



Life cycle assessment of California processing tomato: an evaluation of the effects of evolving practices and technologies over a 10-year (2005–2015) timeframe

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Abstract

Purpose California is the largest US producer of processing tomatoes, generating 96% of all domestic production and nearly 30% of global supply. Processing tomatoes are mostly processed into diced and paste products. Consumers and actors along their supply chains are increasingly interested in understanding their environmental burdens and identifying opportunities for improvements. This study applies life cycle assessment (LCA) to California diced and paste products over a 10-year timeframe to characterize current impacts and historical trends.

Methods The LCA considers a scope from cradle-to-processing facility gate and accords with relevant Product Category Rules as published by the International EPD® System. Extensive primary data were collected for tomato cultivation for the years 2005 and 2015, and from processing facilities for 2005, 2010, and 2015 to understand the effects of evolving practices and technologies. We estimate crop and regional specific nitrous oxide and nitrate leaching emissions using a biogeochemical model, and the USES-LCA model is used to determine potential impacts from pesticide application. A suite of impact assessment categories is included based on the CML method (only global warming potential and freshwater consumption values are in the abstract).

Results and discussion The 2015 results of the study indicate that diced tomatoes are responsible for 0.16 kg CO₂e and 71 L of freshwater per kg, and paste is responsible for 0.83 kg CO₂e and 328 L of freshwater per kg. The main opportunities for improvement include natural gas use in the greenhouse phase, energy for irrigation pumping and fertilizer type in the cultivation phase, and natural gas and electricity use in the facility processing phase. These hotspots are consistent with studies of processing tomato in other parts of the world. Evaluating trends over time showed that technological improvements in the industry had reduced life cycle impacts; for example, global warming potential decreased by 12% for paste and 26% for diced products between 2005 and 2015.

Conclusions Trends over time show increasing efficiency at the cultivation and processing facility stages that have led to reductions in all impact categories evaluated. However, additional opportunities exist beyond efficiency improvements. Fertilizer and pesticide choice are potential opportunities for further reducing impacts. Also, the introduction of renewables in

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each phase of the supply chain (solar-powered irrigation pumps and onsite solar energy generation for facilities) could reduce the overall supply chain GWP₁₀₀ impacts by 9–10%.

Keywords Canned tomatoes · Carbon footprint · Food supply chain · Life cycle assessment (LCA) · Processing tomato · Sustainability · Tomato paste

1 Introduction

California produces 11.6 million metric tons of processing tomato per annum, which makes up ~96% of the total US processing tomato production (CDFA 2016). The challenge of meeting increasing food demands under resource restrictions while also reducing environmental impacts from agriculture has led to the use of life cycle assessment (LCA) to evaluate food products and agricultural systems (Heller et al. 2013). LCA remains a useful decision-making tool for product assessment and supply chain improvements.

Historically, LCAs assessing greenhouse operations for fresh tomato, not processing tomato, have been completed for a number of locations including Spain (Martínez-Blanco et al. 2011; Torrellas et al. 2012), Canada (Dias et al. 2017), Italy (Cellura et al. 2012), southern and central Europe (Ntinis et al. 2017), and Australia (Page et al. 2012). An LCA of processing tomato has been conducted for cultivation in Italy (Del Borghi et al. 2014; De Marco et al. 2018), Greece (Ntinis et al. 2017), Turkey (Karakaya and Özilgen 2011), and with limited data and impact categories in California (Brodt et al. 2013). Processing facility operations for tomatoes have been assessed with LCA in Italy (Del Borghi et al. 2014), Turkey (Karakaya and Özilgen 2011), and California (Amón and Simmons 2016; Brodt et al. 2013). For processing tomato cultivation, most studies identified the primary hotspots for improvement in environmental impacts as fossil fuel use, electricity for irrigation, and fertilizer production. For tomato processing, studies found that electricity and fuel use are two primary hotspots. The current study establishes the first LCA results for California diced and paste tomato products from the greenhouse to processing facility gate using extensive primary data, and seeks to understand the effects of changing cultivation and processing practices over a 10-year timeframe (2005 to 2015) and concerning geographic and facility-level variability.

2 Methods

2.1 Products and production process description

The critical stages for California processed tomato production include the greenhouse, cultivation, and processing operations. Greenhouse operations supply transplants (seedlings

that are 6–9 weeks old). Greenhouse operations mainly occur for 7 months of the year (mid-December to mid-June), but require some minimal heating and electricity for the remainder of the year. Activities for cultivation include pre-plant field preparation, transplanting, irrigation, fertilization, pest management, and harvest. The timing of field operations varies depending on the field location within California. For example, transplanting (planting of seedlings) tends to start in mid-December and continues until mid-April, with operations beginning earlier from south to north in the growing region. Typical processing tomato plant density is 19,760–21,538 plants per hectare (8000–8720 plants per acre) according to data collected for this study. Processing facilities try to maximize utility by running continuously, 24 h a day, 7 days a week during the prime processing period (for 2 or more months), and arrange harvest contracts with growers that specify timing. The raw tomatoes supplied from farmers' fields to the processing facility sit at the facility for a brief time within the season but are not in cold storage. This storage uses minimal additional energy, and what is used is accounted for within the facility. While some Californian processors produce additional specialty products, the dominant products are diced tomatoes and paste, which are either sold in bulk for further processing into tomato sauce, ketchup, and other food products, or are sold in retail-ready packaging for consumers.

