A Baseline Life Cycle Assessment of California Tomato Cultivation and Processing

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Glossary

Abbreviations

CDPR: California Department of Pesticide Regulation
PUR: Pesticide Use Report
EPD: Environmental Product Declarations
EMFAC: EMissions FActors Model
GWP: Global Warming Potential
Ccfb: Climate-carbon feedback, an increase in global warming potential attributable to the positive feedback created when global temperature increases lead to additional releases of carbon into the atmosphere from terrestrial and marine sources.
CML: Centre of Environmental Science impact categories
HTP: Human Toxicity Potential (kg 1,4-dichlorobenzene (1.4-DCB) eq.)
MAETP: Marine Aquatic Ecotoxicity Potential (kg 1.4-DCB eq.)
TETP: Terrestrial Ecotoxicity Potential (kg 1.4-DCB eq.)
FAETP: Freshwater Aquatic Ecotoxicity Potential (kg 1.4-DCB eq.)
AP: Acidification Potential (kg SO_2 eq.)
POCP: Photochemical Ozone Creation Potential (kg C_2H_4 eq.)
ODP: Ozone Layer Depletion Potential (kg CFC-11 eq.)
EP: Eutrophication Potential (kg PO_4 eq.)
Elements ADP: Elements Abiotic Depletion Potential (kg Sb eq.)
Fossil ADP: Fossil Abiotic Depletion (MJ)
C: Caution, a US EPA-designated signal word used on pesticide product labels to describe the level of acute (short-term) toxicity of the product ("Caution" or no signal word are used for the lowest level).
W: Warning, a US EPA-designated signal word used on pesticide product labels to describe the level of acute (short-term) toxicity of the product.
D: Danger, a US EPA-designated signal word used on pesticide product labels to describe the level of acute (short-term) toxicity of the product ("Danger" is used for the highest toxicity level).
RU: Restricted Use, a US EPA designation for a pesticide that requires special licensing for purchase and use of the product. Assigned when a product presents acute and chronic hazards (to humans and/or natural ecosystems) that cannot be addressed through label instructions alone.

Life cycle assessment methodology terms

Greenhouse phase: For the purposes of this report, designates the part of the tomato life cycle that includes all operations involved in producing transplants.
Cultivation phase: For the purposes of this report, designates the part of the tomato life cycle that includes all operations involved in field production of raw tomatoes.
Processing facility phase: For the purposes of this report, designates the part of the tomato life cycle that includes all operations involved in processing of raw tomatoes into final products (paste and diced tomatoes).
Upstream environmental burdens: Processes and related environmental burdens that occur 'upstream' of the system boundary, e.g., environmental emissions associated with manufacturing a fertilizer.
Downstream environmental burdens: Processes and related environmental burdens that occur 'downstream' of the system boundary, e.g., nitrate leaching from fertilizer inputs to field soil in the cultivation phase.
LCI: Life cycle inventory, the detailed accounting of all materials and resources, including energy, flowing in to and out of the product system, also including emissions to air, water and land by a specific substance.
Foreground: Processes assessed using direct measurements based on primary data collected through surveys, e.g., the amount of irrigation water applied in field per area.
Background: Processes assessed using secondary data not measured directly but sourced from databases such as GaBi or Ecoinvent, e.g., the amount of fossil fuel energy required to produce a gallon of diesel.

Interpretive Summary

Study Goal and Scope

This study uses a comprehensive life cycle assessment (LCA) approach to estimate the environmental burdens associated with producing California diced and paste tomato products. The LCA accounts for greenhouse production of transplants, field cultivation of tomatoes, and facility processing of procesing tomatoes into a diced and a paste product. It examines data from two different years, 2005 and 2015, to elucidate trends in agronomic and facility processing practices, and the effects of changing practices on the environmental and health impacts over time. We also conducted a separate assessment of the five processing facilities that reported data in 2010 & 2015 to help identify inter-annual as well as between-facility variability. The study quantifies the following environmental impacts: 100-year global warming potential (GWP_{100}) with climate-carbon feedbacks, total resource use (renewable and non-renewable primary energy sources, water, and mineral resources), ecotoxicity potential, and atmospheric pollution effects (ozone depletion, acidification potential, and photochemical ozone creation). This study is particularly unique in three ways: it includes broad regional estimates of practices over time, it provides a relatively more complete accounting of potential impacts from pesticide use than many published food LCA studies, and it examines nitrate leaching potential from agricultural fields based on biogeochemical modeling.

Results

The results indicate that from greenhouse to processing facility gate, production and combustion of natural gas and diesel contribute the most to environmental impacts (**Table 1**). Secondarily, gypsum production for the cultivation phase is a large contributor to ozone depletion. Fertilizers and in-field fertilizer emissions to air and to soil in the cultivation phase contribute substantially to eutrophication potential and global warming potential, and the grid electricity used in processing facilities contributes to upstream freshwater use.

Table 1 Inputs and processes from greenhouse to processing facility gate contributing the most to environmental impacts.

Impact category	Main contributors across the supply chain	Percent contribution across supply chain	Phase with the highest total contributions
Global warming potential	Natural gas production & combustion	64–69%	Processing facility
Total primary energy	Natural gas production & combustion	62–68%	Processing facility
Freshwater use	Direct water use	69–75%	Cultivation
Acidification potential	Diesel production & combustion	30–39%	Cultivation
Eutrophication potential	Diesel production & combustion	23–30%	Cultivation
Photochemical ozone creation potential	Natural gas production & combustion	38–47%	Processing facility
Ozone depletion potential	Gypsum production	31–36%	Cultivation

Key Messages

Use of the energy and water resources decreased at all phases from 2005 to 2015.

Life cycle energy use efficiency increased by 14% & 28%, for paste and diced product, respectively, and life cycle water use efficiency increased by 41% & 43%, over the supply chain.

Especially notable are water use reductions of 45% at the cultivation phase per kg of harvested tomato. These decreases also translate to a 45% decrease in energy use for irrigation pumping. Processing facilities reduced grid electricity use by 27% and 5%, and water use by 22% and 5% for diced and paste product, respectively. Grid electricity generation also entails significant amounts of freshwater use. As a result, decreases in electricity use translate to reductions in life cycle freshwater use.

***Increases in water and energy use efficiency found in the cultivation phase are highly likely to represent a robust and ongoing trend*.**
Widespread conversion from furrow irrigation to micro-irrigation systems, especially drip as captured in this study's survey data, have also been documented elsewhere. Drip irrigation systems not only enable precision application of water, but also often increase tomato yields, further magnifying efficiency increases on a per yield basis.

The magnitude of many environmental impacts decreased substantially on a per kg of product basis.
Resource use is accountable for a relatively large share (although not 100%) of many environmental impacts, including global warming potential, ozone depletion, photochemical ozone creation, acidification, and eutrophication. However, use of energy resources – especially diesel, grid electricity, and natural gas – at all phases still accounts for a large share of remaining impacts. Fertilizer and gypsum production also contribute significantly to some impacts and there are scenarios used by some growers currently in which these impacts improve.

A substantial amount of variability was found in the processing data, both between facilities and between time points.
The robustness of processing facility results should be further cross-checked with facility experts to verify whether the decreases in resource use represent ongoing trends given that these results represent only two points in time and only two facilities were able to provide full datasets for both of those time points. In addition, we found a substantial amount of variability between facilities and between time points, including in the assessment of the five facilities that provided 2010 and 2015 data, further complicating our effort to infer the robustness of trends for the industry as a whole.

***Relatively high variability between growers and between facilities in resource use efficiency, especially for highly impactful resources such as fertilizers, water, and fossil energy sources, suggests room for improvement industry-wide*.**
Reasons for these variations and potential for improvement must be assessed by industry experts.

Environmental impacts from pesticide use in cultivation and material waste at all phases need to be further researched.
Although this study found that pesticide active ingredient manufacture is not a dominant contributor to any specific impact categories, a preliminary assessment of downstream toxicity impacts after field application suggests that chemicals that can escape into the air and freshwater bodies may pose the greatest risks. However, more work is needed to identify definitive risk levels under specific California climate and production conditions. In addition, data limitations prevented adequate characterization of the waste stream from all phases, especially relating to packaging of inputs, which may incur substantial environmental impacts.

Methods

Life cycle assessment (LCA) is an accounting method that quantifies the processes and associated environmental burdens required to produce a product such as tomato paste. In the LCA, we include the upstream environmental burdens associated with production processes required to produce inputs such as fertilizers, electric power, etc., as well as wastes and co-products generated from the production of diced tomato and tomato paste. The system boundary of the study starts at the raw material extraction and ends at the facility processing gate, using a base unit or functional unit of one kilogram (1 kg) of bulk diced and bulk paste product, and co-product pomace.

This study is predominantly based on three sets of primary data, consisting of survey data collected from greenhouse managers, growers, and processing facility managers, in which they described their operations and quantified their material and energy inputs for the 2005 and 2015 production seasons. These datasets include data from 16 growers for 2005 and 46 growers for 2015, and two processing facilities with complete data for 2005 and 2015. A total of five processing facilities provided complete data for years 2010 and 2015. Therefore, we carried out a separate analysis for the processing facility phase using data for the same five facilities for both 2010 and 2015. All primary data are from the two main processing tomato production regions in California, the San Joaquin and Sacramento Valleys. These primary data were supplemented and validated by an extensive review of literature on current and historical tomato cultivation practices in these two regions. The UC Davis Cost and Return studies, which are available for California processing tomatoes for different production years (2007, 2014, & 2017) and regions (Sacramento Valley & Northern Delta, San Joaquin Valley) were examined, and extension professionals were consulted for validation and clarification of literature findings. Trends in grower and facility practices were assessed for all respondents as well as for the same respondents for each year to understand the variability between growers and facility practices over time. All agrochemicals accounted for in the LCA were compared with the California or county-level reporting data to ensure the study data are representative of regional practices.

The data collected through surveys and the secondary data sourced from standard life cycle databases were used to develop a comprehensive life cycle inventory, which is an accounting of all material and energy inputs and the associated raw material and energy flows and emissions incurred from the manufacture and transport of the inputs. In addition, software and modeling tools such as ArcGIS were used for distribution analysis and other spatial modeling. Where applicable, the LCA methodology put forth by the International Organization for Standardization (ISO) was used to guide life cycle model development and calculations (ISO/TC 207/SC 5, ISO 14044: 2006; ISO/TC 207/SC 5, ISO 14040:2006; ISO 14025:2006), and is consistent with the Environmental Product Declarations, Product Category Rules 2014:09 V1.01 UNCPC 2132 and UNCPC 2139, for the products classified as processed food products, belonging to “vegetable juice” (CPC 2132) and “other prepared and preserved vegetables, pulses and potatoes” (CPC 2139) (CPC 2008).

