Developing Life Cycle Inventory for Life Cycle Assessment of Australian Cotton

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ABSTRACT - Life Cycle Assessment (LCA) is an internationally recognised approach for evaluating the environmental impacts of products and services. In this paper, the potential issues in the development of consistent and comprehensive life cycle inventory (LCI) data are illustrated in the context of Australian cotton industry. These include the diversity and variable nature of farming practices, and the inherent complexities such as the inter-linkages between co-products. For the implementation of LCI, the choices of functional unit and system boundary, definition of regional sub-sectors, methods of energy assessments, and rules of allocations of inputs and emissions are discussed. Overall, collection and maintenance of consistent and comprehensive LCI data can be a long and expensive process and may be more complex than many people tend to think. Close industry involvement is also essential. It has been shown from a case study that for cotton production, the contribution of on-farm indirect "chemical" inputs is particularly important, accounting for up to 50–80% of the total energy input in the life cycle. The need for quantified trade off analysis between alternative systems in the LCA context is also emphasized.

Introduction

Agricultural and food production are essential for humans' survival and development. The food production chains, from primary production to consumer and beyond, can have considerable environmental impact. LCA is an internationally recognised approach for evaluating the environmental impacts of products and services. LCA is often used to compare the environmental damages assignable to products and services, and further to choose the least burdensome one. LCA standards are covered by ISO 14040:2006 and ISO 14044:2006.

Figure 1: Cotton growing areas of Australia

Cotton Farming and Energy Use

Cotton is a product that is mainly used for textile production. The by-products of cotton include cottonseed for producing oil and animal feed. Considerable amount of plant residue biomass is also produced.

In Australia, cotton is mainly farmed in New South Wales and Queensland (Figure 1). Each year, depending on the market and climatic conditions, 1 to 4 million bales of cotton may be produced, with the average for the past 10-15 years being around 2 million bales for 250,000 ha production area per year. Currently, the cotton yield in Australia is in average 1,907 kg lint (8.4 cotton bales) per hectare. This figure is almost two and a half times the world average of 747 kg/ha. Around 80-90% of Australian cotton is irrigated. 98% is also exported.

Instead of growing cotton only, cotton farmers in Australia also typically divide the whole paddock into a number of different plots, so that depending on the prevailing market and soil conditions, he/she may either intensify the cropping system by adding a winter crop in a double-cropping system, or fallow certain number of plots for moisture conservation, or replace cotton with another summer crop. With the advance of biotechnology and increasing awareness of water and energy conservation, conservation farming practices with reduced or zero tillage are being increasingly adopted.

Energy is used pre-farm, on-farm, post-farm (off-farm) for cotton production. It may be alternatively divided into direct energy used, ie. the fuel and electricity consumed on-farm, and the indirect energy (embodied energy) involved in the pre-farm production of all other inputs from equipment to agrochemicals. Post-farm activities include ginning, milling and transport.

Previous LCA Research

Matlock et al. [1] used the LCA method to quantify the required energy use for cotton production over global cotton practices. The results varied from 5.6 GJ (North America East) to 48 GJ (South America, Non-Mechanized) per tonne of raw cotton (including both seed and lint and to the farm gate). The latter value was higher because cotton growers in South America used medium level of irrigation, whilst the North American farmers did not. It was also found that the energy consumption was heavily influenced by irrigation, the amount of fertiliser used and cotton yield.

Table 1 summarizes the energy performance data for cotton production in several countries. Yilmaz et al [2] showed that the energy intensity in agricultural production was closely related with production techniques. He estimated that cotton production in Turkey consumed a total of 49.73 GJ/ha energy, consisting of 21.14 GJ/ha (42.5%) direct energy input and 28.59 GJ/ha (57.5%) indirect energy input. Total sequestered energy in Greece [3] was found to be 82.6 GJ/ha, with irrigation pumping and fertilizers as major inputs.

