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Article *in* The International Journal of Life Cycle Assessment · December 2021

DOI: 10.1007/s11367-021-01994-y

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The International Journal of Life Cycle Assessment (2021) 26:2321–2338
https://doi.org/10.1007/s11367-021-01994-y

The environmental consequences of a change in Australian cotton lint production

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Received: 23 February 2021 / Accepted: 25 October 2021 / Published online: 9 November 2021

Abstract

Purpose Changes in the production of Australian cotton lint are expected to have a direct environmental impact, as well as indirect impacts related to co-product substitution and induced changes in crop production. The environmental consequences of a 50% expansion or contraction in production were compared to Australian cotton production's current environmental footprint. Both were then assessed to investigate whether current impacts are suitable for predicting the environmental impact of a change in demand for cotton lint.

Methods A consequential life cycle assessment (LCA) model of Australian cotton lint production (cradle-to-gin gate) was developed using plausible scenarios regarding domestic regions and technologies affected by changes in supply, with both expansion (additional cotton) and contraction (less cotton) being modelled. Modelling accounted for direct impacts from cotton production and indirect impacts associated with changes to cotton production, including co-product substitution and changes to related crops at regional and global scales. Impact categories assessed included climate change, fossil energy demand, freshwater consumption, water stress, marine and freshwater eutrophication, land occupation and land-use change.

Results and discussion For both the expansion and contraction scenarios, the changes to climate change impacts (including iLUC) and water impacts were less than would be assumed from current production as determined using attributional LCA. However, the opposite was true for all other impact categories, indicating trade-offs across the impact categories. Climate change impacts under both scenarios were relatively minor because these were largely offset by iLUC. Similarly, under the contraction scenario, water impacts were dominated by indirect impacts associated with regional crops. A sensitivity analysis showed that the results were sufficiently robust to indicate the quantum of changes that could be expected.

Conclusions A complex array of changes in technologies, production regions and related crops were required to model the environmental impacts of a gross change in cotton production. Australian cotton lint production provides an example of legislation constraining the direct water impacts of production, leading to a contrast between impacts estimated by attributional and consequential LCA. This model demonstrated that indirect products and processes are important contributors to the environmental impacts of Australian cotton lint.

Keywords Cotton · cLCA · Water · Climate change · Land-use change

1 Introduction

Cotton lint is the most important natural fibre used in the textile industry (Textile Exchange 2020) and is a key agricultural commodity in Australia. Australia is the fourth largest exporter of cotton lint worldwide (USDA 2020) with the majority of cotton lint exported being characterised by its high quality (van der Sluijs 2004): fibres of premium length (29–32 mm) and superior strength (29–34 g of force per tex) (Australian Cotton Shipper Association 2020). As with all products, cotton lint production is associated with environmental impacts, such as greenhouse gas (GHG) emissions,

Communicated by Sarah Jane McLaren.

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freshwater consumption for irrigation, the release of nutrients into the environment and the depletion of fossil energy resources. The threat that climate change poses to humanity (IPCC 2015) means the GHG emissions associated with Australian cotton production have been studied. Multiple studies have examined the carbon footprint of Australian cotton production, all with different production systems (i.e., dryland or irrigated), and various spatial and system boundaries (Maraseni et al. 2010; Tan et al. 2013; Powell et al. 2017; Hedayati et al. 2019). Hedayati et al. (2019) adjusted the values from these studies to a consistent system boundary of cradle-to-port. They showed that cotton lint production had a carbon footprint of 1129 to 3088 kg CO_2-eq per tonne of lint. By comparison, Cotton Inc. (2016) in their global study reported a cradle-to-gin gate carbon footprint of 1500 kg CO_2-eq per tonne of lint. These results reflected the direct impacts from cotton production but lacked an assessment on the indirect impacts derived from co-products, and more importantly, the interaction between cotton and other crops in cotton-growing regions.

Regarding water use, reliable data are available that benchmark irrigation water use, but few studies have assessed water use across the whole cotton lint supply chain. One study reported blue water consumption of 3287 m^3 per tonne of Australian cotton lint for the farm stage, which was below the global average of 4242 m^3 per tonne of lint (Chapagain et al. 2006), but this was not determined from a detailed regional analysis and was based on data that are now dated. Blue water refers to water that was withdrawn from surface or groundwater resources, and is distinct from 'green water' accessible by plants in their root zone, derived from rainfall (Falkenmark 1995). Cotton Inc. (2016) in their study of the global cotton, reported water consumption of just 1559 m^3 per tonne of lint and water stress, as defined by Pfister et al. (2009), of 1993 L H_2O-eq kg^{-1} lint. Other footprints of global cotton production (excluding credits) were fossil energy demand of 14.8 MJ, land occupation of 21.2 m^2a, and eutrophication of 8.5×10^{-3} PO_4-eq kg^{-1} lint. Irrigation, fertilizer production and field emissions were hotspots for environmental impacts during cradle-to-gin gate cotton production (Cotton Inc. 2016).

Reducing the water footprint of global conventional cotton production by replacing 30% of cotton use with polyester was identified as a way in which the fashion industry could reduce its environmental footprint (GFA and BCG 2017). However, the use of attributional life cycle assessment (aLCA) to determine this and the other footprints cited above to inform procurement decisions may be misleading because this life cycle assessment (LCA) methodology estimates the impacts of current production and does not consider the consequences of a change in demand for a particular product on total impacts (Plevin et al. 2014). For example, an increase in the growing area of cotton production in Australia's Murray-Darling basin during the 2015–2016 season increased the amount of water used for cotton. This increase in cotton production also reduced the water utilised for rice crops and irrigated pasture grazing (for dairy) (Gupta and Hughes 2018a). In this case, the regional water stress was not affected negatively by the increased cotton production, because the irrigation water was transferred from other irrigated crops to cotton. At the global scale, it is likely that the reduction of the regional crop production of Australian rice in the Murray-Darling basin induced an increase in demand for rice from suppliers elsewhere. Thus, well-intentioned recommendations for changes to cotton production may change the volume of water consumed by the industry but may have unforeseen subsequent effects at scales ranging from regional to international in crops or commodities other than cotton. The environmental impacts associated with these changes cannot be understood accurately without considering these indirect effects. Further, not accounting for indirect effects related to co-products has been shown to cause misleading findings in other agricultural systems. For example, Gollnow et al. (2014) concluded that increasing milk production per cow in a dairy system would reduce the carbon footprint of milk production. However, an earlier study that included the market effects of co-production (Zehetmeier et al. 2012) found that increasing milk production per dairy cow would not reduce its emissions intensity when both milk and beef production (as a co-product of milk production) remained the same. This difference occurred because fewer dairy cows were required to produce the same volume of milk, resulting in fewer calves for meat production, which induced demand for beef from other systems. Similarly, cottonseed is a major co-product in cotton production, and the implications of a change in cotton production would need to account for changes in cottonseed availability and the different impacts from its substitutes. Cottonseed can be crushed for cottonseed oil (used for human consumption) and cottonseed meal (used for animal consumption). A decline in these co-products would induce demand for, and therefore additional production of, marginal sources of oil (e.g., palm oil) and protein feed (for example, soy meal), to maintain global supplies of these commodities.

The influence of changes in co-product supply and demand was also found to be influential in assessing environmental impacts from wool. Wiedemann et al. (2018) showed that the production of an additional kilogram of fine Merino wool was likely to result in between 42 and 57% less GHG emissions than those estimated for current production because of the substitution effects arising from the co-product system. Further, increasing wool production could reduce the water stress impacts and fossil energy demand of the product, reversing the trend inferred from the environmental footprint of its current production, when avoided impacts from co-products such as sheep meat are also taken into account. The environmental consequences of a change in Australian cotton production are also likely to differ from the impacts of current production when impacts from co-products and market effects are also considered. Thus, understanding the environmental consequences of a change in Australian cotton production is essential to ensure that decisions or policies implemented to reduce environmental impacts achieve that outcome. Accordingly, the present study's purpose was to examine the environmental consequences of plausible scenarios leading to an expansion or contraction of Australian cotton lint production. The analyses included the market effects of changes in co-production and displaced or induced related crop production, and sensitivity analysis was used to test key assumptions.