2.2 Life cycle assessment methodology

A process-based life cycle model is used to evaluate the environmental impacts of processing tomato production in California from the greenhouse to the processing facility gate. As such, the model accounts for energy and resource inputs at every stage, from seed to processed tomato, and the upstream environmental burdens associated with these inputs. The Product Category Rules (PCRs) and the International EPD® framework inform the methods selected in this work. This framework is aligned with the International Standards Organization LCA guidelines (International EPD System 2014; ISO 2006a, b, c) but provides a more specific set of guidelines for the product. Specifically, the methods selected for this study are consistent with the PCRs 2014:09 V1.01 UNCPC 2132 and 2139 UNCPC for products classified as processed food products belonging to “vegetable juice” (CPC 2132) and “other prepared and preserved vegetables,

pulses, and potatoes” (CPC 2139) (International EPD System 2014). While this study is not an EPD of California processed tomato products, following these guidelines facilitates comparability with studies undertaken under the auspices of this PCR.

2.2.1 Goal and scope definition

The goal of this study is to create a baseline LCA for California processing tomato production and diced and paste products, as well as to understand the environmental implications of trends in resource use and associated impacts over time that have resulted from changing technologies and agronomic practices, such as more widespread adoption of drip irrigation. The functional unit is 1 kg of diced or paste product, not including the weight of the packaging. The system boundary includes the cradle-to-processing facility gate, as illustrated in Fig. 1. Some exclusions from the system boundary include packaging materials, solid waste handling and treatment, and non-energy-related processes for wastewater treatment. Tracking packaging materials was beyond the scope of the study in part because of the enormous diversity in bulk and

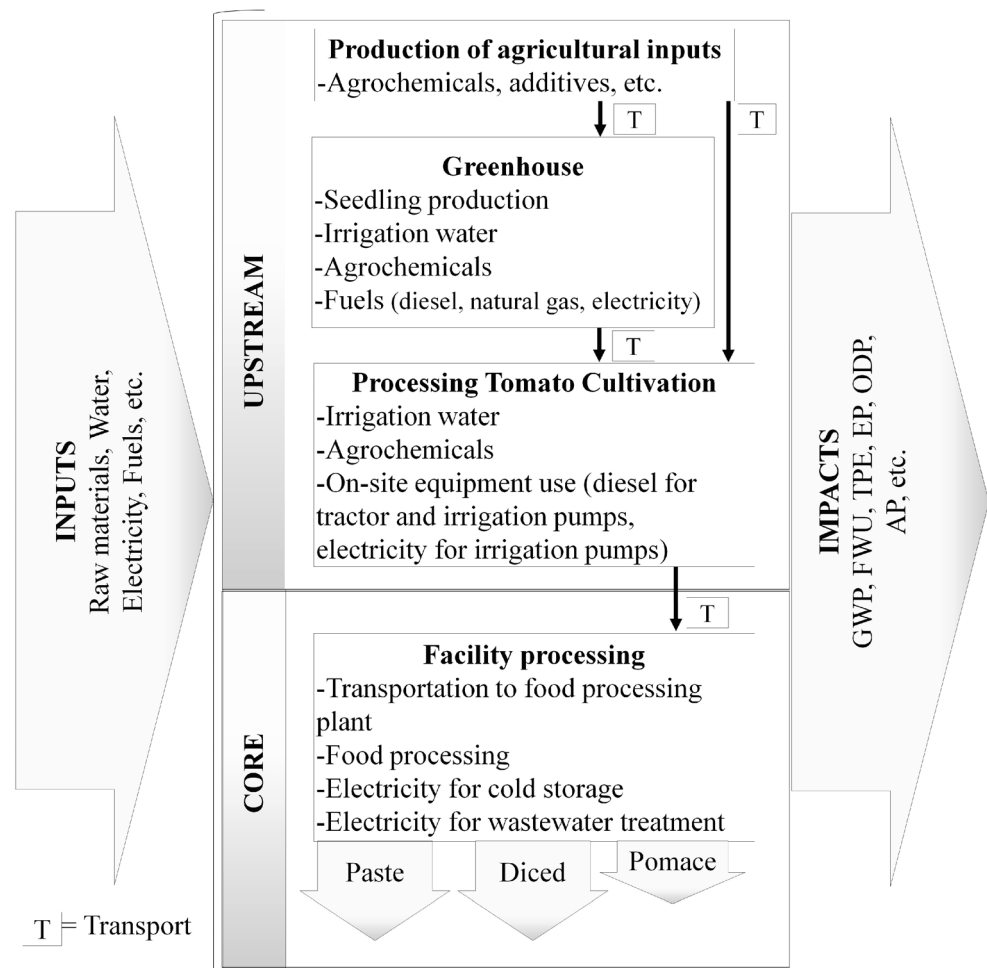
retail-ready packaging choices across facilities. However, as energy and water are tracked on a facility-wide basis, the energy and water associated with packaging processes (e.g., filling or sealing containers) are accounted for in the analysis. Similarly, while wastewater flows and treatment processes are not tracked, the electricity needed to handle wastewater treatment at facilities is included in the system boundary.

