Hence, N_2O emissions from sheep dung and urine are partly offset by the avoided *N* fertiliser N_2O emissions, and for the crop receiving the benefit of the dung and urine, the N_2O emissions associated with an equivalent amount of *N* fertiliser are added to the crop's GHG emissions.

With regard to the agronomic benefits of a break crop in the rotation, a credit is only given to the non-cereal crops as there is ample cereal grown to provide a break for canola and lupins, i.e. growing more cereal will not improve the yield of non-cereal crops as there is already plenty of cereal grown in the rotation to give this benefit. The converse applies in this mixed farming system where growing more non-cereal crops will provided a lift in yield for cereals. This rationale of giving the credit of an avoided product to only some of the crops in the rotation reflects the 'consequential' nature of the modelling when system expansion is used. The relevant question to ask in determining which crop gets a credit is: what would be the consequence of growing an additional hectare of cereal versus the consequence of an additional hectare of non-cereal crop?

Table 2
Summary of avoided products that were credited to a farming activity when a 'benefit' was provided to another farming activity, and the corresponding 'cost' to the activity using the benefit.

Farming activity	'Benefit' imparted to mixed farming system	Avoided product credited to the activity that provides the benefit	Additional 'cost' for the activity that uses the benefit
Sheep production	Additional *N* deposited from sheep grazing crop stubble taken up by non-legume crops	Total of 7.6 t *N* fertiliser for the non-legume crops; based on GHG calculator (Eckard, 2011) estimate of 77 t *N* in dung and urine and retention rates of 20% in the soil (Rufino et al. 2006; Wilkinson, 1977)	Each non-legume crop has an additional 9.2 kg N/ha of urea input to achieve the specified crop yield over and above that actually applied
Sheep production	Control of summer fallow weeds by sheep grazing	One herbicide application/ha cropping land (chemical and tractor inputs)	Each crop has and additional herbicide application over and above that actually applied
All crops	Stubble for sheep to graze in the summer	Additional summer feed of 800 t of dry matter in the form of pasture	Sheep production has an additional input of 800 t of pasture to represent the stubble that they graze in summer
Legume crop and legume pasture in crop rotation	*N* fixed by the legume is available for following non-legume crop in the rotation	10.8 kg N fertiliser/ha for lupin crop and 4.5 kg N fertiliser/ha for annual sown pasture (Pannell and Falconer, 1988)	Each non-legume crop in the rotation has an additional input of 3.6 kg N/ha
Break crops and sown annual pasture	'Break crop' agronomic benefits (excluding additional *N*) that lifts the yield of cereals	Cereal grain production is improved by 0.31 t/ha by break crop and 0.20 t/ha by sown pasture in rotation (Pannell and Falconer, 1988)	Yield for cereals is adjusted down by 0.23 t/ha amount

3. Results

The LCA for each farm product from 'cradle-to-farm gate' is given in Table 3. Using an economic allocation and modelling the benefits of the mixed farming system, for every kilogram of wool produced there was an estimated 28.7 kg CO_2-*e* emitted. Amongst the live animal products, the stud rams had the highest estimated carbon footprint (719 kg CO_2-*e*/ram), largely due to the relative value of these animals within the sheep activity, rather than any specific extra inputs to produce a ram versus a wether or ewe.

Amongst the crops, estimated emissions for the cereal grains averaged 202 kg CO_2-*e*/tonne grain, canola 222 kg CO_2-*e*/tonne and lupins 510 kg CO_2-*e*/tonne, when modelled to include the benefits of the mixed farming system. The significantly higher emissions associated with lupins was predominantly from the lower yield per hectare for this crop and the direct N_2O emissions from legume crop residues, rather than additional inputs to grow the crop.

When a biophysical allocation was applied to co-products within the sheep activity, the share of emissions shifted away from the relatively high value co-products (rams, young wethers) and moved to the heavier surplus stock that consume more pasture (hoggets and cull ewes) and wool (which is produced from the bulk of pasture intake by adult sheep).

When a biophysical relationship (based on area of land used) was applied to the allocation of general farm services to sheep and cropping activities, the GHG emissions attributed to sheep rose when compared to using an economic allocation. The full matrix of results is not presented; a subset of results per FU were 28.7 vs. 28.8 kg CO_2-*e* for wool, 268 vs. 269 kg CO_2-*e* for wethers, and 246 vs. 240 kg CO_2-*e* for wheat, respectively, for economic vs. biophysical allocation, when mixed farming benefits were also modelled. More of the GHG emissions associated with general farm services were allocated to the sheep activity with biophysical allocation as the sheep used proportionally more of the farm area than indicated by their share of farm income.

Table 3
Greenhouse gas (GHG) emissions for sheep co-products and individual crops from the mixed farming system, considered in isolation of the benefits of the mixed farming system and including the benefits of the mixed farming system.

