Australian Government
Cotton Research and
Development Corporation

# FINAL REPORT

## *Part 1 - Summary Details*

**CRDC Project Number:** DAN 1508

**Project Title:** A review of emission methodologies in the Australian cotton industry and development of a detailed study for north-west NSW.

**Project Commencement Date:** 01/07/2014 **Project Completion Date:** 01/12/2015

**(A 12 month project with delayed start, finishing on 01/12/15)**

**CRDC Program: 2.3** 2 Industry

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## Glossary of terms and acronyms

| | |
|---|---|
| **Allocation** | Partitioning the input and/or output flows of a process to the product system under study |
| **Background data** | Data from existing studies, typically included in life cycle inventory databases |
| **Biogenic carbon dioxide** | Carbon dioxide related to the natural carbon cycle |
| **Carbon dioxide equivalents ($CO_2e$)** | A measure used to compare the emissions from various greenhouse gases based upon their global warming potential |
| **Cut-off criteria** | Methods used to determine exclusion of processes from the boundaries of the system under study |
| **Economic allocation** | A method used in the LCA studies to assign the environmental impact of the system under study to its co-products, typically based on the revenue and value of co-products |
| **Foreground data** | Data collected by the LCA practitioner (e.g. process data and emissions) |
| **Functional unit (FU)** | The unit of the assessment in an LCA study. In the comparative LCA studies, it is the unit by which all environmental comparison are made |
| **Inventory** | The raw materials, materials, energy, and emissions flows (in and out) related to a process or system |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **ISO 14040:2006 and ISO 14044:2006** | International standards outlining processes to undertake LCA |
| **Life cycle** | A series of interlinked stages of a product system |
| **Life Cycle Assessment (LCA)** | A science-based method used to quantify the environmental impacts of a product or service over its life cycle |
| **Life Cycle Impact Assessment (LCIA)** | Calculation of environmental impacts from the inventory |
| **Life Cycle Inventory (LCI)** | The compilation of raw materials and emission flows related to a life cycle |
| **Mass allocation** | A method used in the LCA studies to assign the environmental impact of the system under study to its co-products based on the mass of co-products |
| **Monte Carlo simulation** | A mathematical analysis which repeatedly quantifies results by varying random data points within the bounds of uncertainty |
| **Sensitivity tests** | Investigation into the effect of changes in the input data and or assumptions to the outcomes of an LCA |
| **Total Dynamic Head (TDH)** | The total equivalent height that a fluid is to be pumped, taking into account friction losses in the pipe |
| **Uncertainty analysis** | Process of quantifying effects of all uncertainty on the final outcomes, typically undertaken with Monte Carlo analysis |

## Executive summary

This report presents the key outcomes of a collaborative research study between NSW Department of Primary Industries (DPI) and Cotton Research and Development Corporation (CRDC). The study used the science-based method of Life Cycle Assessment (LCA) and aimed to:

(1) produce a clear picture of the greenhouse gas (GHG) emissions profile for a representative cotton production system in North West NSW;
(2) identify the most plausible set of emission reduction opportunities;
(3) create a platform in SimaPro (an LCA tool), through the North West NSW LCA, from which industry can routinely test emission mitigation options or the consequences of new productivity-based technologies in an ongoing way; and,
(4) undertake sensitivity analysis to check whether the case study region is representative of other regions.

We followed the LCA principals, as defined by ISO 14040:2006 Standard [1] and ISO 14044:2006 Standard [2]. The functional unit of the assessment was 1 t (1000 kg) of cotton lint at port, produced between 2011- 2014 by a continuous (back-to-back) cotton production system. A mixture of irrigated and rainfed cotton was modelled, in which irrigated cotton predominated. The system boundaries of the assessment included all processes involved in pre-farm, on-farm, and post-farm stages. The foreground data included that from questionnaires sent to some ginning plants, interviews conducted with some cotton farmers, gross margin data, industry surveys and case study research. Data were also validated by obtaining expert opinion from industry representatives. The background data (e.g. fertiliser production) were accessed from the different sources mainly from the Australian life-cycle inventory (AusLCI).

To assign the calculated CC impact between cotton lint and cotton seed, we followed the relevant hierarchy recommended by ISO 14044:2006. We initially applied the system expansion approach in which the total CC impact of the cotton system is assigned to cotton lint but it is credited for the avoided CC impacts of the products displaced by cotton seed (i.e. animal feed and oilseeds). Through this approach, we calculated the CC impact of the functional unit to range from 1254 kg $CO_2$e to 1307 kg $CO_2$e for four investigated scenarios. As other scenarios are also possible, these results should be treated as subjective. Given this uncertainty, we finally applied the economic allocation approach in which we allocated around 86% of the total CC impact to cotton lint and around 14% of the impacts to cotton seed, in proportion to their revenue.

The CC impact of the functional unit, based on the economic allocation approach, was 1601 kg $CO_2$e. The CC impact of the pre-farm stage, on-farm stage, and the post-farm stage for the functional unit were 407 kg $CO_2$e, 775 kg $CO_2$e, and 419 kg $CO_2$e, respectively. The GHG emission profile of the representative cotton production system indicated that approximately 45% of the total GHG emission are related to the production of nitrogen (N) fertiliser (~17% of the total) and the use of fertilisers (~28% of the total). The processes of drying seed cotton in the cotton ginning plants and the cotton ginning process itself contributed 12% and 9% of the total GHG emissions, respectively. Among the cotton farming practices, the diesel used in the farm machinery; and the electricity and diesel used in the irrigation pumps contributed 8% and 7% of the total GHG emissions.

We developed six GHG emission reduction options, based on the best-practice options reported in the literature and through consultation with experts and cotton farmers, and assessed the options by using the SimaPro platform created in the present study. These options included:

(1) optimum nitrogen application rate;
(2) controlled-release and stabilised N fertilisers;
(3) solar-powered irrigation pumps;
(4) biofuel-powered farm machinery;
(5) legume crops; and,
(6) fertigation.

These options were found to potentially reduce the CC impact of the functional unit by 13.2%, 5.9%, 8.1%, 3.4%, 3.9%, and 2.1% respectively. The applied approach was shown to be an effective and practical platform to routinely test GHG emission mitigation options or the consequences of new productivity-based technologies in an ongoing way.

We assessed whether the case study region was representative of other regions including the emerging cotton production regions (e.g. Sothern NSW). Apart from the cotton production system of Central Queensland, which is characterised by relatively low cotton yield, the cotton production of North West NSW was found to be representative of other regions. The calculated CC impact of the Central Queensland cotton production system was found to be approximately 23% higher than that for North West NSW; whereas the difference in CC impact between other regions and North West NSW did not exceed 10%.

The present study has made some significant contributions to the current knowledge about the impact of cotton production systems and the application of LCA to understand those impacts. From the methodological perspective, we have developed a platform in SimaPro that is capable of handling both consequential and attributional cotton LCA modelling. The platform is also capable of handling complex cotton production systems, such as those involving crop rotation. The GHG accounting methods underpinning the calculations within this new platform are generally cotton-specific and Australian-specific. An example is the emission factor (EF) required to calculate the $N_2O$ emission from the decomposition of cotton residues. The current EF in Australian National Inventory (NIR) 2013 is based on the international studies. The present study calculated this EF based on the research conducted in Australia and used that EF instead of the international EF. From the data quality perspective, we refined some key LCA inventory data for the Australian cotton production systems; addressing sensitivity and reducing data ‘noise’, thereby increasing certainty about our results. Without these refinements, there would an increase of around 30% in the calculated CC impact of the functional unit.

# 1. Introduction

## 1.1 Purpose and content of the study

The cotton industry is an integral part of the Australian economy, worth more than $2 billion per-annum in export earnings and helping to underpin more than 50 rural communities. The industry has established that the sustainable growth depends on measures that improve both economic and environmental aspects of the industry. From the environmental perspective, the industry is striving to improve its performance on key environmental measures, in particular direct and indirect emissions of greenhouse gases (GHGs). These emissions potentially intensify global warming and subsequently affect the Australian cotton industry through changes in temperature and rainfall.

This report presents the methodology used and the results obtained from a study focused on the GHG emissions and mitigation in the cotton production system of North West New South Wales (NSW). The assessments included in the present study are based on the science-based method of Life Cycle Assessment (LCA).

The report initially details the LCA method and its principles (according to the requirements of ISO 14040:2006 [1] and ISO 14044:2006 [2] standards) and then provides the results of the LCA study focusing on the calculation of the climate change (CC) indicator of the cotton production system of North West NSW. The results are challenged through the application of both uncertainty analysis and sensitivity analysis. The former is based on the mathematical analysis of Monte Carlo Simulation and the later includes a set of sensitivity tests which assess the robustness of the results, assuming changes to key input data and modelling assumptions. Following the discussion about the LCA results and their associated sensitivity tests, the report presents the results of the assessments related to the most plausible set of GHG emission reduction opportunities. The report details the opportunities and provides the extent to which each opportunity can reduce the CC impact of the unit of assessment (the functional unit of the LCA). Following the presentation of the results, the report presents a set of conclusions drawn from the results as well as a set of recommendations. The report concludes with suggestions for future research.

The intended audience of the report is the CRDC. Pending the outcomes of this study, the CRDC may expand the audience of the report to include their stakeholders. Some of the outcomes of the study have been already provided to the industry and the research community.

## 1.2 Project aims

The main aims of the project were:

1. Produce a clear picture of the GHG emissions profile for a representative cotton production system in North West NSW.
    1.1. The picture should include information about production system assumptions and the LCA methods employed during the assessment.
    1.2. Consider the appropriateness of National Inventory Report default values and discuss allocation of emissions between co-products.
    1.3. Conduct some sensitivity testing within the North West NSW LCA and describe which changes have the greatest influence on the emissions profile.
2. Identify the most plausible set of emission reduction opportunities.
3. Create a platform in SimaPro, through the North West NSW LCA, from which industry can routinely test emissions mitigation options or the consequences of new productivity-based technologies in an ongoing way.
4. Undertake sensitivity analysis to check whether the case study region is representative of other regions, by applying advice and data from an array of researchers, agronomists and industry representatives.
    4.1. Advise as to whether extrapolation is adequate to obtain a National picture of emissions from cotton, and if further work is required, how that could be done most efficiently.
    4.2. Consider the role of other ‘impact categories’, e.g. biodiversity, eutrophication and water use, depending on methodological development in those areas.

## 1.3 Production system under study

Both rainfed and irrigated cotton systems exist in the region but the dominant system is the irrigated cotton production system. The precise mass fraction of irrigated cotton in the total mass of cotton produced in the region is uncertain, but based on some available information [3], the estimated fraction is approximately 0.96. We acknowledge that the mass fraction of irrigated cotton in the years with high rainfall could be less than 0.96. Given the drought in the region in the past few years, we argue that the recent actual mass fraction of irrigated cotton would not be remarkably less than 0.96. However, we have conducted a sensitivity test to estimate the dependency level of the CC impact of the functional unit to the mass fraction of irrigated cotton (see Section 3.5.1).

We assume that during the timeframe of the assessment (2011-2014), the cotton production system under study is a continuous (back-to-back) cotton system. We challenge this assumption through sensitivity testing in which a breaking crop is incorporated into the cotton system under study.

## 2. Life Cycle Assessment (LCA) method

Life Cycle Assessment (LCA) is defined [1] as “Compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle”. The goal of the LCA presented in the report is to compile and evaluate the inputs (resources) and outputs (greenhouse gas emissions) and calculate the life-cycle climate change impact of cotton production in North West New South Wales. The life-cycle stages included in the assessment are: the pre-farm stage (i.e. the production of transport of raw materials), the on-farm stage (i.e. the cotton farming practices), and the post-farm stage (i.e. cotton ginning and the transport of cotton lint to an export port).

The scope of environmental assessment is limited to climate change (CC) impact. The geographical scope, as per the CRDC advice, is limited to the regions surrounding Narrabri, Moree, and Walgett. The temporal scope limited to the cotton production years of 2011 to 2014. The functional unit of the LCA study is 1 t of mixed irrigated and rainfed cotton fibre (lint), produced in a continuous cotton production system, at an export port.

### 2.1 System boundaries

The system boundary outlines the processes which are to be included in the LCA. The system boundaries are intended to capture at least 99% of environmental impacts associated with the systems. As shown in Figure 1, the system boundaries of the LCA include the processes involved in the pre-farm stage, the on-farm stage, and the post-farm stage.

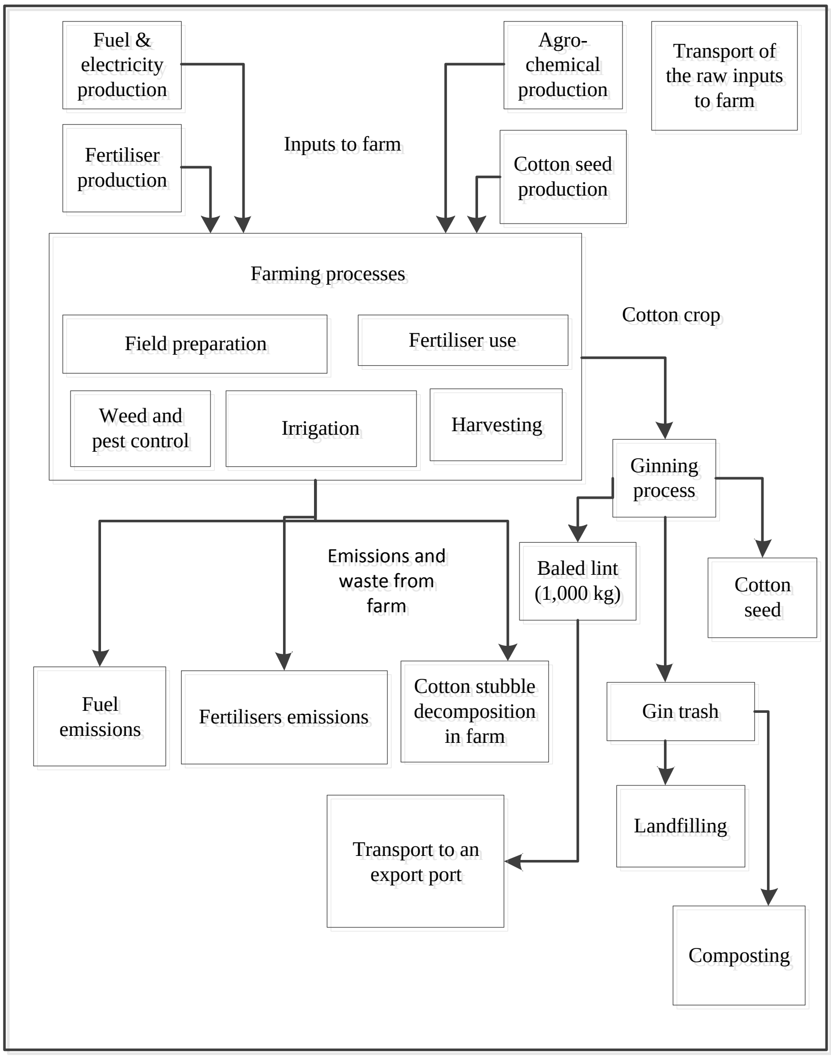

**Figure 1: System boundaries of the study**

## 2.2 Life Cycle Inventory (LCI)

Two types of inventory data are required in LCA: the background data and the foreground data. The background data collected from existing studies and are typically included in life cycle inventory databases such as AusLCI database that we used in the present study assessment. The foreground data are collected by the LCA practitioner. Examples of the foreground data are the inventory data related to the nitrogen (N) fertiliser application rate or the irrigation water use per ha of cotton land.

As presented in Section 2.1, the study involved pre-farm, on-farm, and post-farm stages. Each stage comprises many processes and sub-processes; as such, hundreds inventory data points were required for the assessment. For the background data, we predominantly used data from the Australian Life Cycle Inventory (AusLCI) database, such as those related to the processes included in the pre-farm stage (e.g. the GHG emission associated with the production of diesel). Some background data were collected from other sources including the Australian Bureau of Statistics (ABS), scientific and industry literature, published cotton industry surveys and unpublished industry surveys (see Attachment D). The references for the background data supplied from the sources other than AusLCI database are included below.

Some background data in AusLCI database are based on international databases (e.g. the Ecoinvent databases) and modified for Australian conditions. In the early stage of the study, we reviewed the key background data including the AusLCI data for GHG emission associated with the production of anhydrous ammonia and urea. We checked if these data satisfactorily represented the relevant Australian production systems and, where this was not the case, we conducted refinements accordingly. These refinements have been specified in Table 1.

The foreground data collected and used in the present study are provided in Table 1. The data classified as ‘outputs’ in Table 1, mainly related to the yield of the cotton system. We determined the yield data from several sources including interviews with some cotton farmers, gross margins, from cotton industry surveys, consultants and agronomists (unpublished data) and Life Cycle Strategies (AusLCI database, 2012). We reviewed all yield inventory sources and applied the most representative yield data (as reported in Table 1). As such, the yield data used in the present study should be regarded as ‘the most representative data’, rather than ‘the average data’. We examined the effects of the uncertainty associated with the foreground data on the calculated CC impact of the functional unit through sensitivity tests in which different quantities are assumed for the background data.

The inventory data classified as ‘field-related emissions to air’ in Table 1 are the calculated emissions figures based on the methodologies presented in the Australian National Inventory Report (NIR) 2013. We replaced some of the data available in NIR 2013 with the cotton-specific and Australian-specific (where possible) from literature.

We based the data related to the post-farm stage, questionnaires sent to two ginning plants located in North West NSW. These inventory data have been classified in Table 1 as ‘gin inputs’.

### Table 1: Foreground inventory data

| **Parameter** | **Irrigated cotton** | **Rainfed cotton** | **Unit** | **Note** |
|---|---|---|---|---|
| | **Quantity** | **Quantity** | | |
| Outputs | | | | |
| Cotton lint yield | 10.5 | 5 | bale/ha | Based on the average yield 2011 to 2014, 1 bale=227 kg |
| Cotton lint total mass | 2384 | 1135 | kg/ha | Total mass of cotton lint produced in one hectare |
| Seed/lint ratio | 1.17 | 1.17 | - | Based on the production of 42 kg cotton lint, 49 kg cotton seed, and 9 kg of gin trash per 100 kg of gin output |
| Cotton seed total mass | 2789 | 1328 | kg/ha | Based on the cotton seed to the cotton lint ratio of 1.17 |
| Crop yield | 5172 | 2460 | kg/ha | Total mass of products (cotton lint and cotton seed) |
| Farm inputs | | | | |
| Raw cotton seed for cotton planting | 13 | 13 | kg/ha | Average quantity |
| Irrigation water | 7.7 | 0.0 | ML/ha | Total water used from both surface water (e.g. rivers, dams) and groundwater |
| Diesel for machinery | 122.1 | 103.3 | L/ha | Total diesel used for all farming practices from planting to harvesting (irrigation excluded) |
| Diesel for irrigation pumps | 99.5 | 0.0 | L/ha | Total diesel used for water pumping from surface water and groundwater |
| Electricity for irrigation pumps | 58.5 | 0.0 | kWh/ha | Total electricity used for water pumping from surface water (e.g. rivers) and groundwater |
| Urea | 315.0 | 96.0 | kg/ha | Total mass of the product not the active ingredient |
| Ammonia | 120.0 | 0.0 | kg/ha | Total mass of the product not the active ingredient |
| Mono ammonium phosphate (MAP) | 113.0 | 57.0 | kg/ha | Total mass of the product not the active ingredient |
| Herbicides | 6.6 | 6.6 | kg/ha | Total mass of the product not the active ingredient |
| Growth regulator | 1.59 | 1.59 | kg/ha | Total mass of the product not the active ingredient |
| Insecticides | 0.83 | 0.83 | kg/ha | Total mass of the product not the active ingredient |
| Transport distance | 500 | 500 | km | Average distance between farms and the raw materials suppliers |

|  |  |  |  |  |
|---|---|---|---|---|
| Gin inputs |  |  |  |  |
| Electricity for the ginning machinery | 33.5 | 33.5 | kWh/bale | Average of the actual data from two major ginning plants in the region |
| LPG for seed cotton drying | 2.1 | 2.1 | L/bale | Average of the actual data from two major ginning plants in the region |
| Packaging plastics | 1 | 1 | kg/bale | Average weight of bale plastic (from PET) packaging |
| Transport distance | 35 | 35 | km | Average distance between farms and the gin plant (road freight) |
| Transport distance | 550 | 550 | km | Average distance between the gin plant and an export port (rail freight) |
| Field-related emissions to air |  |  |  |  |
| Direct $N_2O$ emissions from N fertilisers | 2.5 | 0.22 | kg/ha | Calculated based on the Australian NIR 2013 guidelines [4] |
| Indirect $N_2O$ emissions from N fertilisers through leaching & runoff | 0.33 | 0 | kg/ha | Calculated based on the Australian NIR 2013 guidelines and the data from Ringrose-Voase and Nadelko [5] and McHugh, Bhattarai [6] to estimate the mass fraction of N lost through leaching and runoff (FracLEACH). No leaching and runoff for rainfed (dryland) crop (cotton) as per Eder, Blöschl [7]. |
| Indirect $N_2O$ emissions from N fertilisers through atmospheric deposition | 0.25 | 0.02 | kg/ha | Calculated based on the Australian NIR 2013 guidelines [4] |
| Emissions of $CO_2$ that was fixed in Urea | 231 | 70.4 | kg/ha | Calculated based on the Australian NIR 2013 guidelines [4] |
| Emissions of $N_2O$ from cotton residue decomposition in the filed | 0.63 | 0.31 | kg/ha | Calculated based on the Australian NIR 2013 guidelines [4] |
| Gin trash generation and treatment |  |  |  |  |
| Gin trash/lint ratio | 0.21 | 0.21 | - | Based on the production of 42 kg cotton lint, 49 kg cotton seed, and 9 kg of gin trash per 100 kg of gin output |
| Gin trash total mass | 511 | 238 | kg/ha | Based on the gin trash to cotton lint ratio of 0.21 |
| Gin trash composting | 383.2 | 178.5 | kg/ha | Based on the average composting rate of 75%, as per the information obtained from some selected ginning plants, the LCI inventory data for windrow composting systems of solid wastes sourced from NSW EPA [8] but the diesel consumption in the inventory excluded for waste shredding as gin trash contains small particles |
| Gin trash landfill disposal | 127.8 | 59.5 | kg/ha | The AusLCI database for the landfill disposal of garden and green wastes is used as a proxy |
| Transport distance between gin and landfill | 50 | 50 | km | The average distance between the gin plant and the local landfill site |

## 2.3 Life Cycle Impact Assessment (LCIA)

LCIA is the process of calculating environmental impacts from the inventory. We applied the Australian Impact Method (Australian Indicator Set V3) to interpret LCA inventory results but did not include calculate carbon dioxide absorbed by cotton from air during its growth and the carbon dioxide released from the decomposition of cotton waste residues in the field, for consistency with the Australian National Inventory Report (NIR) which regards carbon to have reached a steady state [4]. We calculated the potential life-cycle climate change by multiplying the total emissions of the various greenhouse gases by their respective global warming potentials (GWPs), then added the global warming equivalencies for the various GHGs. The GWPs are based on the GWP values provided by the UNFCCC [9] for a 100-year timeframe. The GWP of the main GHGs of $CO_2$, $N_2O$ and $CH_4$ are 1, 298, and 25 respectively. The $N_2O$ emissions associated with the decomposition of cotton residues were included in the assessment. We performed all impact assessment calculations by using SimaPro 8.0.3.