Some processes required additional modeling. In particular, for the tomato cultivation phase, a biogeochemical model is used to investigate some of the effects of in-field application of nitrogen-based fertilizer, as described in Section 2.3.5. Also, a multi-compartment fate, exposure, and effects model is used to explore the fate of pesticides, as described in greater detail in Section 2.5.1. Finally, because the facilities generate multiple products, an allocation process is required, which is described further in Section 2.4.

2.3 Life cycle inventory

The life cycle inventory (LCI) development consists of two steps: primary data collection via surveys for characterizing

Fig. 1 System boundary indicating the life cycle stages included in the study. Abbreviations: global warming potential (GWP), freshwater consumption (FWC), total primary energy (TPE), eutrophication potential (EP), ozone depletion potential (ODP), and acidification potential (AP)



the foreground systems and reference LCI dataset collection for characterizing the background systems.

2.3.1 Primary data collection

The first step in this project was an extensive review of peer-reviewed literature and other sources of data such as the grower-reported statewide Pesticide Use Report (PUR) database (CDPR 2018) and the University of California cost and return studies (e.g., Miyao et al. 2008). This review of the literature and available data was used to develop surveys for managers and operators at each life cycle stage: greenhouse, cultivation, and processing. The surveys were refined based on the feedback provided during a beta-testing process and then administered to a broader set of greenhouse managers, growers, and processing facility managers. Surveys collected data on material, energy and resource inputs, direct emissions from sites (e.g., wastewater generation), and yield or product quantities for the years 2005 and 2015. Not surprisingly, survey response rates were lower for 2005 data (compared with 2015), especially from greenhouses and processing facilities, due to changes in record-keeping practices within the last 5 to 8 years. Correspondences with processors revealed data recording improved by 2010. Thus, an additional survey was administered to collect 2010 data, which resulted in the information available for further evaluation of 10-year trends (2005, 2010, and 2015) and inter-annual variability at the processing facility phase.

2.3.2 Greenhouse data

Despite several campaigns for additional data, only three greenhouse managers responded to the survey, with only one providing sufficiently complete data and only for the year 2015. Because of this, greenhouse data from a single facility for 2015 were used to represent seedling (transplant) production in all modeled years (2005, 2010, and 2015).

2.3.3 Cultivation data

A total of 16 growers provided complete surveys for both 2005 and 2015, and an additional 30 growers responded with 2015 data only. For accurate representation of the change in grower practices over time, a subset of the grower data was used for the model values that includes growers that reported fertilizer data ($n = 8$) and pesticide data ($n = 13$) for both 2005 and 2015 (see the Electronic Supplementary Material – ESM - S1).

Diesel consumption for on-farm tractor use is estimated based on reported equipment use (hours per hectare) and equipment specifications (e.g., horsepower) coupled with manufacturer-based tractor engine testing data. Irrigation pumps in California operate on diesel or electricity, and

energy demand was estimated based on spatial modeling of surface water delivery infrastructure and groundwater depth overlaid with tomato production maps. Based on the grower survey data collected for this study, an estimated 50% of the processing tomato growers use surface water, and 50% use groundwater, and 60% of the growers use diesel pumps, and 40% use electric pumps. Estimated electricity use is 0.30 kWh per cubic meter (31.16 kWh per ac-in) water for surface water and 2.03 kWh per cubic meter (209.12 kWh per ac-in) water for groundwater, assuming 90% pump efficiency. Calculated diesel use is 0.03 L per cubic meter (0.77 gal. diesel per ac-in) water for surface water and 0.19 L per cubic meter (5.14 gal. diesel per ac-in) water for groundwater. Foreground data collected for the greenhouse and cultivation phases are reported in the ESM - S2. We assessed the variability and uncertainty of the cultivation primary data, and present some of the results of these analyses in the ESM - S3.

2.3.4 Processing facility data

Data were collected from two processing facilities that reported data for 2005 and 2015, and from five facilities that reported data in 2010 and 2015. The water content of the processing tomatoes ranges from 93 to 95% of the tomatoes total weight (based on survey data). The two tomato products assessed require different quantities of tomato; 1.3 kg of fresh tomato is required per kg of diced product, and 6.0 kg of tomato is required per kg of paste product. These ratios are used to link the cultivation stage results to the processing facility model. Foreground data collected for the processing facilities are reported in the ESM - S4.