Table 1: Energy performance data from published literature

Direct Energy Input (GJ/ha)	*Indirect Energy Input (GJ/ha)*	*Total Energy Input (GJ/ha)*	*Researchers*	*Country*
21.14	28.59	49.73	Yilmaz et al [2]	Turkey
-	-	82.6	Tsatsarelis [3]	Greece
3.7 ~ 15.2	-	-	Chen & Baillie [4]	Australia
11.5~13.2	21.9~112.2	47~128	Khabbaz [5]	Australia
5.5~20.5	1.6~ 7.9	-	Nelson et al [6]	USA
-	-	31.24	Pishgar-Komleh, et al [7]	Iran

Uncertainty and Variations of Input Data in LCA Modelling

The quality of a LCA is strongly dependent on the quality of inventory data. Many data in agriculture are highly variable both temporally and spatially, and difficult to track accurately. This is because of the inherent complexities of the nutrient flows involved in land use, and the inter-linkages between co-products. There may be different ways of producing the same product.

Overall, it is estimated that the uncertainty of these data may range from 5% for crop yield to 30 to 50% in fuel uses and other inputs [8]. One machine may be used for multi-purposes. Newer models of tractors will also be more efficient and with lower levels of emissions. Many agricultural inputs in Australia are imported and outputs are exported, so that their energy uses are difficult to estimate.

Methods to Improve the Accuracy of LCA Models

Preparing a LCA is not a simple exercise. It requires a large amount of data and a software to manipulate these data. Lack of high quality data is a very important limitation of a full scale LCA study. To overcome these limitations, care should not only be placed to ensure the accuracy of the systems being modelled and reliability of the data, but also standardizing the assessment methods.

Standardizing function unit and system boundary

The functional unit and system boundary are the two key elements of a LCA analysis. For practical purpose, the functional unit of agriculture is often defined as one kilogram of product, or one hectare of land used. For cotton, the definitions of functional unit in different researches range from one kilogram, bale or tonne of raw cotton [1] or cotton lint [9], to one hectare of land used [2-5]. The system boundaries also vary from the farm gate, export shipping port [5], to the end of life cycle consumer use and disposal of a cotton shirt [9,10].

Define production systems for different regional sub-sectors

It is desirable to define crop production systems as regional sub-sectors of the industry, in order to give appropriate representation of differences in environmental impact [11]. A detailed mapping of crop production operations is necessary so that each major activity of the operations is included.

Regional sub-sectors are often defined using a combination of industry expertise and spatial data such as land use, soil types, and rainfall. Australian cotton production areas may be broadly divided into 3 regions (Table 2): Northern Region (Emerald and Dawson-Callide districts), Central Border Region (Macintyre Valley, Darling Downs, St George-Dirranbandi, Namoi Valley, Gwydir Valley and Bourke), and Southern Inland Region (Macquarie Valley, Tandou and Southern NSW) (Fig. 1). Central Border Region dominates the cotton production in Australia and has a significantly higher proportion of dryland farming than other regions. Central Queensland has more rotation crops than other regions. Some of the data in Table 2 are also subject to variation for different years.

Table 2: Characteristics of three Australian cotton production regions

Cotton systems		*Northern Region*	*Central Border Region*	*Southern Inland Region*
Cotton variety		Gossypium hirsutum (100%)	Gossypium hirsutum (100%)	Gossypium hirsutum (99%), Gossypium barbadense (1%)
% reduced till (% of area)		2%	31%	0%
Irrigation (% of area)		2% dryland 98% irrigated	31% dryland 69% irrigated	0% dryland 100% irrigated
Irrigation Water (ML/ha)		6-8 (ET is high)	3-8 (clay soil holds water)	6-10 (little summer rainfall)
Rotation crops		Wheat, Chickpea, Soybeans	Wheat, Corn, Sorghum and Fallow	Wheat, Chickpea, Soybeans, Canola
% of national crop yield		16%	70%	14%
Yield (bales/ha)	Irrigated	7.0	10	7
	Dry land	1	3	NA

Table 3: Common characteristics of cotton production in Australia

Variety	GM cotton – varieties are supplied by Monsanto & Bayer
Tillage	Conventional tillage for irrigated cotton
Irrigation	About 90% of the cotton production in Australia is from irrigation. Over 90% of irrigated cotton in Australia is grown under furrow irrigation. The average irrigation water use is 6.5~7.5 ML/ha.
Water sources	Mostly regulated water supply is from rivers and dams (by pumping), channels (by gravity feed) and overland flood, and to a less degree from groundwater bore pumping
Yield	> 10 bales/ha for irrigated cotton, 1~3 bales/ha for dryland cotton
Fibre quality	High fibre quality. 98% of Australian cotton production is exported.