1. Introduction

California is the leading producer, followed by China and Italy, of processing tomatoes globally, producing ~12.8 million U.S. tons annually, approximately ~96% of the total U.S. and ~31% of the total global processing tomato production (CDFA, 2016; WPTC, 2017). California faces various challenges related to its agriculture production systems such as water resource limitations, as well as nitrate leaching, and soil and human health risks due to the use and application of various agrochemicals. Life cycle assessment (LCA) is a tool that can help account for a range of environmental impacts stemming from the agricultural industry activities.

The objective of this study is to develop a LCA to estimate the environmental impacts of California diced and paste tomato products, examining greenhouse, cultivation, and processing facility practices comparing two years (2005 & 2015) to elucidate trends in agronomic and processing practices, and effects of changes in these practices and other key variables (e.g., climate, agrochemical regulation, emissions standards) on environmental and health impacts in California over time. We conducted a second processing facility analysis with data reported by five facilities for 2010 & 2015 to help identify inter-annual as well as between processing facilities variability. In the LCA, we include the upstream environmental burdens associated with inputs (e.g., fertilizer, electric power) to the life cycle stages, as well as wastes and co-products generated from the production processes, from cradle-to-processing facility gate, using a functional unit of one kilogram (1 kg) of bulk diced and bulk paste product, and co-product pomace.

2. Background Information

2.1 California Soils, and Climate and Cropping patterns

California's Central Valley provides many suitable areas for processing tomato cultivation in terms of soils and climate. Processing tomato is typically grown in loam and clay loam soils, characterized by their silt, sand, and clay content (Hartz et al., 2008). Sandy soils, which hold less water, are used for early planting of tomatoes because fields can be entered earlier for planting during wet weather and they warm quickly in the spring, allowing for early seed germination and growth (Hartz et al., 2008).

California has experienced temperature changes, an increase of ~1.5ºF in annual average temperature, throughout the last century, since the 1890s (OEHHA, 2013). These temperature changes affect plant growth and development, growing seasons, crop yield, and fruit production. For tomato production, warmer winters may translate to earlier planting dates, but extreme summer heat can also suppress fruit set. Conversely, annual precipitation levels have shown no identifiable trends, essentially due to extreme variation between years.

In general, cropping patterns in California have also changed over the last 50 years (CDFA, 2016). These changes occurred primarily due to the market fluctuations and variability in the price (or value) of the crops produced (Kaffka and Jenner, 2010). The data indicate that processing tomato production in California increased by 18% in the last 20 years (CTGA, 2016).

2.2 Greenhouse Processes

The first process in the processing tomato production is seedling development, through direct or transplant methods. Direct seeding occurs from late-January to mid-May. Greenhouse seedling production for transplants starts in mid-December and goes until mid-April. Inputs to greenhouse systems include but are not limited to pesticides, fertilizers, growing medium, energy, fuel (e.g., propane), as well as paper and plastic packaging waste.

Transplanting may begin as early as mid-February (until early-June). Overall, tomato transplants increased in 1990 in response to increasing costs, for example, for seeds (Miyao et al., 2008), the cost of which is higher for the processor approved seed varieties selected based on their yield potential, and nematode and disease resistance (Hartz et al., 2008). Today, approximately 70–100% of the tomato plants in field are transplanted, whereas the remainder are direct seeded for a total planting density of 8000–8720 plants per acre (according to the grower survey data collected for this study).

2.3 Cultivation Processes

Cultivation areas included in data collection for this study include Fresno, Merced, Kings, Solano, San Joaquin, Sutter, and Stanislaus counties. These are seven of the eight counties with the largest processing tomato acreage in the state (NASS, 2012). One notable feature of processing tomato production is that the growing beds are shaped in the fall before winter rains saturate the soil to facilitate early planting in the potentially wet spring months. In general, field operations tend to begin in fall with bed preparation, disc & roller, chisel, and land planning, followed by listing in December (see operations tables in **Appendix A**).

After field preparation operations, fertilization, pesticide application, and irrigation operations occur. The timing of these field operations (pre-planting, transplanting and irrigation, fertilization, and harvest) varies depending on the field location within California. Transplanting and irrigation of seedlings typically starts earlier in the southern San Joaquin Valley region compared to Northern California (**Appendix A**). Processing tomato irrigation occurs in March through August, depending on the location within California (**Appendix A**). The application of fertilizers and pesticides (including herbicides) begins as early as March (see operations tables in **Appendix A**). Fertilization in the fields includes the application of soil amendments (manure), fertilizers (various), and micronutrients (various), and depends on the grower and field location within the state. For example, growers in the southern San Joaquin Valley tend to apply less fertilizer per acre than growers in northern California. To maintain the condition of the beds, herbicides are often applied in the fall and early spring to control for weeds. The harvesting of processing tomatoes in California typically occurs in July through September.

2.3.1 Cultivation: Pesticides

The application of pesticides in California is regulated by the federal EPA as well as the California Department of Pesticide Regulation (CDPR), which established more stringent rules including stricter worker protection standards for pesticide training, fumigant restrictions, and pesticide hazard communication requirements (CDPR 2011). Today, per the requirements of the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA), the EPA must publish annual reports on pesticide re-registration performance measures and goals (EPA 2013) and per CDPR requirements growers in California must report annual use of pesticide type, active ingredient and quantity per acre, i.e. the Pesticide Use Report (PUR). The range of fertilizers and pesticides and respective application rates for 2005 and 2015 as accounted for in this study are listed in **Appendices B–E**.

Overall, thirteen pesticides used in 2005 and/or 2015 appear on the CalEnviroScreen list of highly toxic and volatile chemicals and/or have been identified by the U.S. EPA as acutely toxic to humans or as a restricted use product due to high environmental and human health risks. In some cases, the amount of product applied decreased, e.g., the application rate of trifluralin decreased by 2%; whereas in other cases, the application rate of products like glyphosate increased by 59% (on average) between 2005 and 2015, according to the survey data collected for this study.

2.3.2 Cultivation: Irrigation

According to the data collected for this study, 50% of the growers shifted to drip irrigation, 13% continued to use furrow irrigation, and 13% used drip irrigation in both 2005 and 2015. According to a previous study, growers' use of drip irrigation increased by ~38% while the use of furrow irrigation decreased by ~37% for all crop types (field, vegetable, orchard, and vineyard) in California, and the trend towards increased use of low-volume irrigation has continued from 2010 until today (Tindula et al., 2013). Overall, the increasing use of drip irrigation compared to furrow irrigation is likely due to the flexibility in scheduling and improved control for irrigators allowed by low-volume irrigation technologies (Tindula et al., 2013). Drip irrigation allows growers to reach and maintain their soils' field capacity or "ideal" water quantity, resulting in higher tomato yield (Hartz and Hanson, 2009).

2.3.3 Cultivation: Mechanical Processes

Within the last 10 years (2005–2015), mechanical cultivation technologies such as pesticide application and irrigation methods continued to advance. Commercial use of the tomato harvester started in 1962 (Thompson and Blank, 2000). By 1995, the proliferated use of the technology reduced labor requirements per U.S. ton of California processing tomatoes by 92% (Huffman, 2012).

In addition to technological advancements, from 1996–2000 the U.S. EPA phased in federal engine emissions standards referred to as "Tiers" that include the least stringent (Tier 1) up to the most stringent (Tier 4) (ARB, 2011) to reduce emissions from off-road diesel engines (OTAQ, 2016). Engine categories are based on horsepower and model year. Applying the tier system increased the stringency of allowable emitted nitrogen oxides (NOx), particulate matter (PM), carbon monoxide (CM), and hydrocarbons (HC). For example, Tier 4 emission standards enforced ~90% reductions in NOx and PM, ~86% reductions in HC, as well as sulfur content regulation in off-road diesel vehicles (DieselNet, 2016).

2.4 Facility Processes

Processing of the tomatoes includes several steps and occurs from early-July to late-September. After harvest, the tomatoes are trucked to the facility and then graded based on, e.g., weight, color, sugar content, mold, and worms. The tomatoes that meet the quality standards are unloaded and sorted primarily based on size (for paste) and color (for diced). Generally, paste tomatoes go through peeling, heating and cooling operations, and then a finisher stage (a pulp tank and screening phase), evaporators and steam injectors (sterilizers), and finally packaging. After sorting, diced tomatoes go through the dicer, shaker, a calcium bath, batching kettles, heating and cooling operations, and then packaging.

Final products from the processing phase include the primary tomato products, diced and paste tomato, as well as the co-product pomace. The price of bulk tomato varies from year to year (**Table 2**). The price of pomace varies from year to year due to water availability and oil prices, e.g., when the price of oil increases corn can be used as an alternative fuel source, which, in turn, reduces the value of corn as a feed crop and increases the tomato pomace value (personal communication, facility manager, 2016). The price of pomace also varies within year due to moisture content of greater than or less than 70%. Pomace is primarily sold and used as a supplement in animal feed (based on survey data). However, pomace can also be used as a soil amendment (Fernandez-Bayo et al., 2017).

Table 2 The prices for paste and diced product, 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

3. Materials and Methods

3.1 Life Cycle Assessment Methodology

A process-based life cycle model is used to evaluate the environmental impacts of processing tomato production in California from raw material extraction through production, from "greenhouse-to-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. Energy use on site at each phase is sourced from the California grid system and referred to as imported energy throughout the report. In the context of this study, upstream environmental burdens refer to the investments of resources and upstream energy inputs, and the emissions of pollution and waste associated with the production of a fuel, grid energy, or a material. Software and modeling tools such as ArcGIS are used for distribution analysis and other spatial modeling. GaBi software is used for access to life cycle inventory databases (Thinkstep 2017). Where applicable, the LCA methodology put forth by the International Organization for Standardization (ISO) is used to guide life cycle model development and calculations (ISO/TC 207/SC 5, ISO 14044: 2006; ISO/TC 207/SC 5, ISO 14040:2006; ISO 14025:2006). The methodological requirements consistent with the Environmental Product Declarations (EPD) was selected to allow for comparability among approaches and results with European processing tomato studies, e.g., DelBorghi et al. (2014). As such, the LCA study is performed according to Product Category Rules (PCR) 2014:09 V1.01 UNCPC 2132 and UNCPC 2139 for the products classified as processed food products belonging to "vegetable juice" (CPC 2132) and "other prepared and preserved vegetables, pulses and potatoes" (CPC 2139) (CPC 2008).

According to the standard LCA framework, the following steps are completed for this study:

1. Goal and scope definition–defining the system boundary and functional unit of analysis.

2. Life cycle inventory (LCI)–identification and quantification of all inputs at each stage of the life cycle included within the system boundary.