2.3.5 Field emission models

This LCA uses a detailed biogeochemical cropping systems model DeNitrification-DeComposition (DNDC) (Li et al. 1992; Li et al. 1994) to estimate direct and indirect nitrogen (N) emissions from N fertilizers and soil carbon changes in Californian processing tomato-cultivated fields. This approach for estimating emissions aligns with the Tier 3 IPCC guidelines outlined by DeKlein et al. (2006).

The DNDC model parameterization includes the use of Kallenbach et al. (2010) soil water and soil pH data, soil bulk density values sourced from the United States Geological Survey soil data maps (USDA 2017), and a literature-reported soil organic carbon value of 0.011 kg/kg soil based on empirical processing tomato crop research by Hurisso et al. (2016). The values used to parameterize the DNDC model are used in the DNDC model only—to estimate the emissions from the field—and the resultant DNDC model output values are used as static values in the LCA model. We compared the resultant DNDC model output values generated for the current study with peer-reviewed literature values, and the DNDC

model results are within the expected range of values for processing tomato in California, i.e., based on empirical research observations.

The resultant averaged percent values of nitrate leaching to nitrogen fertilizer (~5% of N in fertilizer applied) used in the LCA are based on the series of DNDC model runs conducted for this study for different soil types ranging from sand to loam to clays. Based on grower-reported soil type data (from the grower survey), the range of soil types modeled in DNDC relates to field conditions. The average amount of fertilizer modeled in DNDC per year was equal to 209 kg N/ha/year. The resultant DNDC model values for nitrate leaching ranged from 44.27 kg NO₃-N/ha/year in “pure” sands to 1.85 kg NO₃-N/ha/year in “pure” clays. The variability in the DNDC model results (for NO₃-N, etc.) is due, in part, to highly sensitive factors within the DNDC model controlling water flow through soils (e.g., clay fraction and field capacity) and soil N factors (e.g., N input and crop N uptake). The gaseous emissions of N to the soil, water, or air in the forms nitrogen monoxide (NO), ammonia (NH₃-N), and N₂ from fertilizer application are estimated by the DNDC model at 0.28%, 0.04%, and 0.06%, respectively, of the N content of fertilizers applied. Direct and indirect nitrous oxide (N₂O) are estimated at 1.37% of the N content of fertilizers applied.

2.3.6 Other data sources and reference LCIs

Software used to develop the LCIs includes ArcGIS software for estimation of transport distances. We estimated an average of 322 km (200 miles) from greenhouse to field (one-way transport) and 322 km (200 miles) from field to facility (one-way transport). For all materials, the transport distances from the manufacturer to the nearest distribution point to the field (one-way transport) are accounted per material type. Transportation distance details are provided in the ESM - S5.

GaBi software was used to access the Ecoinvent (Wernet et al. 2016) and GaBi (Thinkstep 2017) LCI databases. These data were then used to collect or to develop relevant reference LCI datasets for the LCA models. Metadata for the reference LCIs are available in the ESM - S6.

2.4 Co-product allocation

Final products from the processing phase include the primary tomato products, diced and paste tomato, as well as the co-product pomace. The sale price of tomato and pomace varies from year to year, based on various factors (e.g., oil prices) and the relative price of other potential supplements in livestock feed, like corn. Economic allocation is applied based on the average price based on survey results ($n = 3$) for the respective functional flow (product, e.g., diced tomato, and year (as reported in Table 1)). The economic allocation factor is

Table 1 The averaged relative price for paste and diced products, and pomace co-product (\$/kg) in 2005, 2010, and 2015

Year	Paste price (\$/kg)	Diced price (\$/kg)	Pomace price (\$/kg)
2005	0.72	0.37	0.04
2010	0.74	0.42	0.01
2015	0.98	0.40	0.02

calculated using Eq. (1) for product one (product 1; paste tomato), product 2 (diced tomato), and product 3 (pomace).

Economic allocation factor

$$= \frac{\text{Mass product 1} \times \text{Price product 1}}{\sum_{i=1}^n \text{Mass product } i \times \text{Price product } i} \quad (1)$$

2.5 Life cycle impact assessment

The impact categories considered in this study include 100-year global warming potential (GWP₁₀₀) without climate-carbon feedback mechanisms (as is common practice) reported in kg CO₂ equivalents (kg CO₂e) (Myhre et al. 2013).