To ensure that all relevant environmental impacts were represented in the study, we only excluded those flows which had less than 1% of the cumulative mass or energy of all the inputs and outputs of the LCI model, provided the environmental relevance of the excluded flow is not of concern. An example is the exclusion of the climate change impact associated with the manufacturing and use of small quantity of packaging glues that are used in a cotton ginning plant. In this example, we regarded the CC impact associated with the production and use of the applied packaging glue to be less than 1% of the total life-cycle climate change impact of the functional unit. We performed all impact assessment calculations by using SimaPro 8.0.5.

## 2.4 Calcultion of $N_2O$ emissions from soil and cotton residues

The source and extent of emissions, which comprise total $N_2O$ emissions, are varied. Examples include the process of electricity generation in power plants, combustion of diesel in farm machinery, emissions from N fertilisers in the field, and decomposition of cotton residues in the field. Apart from the $N_2O$ emission from soil and cotton residues, the calculations of other $N_2O$ emissions are based on the methodologies adopted by the Australian Impact Method (Australian Indicator Set V3) and the process-specific methods embedded in the applied background inventory database (AusLCI). These methods are generally consistent with the method and the calculation factors provided in the Australian National Inventory (NIR) [4] (e.g. $N_2O$ emissions from the electricity generation plants).

The calculations of $N_2O$ emissions from soil and cotton residues are mainly based on the methods and calculation factors provided in NIR 2013 [4] and an Australian Government publication related to the carbon farming in Australian cotton farms [10]. We reviewed the literature and found some

Australian-specific cotton-related calculation factors (e.g. FracLEACH) and used those instead of the existing IPCC-based calculation factors. Further details about the applied calculation factors for fertiliser-related $N_2O$ emissions are provided in Appendix A. We also refined the emission factor related to the calculation of $N_2O$ emission from the decomposition of cotton residues that used in NIR 2013 based on the findings of [11]. Further details about these refinements are provided in Attachment A.

### 2.5 Key modelling assumptions

Some key assumptions underpin the LCA modelling conducted in the present study. We assumed that for the temporal scope of the study (2011-2014), no breaking crop was incorporated into the cotton production of North West NSW. As such, cotton was produced in a 'back-to-back' cotton system. We challenge this assumption through the inclusion of wheat, one of the most practiced rotation in Australian cotton systems [12], and discuss the existing limits to calculating the potential CC impact of cotton lint in the rotation systems.

The fraction of irrigation water sourced from surface water (e.g. rivers) used in the analysis (0.8) and that for groundwater (0.2) are based on the ratio between surface water and groundwater for extractive agricultural use in NSW in 2012-2013 [13]. . With regard to the energy source used for water pumping, we assume that 85% of the irrigation water is pumped by diesel-powered irrigation pumps and 15% by electric pumps. This assumption is close to those in the irrigation energy benchmark study in Australian cotton farms [14]. The total dynamic heads for water pumping from surface water and groundwater are assumed to be 8 m [15] and 35 m [16, 17], respectively. The fraction of the cotton land used for the production of irrigated cotton is assumed to be 0.88 of the total cotton land [13]. This figure is close to the national average figures reported by Cotton Australia [18, 19]. All of the above assumptions will be challenged through conducting a set of sensitivity tests in the following sections of the report.

In the sensitivity analysis related to the inclusion of a break crop into the cotton production system under study, we assume inclusion of wheat. The additional modelling information required to calculate the CC impact of cotton grown in the rotation with other crops, includes but is not limited to: the direct emission factor (kg $N_2O$-N emitted per kg of the applied N fertiliser), the extent of the increase or decrease in cotton yield for the cotton grown after the break crop, and the N application rate for the cotton grown after the break crop. More information is available for the rotation system of 'cotton-wheat' than any other cotton rotation systems; and wheat is commonly used in practice.

With regard to the treatment of gin trash, we assume that 75% of the gin trash is stockpiled for the production of gin trash compost and the remainder is sent to landfill located 30 km from the ginning plant. We challenge the fraction of gin trash stockpiled by conducting a sensitivity test in which the fraction is changed from zero to 1.0 and we accordingly calculate the CC impact of the different fractions. In the absence of inventory data for gin trash composting, we use the inventory data for solid waste from a study conducted for NSW EPA [8]. As the current gin trash composting process in the cotton ginning plants exclude waste shredding, we have excluded the diesel use for the waste shredding from the inventory provided by the NSW EPA.

## 2.6 Treatment of co-products

Cotton systems produce multiple products. To deliver the functional unit (1 t of cotton lint at port), a procedure for partitioning the climate change impact of the cotton system under study between its co-products of cotton lint and cotton seed is required. ISO 14044:2006 (ISO 2006b), contains a hierarchal procedure for partitioning:

**Step 1**: Wherever possible, allocation should be avoided by:

(1) Dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes, or
(2) Expanding the product system to include the additional functions related to the co-products.

**Step 2**: Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them; i.e. they should reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system.

**Step 3**: Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them. For example, input and output data might be allocated between co-products in proportion to the economic value of the products.

We considered the above hierarchy to select the most appropriate partitioning procedure in our assessment. With regard to the approaches provided in Step 1 of the hierarchy, the first recommended procedure (i.e. sub-division of the processes) is not practical in cotton systems. For instance, it is not practical to divide the irrigation process into two sub-processes in the way that each sub-process serves only one of the co-products. The second recommended approach (i.e. expanding the product system) is not regarded as an appropriate approach as there are some key uncertainties associated with the approach (see Section 2.7).

Step 2 of the hierarchy requires the allocation of the impacts based on the underlying physical relationships between the co-products of a production system. Often, the mass relationship between co-products is considered as the main physical relationship between co-products. However, we argue that the mass allocation approach is not an appropriate allocation approach as it shifts the majority of the impacts to cotton seed whereas the primary product of cotton systems is cotton lint. As far as we are aware, no other physical relationship between cotton lint and cotton seed has yet been identified and applied in the cotton LCA studies.

In the absence of other appropriate physical relationship, we consider the economic relationship between the co-products of the system under study as the most appropriate partitioning procedure as recommended in Step 3 of the hierarchy. Based on the average cotton lint price of $470/bale and the average cotton seed price of $300/t, we allocate around 86% of the life-cycle CC impact of the cotton system under study to cotton lint and around 14% of the impact to cotton seed. We acknowledge that the cotton lint and cotton seed prices are dynamic in nature and fluctuate [could use intra-annually and inter-annually] within a year and over years. We did not investigate the possible consequence of price change on the life-cycle CC impact of the functional unit, as per the sensitivity analysis that we have conducted in the study (see Section 3.4.1).

## 2.7 Consequential LCA modelling

The system expansion approach, commonly known as consequential modelling, was applied to identify the production systems in the economy affected by the cotton production system under study and then accordingly calculate the CC impact of the functional unit, by taking to the account the relevant environmental credits/penalties to the cotton systems.

To identify the affected systems, we consulted some experts[1] with expertise in consequential modelling, animal feed production or oilseed supply. These consultations helped to identify the productions systems that are more likely affected by the cotton system but no conclusion was drawn regarding the identification of the most sensitive affected system (the marginal displaced product). To deal with this uncertainty, we adopted a methodology centred on conducting sensitivity analysis. For instance, we considered different affected systems and different products balancing metabolism energy and crude protein and oil content for cotton seed and the products displaced by cotton seed. Further details of the methodology used in the consequential modelling are available in Appendix B.

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[1] Some of the consulted experts are: Dr Aaron Simmons (DPI), Professor Annette Cowie (DPI), Dr Robert Lawrence (Integrated Animal Production P/L), Ms Naomi Hobson (LLS), Mr Todd Andrews (DPI), Mr Dale Kirby (LLS), Ms Jayce Morgan (DPI), Ms Sally Balmin (LLS), Ms Kimberly Townsend (Animal Nutritionist at Weston Milling Animal Nutrition), Dr Warwick Stiller (CSIRO), Dr Janelle Montgomery (DPI), Dr Allan Peake (CSIRO), Ms Fiona Scott (DPI), Mr Tim Grant (Life Cycle Strategies), Ms Janine Powell (DPI)

## 2.8 Dealing with uncertainty of inventory data

The background inventory data used in the LCA were supplied from more one source (e.g. AusLCI database, literature). These inventory sources might perform differently if they were assessed against the key data quality criteria (e.g. comprehensiveness and representativeness). To deal with this issue, we conducted uncertainty analysis by using the mathematical approach of Monte Carlo Simulation. The simulation repeatedly quantifies results by varying random data points within the bounds of uncertainty. Monte Carlo Simulation produces a probability distribution curve that shows different probabilities of different outcomes. The statistical data provided by Monte Carlo Simulation are robust indicators of the performance of the results against the conducted uncertainty analysis.

## 2.9 Dealing with biogenic carbon dioxide

In line with the international cotton LCA studies, the IPCC guidelines, and the Australian NIR 2013, the $CO_2$ absorbed during the growth of cotton crop and the $CO_2$ emissions from the decomposition of cotton residues are excluded from the main assessment. This means that carbon cycling is assumed to have reached a steady state. However, in the created platform in SimaPro, we have included the modelling steps required to calculate biogenic carbon dioxide absorbed from the air by cotton crop and the $CO_2$ emission from cotton residue. We will provide, in the sensitivity analysis section of the report, the CC impact of the functional unit if the biogenic $CO_2$ was included in the impact assessment. The $CO_2$ absorbed from the air is calculated based on the equation provided in AusLCI database. The calculation of the $CO_2$ emission from the decomposition of cotton residues (above and below ground residues) is based on the equation provided in NIR 2013 for the calculation of $N_2O$ emission from the decomposition of cotton residues. We consider this equation appropriate for the calculation of the $CO_2$ emission from the decomposition of cotton residues. Appendix B provides the equation (modified) and its associated calculation data.

## 2.10 Greenhouse gas emission reduction oppurtunities

A set of GHG emission reduction options has been developed in the study. These options developed through literature review and consultation with experts and cotton farmers. Examples of the former approach are the option related to the use of controlled-release and stabilised N fertilisers [20] and the option related to the application of optimum N fertiliser rate [21, 22]. Examples of the options developed through the latter approach are the option of ‘fertigation’, which was developed based on the consultation with Dr Dio Antille (from the University of Southern Queensland), and the option of ‘solar-powered irrigation pumps’ that was developed based on the consultation with Mr Scott

Morgan, a cotton farmer who has installed solar panels in his cotton farm in Gunnedah for the general use of solar power.

We also identified some management practices that failed the ‘reality checking’ assessment or failed to prove effective. We excluded these options from the final assessment and report but have briefly described them in Section 3.6.

## 2.11 The representativeness nature of the cotton system under study

We check if the cotton production system of North West NSW could be regarded as an indicative represent of other Australian cotton production regions, from an inventory data perspective from an emissions perspective. These regions include both established cotton production regions (e.g. Darling Downs) and the emerging cotton production regions (e.g. Southern NSW). We considered the assessment to be very challenging as it could require considerable time, if conducted via individual regional assessments (beyond the project time) and through collection of new foreground inventory data. However, we found information available in the cotton industry surveys to be suitable for an indicative comparison between the calculated CC impact of the cotton grown in North West NSW and the cotton grown in other production regions.

It should be noted that, due to the short project timeframe (12 months) some of the data used in the comparative assessment were kept constant across all of the regions, in particular: the total dynamic head (see Glossary of terms and acronyms) of surface water and groundwater, the diesel used in the farm machinery, and the energy used in the cotton ginning processes.

## 2.12 Reviewing cotton LCA studies in Australia and elsewhere

Studies conducted both in Australia and elsewhere have reported different CC impacts and different GHG emission profiles for the cotton lint produced in Australia. We consider this as a challenge for the Australian cotton industry as the industry is uncertain about their actual CC impact performance and the actual GHG emission ‘hot spots’ within the cotton lint supply chain. To address this issue, we conducted a comprehensive review of the past studies aiming to briefly but effectively present the key features of the studies (e.g. system boundaries) and to provide a ground for an indicative comparison among the past studies and the present study with regard to the CC impact of cotton lint.

We considered the comparison, even in an indicative level, very challenging as the compared studies are different in many aspects including: cotton yield, region under study, system boundaries, basis of the assessment (functional unit), allocation procedure, applied carbon credits (e.g. carbon sequestration from manure fertiliser), applied emissions factors, and the inclusion/exclusion of $N_2O$ from the decomposition of cotton residues. To make the comparison feasible within the timeframe of the present study, the inventory used in the past studies (e.g. cotton lint, N fertiliser type and application rate) remained unchanged (as used in the studies) but we used the inventory of the present study for those processes that were excluded from past studies. For instance, if the system boundaries used in any of the past studies only included the pre-farm and on-farm stages, we added the post-farm stage from the present study to the earlier study to achieve similar system boundaries.

## 3. LCA results and the results from analysing climate change mitigation options

This section provides the results of the LCA and its associated uncertainty and sensitivity assessments. We have assigned the total calculated CC impacts of the functional unit to cotton lint and cotton seed based on two methods: the attributional method (the economic allocation approach) and the consequential method (or the system expansion method). The attributional method of mass allocation has been excluded in the assessment. The mass allocation approach allocates the total CC impacts to cotton lint, cotton seed, and gin trash based on their mass production portions of 42%, 49%, and 9% respectively. We argue that the mass allocation is an inappropriate approach as it unfairly allocates more impact to cotton seed than cotton lint, whereas farmers grow cotton to produce cotton lint not cotton seed.

In the economic allocation approach, we have allocated around 86% of the total CC impact to cotton lint and around 14% of the impact to cotton seed in proportion to their contributions to the total revenue gained from 1 ha of cotton land. In the system expansion approach, we have assigned the total calculated CC impact of the cotton system to cotton lint but have credited it for the products displaced by cotton seed (i.e. animal feed and oilseed crops). As the actual products displaced by cotton seed are uncertain, we have developed a set of scenarios in which the most likely displaced products are included. Further details are available in appendix B.

### 3.1 LCA results based on the economic allocation approach

The CC impact for 1 t of mixed irrigated and rainfed cotton at port (i.e. the functional unit), based on the economic allocation approach, is 1601 kg $CO_2e$. The CC impact of the pre-farm stage, on-farm stage, and the post-farm stage are 407 kg $CO_2e$, 775 kg $CO_2e$, and 419 kg $CO_2e$, respectively. The process-specific CC impacts are presented in Table 2. The relative contributions of the processes are shown in Figure 2.

**Table 2: Process-specific climate change impact per the function unit**

| Process | Climate Change Impact (kg $CO_2$e/t lint) |
|---|---|
| Pre-farm stage | |
| Production of synthetic fertiliser | 267.7 |
| Production of herbicides, insecticides, and growth regulator | 55.3 |
| Production of diesel | 42.1 |
| Production of electricity | 23.4 |
| Production of aviation fuel | 1.6 |
| Transport of raw materials to farm (500 km distance) | 15.8 |
| Total for the pre-farm stage | 405.9 |
| On farm stage | |
| Farm machinery | 125.5 |
| Irrigation | 108.0 |
| Decomposition of cotton residues in the field | 75.3 |
| Use of fertilisers | 442.0 |
| Transport of seed cotton from arm to gin | 24.8 |
| Total for the on-farm stage | 775.6 |
| Post-farm stage | |
| Seed cotton drying process (LPG-powered drying process) | 190.6 |
| Gin machinery (electricity-powered operation) | 148.0 |
| Bale packaging | 16.6 |
| Gin trash treatment | 41.8 |
| Cotton lint rail transport to port (550 km distance) | 22.2 |
| Total for the post-farm stage | 419.2 |
| Total for the life-cycle (cradle-to-port) | 1600.6 |

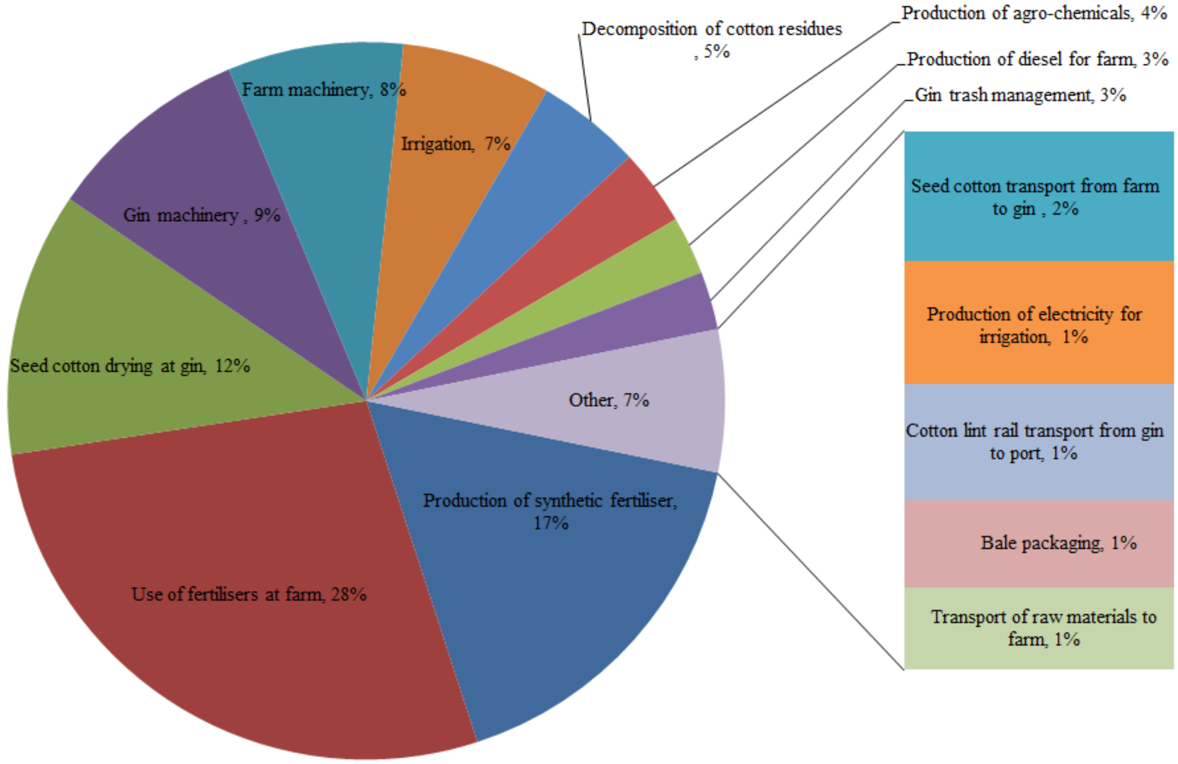


**Figure 2: The relative contribution of different processes in the life-cycle CC impact of the functional unit**

### 3.2 LCA results based on the system expansion approach

Our conference paper: ‘Consequential LCA in cotton production systems: opportunities and challenges’ provides detailed information about the methodology used and the results obtained from the application of the system expansion approach in the cotton system under study. As we modified the inventory related to the CC impact associated with decomposition of cotton residues after the publication of the paper, we present the updated results for the scenarios investigated in that conference paper in Table 3.