2 Methods

2.1 Goal and scope of the study

This study aimed to assess the environmental consequences of expansion or contraction of Australian cotton production by 50%, relative to the average production for 2016–2018, inclusive. This change equated to an increase or decrease in cotton lint production, of 390 kt year^{-1} (Table 1). The system boundary (Fig. 1) was 'cradle-to-gin gate' (i.e., cotton lint ready for transport after being separated from the cottonseed and vegetable matter by ginning processes). The study used a consequential life cycle assessment (cLCA) approach that was compliant with LCA international standards ISO

Table 1 Production statistics for current cotton lint production and production under expansion and contraction pathways[a]

Parameter		Unit	INZ	ICZ	ISZ	DCZ
Current lint production[b]						
Area		ha	31,438	220,166	50,509	122,739
Yield		kg ha^{-1} yr^{-1}	2188	2351	2231	664
Production (cotton lint)		kt yr^{-1}	69	518	113	82
Co-production (cottonseed)		kt yr^{-1}	79	592	129	93
Production contribution (mass basis)[c]		%	8.8	66.3	14.4	10.4
Irrigation water required		ML yr^{-1}	205,394	1,578,170	486,893	0
Expansion						
Additional area		ha yr^{-1}	39,343	24,466	58,085	176,294
Total area		ha yr^{-1}	70,781	244,632	108,594	299,034
Additional production (cotton lint)		kt yr^{-1}	86	58	130	117
Additional co-production (cottonseed)		kt yr^{-1}	98	66	148	134
Additional irrigation water required		ML yr^{-1}	234,210	0	0	0
Crop production displaced to global production	Chickpeas	kt yr^{-1}	−90	−12	−6	0
	Wheat	kt yr^{-1}	0	0	0	−89
	Canola	kt yr^{-1}	−109	−15	0	−4
	Sorghum	kt yr^{-1}	0	0	0	0
	Beef	kt yr^{-1}	0	0	−7	0
	Rice	kt yr^{-1}	0	0	0	−413
Contraction						
Decrease in area		ha yr^{-1}	0	142,779	17,491	23,506
Total area		ha yr^{-1}	31,438	77,387	33,018	99,234
Decrease in production (cotton lint)		kt yr^{-1}	0	336	39	16
Decrease in co-production (cottonseed)		kt yr^{-1}	0	384	45	18
Irrigation water made available		ML yr^{-1}	0	1,023,453	168,606	0
Crop production induced	Chickpeas	kt yr^{-1}	12	0	0	0
	Wheat	kt yr^{-1}	0	421	0	0
	Canola	kt yr^{-1}	0	0	0	0
	Sorghum	kt yr^{-1}	0	714	0	0
	Rice	kt yr^{-1}	0	0	0	138

[a]Production zone abbreviations are explained in Sect. 2.2

[b]Weighted average value for the years 2016–2018 reported by ABS (2017a, 2018a, 2019a)

[c]Percentage contribution to total production across all production zones

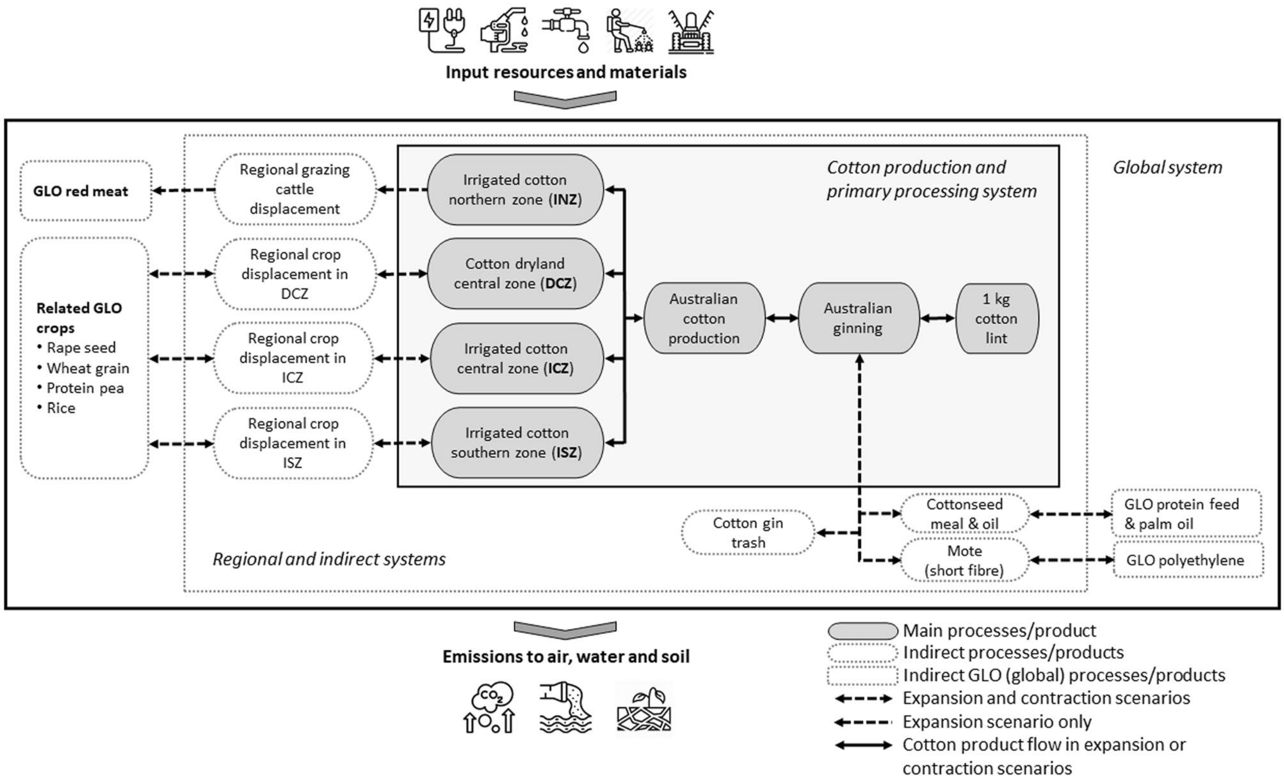

Fig. 1 Cradle-to-gin gate system boundary of Australian cotton production analysed using consequential life cycle assessment (cLCA)

14040 (ISO 2006a) and ISO 14044 (ISO 2006b). The generic framework and guidelines for cLCA suggested by Weidema et al. (2009) were adopted, and the market effects of changes to cotton lint production (see Sect. 3 of the supplementary material) were included. For comparison, an attributional LCA analysis was performed to determine the environmental impacts of 1 kg Australian cotton lint of the current system using economic allocation for co-products (i.e., 14% of cottonseed and 86% of cotton lint) (ALCAS 2015). Methods describing this are reported in the supplementary materials (Sect. 1).

The functional unit (FU) was dependent on the analysis (e.g., expansion, contraction of the current system). For the expansion and contraction analyses, the FU was 1 kg of additional cotton lint, and 1 kg of less cotton lint per year, respectively. The FU of the current system was 1 kg of average Australian cotton lint. These FUs were chosen for relevance to the goal of the study, to downstream supply chain processes and to the reference point for inventory data collection.

2.2 Expansion and contraction pathways

A large-scale change in Australian cotton production due to changes in demand for cotton fibre at the global scale was considered to affect all the major cotton production zones. Commodity prices were assumed to be inelastic in response to this change. This study assessed four major Australian cotton production zones: three irrigated (i.e., Irrigated Northern, Irrigated Central and Irrigated Southern Zones: INZ, ICZ and ISZ, respectively) and one dryland production zone (Dryland Central Zone: DCZ). Descriptions of these zones are found in Fig. 1 and Table 1, and in the supplementary materials (Sect. 1, Table S1, Fig. S1). In Fig. 1 and elsewhere, GLO refers to 'global' and is used to represent average production across all countries. Each production zone's contribution to the changes was determined based on their relative contribution to current production, improvement in productivity and availability of resources, such as available cropland and water.