The following impact categories are considered based on characterization factors from the Institute of Environmental Sciences (CML): ozone-depleting potential (ODP), in kg CFC 11-equivalents; acidifying potential (AP), in kg SO₂ equivalents; photochemical ozone-creating potential (POCP), in kg C₂H₄ equivalents; and eutrophication potential (EP), in kg PO₄³⁻ equivalents. Impact categories for inputs are also considered and include total primary energy, reported as the sum of the renewable and non-renewable sources in megajoules (MJ), and total freshwater use, which includes surface water (lakes and rivers) and groundwater inputs to the system and accounts for water returned to the system after use in turbines and in cooling towers.

2.5.1 Modeling of pesticide application impacts

A separate impact assessment modeling step is required for pesticides because reference LCI datasets for pesticides only reflect production-related impacts, not impacts that occur after application. To address this shortcoming, downstream toxicity impacts from pesticide applications in fields are estimated using the Uniform System for the Evaluation of Substances adapted for LCA (USES-LCA) model (Huijbregts et al. 2000). The pesticide toxicity potentials are calculated for each of the following impact categories: freshwater aquatic ecotoxicity potential (FAETP), marine aquatic ecotoxicity potential (MAETP), terrestrial ecotoxicity potential (TETP), and human toxicity potential (HTP). These potentials express the toxicity of one unit of chemical released into the environment,

relative to one unit of 1,4-dichlorobenzene (1,4-DCB) released into the environment.

2.6 Life cycle assessment model

The process-based LCA model was developed in Microsoft Excel with VisualBasic Macros to support some data management and calculation processes. Results from ArcGIS modeling, DNDC modeling, and USES-LCA were incorporated as static values. Given that the USES-LCA impact categories differ from the other characterization factors used in this assessment, the USES-LCA results are reported and discussed separately.

3 Results

3.1 Summary results

Figure 2 shows the summary impact assessment results for paste and diced tomato products, respectively. The numeric

LCIA results per impact category for each product—for paste and diced tomato—for each year are listed in the ESM - S7.

Hotspots for improvement across the California processing tomato supply chain include natural gas in the greenhouse phase, diesel and electricity use for irrigation pumping and fertilizer type in the cultivation phase, and natural gas and electricity use in the facility processing phase. Over the timeframe of the study (2005 to 2015), supply chain energy and water use efficiencies increased per unit produced for the respective diced and paste products.

3.2 Contribution analysis

The dominant contributor to GWP₁₀₀ within each life cycle phase of paste and diced products in 2005 and 2015 includes natural gas use in the greenhouse phase (80% of greenhouse phase GWP₁₀₀), electricity use for irrigation in the cultivation phase (26–29%), and natural gas use in the processing facility phase (94%) (Fig. 2). The dominant contributor to total primary energy use within each life cycle phase of paste and diced products in 2005 and 2015 includes natural gas use at