3. Impact analysis–accounting for impacts associated with the LCI data using characterization factors. Impact categories considered in the study include greenhouse gas (GHG) emissions calculated in terms of carbon dioxide equivalents (CO_2e) (Myhre et al. 2013); primary energy use (renewable and non-renewable); water use (direct and indirect); and the CML (Centre of Environmental Science) 2001 LCIA methodology (CML).

4. Interpretation of impacts analysis (see the results and discuss sections of this report).

3.1.1 Goal and Scope Definition

The goal of this study is to create a baseline life cycle inventory for processing tomato production and to estimate the primary energy use, GHG emissions, and other environmental impacts to air, water, and soil. The assessment is conducted from greenhouse to processing facility gate for years 2005 and 2015 for estimation of potential hotspots or opportunities for improvement in terms of resource use or emissions reductions, and to assess trends in resource use and impacts over time. We conducted a separate assessment of processing facilities for 2010 & 2015 to help identify inter-annual as well as between processing facilities variability.

The modeled system is 1 kg of product for diced and paste product. The system boundary (**Figure 1**) includes inputs and emissions from the following phases (1) greenhouse, (2) cultivation, and (3) processing facility.

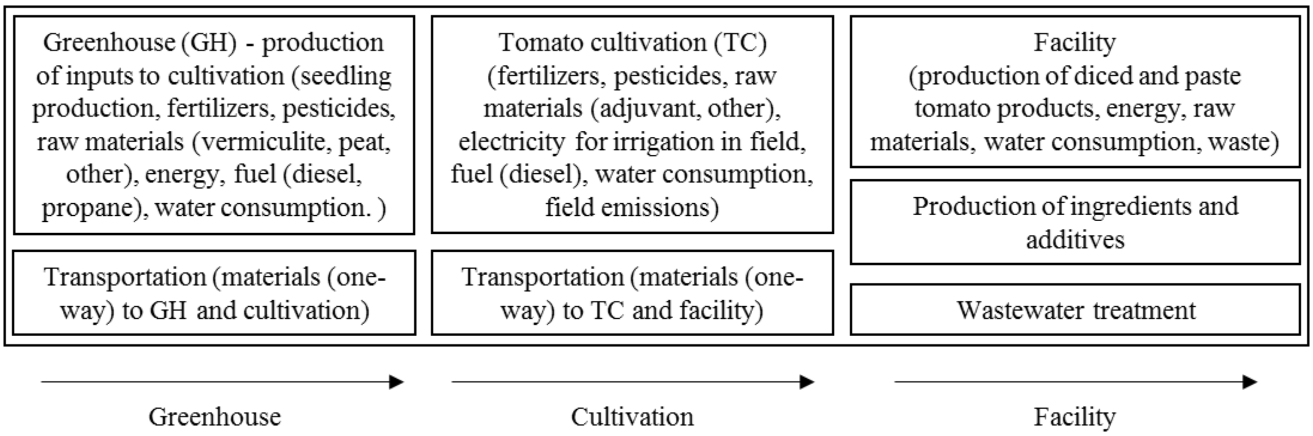

Figure 1 System boundary

3.1.2 System Definition and System Boundaries

The system boundary, showing foreground and background processes are defined in accordance with the common rules within the framework of the International EPD system. The upstream processes consist of environmental information and include raw material extraction and processing. The core processes represent the greenhouse and cultivation phases, including seedling production and planting to harvesting, the facility processing phase, including wastewater treatment as well as transportation of materials to each of the mentioned phases. Due to data limitations, packaging and waste treatment are not accounted for in this system boundary nor in the LCA.

3.1.3 Functional Unit

The functional unit for this study is 1 kg of final product, either diced tomatoes or paste. As such, all resources used, and impacts incurred were calculated based on the production of 1 kg of final product. Packaging is not included in this functional unit.

3.1.4 Allocation

Allocation is the process by which environmental flows associated with a system are divided among various outputs from a single industrial process, i.e. primary products (diced and paste tomato) and co-products (pomace). The ISO14040 LCA standards (ISO 14040: 2006), favor avoiding allocation calculations by subdividing the system based on the different products produced or expanding the system boundaries to include all flows associated with co-products, using mass or economic allocation. Mass allocation may not reflect the primary economic driver of processed tomato production systems; the production of tomatoes, therefore economic allocation is used based on the relative value of co-products, pomace, and products, paste and diced tomato, respectively. Allocation is applied based on averaged price value for the respective functional flow (or product), e.g., diced tomato, and year (**Table 2**). The economic allocation factor is calculated using equation 1 [Eq. 1] for product one (product 1; paste tomato), product 2 (diced tomato), and product 3 (pomace). Eq. 1 shows an example calculation, i.e. for product 1.

$$Economic\ allocation\ factor = \frac{Mass\ product\ 1 \times Price\ product\ 1}{\sum_{i=1}^{n} Mass\ product\ i \times Price\ product\ i} \qquad \text{[Eq. 1]}$$

3.2 Life Cycle Inventory

Life cycle inventory analysis: The LCI step is the accounting process in LCA. It requires that all inputs to the system be linked to lifecycle data, and that all outputs from the system (including co-products) be tracked. The inputs and outputs for a LCI (collectively referred to as environmental flows) determine what environmental impact categories can be included in the next step of the LCA, i.e. the impact assessment. Renewable and non-renewable primary energy, GHGs, criteria air emissions, nitrogen and phosphorous contamination to water, and water use are tracked. The LCI data quantify primary energy and material inputs as well as emissions for a variety of materials including diesel and gasoline fuel, agricultural chemicals, plastics, and other agricultural inputs such as fertilizers. Primary data are collected for each phase of the production process within the system boundary (**Figure 1**).

3.3 Data Sources and Models

The first step in this project was an extensive review of literature and other sources of data such as the California Cost and Return studies for purposes of assessing the current and historical tomato cultivation practices in the two main growing regions in California, the San Joaquin and Sacramento Valleys. The UC Davis Cost and Return studies, which are available for California processing tomatoes for different production years (2007, 2014, & 2017) and regions (Sacramento Valley & Northern Delta, San Joaquin Valley) were examined, and extension professionals were consulted for validation and clarification of data synthesized based on the review results.

3.3.1 Data Collection

Primary data were collected in the form of surveys administered to greenhouse operations managers (for data on inputs to the greenhouse and plants produced at the greenhouse in 2015); growers (for data on inputs to the cultivation system and processing tomato yields in 2005 and in 2015); processing facility operations managers (for data on inputs, emissions, and product quantities in 2005, 2010, and 2015); and the collection (or development) of relevant life cycle inventory (LCI) datasets for the LCA model. For 2005 and 2015, the same 16 growers responded to the survey, in 2015 an additional 30 growers responded to the survey. Five facilities responded for survey years 2010 and 2015, and two responded for 2005 & 2015. One of the primary reason noted for less response in 2005 for growers and processing facility includes changes in state-wide reporting requirements in 2015 versus 2005. Trends in grower and facility practices were assessed for all respondents as well as for the same respondents for each year to understand the change in practices and between growers and facility practices over time.

Non-disclosure agreements (NDAs) were established for each contact provided through Barilla staff (or the staff of affiliated processing firms).

3.3.2 Tomato Greenhouse and Cultivation

Greenhouse and grower questionnaires were developed using the Cost and Return study, and refined through expert consultation (e.g., UC extension specialists) and through beta testing with growers and facility managers. Other data sources include the pesticide use reporting data collected by the state of California and data from the National Agricultural Statistics Service. These data sources provided important information for assessing historic agronomic practices for processing tomato cultivation. Greenhouse life cycle inventory data (**Table 3**) and cultivation inventory data (**Table 4**) used in the LCA include materials inputs to and products from each respective phase. The waste generated in the greenhouse, mainly due to packaging and organic material wastes, are indicated (to landfill and to recycling facility) without including their treatment or processing. As indicated above in the text, the use phase and disposal of packaging were left outside the system boundary.

All the agrochemicals, e.g., Agrimycin, and average amounts of each agrochemical applied with standard deviation are reported in **Appendices C-D** based on the grower reported data collected through surveys for on-farm practices in 2005 and 2015. For accurate representation of the change in grower practices over time, a subset of the grower data is used for the model values that includes growers that reported fertilizer data (n=8) and pesticide data (n=13) for both 2005 and 2015. Data refer to tomato cultivation operations and applications performed per field per year (2005 and 2015). For reference, ALL DATA reported by growers is averaged and provided in the **Appendices C-D** excluding agrochemical materials applied in field if <5 growers applied a material, e.g., Cabrio or Neem, assuming the application of those materials did not represent average California processing tomato growers' practice. For all pesticides accounted for in the LCA, we compared the grower reported per acre application rates with the regional PUR reported application rates for each product's active ingredient to ensure the study data are representative of regional practices.

Irrigation water use is based on grower reported values for 2005 & 2015. Irrigation pump diesel and electricity use were estimated for surface water and groundwater resources based on geographic location within California and groundwater depth. Estimated electricity use is 209.17 kWh/ ac-in water for groundwater and 31.16 kWh/ ac-in water for surface water. Calculated diesel use is 5.14-gal diesel/ac-in water for groundwater and 0.77-gal diesel/ac-in water for surface water. Based on the grower survey data collected for this study it is estimated that approximately 50% of the processing tomato growers use surface water and 50% use groundwater. Approximately 60% of the growers accounted for in this study use diesel pumps and 40% use electric pumps (personal communication, processor field staff, 2017).

To estimate direct and indirect nitrogen emissions from nitrogen fertilizers, and in accordance with the Tier 3 IPCC 2006 guidelines (DeKlein et al. 2006), a process-based model, the DeNitrification-DeComposition (DNDC) model (Li et al. 1992; Li et al. 1994) is used. Direct emissions include nitrous oxide (N_2O) emissions resulting from chemical transformations after N-containing compounds are deposited on the soil such as from fertilizer applications or deposition from the atmosphere and water surfaces. Indirect emissions result from nitrate (NO_3-N) leaching and runoff carrying nitrogen to other places where it is later transformed to N_2O emissions (IPCC 1997). The DNDC model is parameterized using Kallenbach et al. (2010) irrigation data, soil pH and the soil bulk density based on the USGS and grower survey soil data for the study area, and a literature reported soil organic carbon value (0.011 kg/kg soil) for California soil conditions (Hurisso et al., 2016). The model results are considered reasonable, e.g., for nitrogen plant uptake and NO_3-N leaching, in comparison with the results in published literature values (e.g., see Hartz and Bottoms, 2009). The gaseous emissions of N in the forms of N_2O, nitrogen monoxide (NO), and ammonia (NH_3-N) from fertilizer application are estimated based on the DNDC model results, using the calculated average emissions factors 0.37%, 0.28%, and 0.04%, respectively, of the N content of fertilizers applied to field soil (**Tables 4**).