2.2.1 Expansion of Australian cotton production by 50%

The expansion was assumed to occur in all the cotton production zones via a combination of four pathways. The first pathway (P1) used a change in irrigation methods from furrow to centre-pivot/lateral move (CPLM) to increase irrigation water use efficiency (IWUE) across all irrigated cotton production zones. The IWUE of irrigated Australian cotton improved by approximately 40% during the 2001–2012 period (Roth et al. 2013), and by 29% for the last 5 years from an average of 0.7 to 0.5 ML per bale of lint (NSW

DPI 2019). It was assumed that a modest IWUE improvement of 10% was achievable for irrigated Australian cotton in the future. The yield of Australian irrigated cotton production is water-limited (Constable and Bange 2015) – increasing IWUE was not expected to result in higher yields but rather provide more water to expand the area planted to cotton. This increase in land use required the conversion of land occupied for dryland cropping to irrigated cotton production.

The second pathway (P2) occurred via the expansion of cotton into river catchments with available but undeveloped irrigation water and very low water stress index. This expansion was assumed to occur in the Mitchell (Yeates et al. 2014) and the Flinders and Gilbert River catchments of northern Queensland (far-north). This expansion was assumed to convert land from non-irrigated, low-input extensive beef grazing to irrigated cotton production (Fig. 1).

The third expansion pathway (P3) occurred in the ISZ and related to the displacement of irrigated rice by cotton. Water is commonly traded between enterprises and from crops with low economic value to high-value crops (Goesch et al. 2019). For example, 32% of broadacre farms (cotton and rice) and 47% of horticulture farms traded their allocations between 2008 and 2011 (National Water Commission 2011). Hence, it was assumed that P3 did not increase the demand for irrigation water because it was transferred from rice production. The current water application rate at ISZ cotton is 9.6 ML ha^{-1} (Table 2), while it was 11.5 ML ha^{-1} for irrigated rice (Troldahl et al. 2018). Therefore, the irrigation water for 0.83 ha of rice would be needed to irrigate 1 ha of cotton. This required that 0.17 ha of land occupied for dryland cropping be converted to irrigated cotton production.

In P1 to P3, the capacity for cotton to expand in each zone was determined by the availability of irrigation water (where

Table 2 Key inventory data for current cotton lint production in the dryland central zone (DCZ), irrigated central zone (ICZ), irrigated northern zone (INZ) and irrigated southern zone (ISZ)

Parameter	Unit	INZ	ICZ	ISZ	DCZ
Source of water supply[a]					
Irrigation schemes	%	20	5	44	0
Groundwater	%	22	21	20	0
Streams (e.g., rivers, creeks, lakes)	%	32	48	34	0
On-farm storage (e.g., farm dams or tanks)	%	27	26	2	0
Total supply losses	%	11	11	6	0
Irrigation method and application rate					
Centre pivot/lateral move (CPLM)[b]	%	18.0	25.3	7.7	0
Furrow irrigation[c]	%	82.0	74.7	92.3	0
Water applied[c]	ML ha^{-1}	6.53	7.17	9.64	0
Energy use					
Diesel, pumping water[b]	L ha^{-1}	23	118	23	0
Electricity, pumping water[b]	kWh ha^{-1}	2	47	2	0
Diesel, field operations	L ha^{-1}	98	120	98	123
Fertiliser application and emissions factors[c]					
Total N applied	kg N ha^{-1}	304	264	290	38
Total P applied	kg P ha^{-1}	44	44	44	23
Total K applied	kg K ha^{-1}	48	24	53	3
Emission factors					
EF_1[d]	%	2.08	0.75	1.41	0.29
FrachLEACH_N[e]	%	8.5	8.5	8.5	3.0
FrachLEACH_P[f]	%	1.1	1.1	1.1	0.4
FracWET		1.00	1.00	1.00	0.16

[a]Weighted average value for the years 2016–2018 reported by ABS (2017b, 2018b, 2019b)

[b]Averaged portion of irrigation method reported by CRDC (2019)

[c]Fertiliser inputs relative to lint yield were determined from surveys (CRDC 2017b, 2018, 2019), and totals were determined based on the yield data reported by the ABS (2017a, 2018a, 2019a)

[d]Direct emissions from N-fertiliser application calculated based the exponential equation of Grace et al. (2016)

[e]Estimated for irrigated Australia cotton, adjusted with tailwater recycling (see Supp. Sect. 6.1)

[f]Fraction of applied N lost to leaching and runoff, estimated for irrigated Australia cotton, adjusted with tailwater recycling (see Supp. Sect. 6.1)

relevant) and land area, and these limits are summarised in Table S2. The fourth expansion pathway (P4) occurred in the DCZ, where an increase in dryland cotton lint production displaced dryland cereal crops. The increase in production under P4 accounted for the residual supply not contributed by P1, P2 and P3 – of these pathways, P3 and P4 were the largest, followed by P2 (Table S2).

2.2.2 Contraction of Australian cotton production by 50%

A 50% contraction of Australian cotton production was assumed to occur across the ICZ, ISZ and DCZ in response to a reduction in the global demand for cotton fibre (Table 1). In terms of crop mass, the greatest reduction (65% in relative terms) was modelled for the ICZ (Table 1), which accounted for two-thirds of current Australian cotton production (Table 1). Smaller reductions were modelled for the ISZ and DCZ (35 and 19% in relative terms) based on their contribution to the current system. A reduction in INZ production was not considered in the contraction scenario because the price differential between alternative crops was much larger than that for the other zones, where crops such as rice compete with cotton as the most profitable land use (Booth Associates 2014). Because the relatively high-yielding ICZ made up a large portion of the residual current production (i.e., once the INZ was excluded) (Table 1), compared to the expansion scenario, a relatively small change in total area was required to achieve a 50% contraction in overall production.

Similar to the expansion scenario, it was assumed that the water made available from a contraction of cotton production was reallocated to the crops that replaced the cotton in the same zones. In the ICZ, the available irrigation water was used for irrigated wheat or sorghum production, and in the ISZ the water was used for rice production (Table S3). It was estimated that the amount of available water derived from a decline of 1 ha ISZ cotton could be used to grow 0.83 ha rice (see above). In the ICZ, the current water application for cotton production was 7.2 ML ha^{-1} (Table 2), and it was 2.6 ML ha^{-1} for irrigated sorghum and wheat (Scott 2015). Thus, the water made available from no longer growing 1 ha cotton in the ICZ would be available to irrigate 2.8 ha of irrigated sorghum and wheat. With respect to land occupation, assuming the 1 ha used for cotton was transferred to sorghum and wheat, an additional 1.8 ha could be converted from dryland cropping to irrigated cropping.

2.3 Life cycle inventory

The life cycle inventory (LCI) data included the production and transport of all inputs used in cotton production (e.g., energy, fertiliser, farm chemicals, farm operations), inputs from nature required for cotton production (e.g., land, water) and any outputs from the system (e.g., cotton lint and its co-products). Background data such as the generation and supply of electricity and purchased products (such as fertilisers and chemicals) were sourced from the Australian LCI database (Eady et al. 2014) where available, or the ecoinvent 'consequential' database v3.6 (Wernet et al. 2016). Foreground LCI data for the expansion and contraction pathways was developed based on the current cotton production system (Table 2, Supplementary Materials Sect. 1). This was done using data from the Australian Bureau of Statistics (ABS) and cotton grower surveys for the 3 years of the 2016–2018 seasons (CRDC 2017a, 2018, 2019) as well as relevant literature.