Functional Unit (FU) at farm gate	GHG emissions/FU (kg CO_2-*e*)	
	Economic allocation	Bio-physical allocation
Sheep activity − in isolation of benefits		
Merino wool 19.5 μm (kg greasy)	26.6	33.6
Wethers, 12 months (number)	249	146
Cast for age ewes (number)	141	151
Stud rams (number)	667	322
Surplus hoggets, 18 months (number)	223	325
Sheep activity − including benefits		
Merino wool 19.5 μm (kg greasy)	28.7	36.2
Wethers, 12 months (number)	268	158
Cast for age ewes (number)	153	163
Stud rams (number)	719	347
Surplus hoggets, 18 months (number)	250	350
Cropping activities − in isolation of benefits		
Wheat (tonne)	253	
Canola (tonne)	285	
Barley (tonne)	211	
Oats (tonne)	219	
Lupins (tonne)	726	
Cropping activities − including benefits		
Wheat (tonne)	246	
Canola (tonne)	222	
Barley (tonne)	196	
Oats (tonne)	163	
Lupins (tonne)	510	

Ignoring the reference flows between the sheep and cropping activities decreased the carbon footprint of the sheep products to some extent (26.6 vs. 28.7 kg CO_2-*e*/kg wool, Table 3), while the effect on individual crops was more marked, especially for those crops offering N and break crop benefits. For example, the carbon footprint for lupins modelled in isolation was 726 kg CO_2-*e*/t, whereas it dropped to 510 kg CO_2-*e*/t when the benefits to the mixed farming system were explicitly modelled (Table 3).

There were significant interdependencies between the livestock and cropping activities with 800 t of stock feed supplied each year by stubble; this is equivalent to an avoided product of 800 t of natural pasture representing 134.5 t CO_2-*e*. The pasture emissions are associated with the specific inputs for pasture such as super phosphate application and N_2O emissions from the residual pasture dry matter not consumed by the sheep. Conversely, sheep displaced the need for 7.6 t of urea (representing 10.9 t CO_2-*e* from urea manufacture and 28.7 t CO_2-*e* avoided N_2O emissions), based on their N excretion and the assumed loss to the atmosphere. Grazing by sheep in the fallow period avoided the spraying of 830 ha of crop land (representing 4.6 t CO_2-*e*) with 830 kg of herbicide (representing 9.4 t of CO_2-*e*).

Within the cropping rotation, the lupin crop imparted a total N benefit of 0.8 t (representing 2.5 t CO_2-*e* from urea manufacture and 3.0 t CO_2-*e* of avoided N_2O emissions) and the annual legume pasture delivered 4.2 t N (representing 13.0 t CO_2-*e* from urea manufacture and 15.9 t CO_2-*e* of avoided N_2O emissions). The break crop benefit for cereal crops from lupins, canola and the annual pasture phase in the cropping rotation was equivalent to 159.2 t cereal grain (representing approximately 65 t CO_2-*e*).

The GHG emissions associated with each avoided product and crop benefit are summarised (per FU) in Table 4. For instance, for every tonne of canola grown, the crop received a urea benefit equivalent to 25.2 t CO_2-*e* and avoided N_2O emissions equivalent to 30.6 t CO_2-*e* from the *N* left by a previous lupin or sown pasture phase in the rotation. While for every tonne, the canola crop gave a break crop benefit of additional cereal yield equivalent to 29.7 t CO_2-*e*. It should be noted that the net effect on GHG emissions/FU of product (as detailed in Table 4) does not add exactly to the difference in GHG emissions for each product when modelled in isolation or including the two-way reference flows (Table 3), especially for the sheep products. This is because the analysis in Table 4 presents only part of the whole system flows, i.e. that portion directly accounted for as an avoided product or additional input. The results in Table 3 are from modelling the whole system which includes a number of complex feedback loops e.g. flows related to the lupins and wheat grain fed to sheep as a supplement.

4. Discussion

For the case study farm there were significant reference flows between the livestock and cropping activities, in the order of 288 t CO_2-*e*, for a farm with an overall carbon footprint of 2,932 t CO_2-*e*. The absolute values for the reference flows between farm activities will be dependant on the particular combinations of production found on a farm. In this instance, the size of sheep flock determined how much *N* was added to the cropping system while the area of cropping land determined the avoided herbicide use imparted by grazing. Likewise the ratio of area of break crop to cereal determined the benefit that the break crop added to the cropping system. In this instance, the magnitude of the reference flows (approximately 10% of the total) suggests that products from mixed farming systems should be modelled in a way that recognises the benefits passed between farm activities.

This study shows that the impact of modelling these benefits on the resultant product carbon footprint can be large, as

Table 4
Greenhouse gas (GHG) emissions credited to a crop as an avoided product and added to a crop when a benefit was received in the crop rotation.