The averaged values for nitrate leaching (4.04 kg NO_3-N /ac/yr; 0.05% of N in fertilizer applied) used in the LCA are based on a series of DNDC model runs conducted for different soil types (sand, loam, and clay) and the evaluation of variability in the results due to factors controlling water movements (e.g., precipitation, clay fraction, wilting point, field capacity) and soil nitrate (e.g., N input, N form, crop N uptake, pH) (**Table 5**).

Downstream toxicity impacts from pesticide application in field were estimated using the Uniform System for the Evaluation of Substances adapted for LCA (USES-LCA) model, which is a multi-compartment fate, and exposure and effects model (Huijbregts et al. 2000). Chemical abstract service (CAS) numbers of the pesticide active ingredients used in this study were used to identify comparable chemical products available within the USES-LCA model dataset. For each chemical included in the USES-LCA model dataset, the model considers emissions scenarios into five environmental compartments: air, freshwater, agricultural soil, and industrial soil, based on known properties of the chemical. Then, the model estimates a series of toxicity potentials (or the relative impact of the chemical product) after emission to a specific environmental compartment. The 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 (1.4-DCB is a chemical commonly used in mothballs, fumigants, insecticides and other products). HTP is the sum of the carcinogenic (Carc.) and the noncarcinogenic (Non-Carc.) human toxicity potentials. This method of using a reference substance to standardize toxicity of all other substances is similar to the use of carbon dioxide as the reference gas used in the calculation for global warming potential caused by all other climate-forcing gases (Guinee and Heijings 1993; Guinee et al. 1996a, b). The USES-LCA results were considered at the continental scale for purposes of this report because the reporting impact categories used at that scale were more comparable to the upstream environmental impacts reported for this LCA; whereas the USES-LCA regional scale results refer to the chemical fate and transport, e.g., dissolved and suspended solids in fresh water.

Table 3 Life cycle inventory data of the greenhouse phase related to number of processing tomato transplants produced per year.

LCI data	2015 Values	Unit
Total no. of plants produced in greenhouse	3.04E+08	plants/yr
Water use	3.76E-03	kg/kg
Natural gas consumption	1.88E-03	kg/kg
Imported energy	2.14E-03	kWh/kg
Diesel	7.81E-06	kg/kg
Propane	2.28E-05	kg/kg
Vermiculite	1.47E-04	kg/kg
Peat moss from Source 1	3.23E-03	kg/kg
Peat moss from Source 2	1.22E-06	m3/kg
Gasoline	2.20E-05	kg/kg
Manganese EDTA 13%	9.62E-09	kg/kg
Iron EDTA 13.2%	3.03E-08	kg/kg
Nitric acid, ammonium calcium salt 15.5-0-0	4.59E-07	kg/kg
Potassium phosphate 0-52-34	1.36E-05	kg/kg
Magnesium nitrate 11-0-0 Mg 9.5%	9.62E-07	kg/kg
Potassium nitrate 13-0-46	6.98E-06	kg/kg
Potassium sulfate 50 0-0-52	9.35E-06	kg/kg
Streptomycin	1.01E-08	kg/kg
Chlorothalonil	4.36E-08	kg/kg
Boscalid	1.62E-07	kg/kg
Copper hydroxide	9.55E-07	kg/kg
Phosphoric acid	2.10E-06	kg/kg
Mancozeb	1.84E-07	kg/kg
Ammonium chloride	1.58E-07	kg/kg
Propamocarb hydrochloride	3.06E-07	kg/kg
Cyprodinil +Fludioxonil	1.07E-07	kg/kg
Famoxadone+Cymoxanil	8.14E-08	kg/kg
Spinetoram	2.37E-08	kg/kg
Material Transport	7.61E-01	kg/km
Waste (to landfill)	3.04E+08	kg/kg
Waste (to recycling)	3.76E-03	kg/kg

Table 4 Life cycle inventory data of the cultivation phase related to 1 kg of harvested processing tomato-2005 & 2015.

	2005 Values				**2015 Values**			
LCI data	Value	Unit	Value	Unit	Value	Unit	Value	Unit
Total U.S. tons/ha (produced in field)	101.31	US tons/ha	9.19E+04	kg/ha	135.91	US tons/ha	1.23E+05	kg/ha
Diesel	11.99	gal/ac	1.04E-03	kg/kg	12.44	gal/Ac	8.04E-04	kg/kg
Water for irrigation (electricity)	841.15	kWh/ac	2.26E-02	kWh/kg	624.86	kWh/ac	1.25E-02	kWh/kg
Water for irrigation (diesel)	31.0275	gal diesel/ac	2.69E-03	kg/kg	23.05	gal diesel/ac	1.49E-03	kg/kg
Water withdrawal	977553	gal water/ac	9.96E+01	kg/kg	716872	gal water/ac	5.45E+01	kg/kg
Zinc	4.40	lbs/ac	5.37E-05	kg/kg	4.40	lbs/ac	4.00E-05	kg/kg
Gypsum	2000	lbs/ac	2.44E-02	kg/kg	2000	lbs/ac	1.82E-02	kg/kg
UN-32	105.72	lbs/ac	1.29E-03	kg/kg	166.42	lbs/ac	1.51E-03	kg/kg
CAN17	41.63	lbs/ac	5.08E-04	kg/kg	61.52	lbs/ac	5.59E-04	kg/kg
8-24-6 (@N)	3.92	lbs/ac	4.78E-05	kg/kg	5.32	lbs/ac	4.84E-05	kg/kg
8-24-6 (@P)	11.76	lbs/ac	1.43E-04	kg/kg	15.96	lbs/ac	1.45E-04	kg/kg
8-24-6 (@K)	2.94	lbs/ac	3.59E-05	kg/kg	1.79	lbs/ac	1.63E-05	kg/kg
4-10-10 (@N)	6.83	lbs/ac	8.33E-05	kg/kg	6.83	lbs/ac	6.21E-05	kg/kg
4-10-10 (@P)	17.17	lbs/ac	2.09E-04	kg/kg	17.17	lbs/ac	1.56E-04	kg/kg
4-10-10 (@K)	17.17	lbs/ac	2.09E-04	kg/kg	17.17	lbs/ac	1.56E-04	kg/kg
10-34-0 (@N)	1.45	lbs/ac	1.77E-05	kg/kg	1.93	lbs/ac	1.75E-05	kg/kg
10-34-0 (@P)	2.15	lbs/ac	2.62E-05	kg/kg	2.87	lbs/ac	2.61E-05	kg/kg
Aq ammonia	43.62	lbs/ac	5.32E-04	kg/kg	0.00	lbs/ac	0.00E+00	kg/kg
N2O at field (direct + indirect)	2.79	lbs/ac	3.40E-05	kg/kg	3.32	lbs/ac	3.02E-05	kg/kg
NH3 at field	0.45	lbs/ac	5.45E-06	kg/kg	0.68	lbs/ac	6.16E-06	kg/kg
NO at field	0.06	lbs/ac	7.78E-07	kg/kg	0.10	lbs/ac	8.80E-07	kg/kg
N2 at field	0.10	lbs/ac	1.17E-06	kg/kg	0.14	lbs/ac	1.32E-06	kg/kg
Nitrate	4.04	kg/ac	1.09E-04	kg/kg	4.04	kg/ac	8.10E-05	kg/kg
Sulfur	13.63	lbs/ac	1.66E-04	kg/kg	18.86	lbs/ac	1.71E-04	kg/kg
Trifluralin	0.44	lbs/ac	5.37E-06	kg/kg	0.43	lbs/ac	3.91E-06	kg/kg
Lambda cynalothirin	0.31	lbs/ac	3.78E-06	kg/kg	0.15	lbs/ac	1.36E-06	kg/kg
Glyphosate	2.12	lbs/ac	2.59E-05	kg/kg	3.38	lbs/ac	3.07E-05	kg/kg
Chlorothalonil	0.69	lbs/ac	8.42E-06	kg/kg	0.38	lbs/ac	3.46E-06	kg/kg
Rimsulfuron	0.04	lbs/ac	4.88E-07	kg/kg	0.02	lbs/ac	1.65E-07	kg/kg
Oxyfluorfen	0.05	lbs/ac	6.10E-07	kg/kg	0.07	lbs/ac	6.36E-07	kg/kg
Metolachlor	0.45	lbs/ac	5.49E-06	kg/kg	0.86	lbs/ac	7.82E-06	kg/kg
Copper Hydroxide	0.41	lbs/ac	5.00E-06	kg/kg	0.08	lbs/ac	7.27E-07	kg/kg
Adjuvant	0.06	lbs/ac	7.32E-07	kg/kg	0.06	lbs/ac	5.46E-07	kg/kg

[1] Estimated electricity use for groundwater (209.17 kWh/ ac-in water) and for surface water (31.16 kWh/ ac-in water), and [2]calculated diesel use for groundwater (5.14-gal diesel/ac-in water) and for surface water (0.77-gal diesel/ac-in water) are used with the assumption that 50% of the processing tomato growers use surface water and 50% use groundwater, and approximately 60% use diesel pumps and 40% use electric pumps. [3]Averaged 8-26-6 are combined with averaged 8-26-0 for LCI inventory accounting purposes. [4]Averaged transportation miles are based on 2015 manufacturing and processing company profiles (e.g., PotashCorp's current manufacturing and distribution locations).

Calculated emission factors from the Air Resource Board's (ARB) OFFROAD Model were retrieved to analyze tractor data obtained from tomato growers (**Appendices F–G**). Emission factors from the model are based on model year and horsepower (hp). Data not available for specific tractor model years within the OFFROAD Model were substituted with emission factors containing the closest available model year. Diesel as well as diesel combustion are accounted for using GaBi LCIs. For all materials, the transport distances from manufacturer to nearest distribution point to field (one-way transport) are accounted for, for each material type (**Appendix H)**. Transport distances are averaged using georeferenced Google map road mile data between field to facility and greenhouse to field and field to facility locations. Resultant averaged values for greenhouse to field (two-way transport) are 200 miles and from field to facility (one-way transport) 400 miles. The LCI documentation for each phase (greenhouse, cultivation, and processing facility) is provided in **Appendix I**.