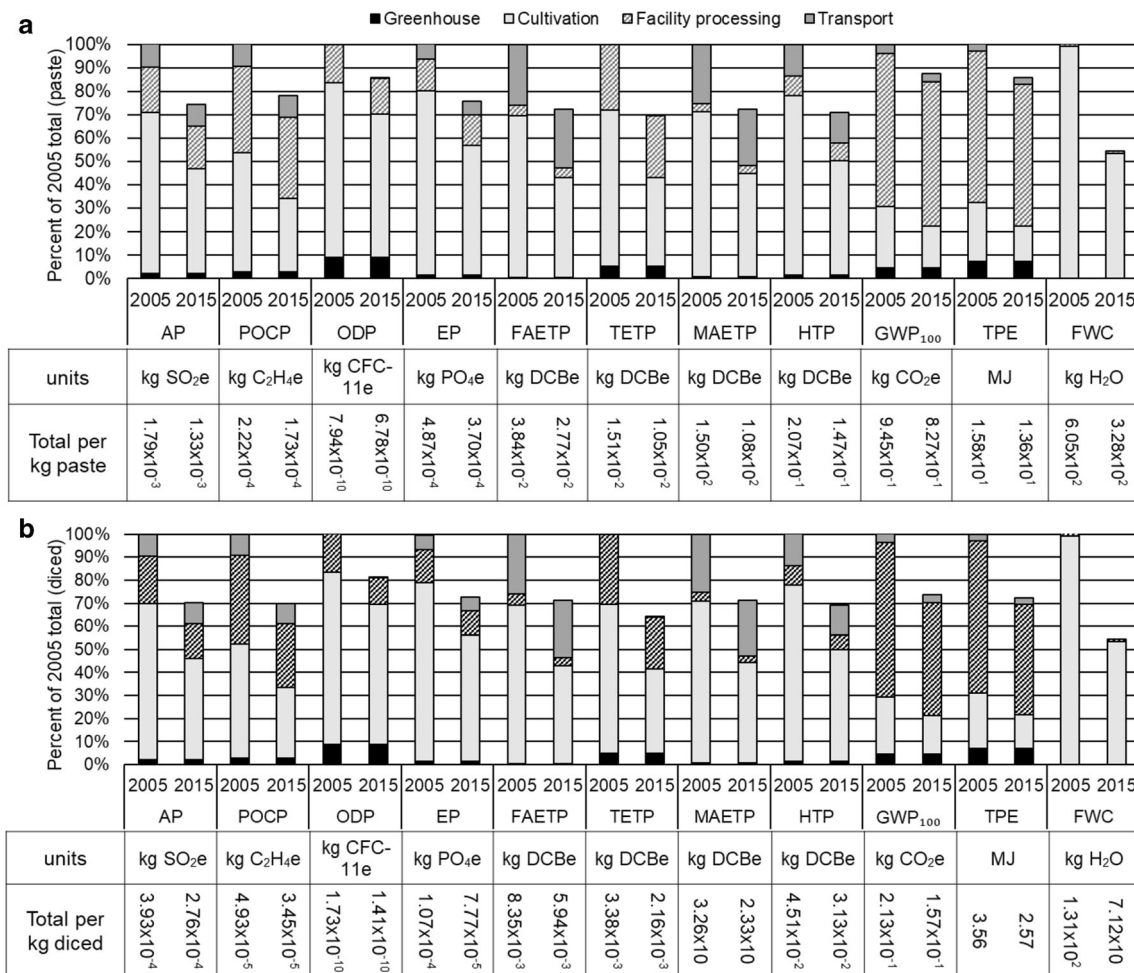


Fig. 2 Impacts by life cycle stage and percent contribution relative to 2005 production for 2005 and 2015 paste (a) and diced (b) products

the greenhouse phase (49% of total primary energy), electricity use for irrigation (29–32%) at the cultivation phase, and natural gas use at the processing facility phase (93%) (Fig. 2). The main contributors to freshwater consumption at the greenhouse phase are electricity use (41%), direct water use in the field in the cultivation phase (98%), and direct water use at the facility in the processing phase (93–95%) (Fig. 2). Analysis of the 2010 and 2015 processing facility data showed similar results to the 2005 and 2015 processing facility comparison and between-facility and inter-annual facility variability (briefly discussed in Section 4.2).

Concerning the CML impact categories included in Fig. 2, in the greenhouse phase, natural gas use contributes to 40% of the total AP impacts for the greenhouse phase, 72% of POCP, and 48% of EP. In the cultivation phase, diesel use contributes to 28–36% of the total EP impacts for the cultivation phase, 44–52% of AP, and 50–55% of POCP. In the facility processing phase, natural gas use is the main contributor to the following impact categories: EP (84–85%), AP (72–73%), and POCP (92–93%). The dominant contributor to the total HTP, MAETP, and FAETP impacts at the cultivation phase is diesel used in on-farm equipment, i.e., tractors and irrigation pumps, accounting for 53–69% of the total impacts in 2005 and 46–62% in 2015. Natural gas use is one of the top contributors to these impacts at the processing facility phase (35–85%) in both years. The main contributor to the TETP impacts is grid electricity at the greenhouse phase (95% of the total TETP impacts) and the processing facility phase (96%). Diesel use in on-farm equipment is the main contributor to TETP impacts at the cultivation phase (77% of the total TETP impacts) in 2005 and (75%) in 2015.

Across the supply chain, transport of materials contributed to less than 1% of the total ODP and TETP impacts; 6–8% of EP; 9–19% of HTP, AP, and POCP; and 25–35% of MAETP and FAETP. Transport of peat from Nordic countries contributes to 60% of the total transport impacts at the greenhouse phase. Impacts associated with the transport of materials to the cultivation phase are attributed mainly to fertilizers (50% of the overall transport impacts) and chemical inputs to the processing facility phase (62%).

3.3 Pesticides: potential downstream environmental impacts

Of the substances compared for this study, mancozeb, chlorothalonil, fludioxonil, rimsulfuron, metolachlor, diazinon, and glyphosate have the highest potential toxic impact in the TETP impact category for the air environmental compartments (as shown in descending order) (ESM - S8). Of these pesticides, chlorothalonil, a fungicide, has the highest toxicity potential in the TETP impact category air, freshwater, agricultural soil, and industrial soil (ESM - S8). Oxyfluorfen has the highest potential toxic impact in the HTP category for

freshwater (ESM - S8). From 2005 to 2015, the use of most of the pesticides mentioned above changed by less than 5% per functional unit. However, in some cases, the number of growers using pesticides decreased from 2005 to 2015, e.g., the use of diazinon decreased from 17 to 12% of all growers surveyed for this study. Chlorothalonil use, on the other hand, nearly doubled from 25 to 40% within this same timeframe.