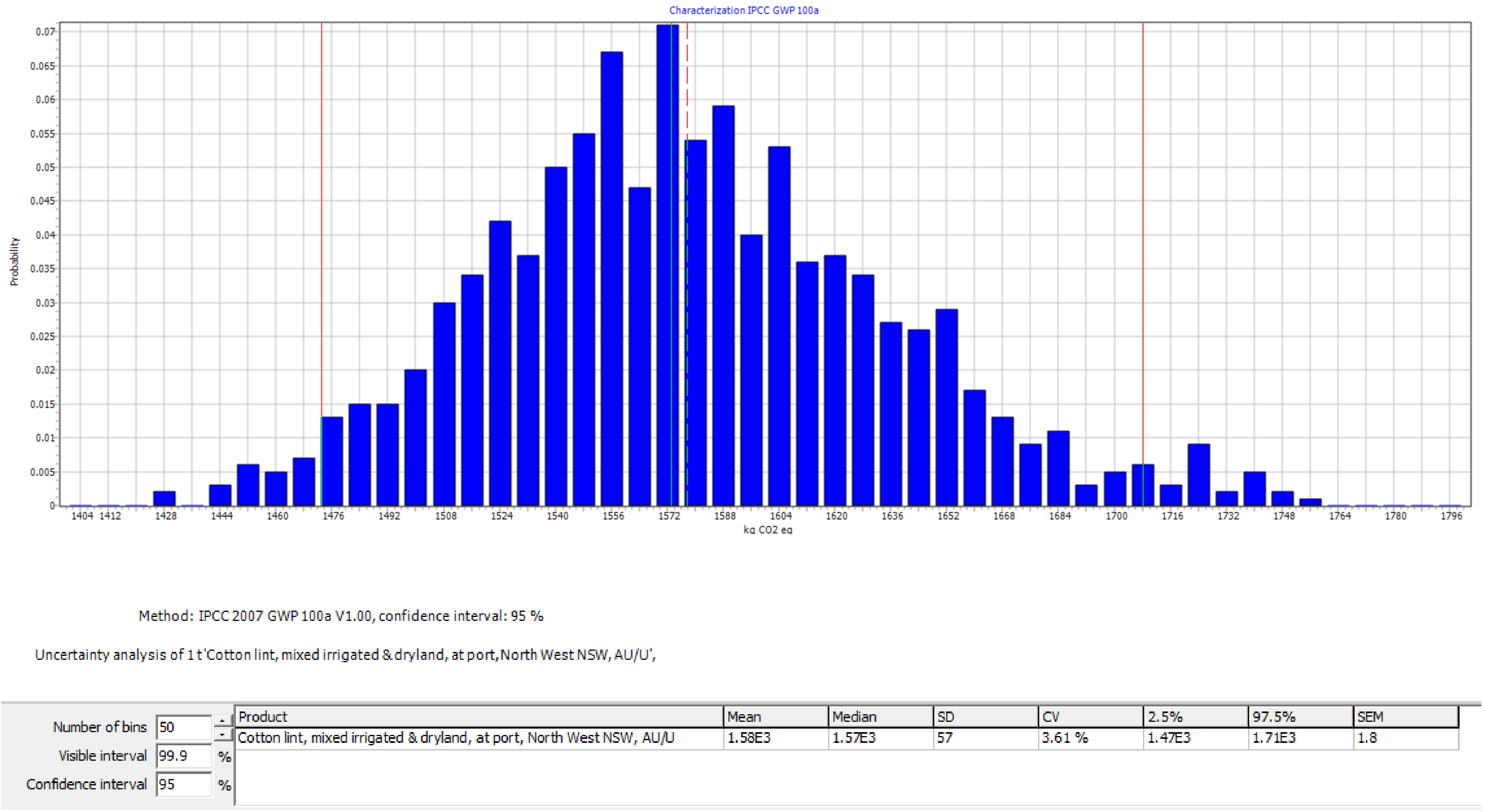
**Table 3: Climate change impact of the functional unit under different system expansion scenarios**

| System expansion scenario | Animal feed systems | | Seed oils systems | | Climate change impact (kg CO$_2$e/t lint) |
|---|---|---|---|---|---|
| | Product displaced by cotton seed | Product balancing CP and ME | Product displaced by cotton seed | Products balancing OC, CP, and ME | |
| Scenario 1 | Wheat | Sorghum | Canola seed | Sorghum and lupins | 1254 |
| Scenario 2 | Wheat | Lupins | Canola seed | Sorghum and lupins | 1306 |
| Scenario 3 | Barley | Sorghum | Canola seed | Sorghum and lupins | 1279 |
| Scenario 4 | Barley | Lupins | Canola seed | Sorghum and lupins | 1307 |

The exact portion of the total produced cotton seed in North West NSW that is used as animal feed was unknown at the time of the publication of the paper. As such, we assumed that, similar to Central Queensland [23] , 90% of the total cotton seed are used as animal feed  in North West NSW and the remainder is crushed for cottonseed oil extraction. To address the uncertainty associated with the assumption, the paper included a sensitivity analysis showing the sensitivity of the CC impact results to the assumed fraction of the cotton used in North West NSW as animal feed. However, we have been advised by Cargill Australia in Narrabri (the only operating oil seed crushing plant in the region) that the plant crushes around 80% of the total cotton seed produced in the region. As such, the results provided in Table 3 are based on the application of 20% of total cotton seed produced in the region as animal feed.

### 3.3 Uncertainty assessment of the results by Monte Carlo simulation

The probability distribution curve and the relevant statistical information of the simulation are provided in Figure 3. The statistical information include mean, median, standard deviation (SD), coefficient of variations (CV), and the standard error of the mean (SEM). We consider the outcomes of the simulation satisfactory.



Method: IPCC 2007 GWP 100a V1.00, confidence interval: 95 %

Uncertainty analysis of 1 t 'Cotton lint, mixed irrigated & dryland, at port, North West NSW, AU/U',

Number of bins 50

Visible interval 99.9 %

Confidence interval 95 %

| Product | Mean | Median | SD | CV | 2.5% | 97.5% | SEM |
|---|---|---|---|---|---|---|---|
| Cotton lint, mixed irrigated & dryland, at port, North West NSW, AU/U | 1.58E3 | 1.57E3 | 57 | 3.61 % | 1.47E3 | 1.71E3 | 1.8 |

Figure 3: Portability distribution curve and the statistical information related to the Monte Carlo Simulation study

### 3.4 Comparison of the LCA results with other studies

We reviewed the studies that calculated the life-cycle CC impact of the cotton lint produced in Australia and summarised the main features of the studies (e.g. the used functional unit, the applied system boundaries). Appendix D provides a summary for each reviewed study. We also made an indicative comparison between the CC impact of cotton lint reported in the present study and those reported in other studies as per the approach detailed in Section 2.11. The results of the comparative analysis are provided in Table 4. It should be noted that in the published report for one of the past studies [24], the study conducted by Cotton Inc. and PE International (now called Thinkstep), there is no reference to the CC impact of Australian cotton. The results reported in Table 4 are based on the information that we have received from the CRDC about that study.

One of the international studies in which the CC change impact of the Australian cotton and the global conventional cotton have been calculated, the study conducted by Systain Consulting [25], includes some critical inventory issues. These issues might be the main reasons for the relatively high reported figures in that study for the CC impact (or referred in that study as carbon footprint) for the global cotton (~ 4600 kg $CO_2$e/ t lint) and for the Australian cotton (~ 3200 kg $CO_2$e/ t lint). The LCA practitioners of that study might have assumed that ‘cottonseed’ is equivalent to ‘seed cotton’. We cross checked the inventory data used in the Systain Consulting study and the inventory data sources used in that study and noted that the yield figures used in the Systain Consulting study are related to ‘cottonseed’ instead of being related to ‘seed cotton’ (see Appendix D for further details). Given the observed inventory issues, we have excluded the Systain Consulting study in Table 4.

**Table 4: Comparison between the climate change impact calculated in this study and the adjusted impact reported in other studies**

| Study | System boundaries | Functional unit | Climate change impact | | Description of the adjustment |
|---|---|---|---|---|---|
| | | | As Reported | Adjusted (kg $CO_2$e / t lint) | |
| This study | Cradle to port | 1 t lint at port | 1601 (kg $CO_2$e/t lint) | 1601 | No adjustment. |
| AusLCI (Current) (for Australia) | Cradle to gin bale press | 1 t lint at gin | 1695 (kg $CO_2$e/t lint) | 1760[*] | Added 42 kg $CO_2$e for gin trash management and 23 kg $CO_2$e for the rail transport of 1 t cotton lint to port. |
| Life Cycle Strategies (2014) (for Australia) | Cradle to gin bale press | 1 t lint at gin | 1164 (kg $CO_2$e/t lint) | 1187 | Added 23 kg $CO_2$e for the rail transport of 1 t cotton lint to port. |
| Cotton Inc. Study ( 2012) (for Australia) | Cradle to gin bale press | 1 t cotton lint produced at gin in Australia | 1163 (kg $CO_2$e/t lint) | 1440 | Added: 43 kg $CO_2$e to cancel the credit given in that study for rotation, 22 kg $CO_2$e for the rail transport to port, 24 kg $CO_2$e for the road transport from farm to gin, 75 kg $CO_2$e for the stubble management, 55 kg $CO_2$e for the production of herbicides, 42 kg $CO_2$e for gin trash management, 16 kg $CO_2$e for bale packaging, |
| Visser et al. (2014) (Darling Downs) | Cradle to gin bale press | 1 bale of cotton lint | 323 (kg $CO_2$e /bale) | 1446 | Converted from kg $CO_2$e/bale to kg $CO_2$e/t (1 t= 4.4 bales) then added 23 kg $CO_2$e to produce the impact result at port. |
| Tan et al. (2013) (for case studies in Namoi Valley | Cradle to farm gate | 1 t of seed cotton produced at farm | 345 (kg $CO_2$e/t seed cotton) | 1129 | Added 179 (kg $CO_2$e per 1 t of seed cotton) to change from 'cradle-to-farm gate' to 'cradle to gin bale press', then calculated for 1 tonne lint, and finally added 23 kg $CO_2$e to convert from cradle to gin bale press to cradle to port basis. |
| Khabbaz et al. (2010) (for Australia) | Cradle to port | 1 ha of cotton land | 2860 (kg $CO_2$e /ha) | 1163 | Divided the reported impact per ha to the seed cotton yield of 5170 kg to produce the impact per kg of seed cotton, then calculated the impact per 1 tonne of lint at gin bale press. Finally added 23 kg $CO_2$e to produce the results at port. |
| Maraseni et al. (2010) (for case studies in Darling Downs) | Cradle to farm gate | 1 t of irrigated cotton lint | 2674 (kg $CO_2$e/t lint ) | 3088 | Added 391 kg $CO_2$e to convert the impact for the cradle to farm gate to the impact for the cradle to gin bale press basis, then added 23 kg $CO_2$e to produce the impact result at port. |
| Maraseni et al. (2010) (for case studies in Darling Downs) | Cradle to farm gate | 1 t of rainfed cotton lint | 1590 (kg $CO_2$e/t lint ) | 2004 | Added 391 kg $CO_2$e to convert the impact for the cradle to farm gate to the impact for the cradle to gin bale press basis, then added 23 kg $CO_2$e to produce the impact result at port. |

[*] In AusLCI, the total GHG emissions per ha of cotton is divided by the collective mass of lint+seed+gin trash; whereas in the present study, the total GHG emissions per ha is divided by the collective mass of lint+seed. If in AusLCI, the mass of gin trash was excluded, the CC impact would be ~ 1890 kg CO2e/t lint.

## 3.5 Sensitivity analysis of the LCA results

This section presents the results of the sensitivity tests conducted to examine the performance of the results against changes in the used inventory, the key modelling assumptions, the applied emission values, and the inclusion of biogenic carbon in the impact assessment.

### 3.5.1 Sensitivity analysis through changing the applied inventory

The results of the sensitivity tests related to the changing of the applied inventory data are provided in Table 5. The term of ‘sensitivity range’ in Table 5 refers to the considered lower-end and the upper-end of the quantity for the relevant inventory. The table also provides the quantity of the inventory used in the main assessment. The CC impact for the lower-end and the upper-end figures are provided in Table 5 for each sensitivity test. The last two columns of the table provide the potential change (in percent) in the CC impact of the functional unit, if the lower-end and the upper-end figures were used in the LCA instead of the applied inventory figure for that sensitivity test.

**Table 5: Results of the sensitivity analysis of the applied inventory**

| Sensitive parameter | Sensitivity range | | Applied quantity in the study | Unit | Climate change impact of the sensitivity range (kg $CO_2$e/t lint) | | % of increase or decrease (-) in the CC impact by using the sensitive range | |
|---|---|---|---|---|---|---|---|---|
| | From | To | | | From | To | From | To |
| Yield of irrigated cotton | 8.5 | 14.5 | 10.5 | bales/ha | 1838 | 1315 | 14.8 | -17.9 |
| Yield of rainfed cotton | 2 | 7 | 5 | bales/ha | 1643 | 1576 | 2.6 | -1.6 |
| Gin trash content in the gin outputs (changing seed/lint ratio) | 6 | 16 | 1.17 | % | 1538 | 1773 | -3.9 | 10.7 |
| Cotton seed price | 200 | 500 | 300 | $/t | 1673 | 1477 | 4.5 | -7.8 |
| Cotton lint price | 400 | 600 | 474 | $/bale | 1565 | 1646 | -2.3 | 2.8 |
| Irrigation water | 5.5 | 9.5 | 7.7 | ML/ha | 1559 | 1639 | -2.6 | 2.4 |
| Fertiliser application rates | 150 | 400 | 255 | kg N/ha | 1194 | 2910 | -25.4 | 81.8 |
| Total dynamic head of groundwater | 15 | 105 | 35 | m | 1560 | 1751 | -2.6 | 9.4 |
| Electricity used at gin | 25 | 45 | 33 | kWh/bale | 1566 | 1655 | -2.2 | 3.4 |
| Heat used at gin for seed cotton drying | 35 | 75 | 51.3 | MJ/bale | 1541 | 1689 | -3.8 | 5.5 |
| Mass fraction of cotton lint in 1 kg of gin output (lint+seed+gin trash) | 0.45 | 0.39 | 0.42 | Fraction | 1622 | 1581 | 1.3 | -1.3 |
| Mass fraction of gin trash that stockpiled (0.0= 100% of gin trash is landfilled, 1.0= 100% of gin trash is stockpiled) | 0.0 | 1.0 | 0.75 | Fraction | 1615 | 1597 | 0.9 | -0.3 |
| Fraction of electrical energy in total irrigation energy (0.0=100% energy is from diesel and 1.0=100% energy is from electricity) | 0.0 | 1.0 | 0.15 | Fraction | 1599 | 1626 | -0.1 | 1.6 |
| Mass fraction of irrigated cotton in total produced cotton (0.0=100% rainfed cotton, 1.0= 100% irrigated cotton) | 0.0 | 1.0 | 0.94 | Fraction | 1184 | 1629 | -26.1 | 1.7 |

### 3.5.2 Sensitivity analysis through changing the cotton production system

The results indicated that the average CC impact of cotton lint produced in that rotation would be around 1574 kg $CO_2$e, which is close to the calculated CC impact of 1601 kg $CO_2$e for the continuous (back-to-back) cotton system. The results of the sensitivity test through changing the cotton production system to rainfed and irrigated cotton system are presented in Table 6.

**Table 6: Results of the sensitivity analysis through changing the cotton production system to rainfed and irrigated cotton**

| Process | Climate change impact (kg $CO_2$e/t lint) | | |
|---|---|---|---|
| | This study | Irrigated cotton | Rainfed cotton |
| Pre-farm stage | | | |
| Production of synthetic fertiliser | 267.7 | 276.0 | 159.0 |
| Production of herbicides, insecticides, and growth regulator | 55.3 | 51.9 | 109.0 |
| Production of diesel | 42.1 | 42.5 | 43.7 |
| Production of electricity | 23.4 | 24.9 | 0.0 |
| Production of aviation fuel | 1.63 | 1.74 | 3.6 |
| Transport of raw materials to farm (500 km distance) | 15.8 | 15.2 | 10.7 |
| Total for the pre-farm stage | 406.9 | 412.2 | 322.0 |
| On-farm stage | | | |
| Farm machinery | 125.5 | 119.0 | 222.0 |
| Irrigation | 108.0 | 115 | 0.0 |
| Decomposition of cotton residues (stubble management) | 75.3 | 75.3 | 75.3 |
| Use of fertilisers | 442.4 | 463 | 122.0 |
| Transport of seed cotton from farm to gin | 24.8 | 24.8 | 24.8 |
| Total for the on-farm stage | 775.5 | 797.1 | 441.1 |
| Post-farm stage | | | |
| Seed cotton drying process (LPG-powered drying process) | 190.6 | 190.0 | 190.0 |
| Gin machinery (electricity-powered operation) | 148.0 | 148.0 | 148.0 |
| Bale packaging | 16.6 | 16.6 | 16.6 |
| Gin trash treatment | 41.8 | 42.9 | 25.8 |
| Cotton lint rail transport to port (550 km distance) | 22.2 | 22.2 | 22.2 |
| Total for the post-farm stage | 419.2 | 419.7 | 402.6 |
| Total for the life-cycle (cradle-to-port) | 1600.6 | 1629.0 | 1165.7 |

### 3.5.3 Sensitivity analysis through changing the fertiliser-related $N_2O$ emission values

The conference paper available in Appendix A provides details of the assessment conducted to examine the sensitivity of the calculated CC impact of the functional unit to the changes in the fertiliser-related $N_2O$ emission values. Given the refinements made in the study after the presentation of the conference paper (i.e. calculations related to $N_2O$ emissions from cotton residues), some changes occurred in the results of the conference paper. The revised results are presented in Table 7.

**Table 7: Results of the sensitivity analysis through changing the fertiliser-related N2O emission values**

| LCA System-boundaries | Climate change impact of cotton lint produced in North West NSW ($kg\ CO_2e/t$ lint) | | | |
|---|---|---|---|---|
| | Using the IPCC emissions values | Using the Australia emissions values | Using the North West NSW emissions values | Using the Queensland emissions values |
| Cradle-to-port | 1810 | 1530 | 1564 | 1550 |
| Within farm boundaries | 1000 | 715 | 752 | 743 |
| Fertiliser use only | 690 | 405 | 442 | 433 |

### 3.5.4 Sensitivity analysis through using inventory of other cotton production regions

Figure 4 presents the results of the sensitivity test in which the key inventory data of the cotton system North West NSW were replaced with the corresponding inventory data forother cotton production regions. The changeable inventory data and their quantities are presented in Table 8.

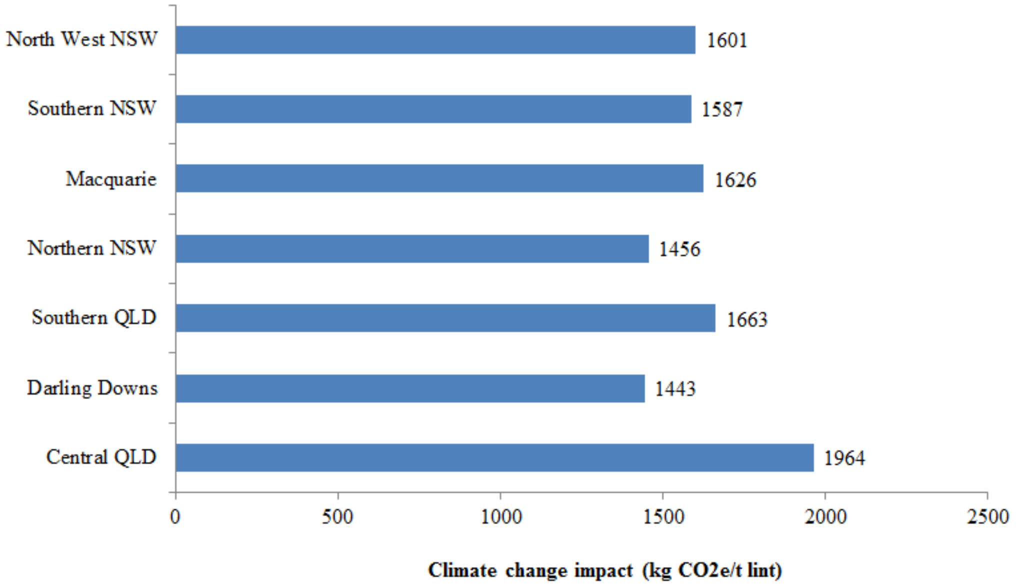


**Figure 4: Comparison between the indicative CC impacts of the different cotton growing regions**

**Table 8: Indicative quantities for the key modelling parameters that applied to calculate the CC impacts of cotton production in various regions**

| Region | Yield (bales/ha) | | NFUE[1] | Total N (kg N/ha) | EF1 & EF4[2] | FracWet[3] | IWUI[4] | Irrigation water use (ML/ha) | Electricity for irrigation (kWh/ha) | Diesel for irrigation (L/ha) |
|---|---|---|---|---|---|---|---|---|---|---|
| | Irrigated | Rainfed | | | | | | | | |
| Central QLD | 7 | Not grown | 7.5 | 211.9 | 0.0037 | 0.71 | 1.51 | 4.6 | 37.0 | 50.3 |
| Darling Downs | 8.8 | 6.35 | 10.7 | 186.7 | 0.0033 | 0.71 | 3.15 | 2.8 | 22.5 | 30.6 |
| Southern QLD | 10.2 | 6.25 | 8.3 | 279.0 | 0.0105 | 0.71 | 1.52 | 6.7 | 53.9 | 73.2 |
| Northern NSW | 10.8 | 5 | 10.6 | 231.3 | 0.0045 | 0.93 | 1.77 | 6.1 | 49.0 | 66.7 |
| Macquarie | 11.8 | 1 | 9.7 | 276.1 | 0.0098 | 0.93 | 1.23 | 9.6 | 77.2 | 105.0 |
| Sothern NSW | 10.6 | Not grown | 11.1 | 216.8 | 0.0039 | 0.93 | 1.13 | 9.4 | 75.6 | 102.8 |
| North West NSW | 10.5 | 5 | 9.34 | 255 | 0.0063 | 0.93 | 1.36 | 7.7 | 61.9 | 84.2 |

[1] Nitrogen Fertiliser Use Efficiency (kg lint/kg of N fertiliser)

[2] Please see Appendix for the description of EF1 and EF4

[3] Please see Appendix for the description of FracWet

[4] Irrigation Water Use Index (bales/ML of irrigation water)

Data sourced mainly from Cotton Growing Practices Survey 2013 [12] and the unpublished industry survey available in Attachment D.

