Journal of Cleaner Production 212 (2019) 139–150

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Carbon intensive but decarbonising quickly? Retrospective and prospective Life Cycle Assessments of South African pome fruit

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ARTICLE INFO

Article history:
Received 11 April 2018
Received in revised form
30 November 2018
Accepted 3 December 2018
Available online 4 December 2018

Keywords:
Attributional life cycle assessment
Climate change
South Africa
Global Warming Potential
Carbon intensity
Eco-efficiency
Agriculture
Pome fruit sector

ABSTRACT

Carbon intensity is an important descriptor of and widely used proxy for environmental impacts of products. Products exported from carbon-intensive economies are becoming vulnerable to soft-trade barriers. Producers and customers thus need to know whether production is becoming cleaner. The purpose of this study was to determine the global warming potential of South African apples and pears (pome fruit) for the years 2000, 2010 and 2020, and compare it to that cultivated and packaged in other countries. The Attributional Life Cycle Assessment (LCA) methodology was used to determine the climate change impact across the main stages of the pome fruit life cycle namely; the farm, packhouse, controlled atmosphere store and cold store. Retrospective LCAs were used to determine the historical environmental impacts for the years 2000 and 2010 and a prospective LCA for the year 2020.

The results obtained from the Intergovernmental Panel on Climate Change (IPCC) impact assessment method indicated a decrease in the aggregated Global Warming Potential (GWP) of pome fruit from 1.52 kg CO_2eq/kg fruit in 2000 to 1.23 kg CO_2eq/kg fruit in 2010 and finally 1.02 kg CO_2eq/kg fruit in 2020 across the four life cycle stages specified. The life cycle stage with the largest contribution to greenhouse gas (GHG) emissions was the Controlled Atmosphere store. At the activity level, the consumption of the national grid electricity in the fruit packaging and storage facilities was identified as the hotspot for all years. The normalised results for the industry show the same rate of decline during the 20-year period and correlate to the increasing trend of eco-efficiency practices implemented within the industry. South African pome fruit GHG emissions for the year 2000 were relatively high compared to similar international studies on apples and pears during the same period. The results for the years 2010 and 2020 indicate a sustained decline in GHG emissions intensity. Improvements are due largely to more intensive farm-stage production coupled with eco-efficiency improvements in all four value-chain stages, with a projected decline in carbon intensity of electricity from the national grid expected to make a significant contribution in the coming years.

1. Introduction

Over the last decade there has been a shift within companies, governments and global organisations to examine the environmental impact of products and services across the economy, particularly for primary industries such as agriculture which is constrained by limited land and water resources. International markets, specifically the European Union (EU), are systematically applying pressure on imported products with a high carbon footprint through potential trade barriers and border tariffs. This has resulted in environmental product declarations (EPDs) and delivery agreements, whereby suppliers are required to demonstrate their environmental sustainability and implement on-going programmes to improve their performance (Peters and Hertwich,

Abbreviations: ALCA, Attributional Life Cycle Assessment; BFAP, Bureau for Food and Agricultural Policy; CA, Controlled Atmosphere; CCC, Confronting Climate Change industry initiative; CLCA, Consequential Life Cycle Assessment; CS, Cold Store; EPD, Environmental Product Declaration/s; EP, Environmental Purchasing; GHG, Greenhouse gas; GWP, Global Warming Potential; IEA, International Energy Agency; IPCC, International Panel on Climate Change; kWp, kiloWatt peak; LCA, Life Cycle Assessment; LCI, Life Cycle Inventory; LCIA, Life Cycle Impact Assessment; MWp, MegaWatt peak; PPI, Producer Price Index; PV, Photovoltaic; REIPPP, Renewable Energy Independent Power Producers Programme; SAFARI, South African Food and Agriculture Reduced Impacts; SSAJRP, Swiss South African Joint Research Programme; SSEG, Small Scale Embedded Generation; WCDoA, Western Cape Department of Agriculture.

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https://doi.org/10.1016/j.jclepro.2018.12.026

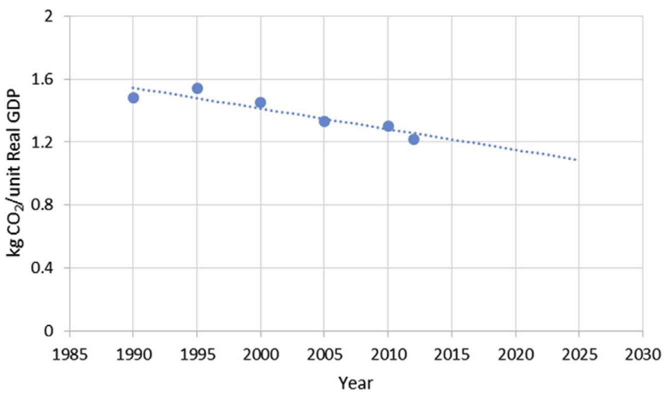

Fig. 1. South African national CO_2 emissions per real GDP (inflation adjusted) for South Africa (derived from International Energy Agency (IEA) (2015).

2007). Procurement strategies aligned with environmental purchasing (EP) are also gaining traction at the retailer level, pressured by consumer expectations (e.g. Ramanathan et al., 2014). Exporting countries such as South Africa have, and will continue to be, impacted due to their role in global value chains (Pineo, 2015). There are many indicators of environmental impact, and hence of cleaner production, with carbon footprint (or greenhouse gas emissions) invariably being one of them and often used as a proxy (e.g. Klemeš et al., 2012; Veleva et al., 2001).

The South African economy has in the past been categorised as carbon-intensive due to an energy and capital intensive development path and an associated set of economic activities termed the minerals-energy complex. All economic sectors rely heavily on coal fired electricity (Brent et al., 2002) with the consequence that South Africa ranks as one of the 20 largest emitters of greenhouse gasses. Also, South Africa exports a substantial amount of its GHG emissions embodied in its products, up to 30% in some cases, which is high in global comparison (Merven et al., 2014).

This carbon intensity of the South African economy has been on the decline since 1990 (Fig. 1). This is not an absolute decoupling of economic growth from carbon dioxide emissions, as the GDP has grown by 108% ("Statistics South Africa," n.d.), with a slower growth of CO_2 emissions (from fuel combustions and cement production) at 48% during the period 1990–2012. This relative decoupling of economic growth from CO_2 emissions has been due partly to the relative decline of the mining sector in favour of a services-based economy and the strong economic growth between the late 1990s and 2007. After 2011, decarbonisation of the electricity supply has been commissioned by government through a private sector power procurement programme.

Within the agricultural sector, specifically fruit and wine, the various industry bodies have developed the Confronting Climate Change (CCC) initiative to measure GHG emissions at multiple life cycle stages within individual agri-businesses. Various other mitigation and adaptation projects and support have been initiated by the Western Cape Department of Agriculture (WCDoA), Green Cape,[1] Stellenbosch University and the African Climate and Development Initiative[2] among others.