4 Discussion

4.1 Cultivation

Over the 10-year period (from 2005 to 2015), based on the data, we observed a range of changing cultivation practices. Diesel use and water use decreased by 23% and 45%, respectively, per unit of harvested tomato. On-farm reductions in water use are tied to reductions in energy and fuel use (used to pump irrigation water) and a shift in irrigation technologies such as drip irrigation. Fifty percent of surveyed growers shifted from furrow to drip irrigation between 2005 and 2015. Among those who did not switch, 13% continued to use furrow irrigation in 2015, and 13% were already using drip irrigation in 2005 (and 2015). The trend towards drip irrigation reflects a broader trend in California, with drip increasing by ~38%, while furrow irrigation decreased by ~37% for vegetable, orchard, and vineyard crops. Low-volume irrigation technologies increase flexibility in irrigation scheduling and improve control of moisture levels (Tindula et al. 2013), and, in the case of tomatoes, increase crop yields (Geisseler and Horwath 2014).

Surveyed growers also made a shift in fertilizer choice; for example, the data show a 25% reduction in the use of 4-10-10 (NPK) and a 10% increase in the use of calcium ammonium nitrate (CAN) 17. Notably, the data collected show there is no clear correlation between water and fertilizer inputs, and yield increases—from 92 to 123 metric tons per hectare (41 to 55 US tons per acre) in 2005 and 2015 respectively—among surveyed growers. In general, while large differences in soil type and thus water holding capacity may account for some of the differences in input rates, these results also suggest that there may be opportunities for some producers to improve water and fertilizer use efficiencies.

4.1.1 Fertilizer-related impact comparison

Ultimately, the upstream impacts need to be balanced with the downstream impacts that occur after field application of the product. A review by Rosenstock et al. (2016) shows that different types of N fertilizers result in different NH₃-N and N₂O emissions after application. For example, although this study has found that urea-based fertilizers (such as UN32) have lower emissions in their production compared with some

blends, Rosenstock et al. (2016) show that they can result in as much as 40% higher $\text{NH}_3\text{-N}$ emissions in the field than mixed ammonia and nitrate fertilizers, such as CAN17. On the other hand, ammonia products (such as aqua ammonia) can lead to 40–60% higher N_2O emissions in the field than urea-based or sulfate fertilizers.

4.2 Processing facility

The results show processing facility practices decreased impacts per functional unit over time (from 2005 to 2015) at the facility processing stage. Natural gas-related effects decreased by 27% and 5% for diced and paste products, respectively. Processing facility grid electricity and water use also reduced by 27% and 5% and 22% and 5% for diced and paste products, respectively. Because grid electricity generation entails significant amounts of freshwater use, decreases in electricity use translate to reductions in life cycle freshwater use.

Although we observed similar general trends in the 2005 and 2015 and 2010 and 2015 data (e.g., for reductions in natural gas use), our observations of the data indicate that evaluation of the between-facility variability requires process or equipment-level data, which is beyond the scope of this project. As such, an only general discussion about the cause of variability is possible. For example, thermal processes, such as evaporation, tend to be more energy-intensive per ton of product than mechanical methods, such as dicing. Energy source (e.g., grid electricity vs. onsite solar energy generation) and the rate of energy use (quantity of energy used per defined timeframe) and water demands vary depending on the product specs (e.g., select color, titratable acidity, and sugar content), which affect process-level equipment and settings (e.g., temperature) applied to produce that product.

Regarding the inter-annual variability, based on feedback from survey respondents, this variability is, in part, a reflection of the tomato throughput for the season. Basically, once the facility is made operational for the season, much of the equipment is kept running regardless of occasional gaps in tomato input. Thus, in high-yield or high-throughput years, the whole facility is more efficient than in low-yield or low-throughput years.

4.3 Comparison with other studies

In the current study, top impacts in greenhouse operations included fuel (natural gas use) for heating and electricity for pumps, lighting, etc. The second most impactful inputs include growth medium materials (vermiculite and peat), contributing to GWP, TPE, and FWC, as well as the AP, POCP, ODP, and EP impacts. For similar impact categories (AP, EP, and POCP), Del Borghi et al. (2014) show that packaging is a leading contributor to POCP (up to ~63% of the total impacts depending on the product and its packaging), and cultivation is the top

contributor to the EP impacts. Some previous studies (e.g., Dias et al. 2017; De Marco et al. 2018) have examined greenhouses using LCA, and another essential factor in determining impacts at this phase in the supply chain is whether the heating is required. In general, because California has a Mediterranean climate, it does not need much heating relative to some of the other regions of study like Canada and Germany.