### 3.5.5 Sensitivity analysis through the inclusion of biogenic carbon dioxide

The results of the sensitivity test in which the modelled biogenic $CO_2$ absorbed from the air by cotton and the biogenic $CO_2$ emission from the decomposition of cotton residue are presented in Table 9.

**Table 9: Results of the sensitivity test relating to the inclusion of biogenic carbon dioxide**

| Process | Climate Change Impact (kg $CO_2$e/t lint) |
|---|---|
| Pre-farm stage | |
| Production of synthetic fertiliser | 268.7 |
| Production of herbicides, insecticides, and growth regulator | 55.0 |
| Production of diesel | 42.1 |
| Production of electricity | 23.4 |
| Transport of raw materials to farm (500 km distance) | 15.8 |
| Total for the pre-farm stage | 405.0 |
| On farm stage | |
| Farm machinery | 126.7 |
| Irrigation | 108.0 |
| Decomposition of cotton residues in the field | 75.3 |
| Use of fertilisers | 442.0 |
| Carbon dioxide ($CO_2$) absorbed from the air by cotton crop | -7.91E3 |
| Carbon dioxide ($CO_2$) emission from residue decomposition | 3.95E3 |
| Total for the on-farm stage | -3.20E3 |
| Post-farm stage | |
| Seed cotton transport from farm to gin (35 km distance) | 24.3 |
| Seed cotton drying process (LPG-powered drying process) | 190.6 |
| Gin machinery (electricity-powered operation) | 148.0 |
| Bale packaging | 16.6 |
| Gin trash treatment | 41.8 |
| Cotton lint rail transport to port (550 km distance) | 22.2 |
| Total for the post-farm stage | 443.5 |
| Total for the life-cycle (cradle-to-port) | -2.40E3 |

### 3.6 Results from the assessment of GHG emisison reduction options

The descriptions of the GHG emission reduction options along with the information related to the extent to which each investigated option can reduce the CC impact of the functional unit are provided in Table 10. In addition to the options presented in Table 10, we investigated some other options. These options are not provided in Table 10 as they either failed the ‘reality checking’ assessment or failed to prove effective. Example of the options that failed the ‘reality checking’ assessment are the option related to the use of organic fertilisers instead of synthetic N fertilisers. Whilst the practice, as reported in the literature [26-29], is used in some Australian cotton growing regions (e.g. Darling Downs), we argue that the use of organic fertilisers including the most common used organic fertiliser of feedlot manure is unviable in North West NSW, due to limited supply. In Queensland the use of organic fertiliser can mainly be attributed to ample supply at a high quality. An organic material audit study conducted by DPI NSW [30] revealed that the annual feedlot manure production in North West NSW is around 147,000 tonnes. Based on the reported application rate of up to 10 tonnes of animal manure per hectare [28], this amount would only be sufficient for three cotton farms with an average size of 5,000 hectares. This calculation assumes that all the feedlot manure is produced in the months required and that it does not have a secondary use (e.g. wheat production).

An example of the options that failed to prove effective is that related to the application of pressurised irrigation technologies including the Centre Pivot technology. While the experiments conducted in the Syria cotton systems [31] show that pressurised irrigation technologies, in compare to furrow irrigation, reduce the required N fertilisers between 25% to 50% and reduce the irrigation water use between 30 to 50%, the research conducted in North West NSW indicate otherwise [32, 33]. In the absence of any nitrogen effectivity and yield increase, the water efficiency of pressurised irrigation would not be enough to balance the excess GHG emission of pressurised irrigation technologies due to the extra fuel that they use in comparison to furrow irrigation. A conference paper has been drafted to provide information regarding the effect of pressurised irrigation technologies on life-cycle CC impact of crops. The abstract of the paper is available in Appendix C.

We also initially considered an option related to energy recovery from gin trash by using thermos-chemical processes such as pyrolysis and use of that energy in the cotton ginning plants. We have excluded the option from full assessment due to the lack of any commercial application of the thermos-chemical energy recovery plants both in Australia and elsewhere.

**Table 10: Greenhouse gas emission reduction opportunities**

| **Mitigation option** | **Description of the option** | **CC impact of the option (kg $CO_2$/t lint)** | **Indicative reduction in the CC impact** | **Scope of the assessment** |
|---|---|---|---|---|
| Optimum nitrogen application rate | Using the economically optimum N fertilizer rate (~180 kg N/ha) for irrigated cotton instead of using the current N application rate around 255 kg N/ ha | **1390**<br>(for N application rate of 180 kg N/ha)<br>**1560**<br>(for the N rate of 240 kg N/ha) | **13.2%**<br>(for N=180)<br>**2.6%**<br>(for N=240) | The main processes influenced by the option were considered to be: the production of N fertilisers, transport of fertilisers to farm, and fertiliser-use. The assessment included the changes in the fertiliser-related emission factors of EF1 and EF4 as these factors are dependent on the N application rate. The applied optimum application rate (180 kg N/ha) is consistent with the figure used by Visser, Dargusch [29].<br>The economically optimum N fertiliser rate could be more than the rate that was considered in the assessment. A recent publication [21] reported that in their study, the N fertiliser rate at which lint yield was maximized was 240 kg N/ha (in Narrabri). If this figure was used in the assessment of the present option, the option would only reduce the climate change impact of the functional unit by 2.6%. |
| Controlled-release and stabilised N fertilisers | The application of controlled-released and stabilised N fertilisers such as polymer coated urea and urea treated with N process inhibitors | 1507 | 5.9% | The only process influenced by the option was fertiliser-use, where the option changes the fertiliser-related emission factors of EF1 and EF4. The extant of changes (52% reduction in each emission factor) were calculated based on a recent US-based study [20]. That study was focused on the implications of 'controlled-released and stabilised N fertilisers' in cotton systems. |
| Solar-powered irrigation pumps | Replacing diesel and electric irrigation pumps in the region with solar-powered irrigation pumps | 1470 | 8.1 % | The option replaces the electricity and diesel used in the irrigation by electricity supplied from solar panels. The AusLCI for solar panels (3 kWp) was used in the analysis. The pre-farm stage would also be influenced by the option as no diesel and electricity for irrigation is required to produce. The GHG emissions related to the transport of raw materials to farm would be also affected by the option. |

| | | | | |
|---|---|---|---|---|
| Biofuel-powered farm machinery | Replacing diesel used in farm machinery (e.g. tractors) with biofuel | 1546 | 3.4% | The option replaces the diesel used in farm machinery with biodiesel produced from methyl ester of rapeseed. The AusLCI was used in the analysis. The $CO_2$ emissions from the combustion of biodiesel was considered biogenic $CO_2$ and thus was not included in the impact assessment. The difference between the density of diesel and biodiesel as well as the difference between the energy intensity of diesel and biodiesel were accounted in the assessment.<br>It is important to note that the assessment excluded the climate change impact caused by 'indirect land use change (ILUC)' as this required extensive research that beyond the capacity of the project. |
| Legume crops | Growing legume crops in rotation with cotton | 1539 | 3.9% | Chickpea crop was considered as the representative of legume crops. The rotation cycle was assumed a chickpea production system and three cotton systems. No credit was given to cotton as a result of N fixing by the chickpea as there is no evidence that cotton farmers reduce the N fertiliser application rate for the cotton grown after legume crops. However, an increased yield of 23% was considered for the cotton grown after the chickpeas. |
| Fertigation | The injection of fertilisers into the irrigation systems | **1567**<br>(without any effect on the $N_2O$ emission)<br>**1400**<br>(with a reduction of 80% in N2O emissions) | **2.1%**<br>(without any effect on the $N_2O$ emission)<br>**12.5%**<br>(with a reduction of 80% in N2O emissions) | The option influences only the CC impact related to the operation of tractors to apply N fertilisers. As the option is based on the application of fertilisers through the irrigation systems, there will be requirement for the operation of tractors for fertiliser application. The saved tractor diesel will also affect the pre-farm stage as no diesel need to be produced for tractors applying fertilisers.<br>Fertigation could also affect the fertiliser-related emission factors. A recent study in Queensland [34] has reported significant reduction in short-term $N_2O$ emissions when fertigation was applied (~80%). If such reduction in N2O emission achieved by fertigation, the option could reduce the CC impact of the functional unit by 12.5%. |

## 4. Discussion and interpretation of the LCA results

The study revealed that the CC impact of the functional unit is highly sensitive to decisions about the treatment of co-products, particularly the way in which the total CC impacts are spread between cotton lint and cotton seed. Whilst the CC impact of the functional unit based on the system expansion approach for all of the four considered scenarios (see Table 3) is less than the CC impact based on the economic allocation approach, the high uncertainties associated with the applied system expansion approach make the approach unacceptable. However, the applied system expansion (consequential) modelling can be used as a practical framework for the future research.

The LCA results indicate that the on-farm stage contributes most to the total calculated CC impact (~47%), followed by the post-farm stage (~27%) and the pre-farm stage (~26%). The GHG emission profile of the cotton production system indicates that the majority of the GHG emissions of the cotton production system (~ 45%) are related to the applied nitrogen fertilisers. The production of nitrogen (N) fertiliser contributes to ~17% (of the total) and the use of fertilisers contributes to ~28% (of the total). The processes involved in the cotton ginning plants are also contribute significantly to the total GHG emissions of the production systems. The processes of drying seed cotton in the cotton ginning plants and the cotton ginning processes contribute to 12% and 9% of the total GHG emissions, respectively. With regard to the cotton farming practices, the diesel used in the farm machinery and the electricity and diesel used by the irrigation pumps contribute to 8% and 7% of the total GHG emissions. The total contribution of transport to the total GHG emissions of the cotton production system is around 4%. Of which, approximately 2% is related to the transport of seed cotton to gin, and around 1% for the transport of agro-chemicals and fuel to farm and the same contribution for the transport of cotton lint to port. The differences between the contributions of the transport stages to the total GHG emissions are caused by the mass of materials transported, the transport distance, and the mode of transport (e.g. truck, rail).

The sensitivity tests conducted for the applied inventory (see Table 5) identified that the calculated CC impact of the function unit is sensitive to four modelling parameters and assumptions. These include yield of irrigated cotton, fertiliser application rate, total dynamic head of groundwater, and the mass fraction of irrigated cotton in total produced cotton. For other modelling parameters, the calculated CC impact of the functional unit is not changed by more than 7% when the modelling parameter/assumption is changed.

An important assumption underpinning the sensitivity tests is that the changes occur ‘in isolation’ of other changes. For instance, in the sensitivity test related to the N application rate, it is assumed that the calculated CC impact of the functional unit would increase around 81.8% if the fertiliser application increases from 255 kg N/ha (the default inventory) to 400 kg N/ha. It can be argued that if the average N application rate of the cotton production system increased from 255 kg N/ha to 400 kg N/ha, it is more likely that other modelling parameters, in particular the cotton yield, would also change. As such, some of the new changes (e.g. increased cotton yield) might balance an increase in the calculated CC impact due to an increase in the N application rate.

The above discussion is supported by the results of a relevant streamlined assessment. In the assessment, the sensitivity of the calculated CC impact of the functional unit to the applied rate of nitrogen fertiliser was investigated under two scenarios. The first scenario assumed that the average nitrogen fertiliser application rate in North West NSW is increased while the average cotton lint is unchanged and the second scenario assumed that the average cotton lint in the region is increased as the N rate is increased. In the modelling, the average Nitrogen Fertiliser Use Efficiency (NFUE) of the region (9.34 kg lint/kg N) was used to calculate the yield relevant to each N application rate. The results of the assessment are shown in Table 11 and Table 12 for the first and the second scenario respectively.

**Table 11: Climate change impact of the functional unit under the first scenario (i.e. the yield of the cotton lint is constant when the N application rate is increased)**

| N rate (kg N/ha) | 150 | 200 | 250 | 300 | 350 | 400 |
|---|---|---|---|---|---|---|
| Lint yield (bales/ha) | 10.5 | 10.5 | 10.5 | 10.5 | 10.5 | 10.5 |
| Climate change impact (kg $CO_2$e/t lint) | 1194 | 1342 | 1564 | 2423 | 2678 | 2910 |

**Table 12: Climate change impact of the functional unit under the first scenario (i.e. the yield of the cotton lint is changed when the N application rate is increased)**

| N rate (kg N/ha) | 150 | 200 | 250 | 300 | 350 | 400 |
|---|---|---|---|---|---|---|
| Lint yield (bales/ha) | 6.2 | 8.2 | 10.3 | 12.3 | 14.4 | 16.5 |
| Climate change impact [2] (kg $CO_2$e/t lint) | 1659 | 1554 | 1585 | 2153 | 2118 | 2055 |

The results presented in Table 11 and Table 12 indicate two different levels of the sensitivity of the CC impacts of the functional unit to the applied N application rate. For instance, based on the first

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[2] There is an irregular rising and falling in the calculated CC impact of the functional unit. These fluctuations are attributed to a number of factors including the changes in the yield of cotton lint and the changes in the emission factors of N fertilisers that were used to calculate the CC impacts. When the N application is increased, the emission factors is increased exponentially, please see Appendix A for further details.

scenario, the CC impact of the functional unit at the N application rate of 400 kg N/ha is around 82% more than the CC impact of the functional unit at the N application rate of 255 kg N/ha that was used as the average N rate in the study. However, based on the second scenario, the CC impact of the functional unit at the N application rate of 400 kg N/ha is around 28% more than the CC impact of the functional unit at the N application rate of 255 kg N/ha.

With regard to the sensitivity of the results to the international (IPCC), national, and regional fertiliser-related $N_2O$ emission values (EVs), the results of the relevant sensitivity test (see Table 7) showed that the calculated CC impact of the functional unit would around 16% more if the IPCC default EVs were used instead of the region-specific EVs. As for the sensitivity of the results to the national and regional EVs, the results of the sensitivity test showed small reductions (between 1.2% to 5.0%) in the CC impact of the LCA systems in North West NSW if the fertiliser $N_2O$ EVs of North West NSW are replaced with the Australian average EVs. With regards to the regional comparison of the results between North West NSW and QLD, the sensitivity results showed a small reduction in (between 0.5% to 2.0%) in the CC impacts of the LCA systems in North West NSW if the fertilisers $N_2O$ EVs of North West NSW are replaced with the QLD average EVs. However, it is important to note that two of the applied emissions factors (EF1 and EF4) for North West NSW and QLD are the same because the current estimations of these factors are based on the nitrogen (N) application rate only, and not based on other factors such as climate, temperature, soil type. As such, the values that we used for EF1 and EF4 may be subject to change in the future when other regional variations (e.g. soil type and climate) are included in the calculations of EF1 and EF4. Further information about the sensitivity test is available in Attachment A.

The sensitivity test relating to the inclusion of a break crop in the cotton system under study revealed that the current body of knowledge surrounding the implication of crop rotation on the CC impact of the functional unit is limited. The only implication considered in the present study (for the case of considering wheat as a break crop) was an yield increase of 23% for the cotton grown immediately after wheat [35]. However, the developed LCA model in the present study is general enough to handle other consequences (e.g. related to the emission factors) if they become known.

The sensitivity analysis conducted, to determine whether the case study region is representative of other regions, revealed that apart from the cotton production system of Central Queensland, the case study region can be considered as an indicative representative of other regions. The calculated CC impact of the Central Queensland cotton production system is around 23% higher than the calculated CC impacts of the system of North West NSW; whereas the calculated CC impact of other cotton production regions are higher/lower than the CC impact of the system of North West NSW by around 2% to 10%. The Central Queensland system is higher due to its relatively low cotton yield.

An important area of discussion is that about the GHG mitigation option of ‘controlled-release and stabilised N fertilisers’. The option is based on the replacement of urea with controlled-release and stabilised N fertilisers such as ‘Entec’ treated products. As such, the option only affects the $N_2O$ emissions from urea that supplies around 63% of the total N fertiliser used in the cotton production system of North West NSW. As stated in Table 10, the option can potentially reduce the CC impact of the functional unit by around 5.9%. An analysis was conducted to check if further reduction in the CC impact of the functional unit can be achieved through increasing the N contribution from urea from 63% to 96%[3] (when no ammonia is used in the cotton system). The results indicate that this would not be an effective GHG reduction strategy, as the GHG reduction observed in one stage of cotton production could be partially offset by an increase in the GHG emission in another stage of the cotton production system. This argument is supported by the results presented in Table 13.

**Table 13: The effects of the GHG mitigation option of ‘controlled-release and stabilised N fertilisers’ under different cotton farming management practices**

| **System boundary of the assessment** | **Cotton farming management practice** | | |
|---|---|---|---|
| | **No use of ‘controlled-release and stabilised N fertilisers’** | **Use of ‘controlled-release and stabilised N fertilisers’ instead of urea only (Scenario 1)** | **Use of ‘controlled-release and stabilised N fertilisers’ instead of both urea and anhydrous ammonia (Scenario 2)** |
| | **Climate change impact (kg $CO_2$e/t lint)** | | |
| Use of fertiliser | 442.4 | 345.7 | 348.7 |
| Production of synthetic fertiliser | 267.7 | 267.7 | 308.7 |
| Cradle-to-port (the functional unit) | 1601 | 1507 | 1547 |

Based on the results presented in Table 13, when the ‘controlled release and stabilised N fertilisers’ are used instead of urea only (Scenario 1), the GHG emission reduction of the cotton production system occurs in the ‘use of the fertilise’ process that is amounted as 96.7 kg CO2e/t lint (442.4-345.7) . However, when the ‘controlled release and stabilised N fertilisers’ are used instead of urea and ammonia (Scenario 2), the GHG emission reductions related to the ‘use of fertiliser’ process is

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[3] Around 4% of the fertiliser-sourced N in the cotton production system is supplied by MAP. No displacement of MAP by urea is considered as MAP is regarded as a phosphorous source in the study than an N source.

partially (~ 93.7 kg $CO_2$e/t lint) offset by the increased GHG emission related to the ‘production of synthetic fertiliser’ process (~41 kg $CO_2$e/t lint). These result a net GHG emission reduction of 52.7 kg $CO_2$e/t lint for Scenario 2. As such, Scenario 2 can potentially reduce the CC impact of the functional unit by around 3.3% whereas Scenario 1 can potentially reduce the CC impact of the functional unit around 5.9%.

## 5. Conclusions

The following conclusions can be drawn from the study:

1. The economic allocation approach is considered as the most appropriate approach to apportion the CC impact of the cotton production system under study between cotton lint and cotton seed.
2. The on-farm stage contributes to around 47% of the total CC impact of the cotton system, followed by the post-farm stage (~27) and the pre-fam stage (~26%).
3. The most GHG-emission-intensive processes are:
    - the use of N fertilisers
    - the production of N fertilisers
    - the process of drying seed cotton in the cotton ginning plants
    - the cotton ginning operations
4. The calculated CC impact of the functional unit is sensitive to the inventory data about: yield of irrigated cotton, fertiliser application rate, total dynamic head of groundwater and the mass fraction of irrigated cotton in total produced cotton.
5. The current IPCC defaults emission values for soil $N_2O$ emission were found not to be appropriate for the LCA studies related to cotton production in North Wales NSW and other regions in Australia.
6. The current body of knowledge surrounding the CC implication of crop rotations on the calculated CC impact of cotton lint is limited. As such, no reasonable comparison can be made between the CC impact of cotton lint produced in ‘back-to-back’ cotton systems and the CC impact of those produced in the ‘rotation’ systems, without considerable further field-based and modelling work.
7. The cotton production system of North West NSW can be considered as an indicative representative of other Australian regions, apart from the cotton production system of Central Queensland. This conclusion is based on the notable differences between the average cotton yield and the average N fertiliser application rate between the cotton systems of North West NSW and the system of Central Queensland.

8. There are good consistencies between the calculated CC impact of the present study and the results of most other studies, if the studies compared based on the same functional unit and the same system boundaries.
9. The investigated GHG emission reduction options have the potential to reduce the calculated CC impact of the functional unit between 2.1% and 13.2%. The options with the highest reduction potential are: optimum nitrogen application rate, use of solar-powered irrigation pumps, and use of controlled-release and stabilised N fertilisers.
10. The fertigation option could be either the least or the second most effective GHG reduction option, depending on whether or not the option reduce fertiliser-related $N_2O$ emission factor of EF1 (see Appendix A for the definition of EF1).