The LCI for related crops, except for rice, that expanded or contracted in response to the change in Australian cotton production were taken from Simmons et al. (2019), with an adjustment for crop yield based on the weighted average for statistical area 4 (SA4) regions (ABS 2016) for the period 2016–2018 (ABS 2017a, 2018a, 2019a) (Tables S4 and S5). An LCI for Australian rice production was developed from input masses used to estimate gross margins (Troldahl et al. 2018). An LCI for pigeon pea sown as a refuge crop was modified from field pea inventory for NSW (Simmons et al. 2019). An LCI for beef production in the far-north regions was sourced from Wiedemann et al. (2015) and modified for local stocking rates. LCI data for the global production of crops and red meat, or their functional equivalent, were sourced from the ecoinvent 'consequential' database v3.6 (Wernet et al. 2016), adjusted with the average yield between 2016 and 2018, and assumed to represent the global market. The use of the consequential database meant that co-production in background data was handled via system expansion, making the approach for handling co-production consistent throughout the model.

Greenhouse gas emissions in the model included CO_2, CH_4 and N_2O, as well as other GHGs most often associated with pre-farm processes. GHGs from LUC were calculated from CO_2 emissions derived from land transformation throughout the supply chain. This included indirect land-use change (iLUC) and direct land-use change (dLUC) impacts. LUC was included for the expansion and contraction scenarios where an increase or decrease in cotton production and co-production induced or avoided LUC. To represent dLUC under the expansion scenario in the INZ, dLUC impacts in the Mitchell River catchment were estimated using FullCAM (Supplementary Sect. 9). Aboveground carbon stocks of native grasslands were 0.18 t C ha^{-1}, and predicted soil organic carbon stocks were greater under irrigated cotton production than for extensive beef cattle production (Fig. S7). To remain consistent with Kyoto Protocol accounting, no dLUC emissions were attributed to irrigated cotton production that expanded into dryland cropping areas as this was classified as 'cropland remaining cropland' (Commonwealth of

Australia 2013). Land transformation outside of Australia in response to the change in crop production was considered an dLUC impact and calculated using the ecoinvent v3.6 'consequential' database (Wernet et al. 2016). iLUC was calculated in accordance with the framework of Schmidt et al. (2015).

For irrigated Australian cotton, a direct emission factor from applied synthetic N-fertiliser (EF_1, where EF refers to an 'emission factor' and the subscript refers to the nomenclature of the IPCC (2006)) for each cotton zone was calculated based on the total N applied using a non-linear exponential equation (a two-component model) (Grace et al. 2016). The indirect N_2O emissions due to atmospheric deposition of NH_3-N originating from synthetic fertilisers (EF_4), for emissions from N-fertiliser leaching and runoff (EF_5), and the mineralisation of crop residues were the values used in Australia's national GHG inventory report to the UNFCCC under the Kyoto Protocol (Commonwealth of Australia 2017). The fraction of fertiliser N available for leaching and runoff (FracWET) was characterised for the average of dryland cotton production in New South Wales (0.246) and Queensland (0.075) (Commonwealth of Australia 2017). Similarly, national inventory report emission factors were used for displaced/avoided crops such as wheat, sorghum, canola and chickpeas (Commonwealth of Australia 2017).

The N_2O emissions from irrigated crops are significantly influenced by the irrigation method used. For irrigated cotton in southern Queensland, Antille (2018) reported that the emissions of N_2O over 30 days were eight times higher for furrow fertigation compared with overhead sprinkler fertigation. Similarly, Maraseni et al. (2012) estimated that soil N_2O emissions were between 25 and 44% lower for CPLM than for furrow irrigated cotton. The present study assumed that the use of CPLM irrigation reduced N_2O emissions from fertiliser use by 50%. GHG emissions associated with on-farm operations, transport of seed cotton from the farmgate to the gin and the ginning process were calculated from the relevant background inventory. Fossil energy demand was assessed by aggregating all fossil fuel energy inputs throughout the system and reporting these per megajoule (MJ) of fossil energy, using lower heating values (LHV). Fossil energy required for the production and transport of all inputs into cotton production was calculated using background inventory data.

Energy use for field operations (Table 2) was based on an energy benchmark for Australian cotton (Chen and Baillie 2009; Cotton Info 2015). The number of in-field operations (i.e., heavy machinery passes over a field to sow, etc.) was based on the AusLCI inventory database for agriculture (Eady et al. 2014), adjusted with the total fuel used per ha (CRDC 2019) and summarised in the Supplementary material (Table S9). The energy was also required to pump water, and an average head pressure was assumed for furrow irrigation and CPLM of 8 and 20 m, respectively (Chen and Baillie 2009). The total energy demand for irrigation included energy to irrigate the fields and energy required for pumping tail water back into the storage dam (for furrow systems). The proportion of diesel and electricity used for pumping was taken from an industry survey (CRDC 2019), and this assumed a pumping efficiency of 80% for electrical pumps and 35% for diesel engines (Foley et al. 2015). Nitrogen (N) fertiliser application rates were estimated for each zone by obtaining the nitrogen use efficiency (NUE) for each cotton zone from three years of data (CRDC 2017b, 2018, 2019) (Table S10) and then calculating the N required to meet the weighted average lint yield (ABS 2017a, 2018a, 2019a). Three forms of fertilisers were considered: urea, anhydrous ammonia and mono-ammonium phosphate (MAP), with the contribution of each type based on fertiliser use in Australian crop production (FAO 2019) (Tables 2, S11 and S12). The mass of P applied as fertiliser was calculated based on the application rate of MAP.

Freshwater consumption refers to water that cannot be released back into the same river catchment due to transpiration/evaporation losses or because it has been incorporated into a product (ISO 2014). The inventory covered all sources and losses associated with foreground and background processes (Tables S6 and S7). For irrigated cotton production, freshwater consumption was estimated as the total of water applied and total water losses before the application, excluding the fraction of tailwater and deep drainage that returned to dams or the river catchment from which it was initially extracted. The same approach was applied for avoided/displaced crops at regional cotton production zones.

For eutrophication impacts, the fraction of P and N fertiliser losses from farms was estimated for Australian irrigated cotton Australia from the literature: 1.1% of the total P applied and 8.5% of total N applied, respectively (Supplementary Sect. 6). All other sources of N and P losses to the environment (e.g., production and transport of system inputs) were calculated from the relevant background inventory processes. The rivers of northern Queensland flow to the Gulf of Carpentaria which is not highly sensitive to nutrient loads. However, the central and southern regions were located inland on river basins where a minimal volume of water flows into the ocean (Argent 2016), so it was assumed that nutrient exports from agricultural fields in the ICZ and ISZ did not contribute to marine eutrophication.

2.3.1 Handling of co-products

Cottonseed, mote (i.e., short lint fibre) and gin trash (i.e., soil and vegetable matter collected with cotton bolls at harvest) are co-products of cotton lint. It was estimated that the lint yield of seed cotton harvested was 41.3%, cottonseed yield was 47.2% and those of gin trash and mote were 10.7% and

0.9%, respectively (van der Sluijs et al. 2017; van der Sluijs 2018). Co-production was handled using a system expansion approach for major and valuable co-products (Fig. 1). For example, cottonseed is a source of oil and protein and can be fed to livestock whole or can be crushed to produce cottonseed oil for human and animal consumption, and cottonseed meal for livestock feed. The cottonseed was assumed to be crushed for oil, so the system expansion assumed that the additional cottonseed oil and cottonseed meal produced avoided equivalent amounts of vegetable oil, as crude palm oil, and crude protein feed for livestock on the global market. Therefore, global market protein feed and palm oil processes from the ecoinvent 'consequential' v3.6 database (Wernet et al. 2016) were used. Mote is a low-grade cotton fibre co-produced in the ginning process that is sold and used to produce other textiles (e.g., bedding and automotive furnishing). It was assumed that the changed supply of mote altered the demand for an equivalent amount of polyethylene terephthalate (PET) fibre in the global market. Gin trash is often returned to cotton fields (van der Sluijs 2017) and was therefore treated as a residual product without substitution.