3.3.3 Tomato Processing

Tomato processing data for diced tomatoes (**Table 6a**) and tomato paste (**Table 6b**) collected from California processing facilities are used to evaluate the facility processing phase. A top-down approach (or black box approach) that does not account for process-level data within facility was used to evaluate processing facilities. The top-down approach examines inputs and outputs at a whole-facility scale and then allocates among the product and co-products produced at the facility gate. There are benefits and drawbacks to this approach selected in accordance with the willingness of cooperating companies to provide data for their respective facilities. The facility phase is assessed using data from the two facilities that reported data in 2005 & 2015, and a second assessment is provided for the five facilities that reported data in 2010 & 2015.

The weight of processing tomato considered in this study is 1.3 kg and 6 kg to 1 kg of diced and paste product, respectively. The natural gas combustion LCI was created using EMFAC values to account for CO_2 emissions generated from the combustion of natural gas (ARB, 2014). In addition, diesel as well as diesel combustion are accounted for using GaBi LCIs. Packing within facility is accounted for in this LCA in terms of total energy (primary and imported) used per annum. For all materials, the transport distances from manufacturer to nearest distribution point to field (one-way transport) are averaged separately for each material type (**Appendix H)**. The use phase and disposal of packaging were left outside the system boundary.

Table 5 Soil texture and corresponding pH and bulk density input into the DNDC model and estimated soil porosity, conductivity, field capacity, and wilting point values used for the crop model simulation of nitrate (NO_3-N) leaching, N plant uptake, nitrous oxide (N_2O), ammonia (NH_3), and nitric oxide (NO).

Soil texture	Clay fraction (0–1)	Soil pH	Soil bulk density (g/m3)	Conductivity (m/hr)	Field capacity (wfps)	Wilting point (wfps)	NO3-N leaching (kg NO_3-N /ha/yr)	N Plant Uptake (kg N /ha/yr)	N_2O (kg N_2O/ha/yr)	NH_3 (kg NH_3/ha/yr)	NO (kg NO/ha/yr)
sand	0.03	6.7	1.6	0.500	0.10	0.05	37.96	148.14	0.72	37.02	0.20
loam	0.19	6.7	1.4	0.015	0.28	0.14	34.10	148.73	0.77	49.03	0.32
clay	0.63	7.5	1.1	0.008	0.42	0.30	2.00	155.75	0.84	61.03	0.10

Fertilizer applied: 209.58 kg N/ha/yr (186.76 lb N/ac/yr; 67% urea; 25% ammonium nitrate; 8% N: P: K blend unspecified).

Table 6a Life cycle inventory data of the facility processing phase related to 1 kg of diced tomato product.

LCI data	2005 Values	2015 Values	Unit
Total tomato product per year	18,654,723	19,997,990	Kg
Grid electricity	0.017	0.012	kWh/kg
Natural gas consumption	0.04	0.032	Kg
Water use	1.59	1.24	Kg
Diesel	3.66E-05	2.87E-05	Kg
Propane	3.44E-05	2.70E-05	Kg
50% Sodium Hydroxide	1.58E-04	1.22E-04	Kg
37% Calcium Chloride	4.89E-04	3.32E-04	Kg
50% Citric Acid	2.86E-07	1.25E-07	Kg
Average material transport	1.77E-07	2.35E-07	kg/km

Table 6b Life cycle inventory data of the facility processing phase related to 1 kg of paste tomato product.

LCI data	2005 Values	2015 Values	Unit
Total tomato product per year	128,263,405	209,757,809	kg
Grid electricity	0.07	0.07	kWh/kg
Natural gas consumption	0.19	0.18	kg
Water use	5.72	5.42	kg
Diesel	1.35E-04	1.34E-04	kg
Propane	1.27E-04	1.26E-04	kg
50% Sodium Hydroxide	5.18E-04	5.09E-04	kg
37% Calcium Chloride	2.17E-03	2.03E-03	kg
50% Citric Acid	1.22E-06	9.69E-07	kg
Average material transport	8.47E-08	7.80E-08	kg/km

Impact assessment translates the LCI into indicators of environmental impact. The impact categories considered in this study include global warming potential (GWP 100-year, reported in kg CO_2 equivalents) with climate-carbon feedback mechanisms (Myhre et al. 2013). The CML baseline characterization factors are used for impact categories ozone-depleting potential (ODP), in kg CFC 11-equivalents, acidifying potential (AP), in kg SO_2, photochemical ozone-creating potential (POCP), in kg C_2H_4 equivalents, and eutrophication potential (EP), in kg PO_4^{3-} equivalents (Guinée et al. 2001).

Description of CML baseline characterization factor units:
CFC-11 is trichlorofluoromethane which contributes to ozone depletion potential. SO_2 is sulfur dioxide, a gas that contributes to the formation of aerosols, which can cause respiratory and other breathing problems among other human health problems, and directly and indirectly interacts with the earth's atmosphere warming and cooling (Satein 2009). C_2H_4 is ethylene which is a volatile organic compound that can contribute to ground-level ozone. PO_4^{3-} is phosphate and can contribute to eutrophication (or overfertilization) of aquatic and terrestrial systems.

Total primary energy use from renewable and non-renewable sources is calculated and reported in units of MJ. Non-renewable primary energy sources include coalbed methane, crude oil, hard coal, lignite, natural gas, oil sand, peat, pit methane, shale gas, tight gas, and uranium. Renewable primary energy sources include geothermal, hydropower, solar wave, and wind power, as well as resources from primary forests. The total primary energy metric is the sum of the renewable and non-renewable sources. Total freshwater use reported in kg of water is the life cycle water use metric used in this assessment. It includes rainwater use, surface water (lakes and rivers), and groundwater use. Upstream as well as direct water use are accounted for in this study. In this study, wastewater to field is considered a pure waste stream, and therefore no upstream burdens are allocated to wastewater.

In addition, the biogeochemical cropping systems model mentioned above in the text, the DNDC model, is used to account for regional processes that result in downstream pollutants, nitrate (NO_3-N) leaching, N plant uptake, nitrous oxide (N_2O) ammonia (NH_3), and nitric oxide (NO).

3.3.4 Life Cycle Assessment Model

The LCA model for processing tomato in California was generated in Microsoft Excel. The model is broken down by year (2005 and 2015), phase (greenhouse, cultivation, and facility processing), transportation, and per input (e.g., fuel, electricity, chemicals). The results are disaggregated based on phase, and secondly by material input—per year. In the 2005 & 2015 processing facility assessment, the grower data for 2005 & 2015 are used; 2015 greenhouse data are used for both years. In the 2010 & 2015 processing facility assessment, the grower data for 2005 & 2015 are averaged for 2010, and the 2015 grower data for 2015 is used; 2015 greenhouse data is used for both years.

4. Results and Discussion

This analysis quantified the GHG emissions, total primary energy (renewable & nonrenewable), freshwater use, and CML impacts per kg paste and diced product (**Figures 2–7; Table 7a&7b**). The results show averaged impacts for processing tomato growers and each phase-wise main contribution to the impact categories is explained in the following.

Overall, the trends observed in the cultivation practices are decreases in total diesel (23%), water (45%), and a shift in fertilizer choice, blend or type, e.g., 25% reduction in 4-10-10 and 10% increase in use of CAN17 (**Table 4**). Within the facility processing phase, total natural gas, imported energy, and water use decreased per kg of paste product produced by 6%, 5%, and 5%, respectively (**Table 7a**). Total natural gas, imported energy, and water use decreased per kg of diced product produced by 27%, 27%, and 22%, respectively (**Table 7b**).

4.1 Global Warming Potential, Primary Energy, and Freshwater Use

The main contributors to GWP_{100} (kg CO_{2e} per kg product) for paste & diced 2005 & 2015 (**Figures 2 & 3; Table 7a&b**) includes natural gas production and combustion in the greenhouse (80%) and processing facility phases (94%) and irrigation water electricity use (26–31%) in the cultivation phase.

The main contributors to total primary energy use (MJ per kg product) for paste & diced in 2005 and 2015 (**Figures 4 & 5; Table 7a&b**) include natural gas in the greenhouse phase (49%); irrigation water electricity use (29–32%) in the cultivation phase; and natural gas (93%) in the facility processing phase. Primary energy use-renewable (MJ per kg product) for paste & diced products in 2005 and 2015 (**Figures 4 & 5**) was highest for imported energy (91%) in the greenhouse phase and irrigation water electricity use (89–90%) in the cultivation phase; and imported energy (94%) in the facility processing phase.

For freshwater use (kg water per kg product) in paste and diced in 2005 and 2015 (**Figures 6 & 7; Table 7a&b**), the main contributors were imported energy (98%) in the greenhouse phase, direct water uses in field (82–83%) in the cultivation phase and imported energy (89–91%) in the facility processing phase.

Natural gas production and combustion and diesel production and combustion contribute the most to the impact categories of GWP, primary energy, and freshwater use, with the nature of their contributions further described as follows. In natural gas production, shale gas and tight gas are the main contributors to primary energy impacts. In natural gas combustion, CO_2, CH_4, and N_2O emissions are the main contributors to GWP_{100}. The GWP_{100} impacts due to diesel and diesel combustion are attributed to CO_2 and CH_4 emissions.

4.2 Other Environmental Impact Categories

4.2.1 Centre of Environmental Science (CML) impact categories

In the greenhouse phase, natural gas production and combustion contributed to 37% of acidification potential, 69% of photochemical ozone depletion potential, and 46% of eutrophication potential. In the cultivation phase, diesel production and combustion contributed to eutrophication potential (29–36%), acidification potential (44–52%), and photochemical ozone creation potential (50–55%). In the facility processing phase, natural gas production and combustion is the main contributor to the CML impact categories, eutrophication potential (84%–85%), acidification potential (72%–73%), and photochemical ozone creation potential (92%–93%).

4.2.2 Potential impacts from pesticides

Of the substances compared for this study, mancozeb> chlorothalonil> fludioxonil>rimsulfuron>metolachlor>diazinon>glyphosate have the highest potential toxic impact in the TETP impact category for the air environmental compartments (in the relative order shown). Of these pesticides, chlorothalonil has the highest toxicity potential in the TETP impact category for four of the five environmental compartments: air, freshwater, agricultural soil, and industrial soil. Oxyfluorfen has the highest potential toxic impact in the HTP category for freshwater. See Appendix J for a complete list of pesticides assessed in this study using the USES-LCA model. Note that five of the pesticides assessed in this LCA were not available in the USES-LCA model database and are therefore only accounted for in terms of upstream impacts, but not downstream (post field-application) impacts.