The South African fruit industry faces a twofold challenge: Firstly, the potential risk of losing a part of the approximately USD 250 million (2013/2014) annual revenue injection from the EU and UK market, due to trade barriers for products with high embodied carbon; Secondly, the mitigation of GHG emissions within the fruit value chain to address the increasing input costs of fossil fuels and the forthcoming national carbon tax as well as the adaptation of agricultural practices to climate change in order to ensure the socio-economic sustainability and climate resilience of the industry. An understanding of the trend in GHG emissions within the pome fruit industry is fundamental in developing mitigation strategies for this sector. In order to determine the trend in the carbon footprint of pome fruit, the Life Cycle Assessment (LCA) methodology was applied in this study.

LCA is a holistic, systems based methodology used to quantitatively assess the environmental impacts of products or services. Up until 2002, the application of the LCA methodology on products and services in South Africa was focussed on the resources industry (metallurgical, fuels, energy), water and waste treatment, paper, sugar and automotive industries (Brent et al., 2002). Since these initial findings, there has been an expansion in areas already covered and new applications specifically on biofuels (e.g. Harding et al., 2008; Stephenson et al., 2010); and within the water sector (as reviewed by Buckley et al., 2011), mainly due to this being a significant constraint on economic expansion and environmental welfare. More recently LCAs have also been done in the municipal solid waste sector (Friedrich and Trois, 2013) and textile industries.[3]

From an agricultural perspective, environmental LCAs have been conducted on a wide range of agricultural products from livestock such as pork (Devers et al., 2012), beef,[4] dairy (Notten and Mason, 2010) and wool production (Brent, 2004), to crops such as wheat (Pineo, 2015) and sugar cane (Mashoko et al., 2010). As part of the South African Food and Agriculture Reduced Impacts (SAFARI) project, carried out in the Swiss South African Joint Research Programme (SSAJRP) 2014–2016, LCAs studies were conducted on the 10 most relevant agriculturally produced food products in South Africa which also included fruit (König, 2015). Alternative energy sources from agricultural feedstock have also been explored using LCA, and include the use of bagasse from the sugar cane industry for co-generation of electricity and production of biofuel (Botha and von Blottnitz, 2006; Melamu and Von Blottnitz, 2011).

Internationally, LCAs in the agricultural sector have been used to determine resource intensity and environmental impacts of a wide range of products. Attributional LCA, specifically on pome fruit, has been done in countries such as New Zealand (Milà i Canals et al., 2006), Switzerland (Mouron et al., 2006b) and (Mouron et al., 2006a) at farm level, and for multiple life cycle stages within the value chain in China (Liu et al., 2010) and Canada (Keyes et al., 2015). Table 1 presents the GWP results from LCAs conducted on pome fruit from the literature.

Very few international LCA studies have GWP results from using more than one impact assessment method and of multiple life cycle stages within the pome fruit product system. Most of the LCAs on pome fruit were conducted at farm level only, except for the study by Liu et al. (2010) and the organic and conventional apple cultivation in Canada by Keyes et al. (2015). Further research in applying the LCA method on multiple life cycle stages in the fruit value chain in other geographical areas, specifically developing countries, could enrich the available data and shed light on practices in these areas.

Prospective LCAs have mainly been done in industries other than agriculture, such as in the energy sector to determine impacts of future energy mixes (Curran et al., 2005; Raugei and Frankel, 2009; Weinzettel et al., 2008), new technologies for energy production and storage (Collet et al., 2011; Wender and Seager, 2011),

[1] www.green-cape.co.za.
[2] http://acdi.uct.ac.za/.
[3] http://tgh.co.za/case_studies/screening-life-cycle-assessment-of-textiles-retailed-in-south-africa/.
[4] http://tgh.co.za/case_studies/life-cycle-assessment-of-south-african-and-namibian-beef-retailed-in-south-africa/.

Table 1
GWP results for life cycle stages in global pome fruit industry.

Source	Geographical area	Life Cycle Stage	kg CO_2eq/kg fruit
Apple {GLO}| production | Alloc Def, U (Stoessel et al., 2012)	Global	Seedling production	
		Farm	0.27
		Transport to retailer	
Milà i Canals et al. (2006)	New Zealand	Farm	0.04–0.095
Mouron et al. (2006a)	Switzerland	Farm	0.05–0.12
Liu et al. (2010)	China	Farm	0.06–0.38
		Processing and cold storage (no packaging)	0.005–0.16
		Transport	0.003–0.007
Keyes et al. (2015)	Canada	Farm (conventional)	0.14
		Packaging and storage	0.19

future transport systems (Spielmann et al., 2005) and other novel carbon mitigation technologies (Sathre and Masanet, 2013). The closest prospective LCAs have come to the agricultural sector were applications in food waste management (Lundie and Peters, 2005) and in the development of a decision support tool for the case of local food production in sustainably designed systems (Yang and Elliot-Campbell, 2017).

According to the known literature, the application of LCA to determine trends over time in the environmental impacts of agricultural products has not been attempted to date. This study combines retrospective and prospective LCAs on an agricultural product across multiple life cycle stages to explore the trend of the environmental impact category climate change over time. A retrospective LCA is used for a snapshot of the industry in the years 2000 and 2010 and a prospective LCA for the year 2020. The results from the LCAs are compared with other international GWP results for pome fruit with similar temporal validity, to determine whether South African pome fruit had or has a relatively high GWP and how this is evolving. Results are presented in the form of carbon intensity of the industry from the year 2000–2020.

2. Materials and methods

2.1. Life Cycle Assessment definitions and typologies

The application of the life cycle concept offers the means to understand, manage and reduce the environmental impacts associated with a product, process or activity by considering all lifecycle stages, from 'cradle-to-grave'. The LCA methodology is defined and detailed in the ISO standards 14040:2006 and 14044:2006 (International Standards Organisation, 2006). Attributional LCA (ALCA) is defined as an approach to determine environmental impacts caused by a product system (Marvuglia et al., 2013) and includes the relevant physical flows to and from the system (Ekvall and Andrae, 2006). An ALCA can be retrospective, in that it determines the historical environmental impact from a current product state or prospective when looking at the impacts of the product system in a future state (Sandén and Karlström, 2007).

According to Frischknecht and Stucki (2010), the Life Cycle Inventory (LCI) modelling approach is dependent on the size of the product system to be investigated. The theory postulates that the economic size of a system determines the degree to which economic relations change from a decision, which in turn impacts the environmental size of the system. This 'economic size criterion' classifies objects under investigation into three groups (Table 2) to which the most appropriate LCI models are assigned namely; ALCA, Decisional and Consequential Life Cycle Assessment (CLCA) and delimits the three classes on their relative economic sizes compared to their contribution to a total. The total is defined either as economical (i.e. total of economic sector or country) or political (i.e. the total of a country or region). The total value of fresh pome fruit production in the 2013/2014 year was ZAR 6.78 billion (USD 660 million) (Hortgro, 2015). The relative share of this industry to the Gross Domestic product of South Africa for this year was approximately 0.17%, which falls into the medium economic size prescribed by Frischknecht and Stucki (2010). This classifies the modelling approach to be either ALCA or decisional as per Table 2, however, the purpose of this study is to report on environmental impacts of the pome fruit industry and not as a decision support; therefore the ALCA approach was applied.