2.4 Impact assessment

The life cycle impact assessment was done using SimaPro v9.1 (Pré-Consultants 2020) for impact categories of climate change, fossil energy, freshwater consumption, water stress, marine and freshwater eutrophication, land occupation and land-use change (LUC). Impacts are reported under three categories: direct, indirect and net impacts. Direct impacts occur as a result of cotton production and ginning, including impacts associated with production inputs. Indirect impacts are associated with co-products (cottonseed, mote and gin trash) or related crops (and other products, such as red meat and polyethylene terephthalate) produced either at regional or global scales. 'Net' impacts refer to the sum of direct and indirect impacts.

For climate change impacts (GHG emissions), the GWP_{100} (global warming potentials) from the Intergovernmental Panel on Climate Change (IPCC) AR5 report of 28 for methane (CH_4) and 265 for nitrous oxide (N_2O) (IPCC 2015) were used. Biogenic carbon stored in cotton lint and its co-products were excluded from the analysis as is typical for LCA studies that do not include the whole supply chain, including end-of-life emissions. GHG emissions associated with LUC were included and reported separately, following guidance from ISO 14067 (ISO 2018). GHG emissions associated with the production and transport of all system inputs were calculated from background inventory data. Fossil energy impacts were assessed using the AusAgLCI indicator set (ALCAS 2015). Marine and freshwater eutrophication were assessed using the ReCiPe 2016 midpoint method (Huijbregts et al. 2016), and land occupation and LUC were assessed using the AusAgLCI indicator set (ALCAS 2015).

Water stress was determined using regional specific water stress index (WSI) values (Pfister et al. 2009), which were determined for SA4 regions (ABS 2016), using spatial software (Google Earth). The WSI is a mid-point indicator that reflects the freshwater withdrawal-to-availability ratio. The average weighted WSI value was calculated by the irrigated cotton production for each zone (Table S8) and normalised with the global WSI (Ridoutt and Pfister 2010). The same process was used to develop WSI values for crops that were displaced/avoided (e.g., rice in the ISZ) in each zone in response to changes in cotton production, and to determine WSI values for avoided and displaced crops on the global market. For commodities on global markets, WSI values for each crop were estimated for specific countries and weighted based on production area and normalised with the global WSI (Ridoutt and Pfister 2010).

2.5 Sensitivity analysis

A sensitivity analysis was used to examine how assumptions made regarding the current, expansion and contraction of Australian cotton lint production affected results. A series of key parameters for expansion and contraction scenarios were tested which considered the impacts of assumptions made regarding IWUE and the proportion of crops that were displaced/increased because of an expansion/contraction cotton production (Table 3).

3 Results

3.1 Production changes

The production of an additional 390 kt of cotton lint in the model required an additional 0.30 Mha of agricultural land for cotton production. It also produced an additional 446 kt of cottonseed (Table 1). The expansion of cotton lint production displaced the production of 746 kt of agricultural commodities (e.g., rice, canola, wheat) to global marginal production to ensure that the supply of these commodities was maintained. In contrast, a reduction of 390 kt of cotton lint production reduced agricultural land occupied for cotton by 0.18 Mha and reduced the supply of cottonseed by 447 kt $year^{-1}$. The increased supply of agricultural land resulted in an additional 1285 kt of commodities being produced and avoided the production of equivalent alternative products (e.g., sorghum, wheat and rice) on the global market (Table 1).

Table 3 Scenarios to test the sensitivity of parameters used to model the consequences of expanding or contracting Australian cotton lint production

Scenario[a]	Parameter	Description
Exp 1	Rice displacement in pathway 3 (80%)	The proportion of crop displaced as rice in the ISZ increased from 73 to 80%
Exp 2	Rice displacement in pathway 3 (100%)	The proportion of crop displaced as rice in the ISZ increased from 73 to 100%
Exp 3	IWUE in pathway 1 and expansion occurring via pathway 2	IWUE improvement in pathway 1 increased from 10 to 20%, and the proportion of expansion occurring via pathway 2 increased from 4.4 to 8.8%
Exp 4	IWUE in pathway 1, rice displacement in pathway 3 and expansion via pathway 4	IWUE improvement in pathway 1 increased from 10 to 20%, the proportion of crop displaced as rice in the ISZ increased from 73 to 100% and expansion occurring via Pathway 4 increased from 30 to 40%
Exp 5	IWUE in pathway 1, rice displacement in pathway 3, the proportion of expansion via pathways 2 and 4 (a)	IWUE improvement in pathway 1 increased from 10 to 20%, the proportion of crop displaced as rice in the ISZ increased from 73 to 80%, the proportion of expansion occurring via pathway 2 increased from 4.4 to 8.8% and the remainder of expansion occurring via pathway 4
Exp 6	IWUE in pathway 1, rice displacement in pathway 3, the proportion of expansion via pathways 2 and 4 (b)	IWUE improvement in Pathway 1 increased from 10 to 5%, the proportion of crop displaced as rice in the ISZ increased from 73 to 100% and expansion occurring via pathway 4 increased from 30 to 60%
Exp 7	Rice displacement in pathway 3, the proportion of expansion via pathways 2 and 4 (a)	150% of expansion occurring via pathway 4, only dryland wheat avoided in pathway 1 and remaining expansion occurring in pathway 2
Exp 8	Rice displacement in pathway 3, the proportion of expansion via pathways 2 and 4 (b)	200% of expansion occurring via pathway 4, only dryland wheat avoided in pathway 1 and remaining expansion occurring in pathway 2
Contr 1	Water availability in the ICZ and ISZ, and proportion of contraction occurring in the DCZ	Water available for cotton production in the ICZ and ISZ reduced by 50% and remaining contraction occurring in the DCZ
Contr 2	Water availability in the ICZ and ISZ, rice production in the ISZ and the remainder of contraction occurring in the DCZ	Water available for cotton production in the ICZ and ISZ reduced by 50%, only dryland wheat replaced irrigated cotton production in the ISZ and remaining contraction occurring in the DCZ
Contr 3	Water availability in the ICZ and ISZ, irrigated cereal production in ICZ and the remainder of contraction occurring in the DCZ	Water available for cotton production in the ICZ and ISZ reduced by 50%, only dryland wheat replaced irrigated cotton production in the ICZ and remaining contraction occurring in the DCZ

[a] 'Exp' and 'Contr' represent 'expansion' and 'contraction' scenarios, respectively

3.2 Impacts from the expansion of cotton production

The modelled expansion of cotton production resulted in changes to both direct and indirect impacts. Changes in indirect impacts were associated with regional crop displacement and induced crop production in the market (Fig. 2). Direct GHG impacts from expansion were slightly higher than impacts from the current production (Fig. S3). When indirect impacts (excluding iLUC) were accounted for, the total impact was 3.0 kg CO_2-eq kg^{-1} lint (Fig. 2). These indirect impacts included a minor reduction in impacts due to co-products (displacement of protein feed and palm oil at the global scale by cottonseed as livestock feed: −0.3 kg CO_2-eq kg^{-1} lint), a larger reduction in impacts due to regional crop displacement (−1.0 kg CO_2-eq kg^{-1} lint), and a large increase in impacts due to induced crop production elsewhere in the world (2.7 kg CO_2-eq kg^{-1} lint).