Results of this LCA for the cultivation stage align with those from previous LCAs of tomatoes. These results include the significant contribution of fossil fuels (diesel) (Del Borghi et al. 2014; De Marco et al. 2018), electricity use for irrigation (De Marco et al. 2018; Ntinis et al. 2017), and fertilizer production and use (Ntinis et al. 2017). The primary data for inputs in the cultivation phase in the current study are similar to those reported in Del Borghi et al. (2014), but the GWP values reported in the current study are on the lower end of the GWP values reported there, ranging from 0.4 to 0.6 kg CO_2e per kg cultivated tomato. The modeled inputs reported in De Marco et al. (2018) are an order of magnitude higher per unit of the final product (e.g., for diesel inputs at the cultivation phase) compared with the current study, resulting in higher reported GWP values in their research. Overall, these studies show that across the supply chain, cultivation is the main contributor to ecotoxicity and human health impacts, including ozone depletion potential (based on CML methodology). Differences between the results of these studies may be due to weight ratios. For example, a wide range of products assessed in the Del Borghi study, including tomato purée, chopped tomatoes, and peeled tomatoes in tomato juice, along with mashed tomato in the De Marco study, do not report weight ratios for all products. Compared with the Brodt et al. (2013) study with the same weight ratios, water impacts are within range of the values observed in the current study ~130 to 610 kg water per kg product, for diced and paste products, respectively. Differences in reference LCIs used, e.g., grid electricity resulted in only slightly different GWP and TPE impact results between the Brodt et al. (2013) study and the current study.

Overall, the main contributions to the impacts at the facility processing phase observed in the current study (i.e., energy and fuel use) are similar to those observed by Karakaya and Özilgen (2011) and De Marco et al. (2018). Across the supply chain, facility processing is the main contributor to total primary energy use—in the current study and in previous studies (e.g., De Marco et al. 2018). One aspect of the processing facility phase which is not assessed in this study is vertical integration with the cultivation phase (and greenhouse phase). However, this aspect of the processing tomato supply chain is worth exploring further given it has proven to increase supply chain energy and water use efficiencies (Benmehaia et al. 2017) and many of the Californian processing facilities are vertically integrated.

Consumer packaging options for both puree and chopped tomatoes include 330–700 g glass bottles with metal or plastic lids, 200 g carton-based containers, and 500–1000 g carton-based containers with plastic caps; and chopped tomatoes containerized in 400–800 g open-top tin-plated steel can with lid (Del Borghi et al. 2014). Given these packaging types and varying sizes for puree and chopped tomatoes, associated fossil GHG emissions range from 0.0743 kg CO_{2e} per kg tomato puree in a 1000-g carton-based container with a plastic cap to 0.8007 kg CO_{2e} per kg of chopped tomato in open-top tin-plated steel can with lid (Del Borghi et al. 2014). Based on the Del Borghi et al. (2014) study, carton-based containers with and without plastic caps have lower impacts than the open top tin and glass bottle. Assuming puree is similar to paste by mass, adding consumer-ready carton-based container packaging impacts to the Californian tomato paste product assessed in this study would increase the global warming potential from fossil-based GHG impacts by 9–11%. However, the total impact from packaging is likely less for the processing facilities in this study, due to packaging their products in large bulk containers (aseptic bags in large re-usable drums or wooden bins) for shipment to food manufacturers. For example, in an earlier study (Brodt et al. 2013), we found that bulk packaging increased the total GHG impacts from transplant production through packaging by less than 2% in the paste product and just under 4% in the diced product.

5 Conclusions

From the greenhouse phase to the facility processing phase, the processes leading to the top five highest environmental impacts include grid electricity, electricity use for irrigation, natural gas use, direct water use, and diesel use. In 2015, total GWP₁₀₀ amounted to 0.827 kg CO_{2e} per kg paste product and 0.157 kg CO_{2e} per kg diced product. In the USA, the total metric tons of tomato paste only amounted to 1.5 million metric tons in 2015 (MS 2019), resulting in an overall footprint of an estimated 1.2 million metric tons of CO_{2e} based on the current study GWP₁₀₀ estimates per kg paste product.

The reductions observed in the overall supply chain in the 10-year timeframe includes GWP₁₀₀ by 26% (diced) and 12% (paste) and total primary energy consumption by 28% (diced) and 14% (paste). Life cycle freshwater consumption decreased by 46% for diced and paste products. The upstream CML impacts which account for toxicity and other adverse impacts also decreased across the supply chain from 2005 to 2015.

One avenue for further reductions in supply chain impacts is the introduction of renewables in each phase of the supply chain (solar-powered irrigation pumps for cultivation and onsite solar energy generation for processing facilities). Our scenario analysis showed that 100% solar replacement for current grid electricity at the processing facility phase only

(in 2005 and 2015) could reduce the overall supply chain GWP₁₀₀ impacts by 9–10%. A second avenue is to increase the use efficiency of the most impactful resources (e.g., fossil energy sources) by way of reducing the total use of these resources. Third, in some cases, switching to different products may reduce impacts, such as fertilizers with lower global warming potentials and pesticides with lower toxicity potentials in both their production and post-application use.

Additional assessment of composition and ultimate fate (e.g., recycled and landfilled) of waste materials from all phases, especially from the packaging of inputs, are needed. These materials have the potential to affect the overall impacts substantially. Finally, a clearer understanding of process-level, within facility, and inter-annual variability would help to decipher some of the high variability between processing facilities for a given amount of throughput in terms of a mass amount of product produced per year.

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