Table 2
Preliminary economic size of the object under investigation in relation to the total size of an economic or political system (Frischknecht and Stucki, 2010).

Economic size	Relative share	LCI model
Small	<0.1%	ALCA
Medium	0.1% > 1%	ALCA/Decisional
Large	>1%	CLCA

2.2. Goal of the study

The goals of this study has been:

1. To determine the GWP results of the pome fruit industry in South Africa for the year 2000, 2010 and 2020. The LCI for the year 2020 is based on forecasts. The results are compared to other international LCAs on pome fruit value chains to determine whether South African pome fruit had/s a relatively high GWP.
2. To determine the trend in the carbon intensity and carbon efficiency of the South African pome fruit value chain from cultivation at farm to Cold Store (CS) gate from years 2000–2010 and to predict a trend from 2010 to 2020.

The audience for this study is the pome fruit industry body (Hortgro), national government and existing and potential international markets. A sensitivity analysis on specific inputs has been done in order to identify the inputs and activities which have the largest impact. As part of the sensitivity analysis, an uncertainty analysis on the models has been applied to determine and quantify the uncertainty introduced into the results of the LCIA due to the cumulative effects of data uncertainty and variability especially for the year 2020 inventory.

SimaPro v. 8.3 software has been used to build the models and perform the impact assessments. The modelling has been done using ecoinvent v. 2.2, 3.0 and 3.3 unit datasets.

2.3. Functional unit and system scope

The functional unit across the value chain is 1 kg *of packaged pome fruit for the export and local market* at the CS gate. Pome fruit refers to the apple and pear varietals currently grown in South Africa. The following life cycle stages have been included in the pome fruit value chain:

1. Farm;
2. Packhouse;
3. Controlled Atmosphere Store (CA);
4. Cold Store (CS);

The pome fruit growing regions in South Africa (Fig. 2) are concentrated in the South Western, Southern and North Eastern regions, with the largest producing region being the Grabouw, Elgin, Villiersdorp and Vyeboom area and second largest the Ceres area.

Data gathering included all inputs into the value chain as defined in the system diagram (Fig. 3) over a period of 1 year or one harvest season. The farm life cycle stage includes all activities at the farm up until the fruit is offloaded at the packhouse gate. The background activities include the production of farming inputs such as machinery, fuel and electricity. The foreground activities include the irrigation, fertilising, harvesting and transport during the production of pome fruit. From the farm, the fruit is transported in crates (plastic or wooden) to the centralised packhouses which are generally off-site. At the packhouses, the pome fruit is either sent directly for packing at the packhouse or first stored in the CA store for a period of time where after it is sent to the packaging lines depending on market timing. At the packaging lines the fruit is graded and sorted and thereafter packed and then palletised. Thereafter, the pallets of packed fruit are stored in the CS facility until transported to the local market or harbour.

Allocation of the environmental burdens was done using a mass allocation for all life cycle stages except the Packhouse stage where an economic allocation was applied. In the packhouse 90% of the environmental burdens are allocated to the export and local market fruit and the remaining 10% to fruit for processing. It is assumed that 25% of pome fruit intake into the packhouse is first stored in the CA facility before being packed in the packhouse. The remainder is sent directly to the packhouse from the farm for packing.

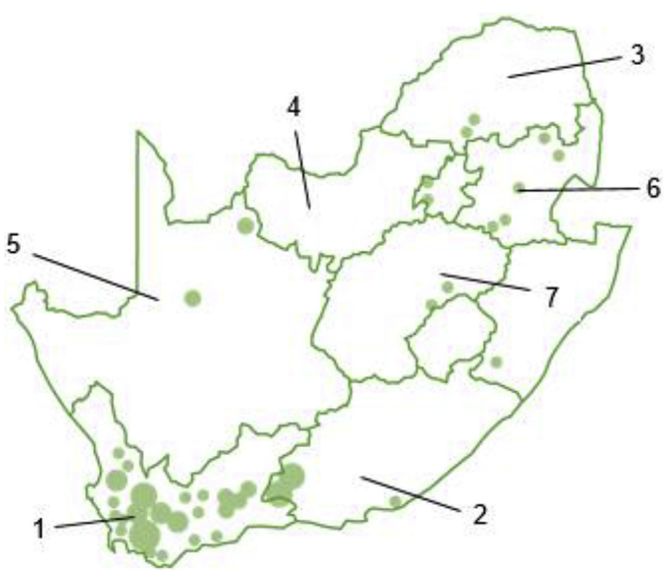

Fig. 2. Pome fruit growing areas in South Africa ("Pome Fruit – Post Harvest Innovation," n.d.). 1 - Western Cape: Ceres, Groenland, Villiersdorp/Vyeboom, Wolseley/Tulbagh, Klein Karoo, Southern Cape, Langkloof West, Piketberg, Somerset West, Stellenbosch, Worcester, Paarl, Franschoek. **2 – Eastern Cape:** Langkloof East. **Other provinces producing between 0-3% pome fruit: 3** – Limpopo, **4** – North West, **5** – Northern Cape, **6** – Mpumulanga, **7** – Free State.

2.4. Impact assessment methods, normalisation and uncertainty analysis

The impact assessment methods which were used for the time series LCA for the years 2000, 2010 and 2020 are the Greenhouse Gas Protocol and the IPCC 2013 GWP (100a) available on the SimaPro v. 8.3 software. These single-issue methods measure the GWP in CO_2eq of each greenhouse gas emitted in order to measure the climate change impact throughout the pome fruit value chain.

The Greenhouse Gas Protocol based on the Product Life Cycle Accounting and Reporting Standard, has the same characterization factors for each substance as the IPCC 2013 GWP (100a) method but also includes the carbon sequestration and biogenic carbon emissions of the system (PRé, 2013). The emissions are also categorised as follows in SimaPro:

- Fossil based carbon (carbon originating from fossil fuels);
- Biogenic carbon (carbon originating from biogenic sources such as plants and trees);
- Carbon from Land transformation (direct impacts) and;
- Carbon uptake (CO_2 that is stored in plants and trees as they grow).

The two impact assessment methods were used to highlight and compare differences in the results. No normalisation factor was available for these impact assessment methods in the SimaPro v. 8.3 software, therefore normalisation of the results was done using the South African total national GHG emissions for each year ("Climate Action Tracker," n.d.).

An uncertainty analysis was conducted on the results for each year to determine and quantify the uncertainty introduced into the results of an LCIA due to the cumulative effects of data uncertainty and variability. Uncertainty was assigned to each dataset using an appropriate probability distribution with corresponding variance. In addition to the basic uncertainty allocation using the probability distributions, additional uncertainty was also applied to the datasets via data quality indicators. These additional uncertainties are based on the pedigree matrix approach (Weidema et al., 2013). Thereafter a Monte Carlo simulation was used to determine the range of uncertainty of the results for the impact category climate change.