The expansion of cotton production facilitated the substitution of cottonseed for global protein feed and palm oil, which was almost entirely responsible for reducing iLUC impacts (Fig. 2). The emissions from iLUC were primarily associated with the avoided land transformation of −1.7 kg CO_2-eq kg^{-1} lint for production of global protein feed, and the remaining contribution was derived

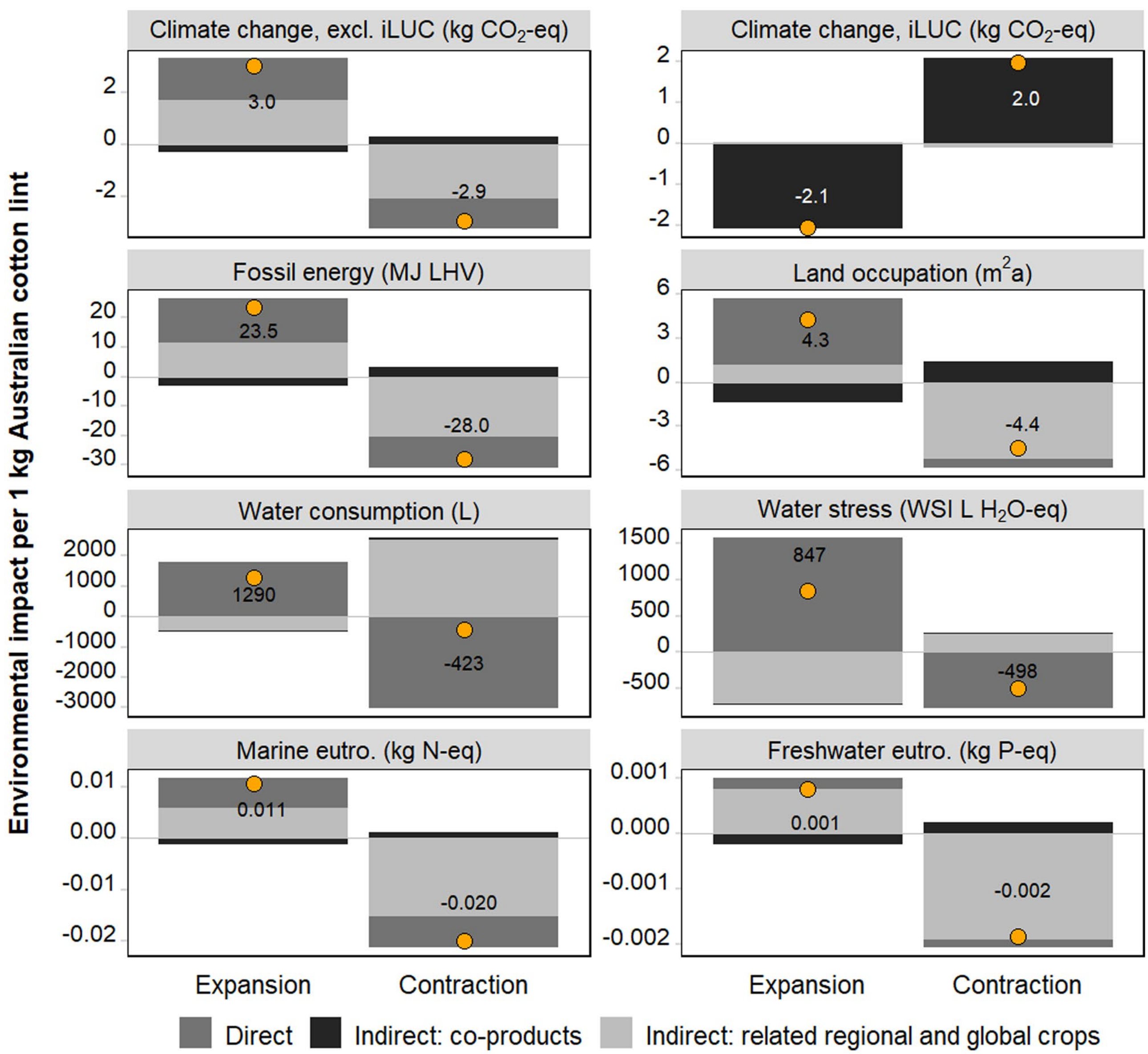

Fig. 2 Direct and indirect environmental impacts of 1 kg of additional cotton (50% production expansion) and 1 kg reduced cotton lint (50% production contraction). Markers and their numeric labels show net impacts

from avoided palm oil production. With the impact of iLUC included, the net impact of additional cotton lint was 1.0 kg CO_2-eq kg^{-1} lint (Fig. 2). Thus, with iLUC included, the GHG emission intensity was lower than emissions determined using aLCA for the current system (Fig. S3).

Direct fossil energy demand for additional cotton lint was 15.1 MJ LHV kg^{-1} lint (Fig. 2), which was similar to the aLCA result for the current system (Fig. S3). However, when the indirect impacts were accounted for, the net fossil energy demand almost doubled (Fig. 2).

Direct freshwater consumption for expanded Australian cotton lint production was 1800 L kg^{-1} lint, whereas the aLCA result for current production was 2500 L kg^{-1} lint (Fig. S3). The lower modelled direct impacts were mainly due to the combination of increased IWUE (P1), and increased dryland production, which requires no irrigation (P4). The indirect impacts of freshwater consumption were −510 L kg^{-1} lint, which was the combination of a reduction in water use for regional crops (i.e., rice in the ISZ) and an increase in the related global crops (i.e., global rice) in response to the changes in Australian crops (Fig. 2). When these indirect impacts were considered, the net freshwater consumption of additional cotton (Fig. 2) was lower than that inferred for the current system using aLCA. Similar results were observed for the net water stress of the additional Australian cotton lint (Fig. 2) and the water stress associated with cotton lint produced from the current system, as assessed using aLCA (Fig. S3).

Direct impacts from freshwater and marine eutrophication (Fig. 2) were modest due to fewer nutrient losses from dryland cotton and irrigated cotton fields with CPLM irrigation systems. Net impacts (Fig. 2) were primarily due to crop displacement at the global scale.

Regarding land occupation, the direct impact (Fig. 2) was primarily due to the increase in non-irrigated annual cropland occupied for dryland cotton production (from 1.4 to 4.5 m^2a kg^{-1} lint for the current system and expansion, respectively). The indirect impacts from co-products and related regional crops (−1.4 and −0.9 m^2a kg^{-1} lint, respectively) were approximately equal to the increase in land occupation impacts from related global crops (2.1 m^2a kg^{-1} lint), such that the net land occupation of additional Australian lint was 4.3 m^2a kg^{-1} lint (Fig. 2).

3.3 Impacts from the contraction of cotton production

The contraction of Australian cotton production consistently reduced the direct environmental impacts of cotton production; however, increased impacts from indirect processes and co-products displacement were also observed (Fig. 2). Contraction of cotton lint production reduced the availability of cottonseed used for livestock feed: this induced the production of the global marginal protein feed and palm oil and contributed to an increase of 2.1 kg CO_2-eq kg^{-1} lint from induced iLUC. Moreover, the iLUC impact from the related GLO and regional crops resulted in a small reduction of − 0.1 kg CO_2-eq. Thus, the total GHG emissions derived from iLUC in the contraction was 2.0 kg CO_2-eq kg^{-1} lint.

The net impacts of contracting cotton production were strongly influenced by changes in the indirect crop processes, especially the reduced GHG emissions and fossil energy demand associated with the reduction of related global crops (Fig. 2). For water, regional crops dominated the indirect impacts (3000 L and 761 L H_2O-eq per kg reduced lint for freshwater consumption and water stress, respectively). Similarly, while direct eutrophication impacts declined in Australia with reduced cotton production (-1.5×10^{-4} kg P kg^{-1} lint), a much larger reduction in freshwater eutrophication was achieved via the reduction of related global crops (-2.0×10^{-3} kg P kg^{-1} lint), while the increase in freshwater eutrophication derived from regional crops was much smaller (1.0×10^{-4} kg P kg^{-1} lint). The same trend was observed for marine eutrophication impacts. Net eutrophication impacts of producing less cotton lint were -1.9×10^{-3} kg P-eq kg^{-1} lint and -2.0×10^{-2} kg N-eq kg^{-1} lint (Fig. 2).