## 6. Recommendations

The following recommendations can be drawn based on the findings of the study:

1. In the process of comparing the results of the present study and other studies, we noted a possible issue in the global cotton LCA study conducted by Systain Consulting [25]. The authors of that study may have considered ‘cottonseed’ and ‘seed cotton’ as similar terms. This could be a main reason why the reported CC impact (referred as carbon footprint in the Systain Consulting study) is relatively high for the average global cotton lint (~4600 kg $CO_2$e/ t lint) and for Australia cotton lint (~3200 kg $CO_2$e/ t lint). We recommend the CRDC to contact Systain Consulting or the organisation that has funded the project (i.e. the Aid by Trade Foundation) regarding the issue.
2. The cotton grown in Australia including the cotton grown in North West NSW might have been included or will be included in the international LCA studies. We recommend only the application of the GHG accounting methodology developed by the IPCC [36].
3. We recommend a dialog between the Australian cotton industry and the Australian Life Cycle Assessment Society (ALCAS) regarding the replacement of some of the existing cotton-related inventory data in AusLCI database with those inventory data that have been developed in the present study. We particularly recommend revising the inventory data related to the heat and electricity used in the Australian cotton ginning plants, as we regard these data not representative for the Australian ginning plants. We can contribute to the proposed dialog, if required. Conducting a study in Queensland, with the same purposes of the present study, could improve the quality of the data presented in AusLCI database.
4. We recommend a dialog between the Australian cotton industry and the Australian Department of Environment regarding the cotton-specific data presented in the National Inventory Report (NIR) 2013. Some of the information available in the NIR 2013 including the equation and data related

the calculation of $N_2O$ emission from cotton residues need revision (please see Attachment A for further details). We can contribute to the proposed dialog if required.

## 7. Limitations of the study

This study provides LCA inventory data of good overall quality on cotton lint production in North West NSW. However, there are some limitations that need to be considered in interpreting the results. These limitations are summarised as follows:

- The outcomes of the study are limited by the quality of data in inventory. Best-available data have been used, whenever possible. Data quality and uncertainty has been assessed through a broad range of sensitivity tests, however the results of this study may change if data quality were to improve. However, it builds in substantial improvements when compared to prior work (Table 11).
- The outcomes of this study are sensitive to the LCA methodology. As such, caution should be applied when comparing the outcomes of this study to another LCA study.
- The outcomes of this study are based on an average over the temporal coverage of the study (2011-2014) are not intended to reflect impacts at any one point in time.
- The CC impact results do not account for timing of greenhouse emissions. The results do not account for the uncertainty associated with global warming potential.
- The calculated CC impact in the study represents potential impact. It is an approximation of environmental impact that would occur if the emitted greenhouse gases actually followed the underlying impact pathway. The impact results are therefore relative expressions only and do not predict actual impacts.
- There is a lack of inventory data related to the GHG emissions associated with the production of ‘controlled-release and stabilised N fertilisers’ in the current Australian Life Cycle Inventory (AusLCI) database. As such, this research assumes that the difference between the GHG emissions associated with the production of urea and the production of ‘controlled-release and stabilised N fertilisers’ is less than the cut-off criteria of the study (1%). Based on this assumption, the AusLCI data for urea was used instead of the AusLCI data for ‘controlled-release and stabilised N fertilisers’ in Section 3.6.

## 8. Contributions of the study to the current cotton LCA practices

The present study benefits the Australian cotton industry and the research community in many ways. The first benefit is related to the application of the system expansion approach in cotton systems (consequential LCA modelling). This application was excluded in the past LCA studies conducted in both Australia and internationally. The study has created a platform in SimaPro by which the CC impact of cotton lint can be calculated based on the system expansion approach. The second benefit is related to the refinements made in the study with respect to the key background data and the key GHG emission accounting methodologies. These refinements (see Table 11) have improved the quality of the calculated CC impact of the functional unit of the present study by 30% and we expect that these refinements can also improve the quality of the CC impact results in the future cotton LCA studies in Australia.

The third benefit of the present study is the development and the execution of a platform in SimaPro for the calculation of the CC impact of cotton systems and the assessment of GHG emission reduction opportunities. The platform has some features that make it superior over the previously developed platforms including the one that is currently available in AusLCI database. The platform developed in the present study is capable of handling both consequential and attributional (e.g. the economic allocation approach) modelling. In addition, the platform includes some modelling steps (features) required for the assessment of the complex cotton production systems (e.g. the production systems involving crop rotation).

**Table 11: The climate change impact of the functional unit with and without the refinements made in the study**

| Process | Climate change impact (kg $CO_2$e/t lint) | | Improvements made in the study |
|---|---|---|---|
| | With the refinements made in the study | Without the refinements made in the study | |
| **Pre-farm stage** | | | |
| Production of synthetic fertiliser | 267.7 | 313.6 | Modifying AusLCI for fertiliser production as per NIR 2013 |
| Production of herbicides/insecticides/growth regulator | 55.3 | 55.3 | No improvements |
| Production of diesel | 42.1 | 40.15 | Modifying AusLCI for irrigation pumps as per Foley, Sandell [14] study |
| Production of electricity | 23.4 | 31.9 | Modifying AusLCI for irrigation pumps as per Foley, Sandell [14] study |
| Production of aviation fuel | 1.6 | 1.6 | No improvement |
| Transport of raw materials to farm (500 km distance) | 15.8 | 14.8 | No improvement, less material is transported to farm in SC1 than SC2 |
| Total for the pre-farm stage | 406.9 | 457.3 | |
| **On-farm stage** | | | |
| Farm machinery | 125.5 | 125.5 | No improvement |
| Irrigation | 108.0 | 98.0 | More electricity is used for irrigation in SC1 than SC2 |
| Decomposition of cotton residues in the field | 75.3 | 215.1 | Calculating cotton-specific emission factor for $N_2O$ emission from cotton residue (see Attachment A) |
| Use of fertilisers | 442.4 | 469.4 | Using Australian-based emission factors than the relevant IPCC factors |
| Transport of seed cotton from farm to gin (35 km distance) | 24.8 | 24.8 | No improvements |
| Total for the on-farm stage | 775.5 | 932.8 | |
| **Post-farm stage** | | | |
| Seed cotton drying process | 190.6 | 370.6 | Modifying AusLCI for the ginning operation based on the data received from two major ginning plants in North West NSW |
| Gin machinery (electricity-powered operation) | 148.0 | 233.3 | Modifying AusLCI for the ginning operation as described above |
| Bale packaging | 16.6 | 16.6 | No improvement |
| Gin trash treatment | 41.8 | 41.8 | No improvements |
| Cotton lint rail transport to port (550 km distance) | 22.2 | 22.2 | No improvements |
| Total for the post-farm stage | 444.0 | 684.5 | |
| Total for the life-cycle (cradle-to-port) | 1600.1 | 2074.6 | |

## 9. Suggested areas for future research

The following subjects are suggested for future research:

**Future research 1:** In line with the international cotton LCA studies, the IPCC guidelines, and the Australian NIR 2013, the $CO_2$ absorbed during the growth of cotton crop and the $CO_2$ emissions from the decomposition of cotton residues were excluded from the assessment. However, the developed platform in SimaPro includes the features enabling the calculation of these $CO_2$ sink and sources. The features are based on the approaches suggested by AusLCI database. We contacted the relevant experts including Dr Michael Bange from CSIRO regarding the applicability of the approaches but no conclusion was made. We suggest

**Future research 2:** We acknowledge that the CRDC has already funded some studies focused on the emission factors for the cotton systems involving crop rotation (e.g. Faba bean as a break crop) and the non-conventional technologies (e.g. the application of fertigation). We suggest further research to quantify the $N_2O$ emission values, particularly EF1 (see Appendix A), for the cotton systems associated with crop rotation and/or associated with non-conventional technologies (e.g. pressurised irrigation technologies). The DPI experts have the expertise for the undertaking this research.

**Future research 3:** During the course of the present study, we consulted some experts within and outside DPI regarding the consequential cotton LCA (the system expansion approach). While the consultations were useful in terms of identifying the production systems that are more likely affected by the cotton production system under study, no conclusion was made regarding the identification of the most sensitive (or marginal) displaced product by cotton seed. We suggest future research involving broad industry engagements regarding the application of consequential LCA in cotton systems.

**Future research 4:** The created platform in SimaPro for the cotton production of North West NSW has demonstrated its ability to be used as an effective and practical platform to test GHG emission mitigation options or the consequences of new productivity-based technologies. We suggest future research to convert the platform from its current form (a SimaPro model) to a Microsoft Excel-based (spreadsheet-based) tool, allowing the Australian cotton farmers to make informed decisions about GHG emission mitigation options based on the life-cycle implications of the options.

**Future research 5:** This research was only focused on the climate change indicator of the cotton production of North West NSW. The future research could consider other environmental indicators (e.g. land use, eutrophication) and the economic indicators (e.g. investment payback period), not only for the development of inventory data but also prior to the application of the GHG emission mitigation options developed in the present study. In particular, it would be beneficial to continue to consider trade-offs between CC impact and water and energy efficiency, especially in the context of investment in infrastructure.

## 10. Communication of the results

Some findings of the present study have been disseminated to both Australian cotton industry and the research community through the presentation in the Australian Cotton Research Conference (September 2015 in Toowoomba) and the presentation in the 1st Australian Conference on Life Cycle Assessment for Agricultural and Food (November 2015 in Melbourne). In the later conference, we presented two peer-reviewed conference papers (Appendix A and Appendix B). The first paper focused on the importance of applying the region-specific fertiliser-related $N_2O$ emissions values and the second on the controversial issue of ‘treatment of co-products’ in cotton systems.

Further communication of the results with the cotton industry and the research community is planned through the following publications:

- A presentation in the International Irrigation Conference and Exhibition (May 2016 in Melbourne) focused on the effect of pressurised irrigation technologies on the life-cycle climate change impact of crops. The case study used in the paper will be the cotton production system of North West NSW.
- A journal paper focused on the effect of pressurised irrigation technologies on the life-cycle climate change impact of crops. The case study used in the paper will be the cotton production system of North West NSW.
- A journal paper focused on the farm-level strategies to reduce the life-cycle GHG emissions of cotton production in North West NSW.
- A journal paper focused on the GHG emission mitigation potential of solar-powered irrigation pumps. The paper will also cover the economic assessment of the solar pumps.

We welcome any collaboration opportunity with the CRDC and other cotton industry associations to develop and disseminate farmers-focused publications such as fact sheets and YouTube videos.

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**Cotton growers:** Mr Scott Morgan, Mr Brendon Warnock, Mr Phillip Morgan

**Cotton ginning plants:** Mr Les Leven (Namoi Cotton), Mr Wayne Towns (Auscott)

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**DPI NSW:** Mr Peter Smith, Mr Rod Jackson, Dr Graeme Schwenke, Ms Fiona Scott, Ms Janine Powell, Mr Patrick Madden, Dr Annette Cowie, Dr Janelle Montgomery, Ms Loretta Serafin, Dr Aaron Simmons, Dr Sally Muir, Dr Gunasekhar Nachimuthu, Mr Jon Baird, Dr Girija Page, Mr Todd Andrews, Ms Jayce Morgan

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## References

1. ABS, *Agricultural Commodities 2012-13*, A.B.o. Statistics, Editor 2014, Australian Bureau of Statistics: Canberra.
2. ISO, *ISO 14040:2006 Environmental management – life cycle assessment – principles and framework*, 2006, International Organization for Standardization: Geneva.
3. RIRDC, *AusAgLCI- A life cycle inventory database for Australian agriculture*, 2014, Rural Industries Research and Development Corporation.
4. Australian Government *National inventory report 2013*, D.o. Environment, Editor 2015.
5. Ringrose-Voase, A. and A. Nadelko, *Quantifying deep drainage in an irrigated cotton landscape*, 2012.
6. McHugh, A., et al., *Effects of subsurface drip irrigation rates and furrow irrigation for cotton grown on a vertisol on off-site movement of sediments, nutrients and pesticides.* Agronomy for sustainable development, 2008. **28**(4): p. 507-519.
7. Eder, A., et al., *Indirect nitrogen losses of managed soils contributing to greenhouse emissions of agricultural areas in Austria: results from lysimeter studies.* Nutrient Cycling in Agroecosystems, 2015. **101**(3): p. 351-364.
8. NSW EPA, *Life cycle inventory and life cycle assessment for windrow composting systems* The Department of Environment and Conservation NSW (DEC), Editor 2006.
9. UNFCCC, *Conference of the Parties held in Warsaw from 11 to 23 November 2013*, 2014, The United Nations Framework Convention on Climate Change (UNFCCC).
10. CRDC, *Cotton Growing Practices Survey 2013*, 2014, Cotton Research and Development Corporation
11. ABS, *Water Use on Australian Farms 2012-13,* A.B.o. Statistics, Editor 2014: canberra.

12. Foley, J., et al., *Farm level benchmarking report of direct energy consumption in Australian irrigated cotton production*, 2015, National Centre for Engineering in Agriculture, University of Southern Queensland: Toowoomba.
13. Welke, R., *Pumping efficiency: how many kWh per ML?* . Irrigation Australia, 2011. **26**(02): p. 19-20.
14. NSW Water, *Lower Gwydir groundwater source: Groundwater management area 004- groundwater status report – 2008*, NSW Department of Water & Energy, Editor 2009.
15. NSW Water, *Lower Namoi Groundwater Source: Groundwater Management Area 001- Groundwater Status Report – 2008*, NSW Department of Water & Energy, Editor 2009.
16. Cotton Australia, *Cotton Annual 2013*, 2013, Cotton Australia.
17. Cotton Australia, *Cotton Annual 2015*, 2015, Cotton Australia.
18. Visser, F., et al., *Application of the Crop Carbon Progress Calculator (CCAP) in a 'farm to ship'cotton production case study in Australia.* Journal of Cleaner Production, 2014.
19. Macdonald, B.C., I.J. Rochester, and A. Nadelko, *High yielding cotton produced without excessive nitrous oxide emissions.* Agronomy Journal, 2015. **107**(5): p. 1673-1681.
20. Tian, Z., et al., *Application effects of coated urea and urease and nitrification inhibitors on ammonia and greenhouse gas emissions from a subtropical cotton field of the Mississippi delta region.* Science of The Total Environment, 2015. **533**: p. 329-338.
21. Antille, L.D. and C.A. McCarthy, *Short-term greenhouse gas emissions from fertigated cotton under furrow and overhead irrigation* in *2015 Australian Cotton Research Conference*2015: Toowoomba.
22. Hulugalle, N., et al., *Managing carbon in cotton-based farming systems*, 2014, Cotton Research and Development Corporation
23. Systain Consulting, *The carbon and water footprint of cotton made in Africa*, 2013, Aid by Trade Foundation.
24. IPCC, *2006 IPCC guidelines for national greenhouse gas inventories volume 4 agriculture, forestry and other land use*, 2006.

# Appendices

## Appendix A: Full text of the first paper presented in AgFoodLCA Conference

# How sensitive is the calculated climate change impact of cotton production in North West New South Wales to fertiliser-related $N_2O$ emission values?

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## ABSTRACT

With the evolution of approaches used to calculate the climate change (CC) impact of cotton production in Australia, there has been a transition from the application of global (IPCC) default emissions values (EVs) for the fertiliser-related $N_2O$ to more localised values. In the study reported here, we used Life Cycle Assessment (LCA) to estimate the climate change impact of cotton production in North West New South Wales (NSW), and tested the sensitivity of applying global versus Australian and/or available region-specific fertiliser-related $N_2O$ EVs. The life-cycle stages included in the analysis were pre-farm, on-farm and post-farm.

We calculated the CC impact of the functional unit (i.e. one tonne of cotton lint) for a cradle-to-port basis as 1687 kg $CO_2$e if the region-specific fertiliser-related $N_2O$ EVs were applied, and 1950 kg $CO_2$e if global average emission values were applied. This represents a 15.6% greater level of impact under the global-average scenario. We also tested the sensitivity of applying global fertiliser-related $N_2O$ EVs versus the Australian and regional values at the 'within farm boundaries' system and, in addition, within the processes involving the use of fertiliser on farm. The impacts were 30.3% higher when the global EVs were applied instead of the North West NSW values, for the 'within farm boundaries' system. This demonstrates the importance of applying country-specific values, in an Australian context. When fertiliser-related $N_2O$ EVs for Queensland were applied instead of those for North West NSW, we observed a low sensitivity of the results to the specific regional fertiliser-related $N_2O$ EVs. This is mainly attributed to the fact that the majority of the EVs that we used to calculate the CC impacts of these regions were the same. As fertiliser-related $N_2O$ emissions are an important contributor of the cradle-to-port CC impact of cotton production in Australia (~20% for North West NSW), further research about the breadth of regional variation is recommended.

**Keywords:** Cotton, N fertiliser, climate change impact, greenhouse gas emissions (GHG), Life Cycle Assessment (LCA), $N_2O$ emissions, emissions factors, IPCC default values

## 1. INTRODUCTION

The increasing global population demands more agricultural products including food, feed, and fibre. An enhanced agricultural production is achievable through different approaches such as minimising crops disease, a better soil health management, and providing more soil nutrition. The latter could be achieved through the application of synthesis nitrogen (N) fertilisers. A draw back associated with the application of N fertilisers is the emissions of nitrous oxide ($N_2O$), which has the global warming potential of 298 times more than carbon dioxide ($CO_2$). The $N_2O$ emissions from the application of N fertilisers along with the $N_2O$ emissions from other sources (e.g. the decomposition of agricultural residues) make the agricultural sector one of the main $N_2O$ emission sources. The extent to which the agricultural sector contributes to the global $N_2O$ emissions is uncertain. Some consider agriculture accountable for about 60% of the total global $N_2O$ emissions [37] and some consider it to make an even greater contribution, about 80% [38].

Nitrous oxide ($N_2O$) emissions from N fertilisers are an important and often challenging aspect of agricultural emissions-related Life Cycle Assessment (LCA) studies. Fertiliser $N_2O$ emissions are often a substantial contributor to the total GHG emissions in agricultural LCA studies [39, 40]. The calculation of fertiliser $N_2O$ emissions is also regarded as a challenging task, as the emissions occur through both direct and indirect pathways. Direct $N_2O$ emissions primarily occur via denitrification in soil from synthetic N fertilisers. Indirect $N_2O$ emissions can occur from runoff and leaching of N, from the volatilised N from the agricultural production systems that is deposited from the atmosphere.

The calculation of both direct and indirect fertiliser $N_2O$ emissions requires the use of emissions values (EVs) for several specific emissions factors (e.g. the amount of the direct atmospheric $N_2O$ emissions per kg of applied N fertilisers) and some partitioning factors (e.g. the fraction of the applied N fertiliser which is lost through leaching/runoff compared to that retained within the system boundary). The types of EVs required for calculating the direct and indirect $N_2O$ emissions from the applied synthetic fertilisers in a cropping system are shown in Fig.1.

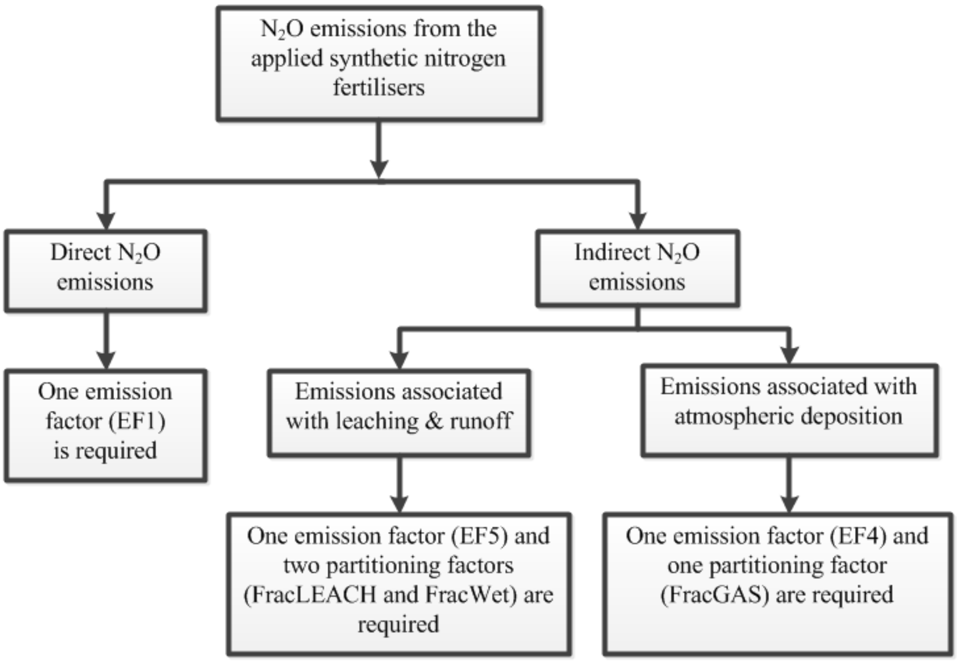

**Fig.1: Emissions values required to calculate the direct and indirect $N_2O$ emissions from synthetic fertilisers**

In the absence of regionally-specific EVs, the values provided by the Intergovernmental Panel on Climate Change [36] are often used. Research conducted in Australia has led to the estimation of the Australian-specific EVs (Table 12).