For the cotton industry in Australia, it is suggested that as the first initial step, only one simplified "representative" farming system (sub-sector) may be adopted (Table 3), as it is believed that this system would be able to represent 80~90% of cotton produced, where furrow irrigation and GM varieties are widely adopted. The further differences in farming practices in different regions may then be accounted for by changing the details of particular processes that are involved.

Methods of energy assessments
Energy assessments may include direct measurement of actual performances in the field, or alternatively by a proxy based protocol and / or a combination of both methods. A proxy based protocol is where energy inputs are assumed or estimated based on practices or tools (eg, rated engine power, engine load (high, med, light), machine width, ground speed and tillage depth and soil types etc) as opposed to direct measurement. A proxy based protocol is generally more economic, but its accuracy may be lower. Research is currently being conducted by the authors to compare the values of energy use in different operations and different regions between default values and direct measurements.

Allocations of inputs and emissions
The application of LCA to agricultural systems is relatively complex because in addition to the main product (eg cotton lint), there are usually by-products and co-products produced (eg cottonseed and cotton stalk biomass). This requires appropriate partitioning of environmental impacts to each product from the system based on certain allocation rules.

The method of allocating emissions to products can affect the estimates. Allocation has become the subject of a body of discussions and debates. For the main products, different approaches to building life cycle inventory may be adopted. For example, for recycling of machinery materials, what percentage of the manufacture inputs should be allocated to the "primary" life i.e. amortise over the expected lifetime and what percentage of materials are for disposal recycling. The influences of these choices may in some cases be significant. In Ecoinvent [12], the convention of units for tractors and other self-propelled machines is hours of use per lifetime, and for farm implement it is hectares of coverage per lifetime. This can also create difficulties.

For by-products and co-products allocation, the current general direction is that system expansion is preferable to allocation, because allocation of inputs and emissions may be avoided by expanding the boundaries of the sub-systems to incorporate the processes of the co-products. Wherever the above is not feasible, the main and co-products may be simply partitioned as either their respective economic value or mass units. The uses of the economic allocation method are very common [9].

As a result of the above data uncertainties and allocation rule changes and differences in adopted farming practices, the overall energy uses and associated carbon footprint of cotton product may vary by up to a factor of 2 to 4 for different ways of allocation and calculating/producing the same product. This has significant implications for carbon labelling. It can also be said that collection and maintenance of consistent and comprehensive LCI data can be a long and expensive process [13] and may be more complex than many people tend to think. Close industry involvement is also essential to obtain an appropriate representation of the real impact of different farming systems.

Example of cotton production in Australia
To illustrate the above, in the following, an example of cotton production in Australia is presented. The case study farm was located in Warrina downs in Dalby region, Queensland [5]. The system boundaries in this project were defined as from field to the export shipping port. Thus, the energy uses associated with cotton ginning and road transportation and the associated machinery have been included. The area of the case study was a 8.7 ha paddock in a complex of 12 combined cotton paddocks with a total area of 366 ha under different cotton varieties and farming practices. The yield was 2188 kg per ha. The fertilisers applied included 300kg/ha of urea, 8 tonnes/ha of manure, and 6.4 kg/ha of other fertilisers. The herbicide application rate was 21.7 L/ha. 3.3 ML/ha of furrow irrigation water was applied. The operations required a total 13 tractor runs employing conventional tillage. This case study farm was typical of the farming system in Central Border

Region (Table 2) and was also typical of the “one representative” farming system defined in Table 3 except of the amount of irrigation water use.

The calculation result for life cycle energy use is shown in Figure 2. The total energy consumption was 59.0 GJ/ha, among which the on-farm indirect energy consumption contributed 82% or 48.0 GJ/ha, consisting of 10.1GJ/ha from urea manufacturing, 26.0 GJ/ha from manure (assuming the equivalent energy content of 3.25 GJ/t), 6.7 GJ/ha from pesticide manufacturing and 4.2 GJ/ha from the embodied energy of farm machinery etc. This was compared with the on-farm direct energy use (13%) which consisted of 2.1 GJ/ha for tractor tillage operations, 1.1 GJ/ha for irrigation pumping, 1.8 GJ/ha for crop harvesting, and 1.6 GJ/ha for crop destruction post-harvest operations. The total energy consumption was also in the broad range of variation found in Table 1.