2.5. Life cycle inventories (LCI)

The sources of data for the LCIs for each of the years differed due to availability and temporal specificity. The LCI for 2010 was developed first and followed by the 2000 and finally the 2020 LCI. The primary data used in the development of the 2010 LCI was raw data from the CCC[5] database, industry experts and literature. The CCC initiative was started in 2008 through the growing need to measure and manage GHG emissions in the South African fruit and wine value chain due to export market access risks. Primary data was gathered through workshops with stakeholders at farms and agro-processing facilities which is then reviewed to form part of the benchmark data. This benchmark data from 2011 to 2015 was used for some of the datasets in the LCI for 2010. The structure of the 2010 LCI was duplicated for the 2000 and 2020 LCIs for consistency.

The primary data for the farm life cycle stage in the year 2000 was obtained from the WCDoA commercial enterprise budgets.

[5] http://www.climatefruitandwine.co.za.

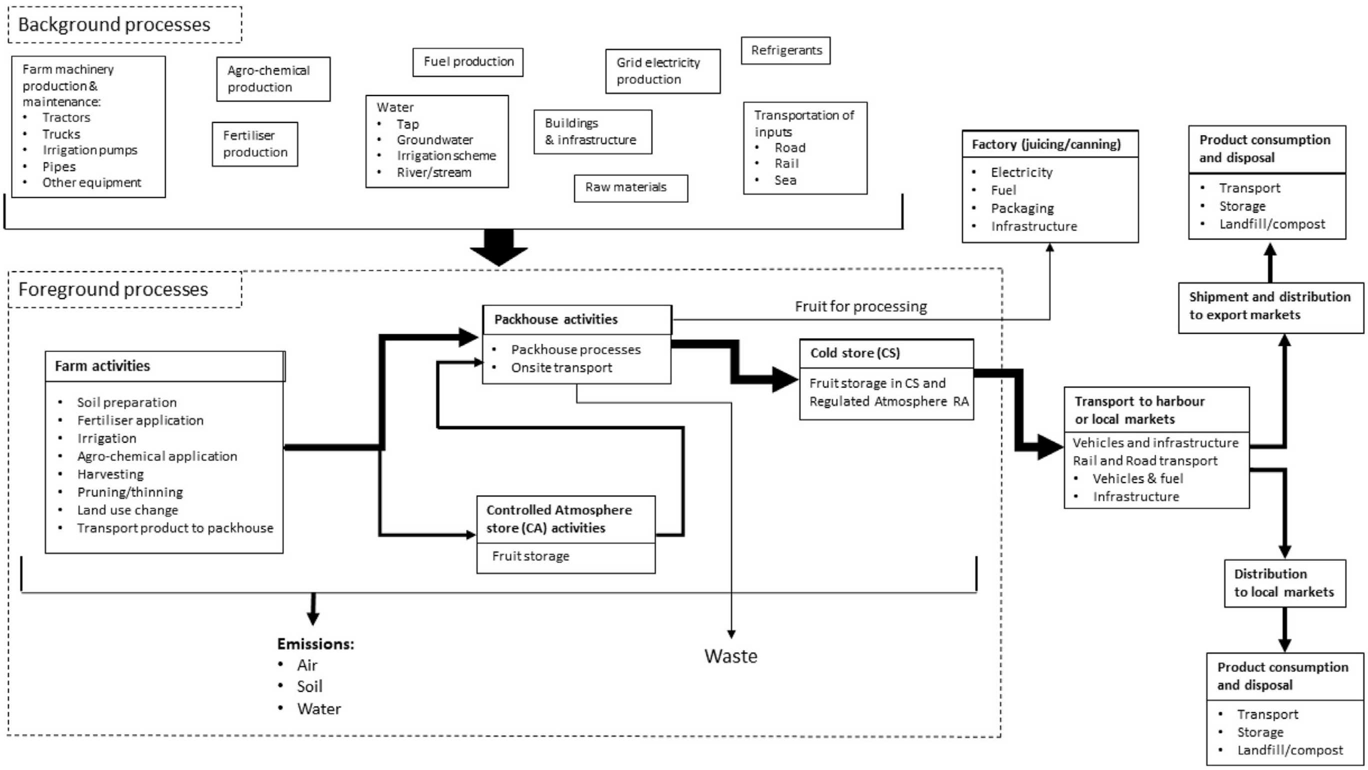

Fig. 3. Pome fruit value chain life cycle stages.

Macro-economic data was provided by Hortgro, the South African deciduous fruit industry body, and all other required data from the literature and industry experts. The LCI for 2020 required forecasts on a number of inputs and outputs. Industry experts were widely consulted along with forecasts from the Bureau for Food and Agricultural Policy (BFAP), the latest Hortgro Deciduous Fruit Statistics reports and relevant literature.

Economic data on industry annual gross revenue was provided by historic Hortgro Deciduous Fruit Statistics reports for years 2000 and 2010 and BFAP for 2020. These annual revenues were adjusted to the Producer Price Index (PPI) from Statistics South Africa and reported in 2010 ZAR to calculate the carbon intensity and carbon efficiency of the industry since 2000.

2.5.1. *Farm inventory*

Table 3 shows annual yields of apples and pears per hectare and total hectares cultivated, which increased by 71% and 8.5% respectively from 2000 to 2020. The year 2010 LCI used the land use, land use change from natural to agricultural land and yield data in the CCC database. For the other years the total industry values were used and land use change values were estimated based on changes in total hectares of orchard.

The irrigation activity on farm is the largest consumer of electricity. The current South African grid electricity ecoinvent dataset was used as input to the farm LCI for 2010 and new grid electricity datasets were created for the LCIs for 2000 and 2020 based on the grid mix and operational output data from the annual reports of the South African electricity public utility Eskom and the Renewable Energy Independent Power Producers Programme (REIPPP) database.[6] The electricity consumption per cubic metre of water irrigated varied from 0.3 to 0.6 kWh. These values are highly variable as each farm has a different pumping head, irrigation layout and water sources. The electricity consumption values for each year were subjected to a sensitivity analysis to determine the impacts on the aggregated GWP results in Section 3.4. The amount of water consumed to irrigate 1 ha of pome fruit orchard was sourced from three local studies; Beukes et al. (2003); Gush and Taylor (2014); van der Walt (2017) and an international study by Pfister et al. (2011). These values were adjusted based on the yields per year and predictions on water consumption by 2020 from industry experts.

The ecoinvent unit datasets for fertilisers included the production and application at farm by agricultural machinery. For the year 2000, fertiliser data was obtained from the WCDoA commercial budgets for the total volume of fertiliser type applied and not per active ingredient i.e. Nitrogen, Potassium and Phosphorus. For the 2010 and 2020 LCIs, the fertiliser datasets represented the total active ingredient amount per fertiliser sourced from the CCC database and industry experts. The agricultural machinery used to apply the various synthetic and organic fertilisers were also included in the LCIs along with the amount of diesel combusted. The emissions to air, soil and water from fertiliser application were modelled according to the formulae in Nemecek and Kagi (2007) and Nemecek et al. (2014).