**Table 12: Description of fertiliser-related $N_2O$ EVs and their values for continuous irrigated cotton systems [4-6, 10, 36]**

| Emission value | Description | Value | | | |
|---|---|---|---|---|---|
| | | IPCC | Australia | North West NSW | QLD |
| EF1 | kg $N_2O$ -N ($N_2O$ as N) is produced per kg of input synthetic N fertiliser | 0.01 | 0.0055 | 0.0063 | 0.0063 |
| EF4 | kg N–$N_2O$ per kg ($NH_3$–N + NOx–N) volatilised | 0.01 | 0.0055 | 0.0063 | 0.0063 |
| EF5 | kg $N_2O$ -N per kg of N that is lost through leaching and runoff | 0.0075 | 0.0075<br>(IPCC default) | 0.0075<br>(IPCC default) | 0.0075<br>(IPCC default) |
| FracGAS | a constant mass fraction of the applied synthetic N fertilisers that volatilises soon after the application/deposition of fertilisers | 0.1 | 0.1<br>(IPCC default) | 0.1<br>(IPCC default) | 0.1<br>(IPCC default) |
| FracLEACH | fraction of total mass of synthetic fertiliser lost by leaching and runoff | 0.3 | 0.12 | 0.12 | 0.12 |
| FracWet | fraction of fertiliser N available for leaching and runoff | 0.932 | 1.0 | 0.932 | 0.713 |

The values presented for EF1 and EF4 are based on the average synthetic N application rate of 246 kg per ha for Australia [4] and 255 kg N per ha for North West NSW and QLD. Other values are currently considered to be independent of the applied N rate. The IPCC EVs are sourced from IPCC [36] apart from the value considered for FracWet. In the absence of any IPCC value for FracWet, we consider that the value is similar to the value applied for North West NSW. The EVs for Australia, North West NSW, and Queensland (QLD) are sourced from the relevant government publications [4, 10, 41] apart from the FracLEACH values for Australia, North West NSW and QLD where these values were calculated based on the research conducted by McHugh, Bhattarai [6] and Ringrose-Voase and Nadelko [5]. It should be noted that no Australian-specific values for FracGAS and EF5 have been estimated to date. The IPCC default values for FracGAS and EF5 are used by the Australian Government in the Australian National Inventory Report [4].

The values presented in Table 12 are for continuous irrigated cotton systems, whereas our assessment is based on the mixed production of irrigated (~94% of the total cotton) and rainfed cotton (~6% of the total cotton). For continuous rainfed crop systems, FracLEACH is considered to be zero [7]. In the absence of any study that has measured EF5 and FracGAS for the rainfed cotton systems, we consider these values similar to those of the irrigated cotton systems (the values presented in Table 12). The values for EF1 and EF4 for the rainfed cotton systems have not been estimated yet; we consider these values to be 0.003 kg N2O-N per kg of input synthetic N fertiliser. We have calculated the figure (i.e. 0.003) based on the synthetic N application rate of 50 kg per ha for the rainfed cotton systems and by using the equation relating EF1 and EF4 to the N application rate in cotton systems [10]. We acknowledge that the equation is for the irrigated cotton systems not the rainfed systems; however, we consider this proxy appropriate as rainfed cotton contributes to a small fraction (~6%) of the total mass of the produced cotton in North West NSW.

## 2. METHODS

We apply the Life Cycle Assessment (LCA) method to quantify the life-cycle climate change (CC) impact of cotton production in North West NSW, adopting the four-step procedure outlined in ISO 14040:2006 [1]. The functional unit of the LCA study is 1 tonne of cotton fibre (lint) at an export port, given that approximately 99% of the cotton grown in Australia is exported [18]. The system boundaries of the LCA study includes the processes involved in the pre-farm stage (i.e. the production of raw materials and their transport to farm), the on-farm stage, and the post-farm stage (i.e. cotton ginning and the transport of cotton lint to an export port). In this paper we test the sensitivity of the results to the applied fertiliser $N_2O$ emissions factors for three different systems (or system scenarios). These systems are shown in Fig.2. The first system (cradle-to-port) is the system with the boundaries specified with the outset solid lines, the second system (within farm boundaries) is the system with the boundaries specified with the dashed lines, and the third system (fertiliser use) is the system with the dotted lines.

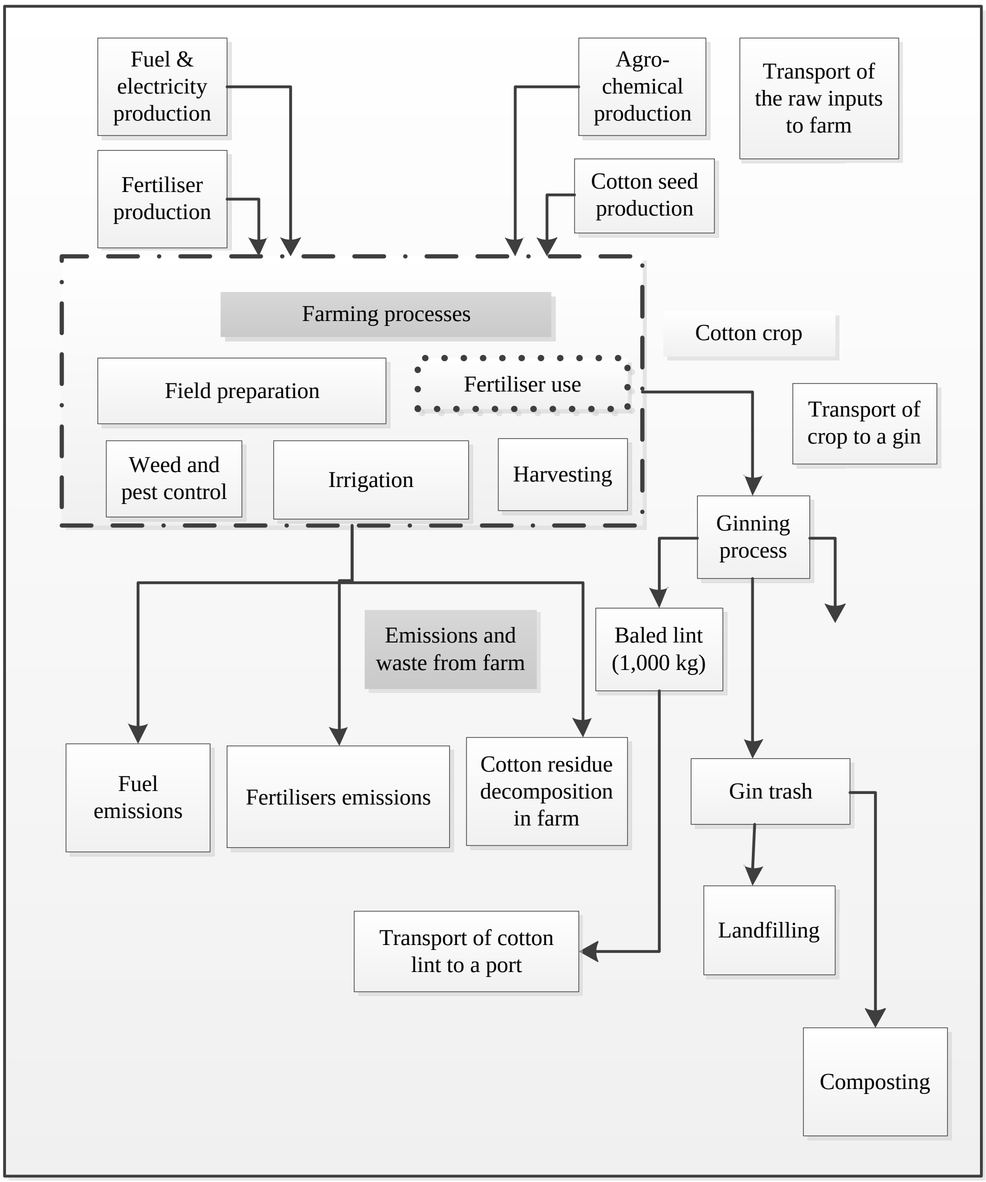

**Fig.2: System boundaries of the LCA study**

The foreground data included that from questionnaires sent to some ginning plants, interviews conducted with some cotton farmers, gross margin data, industry surveys and case study research and validated by experts' opinion from the industry. The background data (e.g. fertiliser production) were accessed from different sources including the Australian life-cycle inventory databases for Australian agriculture [42], and AusLCI database. The inventory for the foreground data and the key modelling assumptions are provided in **Error! Reference source not found.**. We performed all impact assessment calculations by using SimaPro 8.0.3.

We applied the Australian Impact Method (Australian Indicator Set V3) to interpret LCA inventory results but did not calculate carbon dioxide absorbed by cotton from air during its growth and the carbon dioxide released from the decomposition of cotton waste residues in the field, for consistency with the Australian National Inventory Report (NIR) [4]. We calculate the potential life-cycle climate change by multiplying the total emissions of the various greenhouse gases by their respective global warming potentials (GWPs), then adding the global warming equivalencies for the various GHGs. The GWPs are based on the GWP values provided by the UNFCCC [9] for a 100-year timeframe. The $N_2O$ emissions associated with the decomposition of cotton residues are included in the assessment for the both irrigated and rainfed cotton systems.

We allocate the climate change impact of the cotton production system between the co-products (i.e. cotton lint and cottonseed) in proportion to the economic values of the products. We allocate 86% of the impacts to cotton lint and 14% of the impacts to cotton seed. This is consistent with the allocation used in similar studies [24, 27]. The figures are based on our best estimate of the region's average price (2010-2014) of $470 per bale of cotton lint (227kg cotton lint) and $300 kg per tonne of cotton seed. While the prices of both cotton lint and cotton seed in some years might be more or less than the prices considered in the present paper, we consider that the changes would not considerably change the economic allocation figures used in the study.

In this paper, we exclude sensitivity testing of other variables, such as crop yield, irrigation practices and disposal of gin trash. We also exclude sensitivity testing associated with the spreading of the total CC impacts over cotton lint and seed based on the system expansion approach. These factors are covered in related publications that are currently in preparation. The inclusion of inputs and outputs in our assessment is based on mass and energy. We exclude any elementary flows representing less than approximately 1% of the cumulative mass flows or representing less than approximately 1% of the cumulative energy flows.

## 3. RESULTS

Our results indicate that the calculated CC impact, on a cradle-to-port basis, is 1687 kg $CO_2e$ per 1 tonne of cotton lint at port. The relative contributions of the CC impact of the individual processes to the total calculated CC impacts are shown in Fig. 3. As indicated in Fig. 3, fertiliser $N_2O$ emissions are important contributor of the cradle-to-port CC impact of cotton production in North West NSW, contributing to around 20 % of the total CC impact. These include the CC impact from direct $N_2O$ emissions (16.3%), the indirect $N_2O$ emissions associated with atmospheric deposition (1.5%) and leaching and runoff (2.2%).

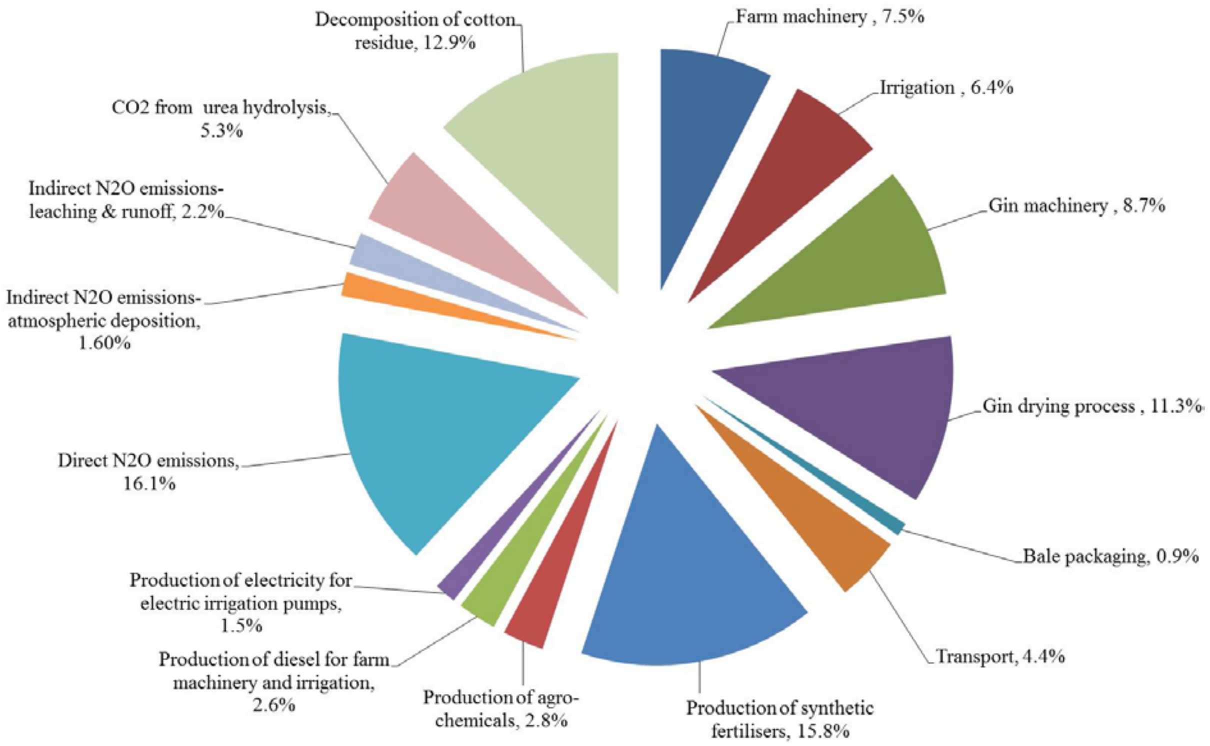

**Fig. 3: The relative contribution of the CC impact of the processes to the total CC impact of cotton production in North West NSW for the cradle-to-port system scenario**

The potential CC impact of cotton lint production for the different system scenarios and under the different fertiliser $N_2O$ EVs are presented in Table 13. The table also provides the percent difference between the CC impact calculated for the functional unit based on the EVs of North West NSW and the CC impact calculated by using the alternative EVs. These values are presented in the parentheses. The positive (+) sign implies less CC impact for North West NSW and the negative (-) sign implies more CC impact for North West NSW.

**Table 13: The CC impact of cotton production for the different system scenarios and under the different fertiliser-related $N_2O$ EVs**

| LCA System-boundaries | Climate change impact of cotton lint produced in North West NSW as kg $CO_2e$/tonne cotton lint | | | |
|---|---|---|---|---|
| | Using the IPCC emissions values | Using the Australia emissions values | Using the North West NSW emissions values | Using the Queensland emissions values |
| Cradle-to-port | 1950<br>(+15.6%) | 1666<br>(-1.2%) | 1687 | 1679<br>(-0.5%) |
| Within farm boundaries | 1143<br>(+30.3%) | 855<br>(-2.5%) | 877 | 868<br>(-1.0%) |
| Fertiliser use only | 689<br>(+61%) | 405<br>(-5.0%) | 427 | 418<br>(-2.0%) |

## 4. DISCUSSION

We found the CC impact of cotton production in North West NSW to be sensitive to the applied fertiliser-related $N_2O$ EVs. The results indicate that by expanding the system boundaries from ‘fertiliser use only’ to ‘within farm boundaries’ and ‘cradle-to-port’, the sensitivity of the CC impact results to the applied $N_2O$ emissions values is reduced. This is attributed to the fact that by expanding the system boundaries, the CC impacts associated with the fertiliser N2O emissions (a constant value) are divided by a greater amount of the CC impact results.

With regards to the sensitivity of the results to the national and regional fertiliser $N_2O$ EVs, the results of the present paper show small reductions (between 1.2% to 5.0%) in the CC impact of the LCA systems in North West NSW if the fertiliser $N_2O$ EVs of North West NSW are replaced with the Australian average EVs. With regards to the regional comparison of the results between North West NSW and QLD, the present paper shows a small reduction in (between 0.5% to 2.0%) in the CC impacts of the LCA systems in North West NSW if the fertilisers $N_2O$ EVs of North West NSW are replaced with the QLD average EVs. However, it is important to note that two of the applied emissions factors (EF1 and EF4) for North West NSW and QLD are the same because the current estimations of these factors are based on the nitrogen (N) application rate only, and not based on other factors such as climate, temperature, soil type. As such, the values that we used for EF1 and EF4 may be subject to change in the future when other regional variations (e.g. soil types) are included in the calculations of EF1 and EF4. As fertiliser $N_2O$ emissions are important contributor of the cradle-to-port CC impacts of cotton production in Australia (~20% for North West NSW), further information about the breadth of regional variation is recommended.

## ACKNOWLEDGEMENTS

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## REFERENCE

1. ABS, *Agricultural Commodities 2012-13*, A.B.o. Statistics, Editor 2014, Australian Bureau of Statistics: Canberra.
2. ISO, *ISO 14040:2006 Environmental management – life cycle assessment – principles and framework*, 2006, International Organization for Standardization: Geneva.
3. RIRDC, *AusAgLCI- A life cycle inventory database for Australian agriculture*, 2014, Rural Industries Research and Development Corporation.
4. Australian Government *National inventory report 2013*, D.o. Environment, Editor 2015.
5. Ringrose-Voase, A. and A. Nadelko, *Quantifying deep drainage in an irrigated cotton landscape*, 2012.
6. McHugh, A., et al., *Effects of subsurface drip irrigation rates and furrow irrigation for cotton grown on a vertisol on off-site movement of sediments, nutrients and pesticides.* Agronomy for sustainable development, 2008. **28**(4): p. 507-519.
7. Eder, A., et al., *Indirect nitrogen losses of managed soils contributing to greenhouse emissions of agricultural areas in Austria: results from lysimeter studies.* Nutrient Cycling in Agroecosystems, 2015. **101**(3): p. 351-364.

8. NSW EPA, *Life cycle inventory and life cycle assessment for windrow composting systems* The Department of Environment and Conservation NSW (DEC), Editor 2006.
9. UNFCCC, *Conference of the Parties held in Warsaw from 11 to 23 November 2013*, 2014, The United Nations Framework Convention on Climate Change (UNFCCC).
10. CRDC, *Cotton Growing Practices Survey 2013*, 2014, Cotton Research and Development Corporation
11. ABS, *Water Use on Australian Farms 2012-13*, A.B.o. Statistics, Editor 2014: canberra.
12. Foley, J., et al., *Farm level benchmarking report of direct energy consumption in Australian irrigated cotton production*, 2015, National Centre for Engineering in Agriculture, University of Southern Queensland: Toowoomba.
13. Welke, R., *Pumping efficiency: how many kWh per ML?* . Irrigation Australia, 2011. **26**(02): p. 19-20.
14. NSW Water, *Lower Gwydir groundwater source: Groundwater management area 004-groundwater status report – 2008*, NSW Department of Water & Energy, Editor 2009.
15. NSW Water, *Lower Namoi Groundwater Source: Groundwater Management Area 001-Groundwater Status Report – 2008*, NSW Department of Water & Energy, Editor 2009.
16. Cotton Australia, *Cotton Annual 2013*, 2013, Cotton Australia.
17. Cotton Australia, *Cotton Annual 2015*, 2015, Cotton Australia.
18. Visser, F., et al., *Application of the Crop Carbon Progress Calculator (CCAP) in a 'farm to ship'cotton production case study in Australia*. Journal of Cleaner Production, 2014.
19. Macdonald, B.C., I.J. Rochester, and A. Nadelko, *High yielding cotton produced without excessive nitrous oxide emissions*. Agronomy Journal, 2015. **107**(5): p. 1673-1681.
20. Tian, Z., et al., *Application effects of coated urea and urease and nitrification inhibitors on ammonia and greenhouse gas emissions from a subtropical cotton field of the Mississippi delta region*. Science of The Total Environment, 2015. **533**: p. 329-338.
21. Antille, L.D. and C.A. McCarthy, *Short-term greenhouse gas emissions from fertigated cotton under furrow and overhead irrigation* in *2015 Australian Cotton Research Conference*2015: Toowoomba.
22. Hulugalle, N., et al., *Managing carbon in cotton-based farming systems*, 2014, Cotton Research and Development Corporation
23. Systain Consulting, *The carbon and water footprint of cotton made in Africa*, 2013, Aid by Trade Foundation.
24. IPCC, *2006 IPCC guidelines for national greenhouse gas inventories volume 4 agriculture, forestry and other land use*, 2006.
25. Linquist, B., et al., *An agronomic assessment of greenhouse gas emissions from major cereal crops*. Global Change Biology, 2012. **18**(1): p. 194-209.
26. Zhang, X., et al. *Evaluating uncertainties in nitrous oxide emission inventories with multi-scale observations for an agriculture-dominated region*. in *AGU Fall Meeting Abstracts*. 2014.
27. Brock, P., et al., *Greenhouse gas emissions profile for 1 tonne of wheat produced in Central Zone (East) New South Wales: a life cycle assessment approach*. Crop and Pasture Science, 2012. **63**(4): p. 319-329.
28. Abeliotis, K., V. Detsis, and C. Pappia, *Life cycle assessment of bean production in the Prespa National Park, Greece*. Journal of Cleaner Production, 2013. **41**: p. 89-96.
29. Australian Government *Equations included in the Irrigated Cotton Calculator under the Carbon Credits (Carbon Farming Initiative—Reducing Greenhouse Gas Emissions from Fertiliser in Irrigated Cotton) Determination 2015*, 2015.
30. Australian Government *National Inventory Report 2012*, 2014.
31. Cotton Inc. and PE Internatioal AG, *The Life Cycle Inventory & Life Cycle Assessment of Cotton Fiber & Fabric* 2012, Cotton Incorporated, Cotton Council International and National Cotton Council.
32. PE International AG, *Cotton made in Africa*, 2012, Aid by Trade Foundation.