Under the contraction scenario, the direct impact of land occupation was −0.6 m^2a kg^{-1} lint. An increase in indirect land occupation impacts associated with global protein feed and palm oil production was more than offset by avoided global crop production (Fig. 2), particularly wheat production. Change in land occupation impacts resulted from transforming dryland into irrigated cropland in the ICZ using water that would have been used to produce cotton. When the indirect impacts were considered, the net land occupation impact was substantially decreased to −4.4 m^2a kg^{-1} lint.

The direct reduced impacts modelled under the contraction scenario were greater than those of current production modelled using aLCA for freshwater consumption and marine eutrophication only (Table S15). When indirect impacts were included, the total reduction in impacts was greater than that inferred from the aLCA results for all impact categories with three exceptions. The exceptions were freshwater consumption and water stress, both of which showed minor changes in impacts compared to the aLCA results for current production, and climate change (including iLUC).

3.4 Sensitivity analysis

The expansion and contraction scenarios relied on assumptions regarding the regional and technological composition of production systems that responded to a change in the demand for cotton lint. To examine the effect of these assumptions on net impacts, 11 alternative expansion and

Fig. 3 The sensitivity of the environmental impacts of 1 kg cotton lint produced in the expansion (Exp 1–8) and contraction scenarios (Contr 1–3) relative to the baseline expansion (Exp-baseline, yellow bars) or the baseline contraction scenario (Contr-baseline, yellow bars)

contraction scenarios were run (Table 3, Fig. 3). The results showed that 8 of the 11 scenarios had results within ~ ± 20% of the expansion and contraction baseline scenarios. Scenarios that frequently varied impacts by > ± 20% across multiple categories were the result of extreme changes, e.g., all expansion achieved via a 150% (Exp 7) or 200% (Exp 8) increase in dryland cotton production with no expansion in ISZ, and the remaining increase from INZ production. These extreme scenarios had lower GHG, energy, water stress (but changes < ± 20% in freshwater consumption due to the low contribution of DCZ to freshwater consumption) and eutrophication impacts. However, expansion reliant on dryland cotton was deemed less reliable and less likely than expansion in the ISZ, where there has been a recent trend of cotton displacing rice production. Similarly, rapid expansion in the INZ (Exp 7) is constrained by the requirements of developing a new region, including large capital investment. Thus, while expanding production into dryland production in the ICZ and through the conversion of pastures into cotton production in the INZ scenarios delivered lower environmental impacts, it was considered less likely to occur in response to an increase in demand than the standard expansion scenario. In contrast, Exp 6, which investigated lower uptake of CPLM where IWUE improvement was expected to be 5% instead of 10%, and displacement of all the rice grown in the ISZ with cotton, resulted in 21% and 34% higher impacts for GHG and water stress, respectively (Fig. 3).

In the contraction scenarios, a similar trend emerged (albeit reversed) with the extreme scenarios (Contr 2 and Contr 3), showing the greatest difference compared to the contraction baseline (Fig. 3). In these scenarios, cotton production contracted primarily due to lack of water supply, and thus either irrigated rice in the ISZ or irrigated wheat and sorghum in the ICZ did not participate in crop transformation, and dryland crops replaced irrigated cotton. The principal effects were large (> 50%) reductions in freshwater consumption and water stress, and moderate (20–30%) reductions in land occupation (Fig. 3).

The model was also reliant on several assumptions with respect to cotton lint yield, water source, the proportion of harvested cotton recovered as lint and GHG emissions factors for fertiliser use. Results show that the sensitivity of estimates of impacts was dependent on the indicator but highly predictable (Figs. S4–S6). For example, increases in yield reduced impacts across all indicators, freshwater consumption and water stress were sensitive to the irrigation rate, and only marine eutrophication was sensitive to the fraction of soil nitrogen inputs lost via leaching (Frac_LEACH).

4 Discussion

The research presented here assessed the environmental consequences of potential changes to Australian cotton lint production in response to an increase or decrease in global demand for cotton lint. This research is important as calls have been made to reduce cotton lint production, primarily due to the crop's water footprint and the fact that Australia is a water-stressed continent (Schwartz 2019). Contrary to such assertions, the stress-weighted water footprint of current Australian cotton production (as determined using aLCA) is lower than that of global production, as is the land footprint, while the carbon and fossil energy footprints of Australian production are almost the same as global production (Fig S3, Cotton Inc. 2016).

Results from this work demonstrate that using aLCA as a basis for assessing a change in the cotton production system can be misleading, which is in line with previous studies (Plevin et al. 2014). Considering net impacts (i.e., including all indirect impacts, such as iLUC), expanding or contracting Australian cotton lint production by 50% produced a smaller change in GHG emission intensity than what would be inferred from the aLCA footprint of the current system. The inclusion of iLUC and market effects substantially influenced the total GHG emissions of cotton lint produced in the expansion and contraction scenarios. Without considering these effects, the contraction scenario might simply be assumed to decrease annual GHG emissions by 580 kt CO_2-eq (Table S16). However, our cLCA results suggested that such a contraction would reduce annual GHG emissions by ~372 kt CO_2-eq (Table S16). Similarly, a 50% expansion in Australian cotton lint production could be assumed to increase annual GHG emissions by 580 kt CO_2-eq, whereas our model indicates that emissions would increase by ~379 kt CO_2-eq (Table S16). Consequently, the cLCA showed that a change in cotton production had a less apparent impact on GHG emissions than expected if the aLCA footprint was used to interpolate impacts from a change in production.

Our findings also demonstrate that using an aLCA water footprint as a basis for change decisions could be misleading. Applying the benchmark annual water consumption (2500 L kg^{-1} lint) of the current system (Supplementary Sect. 7.1), to predict a reduction in water from a 50% reduction in Australian cotton production results in an assumed 960 GL of water 'saved' or implicitly, returned to the environment in the region where it was extracted. However, our results suggested that only 165 GL would be saved (Table S16) and that most of this water-saving would occur overseas rather than in Australia because of market effects (i.e., Australian water was used to grow more crops reducing the demand for water in other parts of the world). Similarly, we found that a 50% expansion in cotton resulted in an additional 500 GL freshwater consumed compared to an estimated 960 GL if requirements are extrapolated from the aLCA footprint of current production (Table S16). A similar trend was observed for water stress impacts: extrapolating water stress impacts from current production would suggest that a 50% increase/decrease in production would increase/decrease water stress impacts by 410 GL H_2O-eq, whereas the impacts of the expansion and contraction scenarios were 330 and −190 GL H_2O-eq, respectively (Table S16).

The substantially lower water impacts of additional cotton lint in this study were reasonable under the tested expansion pathways. First, a total of 78 kt of the additional 390 kt of cotton lint (i.e., 20%) was produced via an increase in IWUE with no increase in water consumption. Second, the expansion of cotton production in the INZ (P2) used unallocated water with low water stress index (Pfister et al. 2011; Yeates et al. 2014). In the ISZ, water was assumed to be transferred between crops, reflecting the legislative basis upon which water is allocated for alternative uses, rather than returned to the environment. In the Murray-Darling Basin, water is a tradeable asset under a cap-and-trade program that can be used on different crops, independent of land resources (Grafton and Horne 2014; Gupta and Hughes 2018b; Goesch et al. 2019). This cap means that no additional water can be extracted from the system for agricultural use and that any new irrigated crop production needs to occur via increased water efficiency measures or by trading with other agricultural or industrial users. Trading is expected to make irrigation available for the next most profitable crop and, in turn, maximise returns on farm assets such as land. The incorporation of this cap on water consumption into the cLCA model produced notable asymmetries between modelled water impacts for the expansion and contraction scenarios (Fig. 2). The issue of water limitations highlights an important limitation in using aLCA to assign environmental impacts to a product: in some jurisdictions, it is legislation, not the mix of commodities or a change in demand that determines the amount of water extracted from the environment.