Pesticide data for 2000 was available in the WCDoA commercial budgets, whereas for the years 2010 and 2020 alternative data

Table 3
Annual yields and land under cultivation (BFAP, 2016; Deciduous Fruit Producers Trust, 2000; Hortgro, 2014).

	2000	2010	2020
Total yield [tonnes]	858 531	1 126 905	1 408 573
Total hectares [ha]	36 396	35 136	39 493

[6] https://www.ipp-projects.co.za/ProjectDatabase.

sources were used such as literature and spray programmes. The machinery for the pesticide application was also included in the LCI along with diesel consumption. In order to record the emissions to air, soil and water; the mobility indices for each pesticide was referenced in Dabrowski et al. (2014: 32).

The diesel consumption of agricultural machinery during the harvesting and pruning activities was also taken into account. In addition, the transport of the fruit to regional packhouses and cooling facilities and delivery of fertilisers and pesticides to the farm was modelled using an average distance of 50 km. In the 2000 LCI, the vehicles conform to Euro 1 emission standards and for the 2010 and 2020 LCI to Euro 2 standards. South Africa complied with Euro 2 emission standards in 2006 but the adoption of the later standards has not occurred due to the delay in converting to cleaner fuels at local refineries.[7]

2.5.2. Fruit packaging and storage

The fruit intake into these life cycle stages are graded into four categories; export market, local market, processing and drying and waste. The two product outputs in the agro-processing LCIs are the consumer grade (local and export grade) and processing grade fruit. The waste component (organic and inorganic) is classified as an emission to the environment. The fruit from farm is directly sent for packing at the packhouse or is first stored for a period in the CA store before being packed. For the three models, it is assumed that 25% of fruit from farm is first stored in the CA store before being packed. This assumption was tested in the sensitivity analysis and results are in Section 3.4.

Electricity values for the LCIs were obtained from a benchmark study of energy usage in export fruit production, packing and cold storage operations in South Africa by Bouwer et al. (2010). Data for agro-processing facilities was not available prior to 2010 and the raw data from the CCC database was substantially lower than the figures in this energy benchmark study. The range of electricity consumption values for packhouses was 30–45 kWh per ton fruit packed and for the CA and CS facilities, 5 to 15 kWh per cold unit. A cold unit is the amount of electricity consumed in kWh per 1000 kg of fruit per day. Industry experts predict a 5% reduction in grid electricity consumption per ton fruit in the packhouse and a 10%–15% reduction for the CA and CS facilities by the year 2020. In addition to the improvement in electrical efficiency, there is a growing trend of photo-voltaic installations on packhouse and cold storage roofs which will further reduce the GWP result. At the agro-processing life cycle stage the installation of renewable Small Scale Embedded Generation (SSEG) electricity, specifically photovoltaic (PV), is a viable proposition and gaining substantial ground due to the energy profile of these facilities (Janse van Vuuren, 2015). Currently, photovoltaics mounted on packhouse roofs supplement the grid electricity demand. As at June 2017 there was 551 kW peak (kWp) installed capacity on pome fruit packhouses according to the PQRS[8] database. In the case of photovoltaics, the maximum possible output of a solar energy generator operating under standard conditions is defined as the peak output, with the unit of measure in Watts peak (p). PQRS has an extensive database on SSEG PV capacity in the commercial, industrial and domestic sectors in South Africa. It is predicted that by the year 2020 there will be approximately 1.25 Megawatt peak (MWp) installed capacity on packhouses packing pome fruit using the compound annual growth rate of 23% annualised from 2013 to 2016. The time period the fruit spends in the CA or CS can also reduce energy demand but this is not dependent on the facilities management and rather on external market timing.

The floor area of the agro-processing facilities and length of conveyor belts per kg fruit packed and cooled were determined from Google maps, literature and site visits. The life expectancy of the buildings were 50 years and the conveyor belts 25 years according to (Kellenberger et al., 2007). Floor area and conveyor belt lengths were extrapolated for the years 2000 and 2020 LCIs based on tonnages of fruit packed and cooled. Water consumption was obtained from three sites for the 2015 year. These figures were extrapolated according to tonnages packed for each of the LCI models.

The main packaging, according to total weight, used for pome fruit was and will still be corrugated cardboard boxes by 2020. The CCC database provided the weight of corrugated cardboard used during one year for the 2010 LCI. For the 2000 and 2020 LCI, a calculation was made based on the number of boxes sent for export through the Perishable Products Control Board. This was extrapolated for local market volumes. In 2000 only wooden bins were used for harvest and storage and pome fruit packaging was mainly corrugated cardboard with divider sheets. By the year 2010 a great deal more plastic was used for packaging in the form of plastic bins, low density polyethylene (LDPE) bags, polystyrene and polyethylene terephthalate (PET). By 2020 it is predicted that the export market will make use of a combination of Reusable Plastic Containers (RPC), wooden bulk bins (orchard run bins), corrugated cardboard for the local market fruit still packaged in LDPE bags and a declining amount of laminated bio-based polypropylene for the 'flow wrap' packaging (from 2016). The decline in plastic packaging by 2020 is due to a growing number of policies and strategies globally and especially in the countries importing South African pome fruit (EU and UK) to phase out single use plastic packaging.[9] The year 2020 LCI has a larger proportion of high density polyethylene (HDPE) and polypropylene (PP) due to more plastic bins being used for harvest and storage and Reusable Plastic Containers (RPC) used for export and local fruit.

The waste component in Fig. 3 includes organic (fruit) as well as inorganic (packaging) waste. Organic waste decreases from 15% of total yield (Milà Canals et al., 2007) to less than 1% in 2020. Recycling rates of paper and plastic based packaging also increases substantially rerouting waste volumes away from landfill.

3. Results

This section discusses the GWP results from the LCAs for each of the years 2000, 2010 and 2020. The results are given as aggregated values for all life cycle stages of the pome fruit, per life cycle stage and per activity which provides insight on the carbon intensive hotspots. The emerging eco-efficiency of the pome fruit industry is also discussed in detail and provides a possible explanation for the declining trend.

3.1. GWP of pome fruit value chains

Table 4 summarises the cumulative GWP result of the pome fruit value chain for each year using the two impact assessment methods as well as the median GWP result from the uncertainty analysis.

The results show a 19% decline in GWP between 2000 and 2010 and project a further 20% decline between 2010 and 2020. The difference in the results is explained by the CO_2 uptake component that the GHG Protocol method takes into account as discussed in Section 2.4. This difference is most pronounced in the packhouse

7 http://www.sapia.org.za/Key-Issues/Cleaner-fuels-II.

8 http://pqrs.co.za/: Solar PV related news and information for Africa.

9 http://www.wrap.org.uk/content/the-uk-plastics-pact.

Table 4
GWP impact assessment results and median results for pome fruit value chains according to GHG Protocol and IPCC methods.