We briefly evaluated each of the pesticides in terms of EPA and CalEnviroScreen standards, and percent use in 2005 and 2015 processing tomato fields in California. Chlorothalonil is listed in CalEnviroScreen as highly toxic and volatile; whereas the EPA signal word for chlorothalonil is caution (the lowest risk designation). Overall, the EPA signal word for most of the pesticides listed above is caution, except for rimsulfuron, diazinon, and oxyfluorfen. Rimsulfuron and diazinon are designated as restricted use pesticides. The EPA signal word for oxyfluorfen is warning. This apparent discrepancy in the relative rankings of pesticide active ingredients between EPA signal words and the USES-LCA toxicity potentials is likely due to the different ways these categorizations and values are derived. The EPA signal words are based on experimental observations of acute toxicity during direct exposure to different concentrations of the chemical, while the toxicity potentials are derived from modeling of emissions into the environment and take both acute toxicity and distribution within the environment into account.

The percent use of each of the above-mentioned pesticides either decreased or increased slightly (by 1-5%) within the study timeframe, e.g., diazinon use decreased from 17% to 12% of growers. The exceptions are chlorothalonil and metolachlor. Chlorothalonil use nearly doubled from 25% to 40%. Metolachlor use decreased from 42% to 26%. **Appendix D** provides more information about the EPA and CalEnviroScreen indicators and the pesticides used in 2005 and 2015 for processing tomatoes in California, based on this study's survey results.

Overall, the downstream pesticide impacts require critical assessment in cases where the formation of pesticide transformation products and metabolites may be more toxic than the primary active ingredient (or substance). For example, in terms of freshwater toxicity potential, "glyphosate can be 10 times larger when including its transformation" (vanZelm 2014). Also, chemicals accumulate in plants and cold-blooded and warm-blooded organisms (Golsteijn et al. 2012; vanZelm 2014); these USES-LCA generated bioaccumulation results are not accounted for in this study. Overall, our results indicate that careful consideration of what happens to a chemical once it is released into the environment, and how it moves through the environment, is an important component when assessing impacts of pesticide use.

Glyphosate provides a case in point. The results show that the production of glyphosate is not a main contributor to any of the main environmental impacts generated from the cultivation phase. Yet, the application of this chemical is concerning due to its increased use in agricultural production systems and related potential negative environmental impacts after application. The grower survey data show a 59% increase in the use of glyphosate from 2005 to 2015 (an equivalent of an 19% increase when calculated based on one kg of harvested tomatoes) (**Table 4**).

Special Focus: Trends in Glyphosate Use

Glyphosate is a broad-spectrum herbicide that is used in conventional tomato production to control cool season weeds on planting beds, prior to transplanting tomatoes. It is sometimes used to control particularly troublesome perennial summer weeds, such as bindweed, after the harvest. Glyphosate cannot be used during the growing season, as it would damage the tomato plants. Among this study's survey respondents, the average application rate of glyphosate increased from 2.12 lbs active ingredient per acre in 2005, to 3.38 lbs/acre, an increase of 59%. This increase is likely attributable to both an increase in application rates, and an increase in number of applications per season, from approximately 2 to 2.5 applications per year, on average. The patent for Round-Up, the original glyphosate herbicide, expired in 2000, with the effect that during our study period of 2005-2015, new glyphosate products entering the market and driving the price down could possibly have spurred an increase in application rates and frequencies. In the past, another herbicide, devrinol, was used more frequently for similar purposes as glyphosate. Both devrinol and glyphosate carry an EPA "Caution" label, which indicates the lowest level of risk of three possible designations of acute toxicity, and neither is included on CalEnviroScreen's list of higher risk pesticides. However, conflicting scientific reviews on the carcinogenicity and the persistence of glyphosate in the environment continue to confound any concrete conclusions about the risks of its use currently. Other herbicides used during the same time of year include oxyfluorfen (Goal), which carries an EPA "warning" label, and carfentrazone (Shark), which carries a caution label, and neither is on the CalEnviroScreen's higher risk list. A non-herbicide option for controlling weeds prior to spring planting is shallow tillage, but UC weed management experts report that this option may not be viable for early transplanting during particularly wet years, when tillage equipment could damage the planting beds and condition of the soil. However, the recent development of increasing weed resistance to glyphosate suggests that in the future growers may increasingly look to alternative herbicides or other weed control practices.

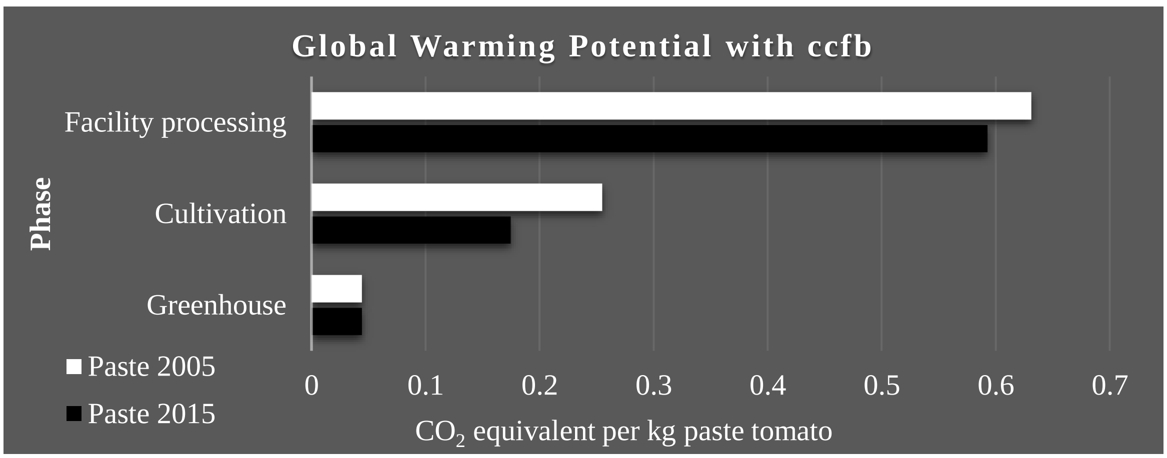

Figure 2 Global Warming Potential (GWP_{100}) with climate-carbon feedback (ccfb) in kg of CO_2e per kg of paste tomato product – 2005 & 2015.

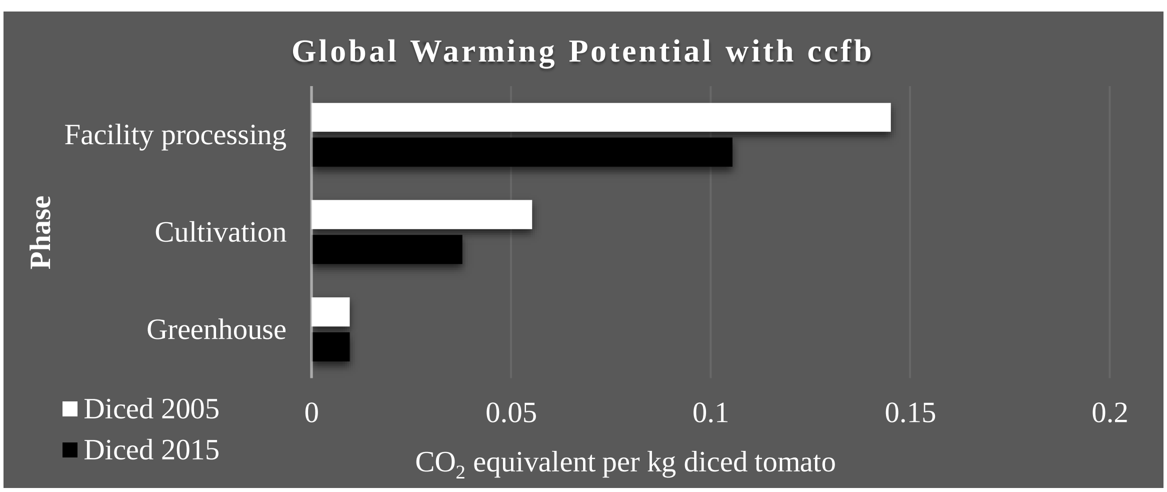

Figure 3 Global Warming Potential (GWP_{100}) with climate-carbon feedback (ccfb) in kg of CO_2e per kg of diced tomato product – 2005 & 2015.

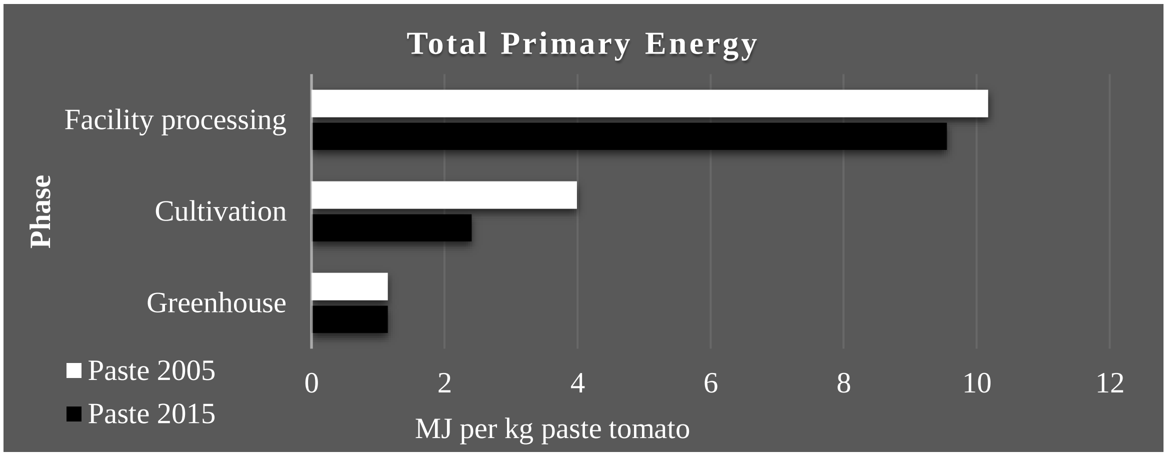

Figure 4 Total primary Energy (renewable & non-renewable) consumed in MJ of primary energy per kg of paste tomato product – 2005 & 2015.