We noted interactions between IWUE and several impact categories. Increased IWUE, as was expected, result in lower field emissions of N_2O, because it reduces microsites for denitrification (Tiedje et al. 1984). Despite the increased energy required for high-pressure systems per megalitre of water used, the total volume of water applied was lower, which resulted in a net decrease in energy demand per kilogram of lint. Further, eutrophication impacts in CPLM systems were lower due to reduced runoff. The assumption of expansion via the implementation of these systems is robust because the use of pressurised irrigation systems is increasing (Roth et al. 2013). Moreover, the sensitivity analyses (Fig. S5) showed increasing the IWUE from 10 to 20% under expansion pathway P1 produced further reductions in freshwater consumption and water stress. Along with increased IWUE, increasing cotton yield by 20% and increasing the lint portion by 10% under an expansion scenario also reduced impacts accompanied by a decrease in land occupation (Fig. S5). These scenarios are therefore consistent with intensification as a low-impact means of increasing cotton production. However, because the inventory data were not causally linked (e.g., fertiliser did not scale with water inputs), these trends are suggestive rather than definitive. Nonetheless, the results are consistent with lower impacts upon efficiency gains within intensive cotton production systems (Powell et al. 2017; Antille 2018), the impacts of which may be greater than alternative production systems (e.g., organic, certified) (Shah et al. 2018; Sandin et al. 2019).

At the global scale, the consequence of Australian cotton lint production changes would indirectly affect other commodities via changes in related crop production. These indirect impacts were expected because changes in levels of production of commodities affect price, and this would, in turn, drive production changes elsewhere to restore equilibrium in supply and demand. There is a clear need for models of changes in production to include these plausible market effects, despite some uncertainty, because there is little doubt that market effects occur (Mayer et al. 2005; Searchinger et al. 2008; Meyfroidt et al. 2010, 2013; Kastner et al. 2011; Chaudhary and Kastner 2016). In this study, the model suggests that climate change impacts associated with iLUC from avoided or induced co-products (e.g., cottonseed) associated with an expansion or contraction, respectively, of cotton lint production, had a greater impact on net GHG emissions than the direct or indirect (excluding iLUC) emissions associated with cotton production itself (Fig. 2). Across all impact categories considered, the importance of direct impacts on net impacts was highly variable. Indirect impacts were relatively large for freshwater consumption and water stress, and land occupation, which increases the importance of quantifying indirect impacts that are not included in an aLCA study of a commodity, by considering the complex effects of changes in supply on the environmental impact of local and global crops. Consideration of these indirect impacts minimises the likelihood of unintended consequences arising from burden-shifting associated with displaced or induced crop production.

While climate change (including iLUC) and water impacts were less for the expansion or contraction scenarios than would be expected from the current production, the opposite held true for the net impacts of other impact categories (Table S15). Increases in fossil energy, eutrophication and land occupation total impacts in the expansion scenario were greater than what could have been expected from current production. Under the contraction scenario, reductions in these same impacts were again much greater than what could have been expected from current production. The substantial changes in the freshwater and marine eutrophication impacts were mostly indirect, and primarily from related global crops. In contrast, the direct freshwater and marine eutrophication impacts were broadly comparable to impacts of the current system determined using aLCA (Table S15). Land occupation impacts were much larger for both expansion and contraction than what would be inferred for current production using aLCA. Thus, in general, where the change in impacts was greater than what would be expected from current production as determined using aLCA, the absolute change under the contraction scenario was similar or greater to the change under the expansion scenario. The sensitivity of fossil energy, eutrophication and land occupation impacts to changes in production highlights the importance of multiple impact categories for identifying trade-offs.

Population growth is expected to increase global demand for all fibre types, including cotton lint (OECD, FAO 2020). The present study focussed on the on-farm production of Australian cotton lint. However, the environmental consequences of a change in demand for this commodity can be more fully understood by modelling the consequences of replacing a product made from cotton with another made from alternative fibres (e.g., a cotton garment replaced by polyester and/or wool garments). In the case of a contraction of cotton production, for example, the cotton needs to be replaced with an alternative fibre and the impacts of producing the alternative fibre need to be considered. Such a study should also show the impacts of not consuming these products because a reduction in demand could be brought about by addressing the overconsumption of garments in the developed world, independent of changes in demand for alternative fibres. Future research is needed to evaluate the consequential impacts on the full supply chain, particularly considering some have called for the substitution of cotton with polyester to reduce water impacts (GFA and BCG 2017). Comparisons to contrasting fibres may require careful consideration of a broader suite of impact categories than those assessed here, including emerging issues such as microplastic particles emissions (Henry et al. 2019; De Falco et al. 2020; Quantis 2020).

This research presents one out of many possible options for modelling the impact of an expansion or contraction in the production of Australian cotton lint using cLCA. One alternative would be to model price elasticities. Expanding cotton production by 5% may have a minor effect on the price of cotton, but expanding production by 50% may put downward pressure on cotton prices across all grades given the high quality and volume of Australian lint. Modelling such reduced returns to Australian producers could change the profile of regional crop displacement and could reduce cotton production by marginal producers elsewhere in the world. However, all cLCA models must necessarily balance simplicity and comprehensiveness. Disincentives for increased model comprehensiveness include the decreased marginal returns for continued investment in model complexity. Unlike aLCA, additional complexity (such as adding more causal relationships) may not converge an impact assessment toward a final answer, and system expansion may reduce the ability of decision makers (for who the model was designed) to comprehend or feel responsible for the implications of their choices (Ekvall 2019). Because a cLCA model cannot be fully comprehensive, the present work cannot quantify the *ultimate* environmental consequences of a change in Australian cotton production. Rather, the model presented and others like it are best considered a representation of part of a system, with boundaries that were chosen to match the subjective goal and context of the study.

5 Conclusions

This study has presented a consequential analysis of the environmental impacts of changes in Australian cotton production. It is a sophisticated study that took into account the complexity of changes in land occupation and water consumption that would be brought about with an expansion or contraction in demand for Australia cotton. While these results were necessarily reliant on uncertain assumptions of future change, a sensitivity analysis showed that the majority of alternative, plausible scenarios for achieving change affected the result of the primary assumptions by $< 20\%$. This suggests that the results presented here were sufficiently robust to indicate the quantum of changes that could be expected from such a change in the production of Australian cotton lint. While not the emphasis of the present study, we found that intensification pathways to expand cotton production decreased environmental impacts across a broad set of indicators. Consequently, further studies focusing on increasing supply with the least environmental impacts would be beneficial.

Across all impact categories, we found large variation in the importance of indirect impacts to net impacts. iLUC was an important determinant of climate change impacts, and for contraction scenarios, indirect impacts were larger than direct impacts across almost all impact categories (freshwater consumption and water stress being exceptions). With the significance of these indirect influences acknowledged, it was not surprising that this study revealed that using aLCA to extrapolate from the current footprint to predict the impacts of a change in cotton demand was inaccurate. Specifically, we found that aLCA would over-predict the impacts on climate change emissions and water use (i.e., freshwater consumption and water stress) of expanding or contracting cotton production. Conversely, the impacts of fossil energy, eutrophication (freshwater and marine) and land occupation under expansion or contraction scenarios would be under-predicted by extrapolating current production. As such, inferring the likely change in environmental impacts based on an aLCA model of current production, without considering the complex array of changes in technology and the production of related crops, at a regional and global level, is unreliable. This fact highlights the importance of detailed, consequential modelling to guide decisions associated with changes in cotton lint production.

Considering this study investigated only the impact of a change in cotton production and not the impact on the textiles supply chain, further research is needed to extend the system boundary and analyse the implications of these findings for comparative assessment of cotton and alternative textiles.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1007/s11367-021-01994-y.

Acknowledgements Allan Williams (CRDC) is acknowledged for his review and input to drafts of this manuscript. Also, we thank the anonymous reviewers who provided constructive feedback during the review process.

Funding This research was funded by the Cotton Research & Development Corporation (CRDC, grant number CRDC1911) matching research and development funding from the Australian Government.

Data availability Inventory data generated or analysed during this study are included in the supplementary materials.

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