Year	kg CO_2eq/kg fruit		Median kg CO_2eq/kg fruit	
	GHG	IPCC	GHG	IPCC
2000	1.46	1.52	1.61	1.66
2010	1.18	1.23	1.20	1.15
2020	0.92	1.02	1.08	0.97

life cycle stage due to the use of wooden bins and pallets.

The GWP results in Table 4 were extrapolated to the industry total and normalised to the total annual GHG emissions in South Africa ("Climate Action Tracker", n.d.) for the years 2000 and 2010 and a predicted total annual GHG emissions for the year 2020. The normalised pome fruit industry emissions (Fig. 4) show a decline of 13% between 2000 and 2010 and from 2010 to 2020 there is an indication of a possibly more accelerated decline of 19%.

Fig. 5 and Fig. 6 show the GWP results per life cycle stage for both impact assessment methods; Note that the GWP result for the value chain is not the sum of the individual life cycle stages as the fruit does not all move from one stage to the next in series. As stated in Section 2.3, it is assumed that 25% of fruit from the farm is first sent to the CA store before packing with the remaining 75% sent directly to the packhouse. Only the fruit for export and local market is then sent to the CS. There is a clear indication of a decline in GWP results for all life cycle stages from 2000 to 2020. The decline in GHG emissions for the CA and CS facilities is due to the predicted decrease of 10%–15% in grid electricity consumption per cold unit by the year 2020 (see section 2.5.2).

It is evident that the CA store contributed the largest share to the total GWP result for all years due to the grid electricity consumption for cooling coupled with the duration of time the fruit is stored. Moving from the life cycle stage to activity level, it was found that the electricity consumption in the agro-processing facilities contributed 71%–78% to the total aggregated GHG emissions for each year. The irrigation activity at farm was ranked second at 7%–10% of total GHG emissions for each year. Fig. 7 is a graphical presentation of the contribution of the activities to the total GWP result for each year. Possible reasons for the declining GWP results from 2000 to 2020 as shown in Fig. 7 are discussed in detail in Sec. 3.2.

3.2. *Eco-efficiency trends*

Eco-efficiency is an aspect of sustainability relating the environmental performance of a product system to its value (ISO, 2012). Eco-efficiency trends within the pome fruit value chain contributing to an improved environment were identified more generally to provide an explanation for the declining GWP results from the year 2000–2020. The pome fruit product system value for all fruit grades has increased annually at an above inflation rate of 8.7% according to data supplied by the Bureau for Food and Agricultural Policy (BFAP) and the South African deciduous fruit industry body

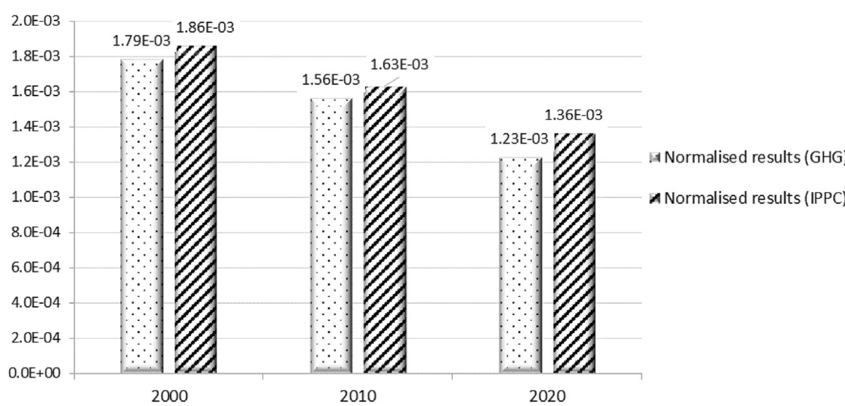

Fig. 4. GWP results for pome fruit industry normalised to national GHG emissions.

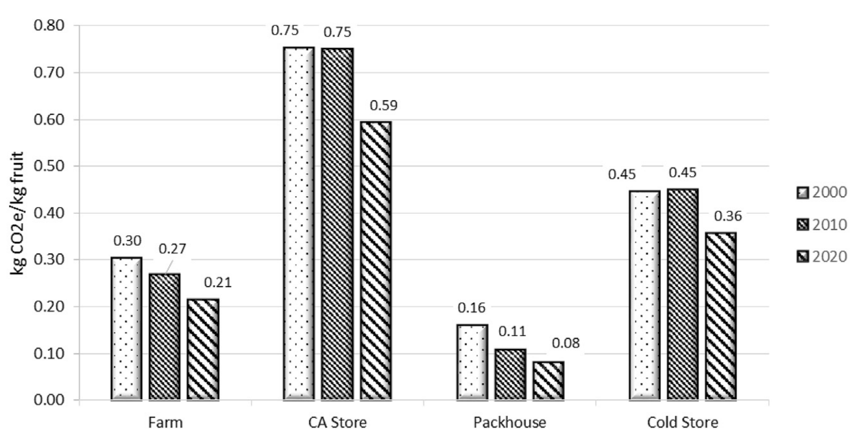

Fig. 5. GWP results per life cycle stage according to GHG Protocol method.

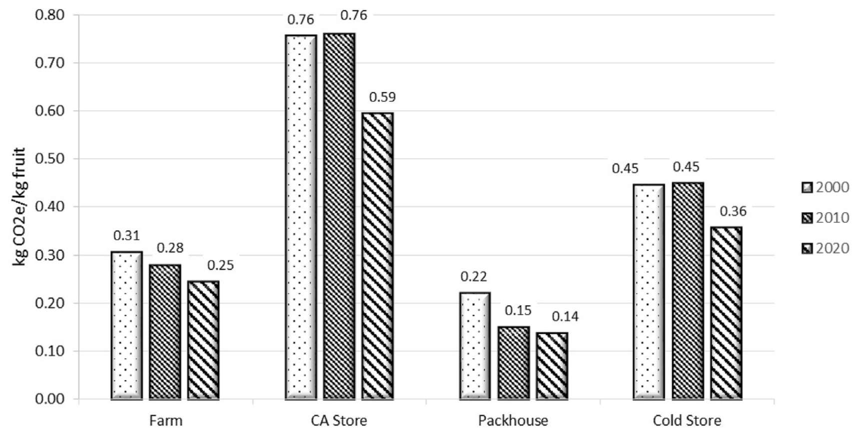

Fig. 6. GWP results per life cycle stage according to IPCC method.