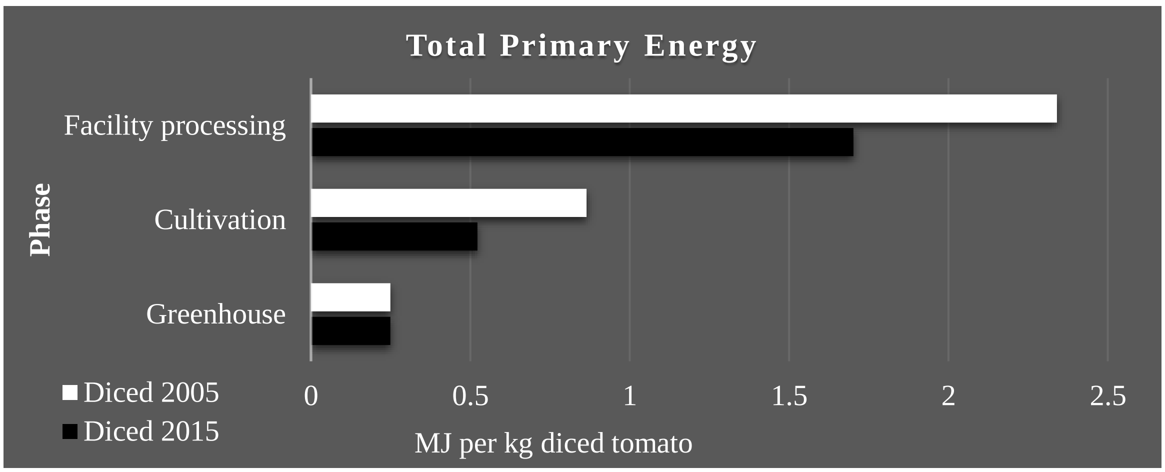

Figure 5 Total primary Energy (renewable & non-renewable) consumed in MJ of primary energy per kg of diced tomato product – 2005 & 2015.

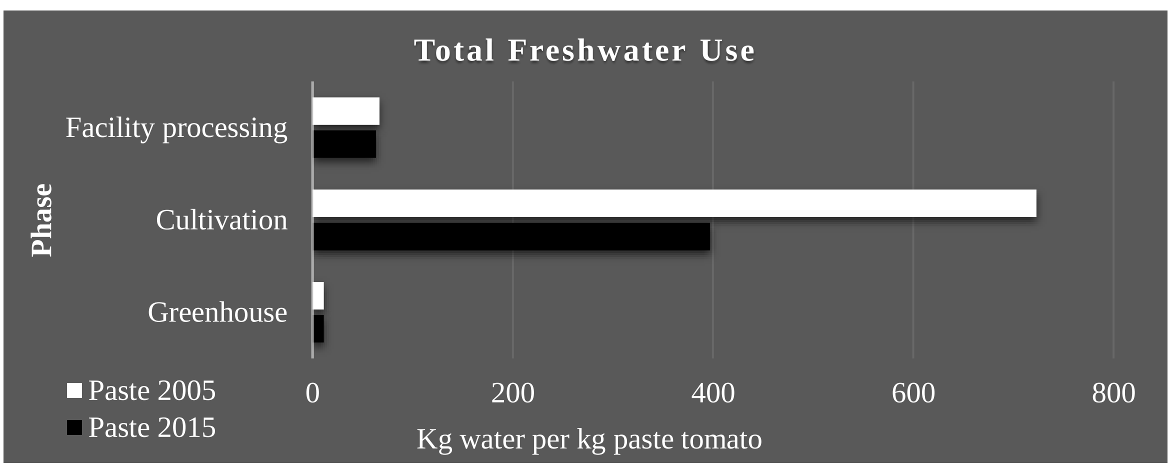

Figure 6 Total freshwater use in kg of water per kg of paste tomato product – 2005 & 2015.

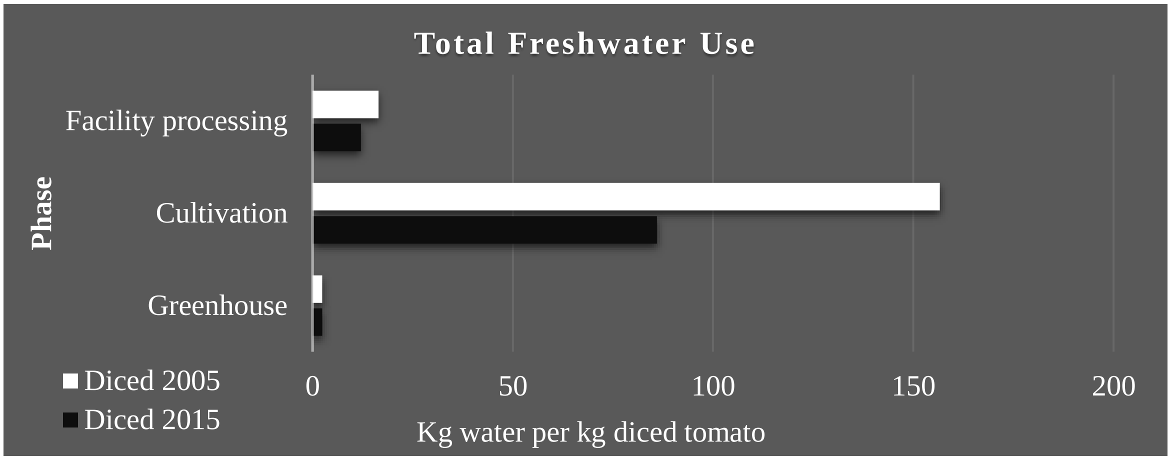

Figure 7 Total freshwater use in kg of water per kg of diced tomato product – 2005 & 2015.

Table 7a. Life cycle impact assessment results for Global Warming Potential (GWP_{100} with climate-carbon feedback), Total Primary Energy Use, Freshwater use, Acidification Potential (AP), Photochemical Ozone Creation Potential (POCP), Ozone Layer Depletion Potential (ODP), and Eutrophication Potential (EP) per kg of paste tomato product – 2005 & 2015.

Paste 2005	Greenhouse[1]	Cultivation	Facility processing	Total
AP (kg SO2 eq.)	4.06E-05	1.23E-03	3.48E-04	1.62E-03
POCP (kg C2H4 eq.)	6.54E-06	1.13E-04	8.21E-05	2.02E-04
ODP (kg CFC-11 eq.)	7.10E-11	5.94E-10	1.28E-10	7.93E-10
EP (kg PO4 eq.)	7.37E-06	3.83E-04	6.67E-05	4.57E-04
GWP 100 w/cc fb	4.42E-02	2.55E-01	6.31E-01	9.31E-01
Total Primary Energy (MJ)	1.15E+00	3.99E+00	1.02E+01	1.53E+01
Total Freshwater Use (kg)	1.12E+01	7.23E+02	6.68E+01	8.01E+02
Paste 2015	Greenhouse	Cultivation	Facility processing	Total
AP (kg SO2 eq.)	4.06E-05	7.99E-04	3.27E-04	1.17E-03
POCP (kg C2H4 eq.)	6.54E-06	6.97E-05	7.71E-05	1.53E-04
ODP (kg CFC-11 eq.)	7.10E-11	4.86E-10	1.20E-10	6.77E-10
EP (kg PO4 eq.)	7.37E-06	2.70E-04	6.27E-05	3.40E-04
GWP 100 w/ cc fb	4.42E-02	1.75E-01	5.93E-01	8.12E-01
Total Primary Energy (MJ)	1.15E+00	2.41E+00	9.55E+00	1.31E+01
Total Freshwater Use (kg)	1.12E+01	3.97E+02	6.34E+01	4.72E+02

[1]Greenhouse results are based on 2015 data only.

Table 7b. Life cycle impact assessment results for Global Warming Potential (GWP_{100} with climate-carbon feedback), Total Primary Energy Use, Freshwater use, Acidification Potential (AP), Photochemical Ozone Creation Potential (POCP), Ozone Layer Depletion Potential (ODP), and Eutrophication Potential (EP) per kg of diced tomato product – 2005 & 2015.

Diced 2005	Greenhouse[1]	Cultivation	Facility processing	Total
AP (kg SO2 eq.)	8.79E-06	2.66E-04	8.09E-05	3.56E-04
POCP (kg C2H4 eq.)	1.42E-06	2.45E-05	1.89E-05	4.48E-05
ODP (kg CFC-11 eq.)	1.54E-11	1.29E-10	2.91E-11	1.73E-10
EP (kg PO4 eq.)	1.60E-06	8.29E-05	1.54E-05	9.99E-05
GWP 100 w/cc fb	9.58E-03	5.53E-02	1.45E-01	2.10E-01
Total Primary Energy (MJ)	2.49E-01	8.64E-01	2.34E+00	3.45E+00
Total Freshwater Use (kg)	2.43E+00	1.57E+02	1.65E+01	1.76E+02
Diced 2015	Greenhouse	Cultivation	Facility processing	Total
AP (kg SO2 eq.)	8.79E-06	1.73E-04	5.87E-05	2.40E-04
POCP (kg C2H4 eq.)	1.42E-06	1.51E-05	1.37E-05	3.03E-05
ODP (kg CFC-11 eq.)	1.54E-11	1.05E-10	1.99E-11	1.41E-10
EP (kg PO4 eq.)	1.60E-06	5.85E-05	1.12E-05	7.13E-05
GWP 100 w/ cc fb	9.58E-03	3.78E-02	1.05E-01	1.53E-01
Total Primary Energy (MJ)	2.49E-01	5.22E-01	1.70E+00	2.47E+00
Total Freshwater Use (kg)	2.43E+00	8.60E+01	1.21E+01	1.00E+02

[1]Greenhouse results are based on 2015 data only.

4.3 Comparison between Facilities in 2010 and 2015

Like the 2005 and 2015 comparison, in the comparison between 2010 and 2015 facility data for five facilities, we see a decrease in overall GWP_{100}, primary energy, and freshwater use impacts (**Table 8a&b)**). The GWP_{100} impacts decreased by 24% and 2% in diced and paste production, respectively, due to a 30% and 4% reduction in total natural gas use per kg, for diced and paste product, respectively. Primary energy (total) decreased by 24% and 2% in diced and paste production, respectively, also primarily due to a reduction in total natural gas use per kg product. Freshwater use decreased by 7% and 1% in diced and paste products, respectively, and primarily due to a 52% and 34% reduction in direct total freshwater use per kg diced and paste product, respectively. In 2010 and 2015, water use and variability between facilities amounted to 438,410,167±283,278,656 gallons in 2010 and 265,350,476±109,254,275 gallons in 2015. Total average energy use and variability between the energy requirements for the five facilities surveyed in 2010 and 2015 amounted to 11,143,495±3,646,921 kWh in 2010 and 12,530,370±4,457,285 kWh in 2015. This variability between facility is likely due to process-level variability, e.g., in evaporator technology onsite, and is explored further in the **Appendix J**.

We also found inter-annual variability, due to variability in the overall tomato throughput for the season. Based on our discussions with facility managers, 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. The LCA model results are based on total throughput, mass amount of product produced within a year, and therefore are impacted by the inter-annual and between facility variation in total amount of production of each product, diced or paste product.

4.4 Process-level Comparison within Facilities

In this section, we provide a brief explanation of some of the process-level variability that different facilities manage based on water and energy flows.