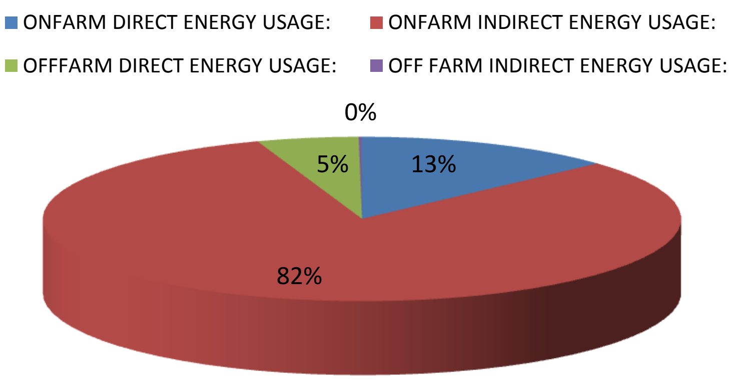

Figure 2: Life cycle energy profile to produce a bale of cotton

The most significant energy input in this case was on-farm indirect “chemical” inputs. This was because with the current manufacturing technology, the production of one kg of nitrogen fertilizer and 1 kg of pesticides would respectively “indirectly” require some 65 MJ and 196 MJ of primary energy input [5] which are equivalent to 1.5 and 5 kg of fuel use respectively. This illustrates that it is very important to reduce not only the on-farm energy uses but also the embodied energy. In this regard, the precision agriculture technology such as the variable-rate fertilizer applications may offer significant benefits. The contribution of embodied indirect energy of on-farm machinery in this case study was only 7% so the influence of the method of allocation and recycling of machinery materials was relatively small. Similarly, the contribution from off-farm activities was also relatively unimportant, making up only 5% of total energy use in this case.

Allocation choice for cotton by-product is highly important. In most of current studies, allocations were only made to main product of cotton fibres [1-7], possibly because researchers were unfamiliar with the cotton industry and the use of by-products (cottonseed and cotton stalk biomass). However, based on economic values, only around 85 % of emissions may be allocated to cotton fibres (lint). This is similar to 84% used in the US study [9] and can be justified in Australia because the value of cottonseed is currently around $300/t in comparison with $1982/t ($450/bale) of cotton lint. The weight ratio of cotton-seed cotton-lint may be about 1.2:1 in Australia. The range of cotton stalk/straw biomass /cotton-lint ratio may be 0.95-2.0. However, the straw is currently ploughed back into the soil to increase the soil organic matter, so its monetary value is unclear and difficult to quantify.

Conclusion

The sustainable development of modern industry and society has been identified as a significant national and international issue. Life Cycle Assessment (LCA) has been increasingly used to analyse and quantify the environmental impacts. In this paper, the diversity of farming practices and systems, and difficulty in obtaining accurate data due to the highly variable nature of agriculture have been illustrated, using cotton production in Australia as an example. The variations and implication in the choices of functional unit and system boundary, definition of regional sub-sectors, methods of energy assessments, and rules of allocations of inputs and emissions have been discussed. For cotton production, it has been shown from a case study that the contribution of on-farm indirect "chemical" inputs could be very important, accounting for up to 80% of the total energy input in the production. This highlighted the great importance of obtaining accurate data for this category of inputs for high-input crops.

Collection and maintenance of consistent and comprehensive LCI data can be a long and expensive process [13]. This is mainly because it has to be well-founded and well accepted by a wide range of stakeholders. A standardised "template" of drop-down menus or other capabilities would be a great help for the LCA practitioners, reducing the chance of error and the project cost and delivery time. Further research is also needed, in order to better understand and manage uncertainty in samples, populations and means and to interpret and use the results. Quantified trade off analysis of between water use and energy use of different irrigation systems in the LCA context is also important. Similar question also needs to be answered for the trade off of reduced tillage with the increased energy use associated with the manufacture and applications of herbicides. There were some anecdotic evidences showing that farms under furrow irrigation may use higher fertiliser consumption rate than that of pressured irrigation [14].

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