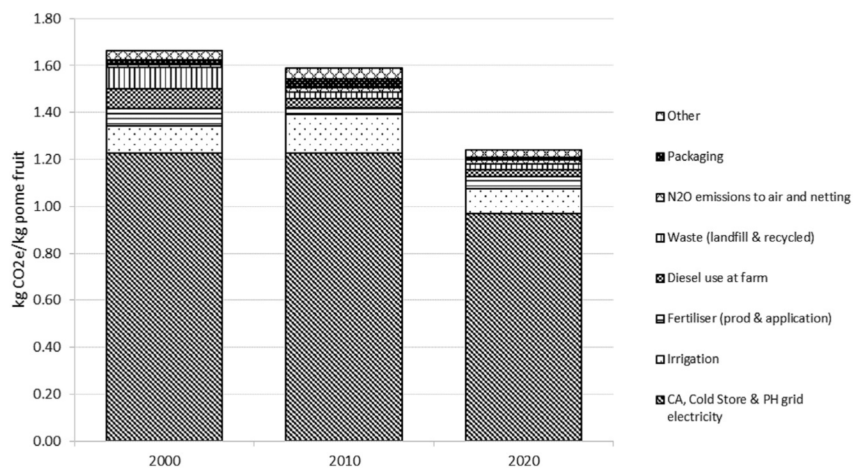

Fig. 7. Activity contribution to total GWP of pome fruit value chain per year indicating carbon intensive 'hotspots'.

Table 5
Irrigation practices for each time period.[10]

	2000	2010	2020
Yield [tonnes/ha][a]	21	31	36
Irrigation technologies [m3/ha]	Micro-sprinkler long range ≈6000	Micro sprinkler (long and short range) ≈6222	Micro sprinkler short range. Soil probes, optimization of irrigation system. ≈5200
Pumping system efficiency	70%	70%	75%
Grid electricity[b] [kg CO_2eq/kWh]	1.25	1.25	1.15
Other			Netting or draping of trees. Plastic mesh for mulch.

[a] Over 25 year lifespan of orchard including establishment phase.
[b] IPCC GWP 100a.

Hortgro. Parallel with this increase in economic value, four areas where eco-efficiency trends were observed are the irrigation practices (Table 5), diesel usage at farm (Table 6), fertiliser use (Table 7) and in the Packhouse and CS facilities (Table 8).

Table 5 illustrates the changing practices which affect GHG emissions including a cleaner energy mix driving the irrigation pumps, more efficient water management practices and the use of irrigation technologies which consequently drives down electricity use for pumping. The increase in yields per hectare is also a factor which lowers the GHG emissions per functional unit.

[10] http://www.hortgro-science.co.za/net-gain-amid-water-climate-challenges/.

Table 6
Diesel usage trends across time periods.

	2000	2010	2020
Diesel use per ha [L]	487	398	180–270

Table 7
Changes in nitrogen fertiliser application across time periods.

	2000	2010	2020
Tree density per hectare	941–989	1229–1272	1666–2000
Nitrogen applied per hectare [kg]	67	103	153
N_2O emissions to air per hectare [kg/ha]	1.12	2.24	2.58

Table 8
Changes in packhouse and cold storage inputs and outputs.

	2000	2010	2020
Electricity	100% grid	100% grid	95% grid, 5% PV
Bins	Wooden	84% Wooden 16% Plastic	50% Wooden 50% Plastic
Packaging	Only cardboard and trays (paper and polystyrene) used. Fruit packed loose.	Combination of corrugated cardboard and plastics (PP, PET, LDPE).	Combination of RPC, wooden bins, bio based PP and corrugated cardboard.
Transport (forklifts)	Liquid Petroleum Gas (LPG) and diesel	LPG and electricity	Only electricity
Organic waste (fruit)	15%	1%	1%
Packaging kg CO_2eq/kg fruit (GHG Protocol)	0.01	0.03	0.01

Table 6 shows the decrease in diesel use in the orchards per hectare due to more efficient pesticide spraying, harvesting and pruning activities which also contributed to the decreasing GHG emissions of the system.

However, with the increasing tree densities there has been an increase in the application of nitrogen fertilisers which leads to higher GHG emissions (production and application) as presented in Table 7. Even with the increase of nitrogen consumption the increase in yield leads to a lower GHG emissions per kg fruit.

Table 8 shows how the changing practices in the packhouse and cold storage life cycle stages has also had an impact on the GHG emissions. The use of PV as an energy source and the changing national electricity grid mix has been the largest factors in the declining GHG emissions along with the generation of less organic waste. The GHG emissions from the bins and packaging remains relatively stable. These changing practices along with the increase in yields could provide a causal explanation to the declining GHG emissions of South African pome fruit.

3.3. Carbon intensity trend in the pome fruit industry

Using the GWP results and industry revenue of the pome fruit value chain, it is possible to determine the carbon intensity of the industry for each of the years in question using Equation 1. The carbon efficiency indicator is determined as the inverse value of the carbon intensity.

$$Carbon\ intensity_i = \frac{total\ kg\ CO_2e_i}{total\ industry\ revenue\ PPI\ (ZAR\ 2010)i}$$

where i = year of LCA.

Equation 1: Formula to determine carbon intensity of pome fruit industry in year *i*.

Table 9 shows the industry revenue for each of the years calculated in 2010 ZAR adjusted for PPI. The price per ton is a weighted average for the export and local market fruit based on the tonnages per grade. The PPI for grouping ‘Fruits and Vegetables’ from Statistics South Africa is used to adjust the monetary values to 2010 ZAR. The industry revenue in 2010 USD is also presented in Table 9 using the 2010 exchange rate.

The data in Table 9 indicates that since the year 2000 there has been a 7.2% compound annual growth rate in the price received per ton of export and local pome fruit (2010 ZAR). However, input costs have grown significantly in the same time period which has led to the drive in increasing grade 1 and 2 yields per hectare in order to be economically sustainable. Since 2000, there has been an 82% increase in product output coupled with an improvement in eco-efficiency as discussed in Section 3.2. Fig. 8 illustrates the carbon intensity for each of the years.

3.4. Sensitivity analysis

The objective of the sensitivity analysis was to assess the reliability of the final results taking into account uncertainties in the data, allocation methods and assumptions. The sensitivity analysis tested the impact of two scenarios which have high uncertainty, namely; electricity consumption per m^3 water pumped for irrigation and the proportion of fruit from farm first stored in the CA facility before being packed.

The year 2000 electricity consumption value was a single data point of 0.3 kWh per m^3 of water pumped for irrigation, which was considerably lower than the value for the other LCIs. Adjusting this value to 0.54 kWh, which is the average for 2010 and 2020, had a significant impact on the GWP result for 2000. The GWP result for the farm life cycle stage increased from 0.30 to 0.39 kg CO_2eq/kg fruit and the total GWP result for the product system increased by 10%. The other scenario of adjusting the proportion of fruit intake into the packhouse from the CA was also analysed. Some packing facilities report that up to 75% of packhouse intake is first stored in the CA. With 75% of fruit first stored in the CA before being packed, lead to a 44% increase in the GWP result for all years according to the GHG Protocol and IPCC impact assessment methods.

4. Discussion

On the basis of the results obtained, a comparison with other pome fruit LCAs is possible, and hotspots and trends in carbon intensity can be discussed.

4.1. Comparison to pome fruit produced in other countries

The farm stage is included in all pome fruit LCA studies. For the period around 2000, farm-stage GHG emissions in New Zealand and Switzerland (as shown in Table 1) in the range of 0.04–0.12 kg

Table 9
Annual industry revenue for Grade 1 and 2 apples and pears adjusted for PPI to 2010 ZAR and 2010 USD.