## Appendix B: Full text of the second paper presented in AgfoodLCA Conference

# Consequential LCA in cotton production systems: opportunities and challenges

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## ABSTRACT

We consider the cotton production system of North West New South Wales (NSW) in Australia as a reference system and the climate change (CC) impact of that system as a reference impact indicator to discuss the opportunities and challenges associated with the application of Consequential Life Cycle Assessment (CLCA) in cotton systems. In addition, the present paper aims to open debate among the research community about CLCA in cotton production systems. We researched primary consequences of displacing animal feed and seed oil (canola seed) without considering the secondary consequences of further downstream displacements associated with the co-products of cotton seed crushing (i.e. cottonseed meal, cottonseed hull, and cotton linter). This will depend upon further development of models that capture the various primary and secondary consequences. For the treatment of the co-products of the system, we apply both the consequential (system expansion) approach and the attributional approaches.

Our results indicate that the calculated CC impacts associated with the functional unit (i.e. 1000 kg cotton lint produced in North West NSW and transported to an export port) are sensitive to the applied co-product treatment approaches. The applied system expansion approach calculated the impacts in the range of 1288 kg CO2e to 1552 kg CO2e for four different system expansion scenarios. The CC impacts based on the attributional approaches of mass allocation and economic allocation were calculated as 770 kg CO2e and 1687 kg CO2e respectively.

The main opportunity associated with the application of CLCA in cotton systems is the ability through CLCA to identify and measure the potential consequence of cotton seed production on other production systems in the economy and to relate these consequences to cotton lint. The main challenges associated with CLCA are the lack of universally accepted methods to identify the products that are most affected by cotton systems (the sensitive products) and measure the extent to which those products are affected by cotton production.

**Keywords**: Cotton, climate change impacts, greenhouse gas emissions (GHG), life cycle assessment (LCA), system expansion, consequential LCA, allocation

## 1. INTRODUCTION

Agricultural production systems often generate two or more products. In Life Cycle Assessment (LCA) studies, the treatment of co-products, or the distribution of the overall inputs (resources) and outputs (emissions) between co-products, is an important and often controversial subject. The treatment of co-products, one the most controversial issues in the development of the methodology for LCA [43], has been addressed in ISO 14044:2006 Standard [2]. The most preferred approach in the hierarchy outlined by this Standard is to divide the involved processes into two or more sub-processes and to collect the input and output data related to these sub-processes. The next preferred approach is the system expansion approach, which is based on expanding the system under study to include the additional functions related to the co-products. The system expansion approach takes into account the consequence of co-production on other production systems in the economy. For this reason, LCA studies based on the system expansion approach are often referred as Consequential Life Cycle Assessment (CLCA) studies [44, 45]. The so called attributional LCA (ALCA) is often applied to studies dealing with relatively contained (in terms of system boundaries) products or systems [44], or as a basis from which CLCA studies can be developed.

As for some systems such as milk production [46] and seafood production [47], it is not practical in the cotton systems to divide the processes involved in cotton production systems (e.g. irrigation) into two or more sub-processes to collect the input and output data related to the sub-processes. As such, according to ISO 14044:2006, the system expansion approach is recommended. However, little is known about the application of the system expansion approach in cotton production systems, perhaps due to the challenges that appear when these systems are expanded. The present paper explores these challenges along with a view to some opportunities associated with the application of consequential LCA in these systems. To facilitate the discussion, we consider the cotton production system in North West New South Wales (NSW) as a reference system and calculate the impact indicator of climate change (CC) of that system based on the system expansion approach and via the attributional approaches of mass allocation and economic allocation.

We acknowledge that the consequential modelling in some LCA studies comprises consideration of the marginal sources or technologies (e.g. fertilisers produced from the marginal sources or irrigation water supplied by the desalination technologies) [48]. The applied CLCA in the present paper excludes any LCA modelling based on the consideration of marginal sources or technologies as we were unable to find evidence of current or proposed future applications of marginal sources or technologies that are likely to lead to this type of consequential modelling.

## 2. METHODS

We conducted an (LCA) to quantify life-cycle climate change (CC) impact of cotton production in North West NSW, adopting the four-step procedure outlined in ISO 14040:2006 [1]. The functional unit of the LCA study is the production of 1 tonne cotton fibre (lint) and its transport to an export port, given that approximately 99% of the cotton grown in Australia is exported [18]. The system boundary of the LCA study includes the processes involved in the pre-farm stage (i.e. the production of raw materials and their transport to farm), the on-farm stage, and the post-farm stage (i.e. cotton ginning and the transport of cotton lint to an export port).

The foreground data included that from questionnaires sent to some ginning plants, interviews conducted with some cotton farmers, gross margin data, industry surveys and case study research. Data were also validated by obtaining expert opinion from industry representatives. The background data (e.g. fertiliser production) were accessed from the different sources including the Australian life-cycle inventory[42], AusLCI database [49], and the Ecoinvent database [50]. We perform all impact assessment calculations using SimaPro 8.0.3 [51]. The inclusion of inputs and outputs in our assessment is based on mass and energy. To ensure that all relevant environmental impacts were represented in the study, we have excluded only those flows that had less than 1% of the cumulative mass or energy of all the inputs and outputs of the LCI model, provided the environmental relevance of the excluded flow is not a concern. An example is the exclusion of the CC impact associated with the manufacturing of small quantity of packaging glues that are used in a cotton ginning plant. In this example, we regarded the CC impact associated with the production of use of the applied packaging glue to be less than 1% of the total life-cycle CC impact of the product.

We apply the Australian Impact Method (Australian Indicator Set V3) to interpret the LCA inventory results but exclude carbon dioxide absorbed by cotton from air during its growth and the carbon dioxide released from the decomposition of cotton residues in the field (i.e. biogenic CO2). We calculate the potential life-cycle climate change by multiplying the total emissions of the various greenhouse gases by their respective global warming potential (GWPs) (http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf), then adding the global warming equivalencies for the various GHGs for a 100-year timeframe.

With regard to the treatment of the co-products, in the mass allocation approach, we allocate the total impacts of the cotton system not only to cotton lint and cotton seed, but also to cotton gin trash. We allocate the total impacts of the system in proportional to the relative mass output of the co-products form a typical ginning plant in North West NSW (42% cotton lint, 49% cotton seed, and 9% gin trash). As there is no recognised economic value for gin trash, during economic allocation we distribute the total CC impacts of the cotton system between cotton lint and cotton seed, on the basis of, cotton lint contributing 86% of the income from one ha of cotton land and cotton seed contributing to 14% of the total income. The figures are based on the average price (2011-2014) of $470 per bale of cotton lint (227kg cotton lint) and $300 kg per tonne of cotton seed. While the prices of both cotton lint and cotton seed in some years might be more or less than the prices considered in the present paper, we consider that the changes would not considerably change the economic allocation figures used in the study.

In the system expansion approach, we apply the approach developed by Weidema [43]. The four-step method includes four decision rules that facilitate the identification of independent co-products (the co-products which determine the production volume of a production system) and the dependent co-product. The method is also useful in identifying and measuring the potential consequence of co-products of a system on other production systems in the economy. Cotton seed, the dependent co-product is used as animal feed[4] and as seed oil. As such, the production of cotton seed affects the animal feed and seed oil production systems. The animal feed production systems are varied including those for grain-based (e.g. wheat, feed barley) animal feed. The production systems for seed oil products are also varied, including those for canola production. The system boundary for the cotton production system under study (solids lines) and those for the expanded system (dashed lines) are shown in Figure 5.

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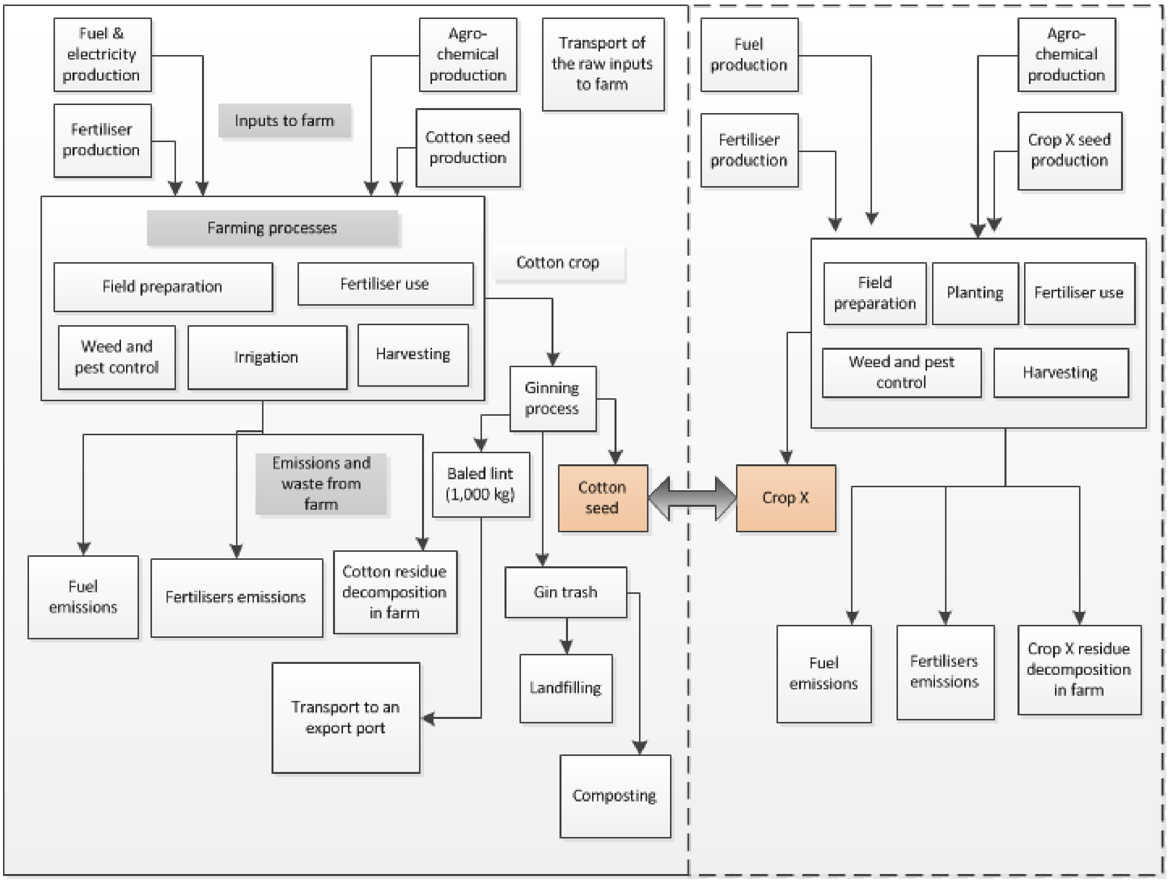
[4] There are some recommendations for the maximum daily use of cotton seed as animal feed for different animals (http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0005/96008/white-cottonseed-a-supplementary-feed.pdf)



*Please refer to Table 1 for the information related to crop X

**Figure 5: System boundaries of the reference system (solid lines) and its expanded systems (dashed lines)**

In the present paper, we limit our assessment to identifying and measuring the consequences of cotton production on grain-based animal feed namely wheat and barley, and on the production of canola seed. We regard this as a reasonable approach given that we aim to explore the challenges and opportunities of expanding cotton production systems. Whilst there are other potential flows on effects, this substitution provides sufficient rigour to underpin this methodological exploration.

Another important aspect of the system expansion approach in cotton systems is to determine the displacement ratio or the amounts of wheat and feed barley (animal feeds) and canola seed (seed oil) that are displaced by one additional kg of cotton seed. The value of any animal feed depends mainly on the concentration of Metabolised Energy (ME) and Crude Protein (CP) in the dry matter (DM) of that feed [52, 53]. As such, to determine the displacement ratio between cotton seed and wheat or barley, it is important to ensure that after displacement, cotton seed provides exactly the same amount of ME and CP that were previously provided by wheat or barley. Often, the balance between the ME and CP between two animal feeds is achieved through the inclusion of a third animal feed into the animal feed. In the present paper, we consider sorghum and lupins as the agents to balance ME and CP. In addition to ME and CP, the Oil Content (OC) of cotton seed and canola seed also contributes to the estimation of the displacement ratio. As such, to estimate the displacement ratios for the animal feed systems, we simultaneously balance the two animal feed systems of cotton seed and wheat (or barley) based on their ME and CP contents. Likewise, to estimate the displacement ratios for the seed oil systems, we simultaneously balance the two seed oil systems of cotton seed and canola seed, based on their ME, CP, and OC contents. We consider sorghum and lupins as plausible substitutes but purely to facilitate the ME, CP, and/or OC of the systems. Data related to ME and CP of the products are available in NSW DPI [52] and data for ME, CP, and OC of canola seed are available in Weightman, Patrick Garland [54]. We considered several different substitutions including a system which displaces urea that is currently added to stock feed mixes. Urea is commonly added in small quantities as a means of increasing crude protein. However, we are currently exploring the relative toxicity to livestock of cotton seed versus urea before progressing this analysis.

## 3. RESULTS

We followed the decision-tree presented by Weidema [43] to calculate the CC impacts of cotton lint based on the system expansion approach. The dependent co-product of the system under study (i.e. cotton seed) is considered to displace other products and be fully used. As such, according to the decision tree [43], we follow Rule 1 and Rule 2 of the procedure developed by Weidema [43]. These rules require ascribing all of the impact of the cotton production system to cotton lint but credit the lint for avoided GHG emissions associated with the production of those products that are displaced by cotton seed.

The exact portion of the total produced cotton seed that is used as seed oil is unknown for North West NSW. However, in another Australian cotton growing region of Central Queensland, around 90% of the produced cotton seed is used as animal feed [23]. Given the existence of a large seed oil crushing plant in North West NSW (in Narrabri) [23], it is more likely that more cotton seed is crushed in North West NSW than in Central Queensland. However, as the actual figure is unknown, we assume that similar to Central Queensland, 90% of the total cotton seed are used as animal feed and the remainder is crushed for cottonseed oil extraction. The CC impact results are presented in Table 15. We challenge the assumption regarding the fraction of cotton seed used as animal feed in a sensitivity analysis study in which we assigned different values for the considered fraction. The results of the sensitivity analysis are presented in Table 14.

**Table 15: Climate change impact of the functional unit under different system expansion scenarios**

| System expansion scenario | Animal feed systems | | Seed oils systems | | Climate change impact (kg $CO_2$e/t lint) |
|---|---|---|---|---|---|
| | Product displaced by cotton seed | Product balancing CP and ME | Product displaced by cotton seed | Products balancing OC, CP, and ME | |
| Scenario 1 | Wheat | Sorghum | Canola seed | Sorghum and lupins | 1288 |
| Scenario 2 | Wheat | Lupins | Canola seed | Sorghum and lupins | 1524 |
| Scenario 3 | Barley | Sorghum | Canola seed | Sorghum and lupins | 1399 |
| Scenario 4 | Barley | Lupins | Canola seed | Sorghum and lupins | 1552 |

**Table 16: Results of the sensitivity analysis study**

| System expansion scenario | Climate change impact (kg $CO_2$e/t lint) | | | | | |
|---|---|---|---|---|---|---|
| | Fraction of the total produced cotton seed used as animal feed | | | | | |
| | 1.0 | 0.8 | 0.6 | 0.4 | 0.2 | 0.0 |
| Scenario 1 | 1272 | 1305 | 1339 | 1372 | 1405 | 1439 |
| Scenario 2 | 1534 | 1515 | 1496 | 1477 | 1458 | 1439 |
| Scenario 3 | 1395 | 1404 | 1413 | 1421 | 1430 | 1439 |
| Scenario 4 | 1566 | 1539 | 1512 | 1485 | 1459 | 1439 |

The CC impact of the functional unit based on the mass allocation and economic allocation approaches was 770 and 1687 kg $CO_2$e respectively.

## 4. DISCUSSION

Our results indicate that the calculated CC impacts associated with the functional unit are sensitive to the applied co-product treatment approaches, especially when mass and economic allocations are compared. When the system expansion approach is applied, calculated impacts range from 1288 kg $CO_2$e to 1552 kg $CO_2$e for four different system expansion scenarios. The differences among the impacts of the system expansion scenarios can be related to the different products that were employed to balance the CP, ME, and OC between the cotton systems and the affected systems. The sensitivity analysis revealed that the results are also sensitive to the fraction of the total produced cotton seed in the region that is used as animal feed. In Scenario 1 and Scenario 3, the CC impact increased when a lower fraction of the total cotton seed was used as animal feed, whereas in Scenario 2 and Scenario 4 the trend was reverse. As such, when an additional unit of cotton seed displaces other products used in animal feed in North West NSW, this does not necessarily lead to a reduction in the CC impact of cotton lint.

We argue that the mass allocation approach is not an appropriate approach for the treatment of co-products in cotton systems as the majority of the CC impacts are shifted towards cotton seed which is not the primary product of these systems. So, uncertainty about whether to attribute emissions to gin trash becomes only a minor consideration. The differences between the CC impacts calculated by the economic allocation and those calculated for the system expansion scenarios (Table 15) are greater for Scenario 1 and Scenario 3 than for Scenario 2 and Scenario 4. The most substantial difference in the CC impact is between the economic allocation approach and Scenario 1 (23.6% lower for Scenario 1).

In this study, we researched the primary consequences of displacing animal feed and seed oils by cotton seed without considering the secondary consequences of further downstream displacements associated with the co-products of cotton seed crushing (i.e. cottonseed meal, cottonseed hull, and cotton linter). This will depend upon further development of models that capture the various primary and secondary consequences. We intend for the present paper to open debate among the research community about consequential LCA in cotton production systems.

The main opportunity associated with the application of CLCA in cotton systems is the ability to identify and measure the consequence of additional cotton crop production on other production systems in the economy and to relate these consequences to the CC impacts of cotton lint. The main challenges associated with CLCA are the lack of the universally accepted methods to identify the products that are most affected by additional cotton production) and to measure the extent to which those products are affected by cotton production.

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## REFERENCES

1. ISO, *ISO 14040:2006 Environmental management – life cycle assessment – principles and framework*, 2006, International Organization for Standardization: Geneva.
2. ISO, *ISO 14044:2006 Environmental management -- Life cycle assessment -- Requirements and guidelines*, 2006, International Organization for Standardization: Geneva.
3. ABS, *Agricultural Commodities 2012-13,* A.B.o. Statistics, Editor 2014, Australian Bureau of Statistics: Canberra.
4. Australian Government *National inventory report 2013,* D.o. Environment, Editor 2015.
5. Ringrose-Voase, A. and A. Nadelko, *Quantifying deep drainage in an irrigated cotton landscape*, 2012.
6. McHugh, A., et al., *Effects of subsurface drip irrigation rates and furrow irrigation for cotton grown on a vertisol on off-site movement of sediments, nutrients and pesticides.* Agronomy for sustainable development, 2008. **28**(4): p. 507-519.
7. Eder, A., et al., *Indirect nitrogen losses of managed soils contributing to greenhouse emissions of agricultural areas in Austria: results from lysimeter studies.* Nutrient Cycling in Agroecosystems, 2015. **101**(3): p. 351-364.
8. NSW EPA, *Life cycle inventory and life cycle assessment for windrow composting systems* The Department of Environment and Conservation NSW (DEC), Editor 2006.
9. UNFCCC, *Conference of the Parties  held in Warsaw from 11 to 23 November 2013,* 2014, The United Nations Framework Convention on Climate Change (UNFCCC).
10. Australian Government *Equations included in the Irrigated Cotton Calculator under the Carbon Credits (Carbon Farming Initiative—Reducing Greenhouse Gas Emissions from Fertiliser in Irrigated Cotton) Determination 2015*, 2015.
11. Muhammad, W., et al., *Crop residues and fertilizer nitrogen influence residue decomposition and nitrous oxide emission from a Vertisol.* Biology and Fertility of Soils, 2010. **47**(1): p. 15-23.
12. CRDC, *Cotton Growing Practices Survey 2013*, 2014, Cotton Research and Development Corporation
13. ABS, *Water Use on Australian Farms 2012-13,* A.B.o. Statistics, Editor 2014: canberra.
14. Foley, J., et al., *Farm level benchmarking report of direct energy consumption in Australian irrigated cotton production*, 2015, National Centre for Engineering in Agriculture, University of Southern Queensland: Toowoomba.
15. Welke, R., *Pumping efficiency: how many kWh per ML?* . Irrigation Australia, 2011. **26**(02): p. 19-20.
16. NSW Water, *Lower Gwydir groundwater source: Groundwater management area 004-groundwater status report – 2008*, NSW Department of Water & Energy, Editor 2009.
17. NSW Water, *Lower Namoi Groundwater Source: Groundwater Management Area 001-Groundwater Status Report – 2008,* NSW Department of Water & Energy, Editor 2009.
18. Cotton Australia, *Cotton Annual 2013*, 2013, Cotton Australia.
19. Cotton Australia, *Cotton Annual 2015*, 2015, Cotton Australia.