Functional Unit (FU) at farm gate	GHG emissions/FU (kg CO_2-*e*)				
	Urea	N_2O emissions	Weed control	Provision of sheep feed	Cereal break crop effect
Merino wool 19.5 μm (kg greasy)	−0.1	−0.3	−0.2	1.5	–
Wethers, 12 months (number)	−1.2	−3.0	−1.5	13.9	–
Cast for age ewes (number)	−0.7	−1.7	−0.8	7.9	–
Stud rams (number)	−3.3	−8.0	−3.9	37.3	–
Surplus hoggets, 18 months (number)	−1.2	−2.8	−1.4	13.0	–
Wheat (tonne)	16.5	20.0	–	−65.4	–
Canola(tonne)	25.2	30.6	–	−86.4	−29.7
Barley (tonne)	14.8	18.0	–	−49.4	–
Oats (tonne)	16.0	19.5	–	−110.2	–
Lupins (tonne)	−32.6	−39.6	–	−97.9	−45.5

demonstrated for lupins which offered significant benefits to the cropping system, which reduced its carbon footprint by 30% when taken into account. However, in other instances there was little change to the final value as with wheat and barley. The size of the effect of including the benefits will largely depend on the magnitude of the benefit and the balance of flows between products. The benefit provided by crop stubble to the sheep flock outweighed the agronomic benefits the sheep provided to the crops, so although the two-way flows were quite large they cancelled each other out to some extent (Table 4).

The carbon footprint results of this case study relate to the mixed farming enterprise studied and care should be taken in extrapolating to other systems. When being used by LCA practioners (or when adding data to the Australian national Life Cycle Inventory for agriculture), the farm products should be specified as coming from a particular 'system', e.g. wool or wheat produced from mixed sheep-wheat system in south western Australia.

Nonetheless, the case study results add to the inventory of global warming impacts of agricultural products. For instance, the carbon footprint of a kilogram of wool at the farm gate from a mixed farming system was 28.7 kg CO_2-*e*, using economic allocation. Other estimates (Barber and Pellow, 2006) for wool production are 1 kg CO_2/kg for New Zealand Merino wool where there was no accounting for non-CO_2 emissions such as methane and N_2O, through to 31 kg CO_2-*e*/kg wool for Merino fine wool produced on the New England Tablelands, in Australia (Eady, unpublished data). More studies are required to begin to build a library of results for Australian wool from different regions.

Assuming a dressing percentage of 53%, the carbon footprint of meat from the wethers was 12,640 kg CO_2-*e*/t at the farm gate, in comparison with values such as 17,400 kg CO_2-*e*/t for UK lamb (Williams et al. 2006) and 15,200 kg CO_2-*e*/t for New Zealand lamb (Ledgard et al. 2010). This type of information will be essential for determining the carbon footprint of food and fibre products, as retailers move to product labelling.

As demonstrated with the sheep co-products, choice of method to deal with co-production can have an impact on LCA results. The complexity of system expansion is likely to preclude the application of this approach to some agricultural products, particularly livestock. Where biophysical allocation has been used, it has been based on a range of relationships with some showing a more logical functional relationship than others. Barber and Pellow (2006) used output mass where 1 kg barley = 1 kg wool = 1 kg dressed carcase weight, while other studies have used resource inputs such as area of land or energy requirements (Cederberg and Stadig, 2003; Eady and Ridoutt, 2009; and this study). To be valid, a biophysical allocation should be based on some type of functional relationship and these can be complex and time consuming to model, as was the nutrient requirements for each class of sheep in this study. There are also arbitrary decisions to make; for instance, the level of nutrients allocated to the breeding ewe for wool production verses the cull ewe for meat at the end of her reproductive life.

Economic allocation is open to vagaries of market fluctuations but it is at least consistent in application. Where it is not practicable to divide the product system into sub-processes or expand the product system to include additional functions related to the co-products, the recommendation in existing guidelines for carbon footprinting (e.g. British Standards, 2008) is to use the economic value of the co-products. In many instances this is likely to be the preferred option for livestock co-products but it does shift the environmental burden to the higher value co-products and away from the high resource use products.

The use of an economic or biophysical allocation of general farm services to the farm activities, in this case, had a small effect on results. In this circumstance, the choice of which to use is likely to be driven by the ease of data collection; often it is much easier to gain economic values rather than drill down to resource allocation records on-farm.

The overall approach in this case study was to use the whole suite of approaches recommended in the ISO guidelines to model co-production at the farm level, in an attempt to best represent the mixed farming system. The interdependencies between co-products were explicitly recognised and modelled by system expansion; production from the farming system was broken into sub-processes where inputs and outputs could be clearly identified to a particular product; and where there was remaining co-production that could not be dealt with by these former approaches, allocation was used with an investigation into the impact of choice of allocation method on the final result. This overall approach is suggested by the authors as an appropriate framework in which to approach LCA modelling of agricultural products from mixed farming systems.

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