Year	Total mass [ton]	ZAR per ton for export and local market fruit (2010 ZAR)	Industry revenue (local and export) 2010 ZAR million	Industry revenue (local and export) 2010 USD million
2000	513 949	2 176	1 119	153
2010	754 648	5 126	3 868	528
2020	935 286	8 804	8 233	1125

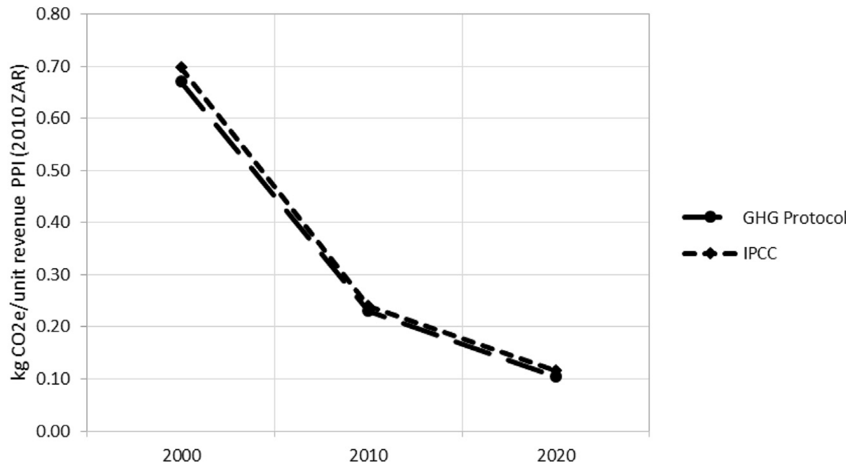

Fig. 8. Carbon intensity trend for pome fruit industry since year 2000.

CO_2eq/kg fruit were significantly lower than for pome fruit cultivation in South Africa (Figs. 5 and 6) of 0.30 kg CO_2eq/kg fruit. The GWP results for farm reported by Stoessel et al. (2012), Liu et al. (2010) and (Keyes et al., 2015) around the year 2010 were in the range of 0.06–0.38 and are comparable to the South African farm emissions of the same year of 0.25 kg CO2eq/kg fruit. For the agro-processing stages the result for the packhouse of 0.15 kg CO_2eq/kg fruit was similar to the LCA result found by Liu et al. (2010). However, the GWP results for the packhouse and cold storage facilities by Keyes et al. (2015) was considerably lower than the results for South Africa, which highlights the considerable impact the CA and CS life cycle stages have on the overall GHG emissions of pome fruit.

4.2. Hotspots in carbon intensity of the industry

Across all years, the input to the value chain with the largest contribution to impact category climate change was the national grid electricity. Electricity use in the agro-processing facilities and irrigation on farm was ranked first and second according to the GWP results for all years (Fig. 7). This ranking of results held true using both the GHG Protocol and IPCC impact assessment methods. The life cycle stages with the highest GWP per kg fruit result across all years were the CA and CS facilities (Figs. 5 and 6). The sensitivity analysis in Sec. 3.4 indicated that increasing electricity consumption for irrigation at farm as well as the differences in the volumes of fruit first stored in the CA before being packed, leads to a 10% and 44% increase respectively in the GHG emissions of the pome fruit. These findings once again highlight the significant impact the national grid electricity had on the results. In this regard, the expected contribution of the renewables build programme, as well as of the commissioning of more efficient new coal power plants coupled with the decommissioning of old stations is expected to significantly reduce electricity-related emissions of all South African products as the country implements its nationally determined contribution to the international climate change mitigation effort.

4.3. Trends in carbon intensity of the industry

Taking into account all life cycle stages, the pome fruit GWP results for the years 2000, 2010 and 2020 in Table 4 indicate a decrease in GHG emissions per kg fruit from the year 2000–2020. This trend was replicated when the results per unit of production were extrapolated to the annual market output and normalised in Fig. 4 to total GHG emissions for South Africa for each of the years. Whilst the pome fruit industry has grown by 80% (production tonnage) and its revenue has multiplied 7-fold, its attributed share of national greenhouse gas emissions has shrunk from 0,18% in 2020 to an estimated 0,12% in 2020.

The results from the LCIAs and gross industry revenue for each year (2010 ZAR, PPI) in Table 9 was used to determine the trends in the carbon intensity of the pome fruit industry in Fig. 8. It was found that there has been a 66% decline in industry carbon intensity from 2000 to 2010 with a slower decline of 53% from 2010 to 2020. In total there has been an 8.6% annualised decrease in carbon intensity from 2000 to 2020 and a 10.5% annualised increase in total gross industry revenue for the same period. Since the year 2000 there has also been an 84% absolute decrease in carbon intensity of the industry. From these findings, it can be concluded that the carbon intensity of the South African pome fruit industry has indeed declined from the year 2000. These trends indicate a relative decoupling of total pome fruit industry GHG emissions from the growth in gross industry revenue between 2000 and 2020 as during this period total GHG emissions increased by 18% while the industry revenue grew by 113%. Significantly, total GHG emissions related to the pome fruit industry may have peaked in the 2010–2020 period despite increasing production and sales revenue.

5. Conclusions

The GWP of South African pome fruit was relatively high compared to other global LCA results in the year 2000. By 2010 however, the GWP per supply chain stage were comparable to other producing regions, except for the electricity-intensive fruit storage stages. The GWP results indicate a substantial decline from the year 2000–2020, of about 20% per decade per unit of fruit produced and, more strongly so at 66% and 53% per decade, per real unit of economic value created (local currency). Overall, there is a relative decoupling of GHG emissions from the gross industry revenue. This decline is evident in all four production stages as well as for all key value chain activities, with the largest contributor to total aggregated GWP results remaining the grid electricity input at fruit packaging and storage.

This research added to the body of work of assessing production practices applied to pome fruit production and should serve as an example for developing economies who are also exporters in the global market and who might face trade barriers due to products with high embodied carbon. The trend in declining carbon-intensity has shown that national policies and cleaner practises within the pome fruit life cycle stages (e.g. more efficient irrigation practices and decreasing fuel, fertiliser and agro-chemical consumption per kg fruit at farm, and the changing electricity mix due to the increasing use of renewable sources amongst others) already implemented and predicted to be implemented, have and is predicted to contribute to the further decarbonisation of the sector. These practises are being implemented without compromising on production yields leading to the overall decline in GHG emissions per kg of pome fruit.

Funding

This work was supported in part by the South African Food and Agriculture Reduced Impacts (SAFARI) project, a CleanTech and GreenTech project between the University of Cape Town and Zurich University of Applied Sciences; through a grant received from the Swiss – South African Joint Research Programme (SSAJRP) 2014–2016.

Acknowledgements

We thank those stakeholders in the South African pome fruit industry (consultants, industry bodies and researchers) who assisted by providing data and insights.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2018.12.026.

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