20. Tian, Z., et al., *Application effects of coated urea and urease and nitrification inhibitors on ammonia and greenhouse gas emissions from a subtropical cotton field of the Mississippi delta region.* Science of The Total Environment, 2015. **533**: p. 329-338.
21. Macdonald, B.C., I.J. Rochester, and A. Nadelko, *High yielding cotton produced without excessive nitrous oxide emissions.* Agronomy Journal, 2015. **107**(5): p. 1673-1681.
22. Roelandt, C., B. Van Wesemael, and M. Rounsevell, *Estimating annual N2O emissions from agricultural soils in temperate climates.* Global Change Biology, 2005. **11**(10): p. 1701-1711.
23. QLD DAFF, *Pre feasibility study of the commercial viability of a Central Queensland Multi-crop Oilseed processing facility and its impact on grower returns*, F.a.F. Queensland Department of Agriculture, Editor 2013.
24. Cotton Inc. and PE Internatioal AG, *The Life Cycle Inventory & Life Cycle Assessment of Cotton Fiber & Fabric* 2012, Cotton Incorporated, Cotton Council International and National Cotton Council.
25. Systain Consulting, *The carbon and water footprint of cotton made in Africa*, 2013, Aid by Trade Foundation.
26. Moritz, N. and W. Kordula, *The carbon and water footprint of cotton made in Africa*, 2013, Aid by Trade Foundation.
27. PE International AG, *Cotton made in Africa*, 2012, Aid by Trade Foundation.
28. Khabbaz, B.G., *Life cycle energy use and greenhouse gas emissions of Australian cotton: impact of farming systems*, 2010, University of Southern Queensland.
29. Visser, F., et al., *Application of the Crop Carbon Progress Calculator (CCAP) in a 'farm to ship'cotton production case study in Australia.* Journal of Cleaner Production, 2014.
30. Scott, M.K.A., *Organic Material Audit for North West New South Wales* N.D.o.P. Industries, Editor 2012.
31. Janat, M., *Response of Cotton to Irrigation Methods and Nitrogen Fertilization: Yield Components, Water-Use Efficiency, Nitrogen Uptake, and Recovery.* Communications in soil science and plant analysis, 2008. **39**(15-16): p. 2282-2302.
32. Constable, G., I. Rochester, and A. Hodgson, *A comparison of drip and furrow irrigated cotton on a cracking clay soil.* Irrigation Science, 1990. **11**(3): p. 137-142.
33. Hodgson, A., et al., *A comparison of drip and furrow irrigated cotton on a cracking clay soil.* Irrigation Science, 1990. **11**(3): p. 143-148.
34. Antille, L.D. and C.A. McCarthy, *Short-term greenhouse gas emissions from fertigated cotton under furrow and overhead irrigation* in *2015 Australian Cotton Research Conference*2015: Toowoomba.
35. Hulugalle, N., et al., *Managing carbon in cotton-based farming systems*, 2014, Cotton Research and Development Corporation
36. IPCC, *2006 IPCC guidelines for national greenhouse gas inventories volume 4 agriculture, forestry and other land use*, 2006.
37. Linquist, B., et al., *An agronomic assessment of greenhouse gas emissions from major cereal crops.* Global Change Biology, 2012. **18**(1): p. 194-209.
38. Zhang, X., et al. *Evaluating uncertainties in nitrous oxide emission inventories with multi-scale observations for an agriculture-dominated region*. in *AGU Fall Meeting Abstracts*. 2014.
39. Brock, P., et al., *Greenhouse gas emissions profile for 1 tonne of wheat produced in Central Zone (East) New South Wales: a life cycle assessment approach.* Crop and Pasture Science, 2012. **63**(4): p. 319-329.
40. Abeliotis, K., V. Detsis, and C. Pappia, *Life cycle assessment of bean production in the Prespa National Park, Greece.* Journal of Cleaner Production, 2013. **41**: p. 89-96.
41. Australian Government *National Inventory Report 2012*, 2014.
42. RIRDC, *AusAgLCI- A life cycle inventory database for Australian agriculture*, 2014, Rural Industries Research and Development Corporation.
43. Weidema, B., *Avoiding co‐product allocation in life‐cycle assessment.* Journal of industrial ecology, 2000. **4**(3): p. 11-33.
44. McManus, M.C. and C.M. Taylor, *The changing nature of life cycle assessment.* Biomass and Bioenergy, 2015.

45. Thomassen, M., et al., *Attributional and consequential LCA of milk production.* The International Journal of Life Cycle Assessment, 2008. **13**(4): p. 339-349.
46. Ayer, N.W., et al., *Co-product allocation in life cycle assessments of seafood production systems: review of problems and strategies.* The International Journal of Life Cycle Assessment, 2007. **12**(7): p. 480-487.
47. Flysjö, A., et al., *How does co-product handling affect the carbon footprint of milk? Case study of milk production in New Zealand and Sweden.* The International Journal of Life Cycle Assessment, 2011. **16**(5): p. 420-430.
48. Schmidt, J., *System delimitation in agricultural consequential LCA.* The International Journal of Life Cycle Assessment, 2008. **13**(4): p. 350-364.
49. ALCAS, *Australian Life Cycle Inventory Database (AusLCI)*, A.L.C.A. Society, Editor 2013: Melbourne.
50. Ecoinvent Centre, *Ecoinvent data v3.1*, 2013, Swiss Centre for Life Cycle Inventorie: Dübendorf.
51. PRé Consultants, *SimaPro software*. Website: https://www.pre-sustainability.com/simapro, (accessed December 2013), 2008.
52. NSW DPI, *Full hand feeding of beef cattle – management*, N.D.o.p. Industries, Editor 2007.
53. VIC DEPI, *Feed Value of Selected Foodstuffs*, V.D.o.E.a.P. Industries, Editor 2002.
54. Weightman, R., et al., *Nutritional value of oilseed rape and its co-products for pig and poultry feed: potential improvements and implications for plant breeders*, 2014, HGCA.
55. Khabbaz, B.G., G. Chen, and C. Baillie. *Energy and greenhouse gas emissions of Australian cotton: from field to fabric*. in *Proceedings of the XVIIth World Congress of the International Commission of Agricultural and Biosystems Engineering (CIGR 2010)*. 2010. International Commission of Agricultural and Biosystems Engineering (CIGR).

**Appendix C: Abstract submitted to 2016 International Irrigation Conference**

# The effect of pressurised irrigation technologies on the life-cycle climate change impact of crops

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## ABSTRACT

Water is a major limiting factor for crop production in Australia and in many other countries. Pressurised irrigation uses less irrigation water than conventional irrigation technologies, making it an attractive means to maximise crop production per unit of irrigation water used. However, there are concerns about the implications of pressurised irrigation on the life-cycle climate change (CC) impact of crops. This paper compares the CC implications of pressurised irrigation technologies against conventional irrigation technologies. Here we consider furrow irrigation (FI) to represent conventional irrigation technologies and Centre Pivot (CP) technology to represent pressurised irrigation.

We used the cotton production system in North West New South Wales (Australia) as a case study, where more than 95% of cotton is irrigated. While FI technology is the dominant irrigation technology in the system, there are recent examples of CP technology in the region. Differences in the source of irrigation water supplied, as well as energy sources makes the cotton system an appropriate case study.

We used the Life Cycle Assessment (LCA) method to compare the CC implications of CP and FI technologies. The LCA method allowed us to measure and compares the CC implications of the FI and CP irrigation technologies, not only at the farm-level but also at the pre-farm-level, where the diesel and electricity are produced. The life-cycle stages in the LCA assessment are pre-farm, on-farm, and post-farm.

Our results indicated that the life-cycle CC impacts of 1 tonne of irrigated cotton lint at port (the functional unit) are 1600 kg $CO_2$e and 1890 kg $CO_2$e for FI and CP technologies, respectively. While CP technology reduces irrigation water by ~ 30% compared to FI technology; CP increases the life-cycle CC impact of 1 tonne cotton by ~ 18%. The excess CC impact can be balanced if either the yield of cotton lint is increased by ~ 18%, or the nitrogen (N) fertiliser application rate is reduced by ~ 26%. The excess CC impact could also be achieved by both increasing the lint yield and decreasing the N application rate, each by ~ 10%.

The methodology used in this paper is general enough to be used in other crop systems; however, the ‘magnitude of effect’ of CP technology on the life-cycle CC impact of other crops could be different to those reported in this paper. This is attributed to the fact that the implications of pressurised irrigation systems on the life-cycle CC impact of crops are ‘crop-specific’ and ‘region-specific’. This paper recommends further field-based research to identify and measure other effects of pressurised irrigation technologies on the life-cycle CC impact of crops, especially the effects on the soil nitrous oxide ($N_2O$) emissions.

## Appendix D: Review of the cotton LCA studies

This appendix discusses the Australian and international studies aimed to calculate the life-cycle GHG emission associated with the production of cotton.

## 1. Australian studies

### 1.1 Visser et al. (2014)

The study used a carbon footprint tool called Crop Carbon Progress Calculator (CCAP) to calculate the carbon footprint of irrigated cotton in a farm based in Dalby district of the Darling Downs region in Queensland. The results are presented in both GHG emissions per 1 ha of cotton land and per 1 bale of cotton lint at the gin bale press. The considered cotton farm in the study supplied around half of its used nitrogen fertiliser from the synthetic fertilisers of urea and anhydrous ammonia and another half from manure. As such, the study considered ~550 kg CO2e/ha GHG emissions credit for the carbon sequestration associated with the application of manure (the carbon inputs to the soil from the applied manure). The study also investigated a scenario in which the gin trash produced in the farm (composted in the gin plant) would return to the soil and used as fertiliser. The study concluded that the scenario would produce a net carbon credit of 493 kg CO2e per ha.

No information is available in the study regarding the applied allocation procedure for assigning the calculated GHG emissions between cotton lint and seed. Presumably, the study assigned the total calculated GHG emissions per ha to cotton lint. No information is also provided in the study about the inclusion of N2O emissions from the decomposition of cotton residues in the assessment. As such, the study might have excluded that GHG emission source from its assessment.

### 1.2 AusLCI database (2014)

The AusAgLCI life cycle inventory database [42] provide the inventory data (for the cradle to gin bale press basis) for cotton production in three Australian cotton growing regions called ‘central zone’, ‘northern zone’, and ‘southern zone’. For the ‘central zone’ region, the inventory for both irrigated and rainfed cotton are available whereas the inventory for irrigated cotton is available for the two other regions. The inventory provides the opportunity to calculate the CC impact of cotton production in Australia with and without the inclusion of CO2 absorbed by cotton crop during its growth and the CO2 emissions from the decomposition of cotton residues in the field. The database is the current most comprehensive resource to calculate the CC impact and other environmental impacts of cotton production in Australia. CRDC commissioned a consulting company (Life Cycle Strategies), who was involved in the development of AusAgLCI to make a comparison between the environmental impacts of cotton production in Australia versus the corresponding impacts reported in a global study [24].

### 1.3 Tan et al. (2010)

The study calculated the CC impact of cotton production in a ‘cradle to farm gate’ basis for some case studies in Namoi Valley. The study provides a detailed profile of the GHG emissions of the case studies. No allocation has been applied to assign the calculated CC impact to cotton lint and cotton seed and the results are based on 1t of seed cotton at the farm gate. No information is available in the study regarding the N2O emissions associated with the decomposition of cotton residues in the field, as this aspect was not included in the NIR at the time. As such, that GHG emission source might have been excluded in the study.

### 1.4 Khabbaz et al. (2010)

The study calculated the energy and GHG emissions of Australian cotton in a cradle to gin bale press basis. The results are reported based on the GHG emissions per 1 ha of cotton land. The Khabbaz, Chen [55] study is based on a master thesis conducted by the lead author [28] conducted at University of Southern Queensland in which the energy and GHG emission associated with cotton production in some case studies in Queensland was calculated.

### 1.5 Maraseni et al. (2010)

The study quantified the GHG emissions from three farming systems in the Darling Downs region of southern Queensland in a ‘cradle to farm gate’ basis. The results are reported in both GHG emissions per 1 ha of cotton land and per 1 t of cotton lint. No information is available regarding the allocation procedure to assign the total calculated GHG emissions to cotton lint and seed; as such, he study might have assigned all of the emissions to cotton lint. There is also a lake of information about the inclusion of N2O emission from the decomposition of cotton residues in the field. Thus, that emission source might have been excluded from the assessment. The study provides the GHG emissions for rainfed and irrigated cotton separately.

## 2. International studies

### 2.1 ‘Cotton Inc. and PE International’ study

The Cotton Foundation funded a project called “Life Cycle Assessment of Cotton Fibre and Fabric” and managed by Cotton Incorporated (Cotton Inc.), Cotton Council International and the National Cotton Council. The project was conducted by Cotton Inc. and PE International (now called Thinkstep). We refer this study as ‘Cotton Inc. and PE International’ study hereafter and cited as [27].

The study was conducted in 2012 and was based on the ‘cradle-to-grave’ basis (i.e. from the extraction of raw materials to the end-of-life stage of a cotton-made garment). The environmental impact categories included in the study are: acidification potential, eutrophication potential, global warming potential, ozone depletion potential, photochemical ozone creation, primary energy demand, water used, water consumed, ecotoxicity potential, and human toxicity potential. Cotton fibre production data were collected by production regions within the USA (4 regions), China (3 regions), and India (3 regions) and represented the years 2005 to 2009 (averaged to reduce variation due to weather and other environmental conditions). The USA, China, and India were considered to represent 67% of the world’s cotton fibre production in 2010.

With regard to the CC impact of cotton production, the study calculated as 1808 kg CO2e for 1 t cotton lint at gin bale press. The main GHG emissions sources was identified as fertiliser production (~32%), field emissions (~24%), ginning process (~19%), tractor operation (~11%), and transport (~2%). The study also assigned a GHG emissions credit, equals to 8% of the total GHG emissions, for the nutrient transferred from the previous rotated crop to the cotton system (called crop rotation credit in the study). Little information is available in the study about the given GHG credit.

## 2.2 ‘Cotton made in Africa’ studies

In 2005, the Aid by Trade Foundation (AbTF) funded an initiative called ‘the cotton made in Africa (CmiA)’ to advance the cultivation of sustainable cotton and increasing its market share internationally[26]. To date, the AbTF has funded two LCA studies to assess the environmental impact of lint cotton produced under the requirements of CmiA verification scheme. The first study was conducted by Systain Consulting [26] and the second study was conducted by PE International AG that is now called Thinkstep [27]. These two studies are briefly described below.

### 2.2.1 Systain Consulting study

The study [25] analysed the carbon footprint (CF) and the water footprint (WF) of cotton production in Africa. The CF evaluation was carried out based on requirements of the of Intergovernmental Panel on Climate Change [36] for carbon accounting .with regard to the CF aspect, the study calculated the CF of CmiA as 1.92 kg CO2e and concluded that the CmiA is significantly better than average conventional cotton, which calculated to have a CF of 4.64 kg CO2e. Key drivers of CmiA’s carbon foot-print are reported to be: mineral fertiliser production (52%), N2O fertiliser soil emissions (17%) and livestock emissions due to the use of draft animals (12%). In contrast, the key GHG emission drivers of conventional cotton reported to be: mechanical energy (34%), fertiliser production (33%) and fertiliser soil emissions (10%).

The CF was evaluated as production-weighted averages for both CmiA and conventional cotton. The cotton production data for seven countries in Africa (Benin, Burkina Faso, Côte d´Ivoire, Malawi, Mozambique, Zambia, and Cameroon) used for CmiA and the cotton production data for eight countries (China, India, USA, Pakistan, Brazil, Uzbekistan, Turkey, and Australia) used for the conventional cotton. These countries were considered to represent around 85% of the total global cotton lint production in 2009. The study also provided a comparison between the CFs of different regions involved in the assessment (Figure 6).

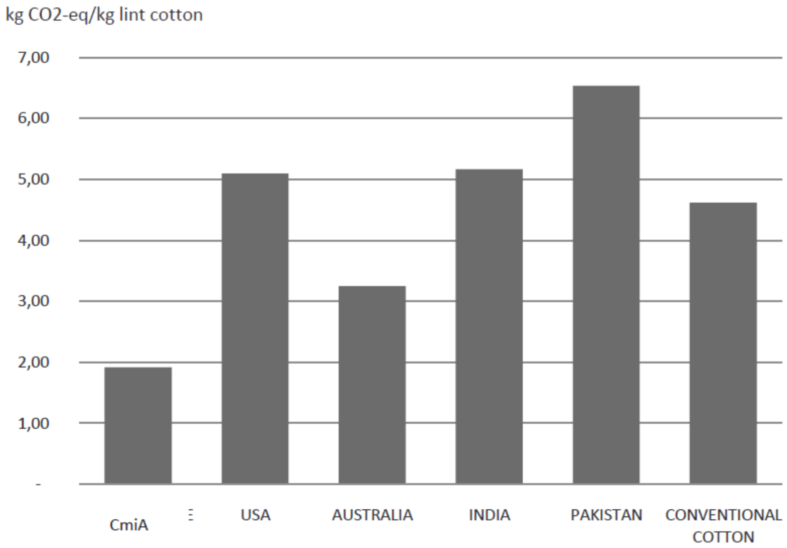

**Figure 6: Comparison of carbon footprints of different farming systems as calculated in the Systain Consulting study**

As sown in Figure 6, the CF of conventional cotton grown in Australia was calculated to be around 3.1 kg CO2e per kg of lint, lower than the average CF for conventional cotton (~4.6 kg CO2e per kg of lint). The study attributed the lower CF of Australian cotton to its high lint yield, around 43% more than the lint yield considered for USA. As such, in compare to USA, the total GHG emissions for Australia is spread over more weight of cotton lint and thus results in lower CF value per kg of cotton lint.

### 2.2.2 PE International Study

As opposed to Systain Consulting study, the PE International study considered only Zambia and Ivory Coast as the representatives of the African countries in the CmiA assessment but included more environmental impact categories in the assessment (climate change, eutrophication, acidification, water use/consumption). The PE International study also did not compare the impacts for the different regions nor calculated the environmental impacts of conventional cotton cultivation.

As per climate change indicator, the PE International study calculated the potential impact on climate change of CmiA cultivation as 1037 kg CO2e for 1 t of cotton lint. The most significant GHG emission source throughout the supply chain (cradle to gin bale press) was identified as agriculture, contributing to about two third (84%) of the total GHG emissions. Other GHG emission sources identified as the GHG emissions associated with the ginning process (~12%) and transport (~4%). In the agriculture stage of CmiA assessment, about two third of the emissions sourced from on-farm stage and one-third of the GHG emissions came from the pre-farm stage of cotton production. The latter included the production of N fertiliser (~16%) and pesticide production (~5%). The practice of burning cotton residue in the field was calculated to contribute around 8% of the GHG emissions of the agriculture stage.

## 3. Comparison of the international studies

This section compares the results of the international LCA studies in which the CC impact of conventional cotton cultivation in the global level were calculated. These include the PE International AG [27] study and the Systain Consulting [25] study. While the functional unit of both studies were similar (i.e. one t of cotton lint at gin bale press), the CC impact calculated in the studies are greatly different (~1800 kg CO2e for the Cotton Inc. and PE International study and ~4600 kg CO2e for 1 t cotton lint). Given the lack of sufficient information available in the published version of the studies, it is challenging to identify the exact reasons causing this difference. However, the following reasons might partially justify the difference.

1. In the Systain Consulting [25] study, the calculated CC impact of cotton system has been assigned to cotton lint only; whereas, the impact has been allocated to both cotton lint and cotton seed in the PE International AG [27] study.
2. The GHG emission accounting in the Systain Consulting [25] study is based on requirements of the of Intergovernmental Panel on Climate Change [36]; whereas a process-based agrarian simulation model developed by PE International and the University of Stuttgart, Germany, was used for cotton production and cultivation. This model covers a multitude of input data, emission factors, and parameters [24].
3. Possible calculation errors in the Systain Consulting [25] study. The average global lint yield in the Systain Consulting [25] study is about half of the corresponding figure in the Cotton Inc. and PE Internatioal AG [24] study (~0.7 t lint/ha versus ~1.3 t lint/ha) . This could be mainly related to the misinterpretation of the yield data (using cottonseed data instead of the seed cotton data) in the Systain Consulting study. As such, in compare to the Systain Consulting study, in the Cotton Inc. and PE Internatioal AG [24] study, the total calculated GHG emission per ha is divided over more weight of cotton lint in compare. This results in lower CC impact per unit of cotton lint in the Cotton Inc. and PE Internatioal AG [24] study in compare to the Systain Consulting [25].

## Attachments

### Attachment A: Calculations relating to $N_2O$ emissions from cotton residues

Refer attached spreadsheet.

### Attachment B: Calculations relating to biogenic $CO_2$

Refer attached spreadsheet.

### Attachment C: Emission factor relating to the production of nitrogen fertilisers

Refer attached spreadsheet.

### Attachment D: Unpublished industry survey used in the study

Refer attached spreadsheet.