Water is used within facility for heat transfer applications, such as breaking, as well as other direct water uses including to remove the tomatoes from transport vehicles, to move tomatoes through the sorting process, and to wash tomatoes. Other than direct water use, indirect water use is considered any water use outside of the facility to produce resources needed for the facility to function, e.g., irrigation to produce tomatoes, water use in cooling towers at power plants that produce the facility's electricity, etc. Water may be treated onsite and/or discharged from facilities to a lagoon or nearby field. Discharge regulations are in accordance with Title 22 California Code of Regulations (2014). Water treatment off facility site and or handling of water in nearby fields is not accounted for in this study.

Energy source (e.g., grid electricity vs. on-site solar energy generation) and the rate of energy use (quantity of energy used per defined timeframe), as well as water demands vary depending on the product specifications. For example, a product may require select color, titratable acidity, and sugar content for a specific batch of product, and these specifications affect the process-level equipment and equipment settings (e.g., temperature) applied to produce that product. In general, energy use and water requirements for tomato processing can be split into three categories: thermal processing of tomatoes, mechanical processing of tomatoes, and movement of tomatoes between processes (see table and explanation in **Appendix J**).

Table 8a. Life cycle impact assessment results for Global Warming Potential (GWP100) with climate-carbon feedback (ccfb), Total Primary Energy Use, Freshwater use, Acidification Potential (AP), Photochemical Ozone Creation Potential (POCP), Ozone Layer Depletion Potential (ODP), and Eutrophication Potential (EP) per kg of paste tomato product – 2010 & 2015.

Paste 2010	Greenhouse	Cultivation	Facility processing	Total
AP (kg SO2 eq.)	4.06E-05	7.99E-04	3.03E-04	1.14E-03
POCP (kg C2H4 eq.)	6.54E-06	6.97E-05	6.92E-05	1.45E-04
ODP (kg CFC-11 eq.)	7.10E-11	4.86E-10	1.72E-10	7.29E-10
EP (kg PO4 eq.)	7.37E-06	2.70E-04	5.76E-05	3.35E-04
GWP 100 w/cc fb	4.42E-02	1.75E-01	5.27E-01	7.46E-01
Total Primary Energy (MJ)	1.15E+00	2.41E+00	8.48E+00	1.20E+01
Total Freshwater Use (kg)	1.12E+01	3.97E+02	5.93E+01	4.67E+02
Paste 2015	Greenhouse	Cultivation	Facility processing	Total
AP (kg SO2 eq.)	4.06E-05	7.99E-04	2.92E-04	1.13E-03
POCP (kg C2H4 eq.)	6.54E-06	6.97E-05	6.68E-05	1.43E-04
ODP (kg CFC-11 eq.)	7.10E-11	4.86E-10	1.51E-10	7.08E-10
EP (kg PO4 eq.)	7.37E-06	2.70E-04	5.56E-05	3.33E-04
GWP 100 w/ cc fb	4.42E-02	1.75E-01	5.09E-01	7.28E-01
Total Primary Energy (MJ)	1.15E+00	2.41E+00	8.19E+00	1.17E+01
Total Freshwater Use (kg)	1.12E+01	3.97E+02	5.59E+01	4.64E+02

[1]Greenhouse and cultivation results are based on 2015 data only.

Table 8b. Life cycle impact assessment results for Global Warming Potential (GWP100) with climate-carbon feedback (ccfb), Total Primary Energy Use, Freshwater use, Acidification Potential (AP), Photochemical Ozone Creation Potential (POCP), Ozone Layer Depletion Potential (ODP), and Eutrophication Potential (EP) per kg of diced– 2010 & 2015.

Diced 2010	Greenhouse	Cultivation	Facility processing	Total
AP (kg SO2 eq.)	8.79E-06	1.73E-04	1.28E-04	3.10E-04
POCP (kg C2H4 eq.)	1.42E-06	1.51E-05	2.88E-05	4.53E-05
ODP (kg CFC-11 eq.)	1.54E-11	1.05E-10	8.13E-11	2.02E-10
EP (kg PO4 eq.)	1.60E-06	5.85E-05	2.42E-05	8.43E-05
GWP 100 w/cc fb	9.58E-03	3.78E-02	2.19E-01	2.66E-01
Total Primary Energy (MJ)	2.49E-01	5.22E-01	3.52E+00	4.29E+00
Total Freshwater Use (kg)	2.43E+00	8.60E+01	2.57E+01	1.14E+02
Diced 2015	Greenhouse	Cultivation	Facility processing	Total
AP (kg SO2 eq.)	8.79E-06	1.73E-04	8.97E-05	2.72E-04
POCP (kg C2H4 eq.)	1.42E-06	1.51E-05	2.02E-05	3.68E-05
ODP (kg CFC-11 eq.)	1.54E-11	1.05E-10	5.02E-11	1.71E-10
EP (kg PO4 eq.)	1.60E-06	5.85E-05	1.70E-05	7.71E-05
GWP 100 w/ cc fb	9.58E-03	3.78E-02	1.54E-01	2.01E-01
Total Primary Energy (MJ)	2.49E-01	5.22E-01	2.47E+00	3.24E+00
Total Freshwater Use (kg)	2.43E+00	8.60E+01	1.74E+01	1.06E+02

[1]Greenhouse and cultivation results are based on 2015 data only.

4.5 Fertilizer Comparison

The objective of the fertilizer comparison is to determine the impacts per type and quantity of fertilizer. All fertilizer types reported per grower data are considered in this fertilizer comparison. The results are presented on a per kg of fertilizer type basis. However, average amounts of each agrochemical applied with standard deviation are reported in **Appendices C-D** based on the grower reported data collected through surveys for on-farm practices in 2005 and 2015 as indicated above in the text.

For GWP_{100}, kg of CO_2e per kg of N per fertilizer type was highest for CAN17 (53-54%) (**Figure 8**). For total primary energy (renewable & non-renewable), impacts were highest for CAN17 (29%) and 10-34-0 (18%). For primary energy-renewable, impacts were highest for CAN17 (21%) and 10-34-0 (20%) (**Figure 9**). For freshwater use and kg water per kg of N fertilizer, the impacts were highest for 10-34-0 (24%) and 8-24-6 (22%) (**Figure 10**).

The main contributors for each fertilizer and impact categories GWP, primary energy, and freshwater use are indicated in the following. In CAN17 and 4-10-10 production, CO_2, CH_4, and N_2O are the main contributors to the GWP_{20} and GWP_{100}. Crude oil, natural gas, and uranium are the main contributors to the primary energy impacts. In aqua ammonia production, CO_2 and CH_4 are the main contributors to the GWP_{20}. In 10-34-0 and 8-24-6 production, water from the ground, lakes, and rivers are the main contributors to the freshwater use impact. The CML impact categories indicate the top category due to fertilizer production, and more specifically CAN17 production (upstream) and ammonia and nitrous oxide emissions as eutrophication potential (73%) (data not shown). Aqua ammonia production (upstream) was the main contributor to terrestrial ecotoxicity potential (27%) (data not shown).

Ultimately, these upstream impacts will 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 large differences in ammonia and nitrous oxide emissions after application. For example, urea-based fertilizers (such as UN32) can result in as much as 40% higher ammonia emissions than mixed ammonia and nitrate fertilizers, while ammonia products (such as aqua ammonia) can lead to 40-60% higher nitrous oxide emissions than urea-based or sulfate fertilizers. As such, the higher upstream GWP and eutrophication potential of CAN17 may, at least in part, be compensated by lower downstream impacts, especially when compared to aqua ammonia and UN32. As these field emissions vary by soil type, moisture status, and other local circumstances, calculating these downstream impacts for the entire tomato-growing region of California is beyond the scope of the current study. In addition, we should note that nitrate-containing fertilizers are also more likely to lead to nitrate leaching into groundwater than ammonia or ammonium-based fertilizers.

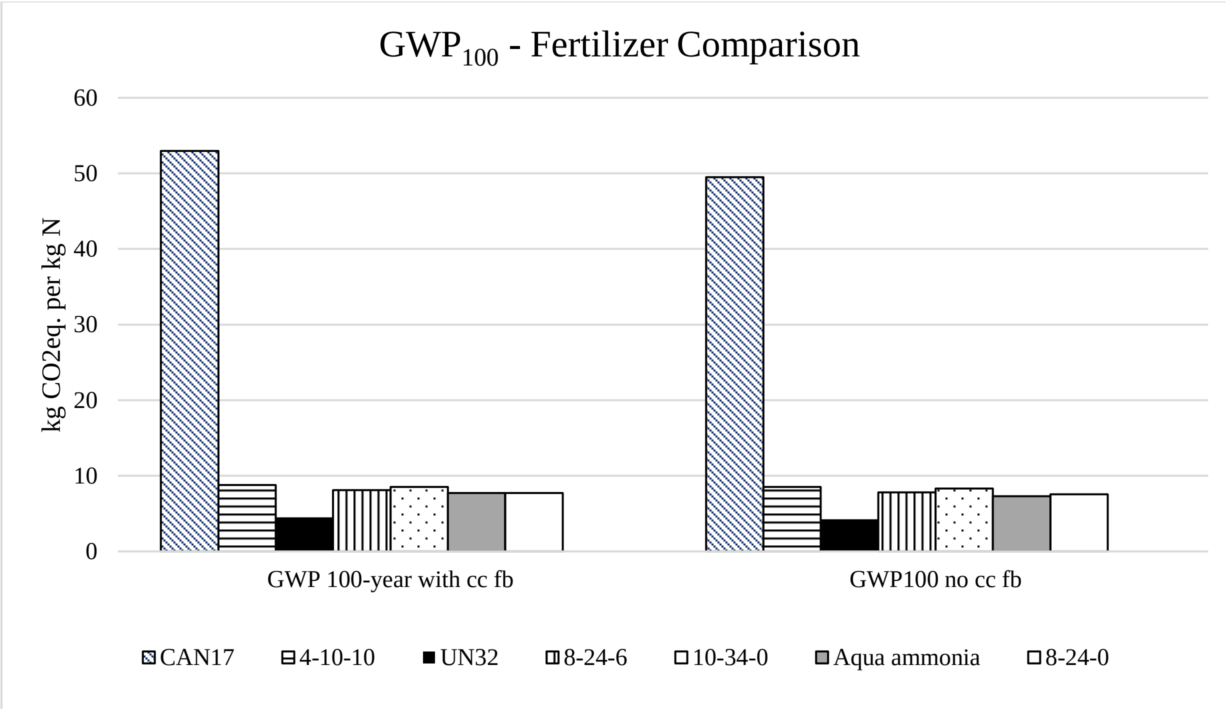

Figure 8 Global Warming Potential 100-year (GWP_{100}) with climate-carbon feedback (ccfb) and without climate-carbon feedback (wo ccfb) in kg of CO_2e per kg of N per fertilizer type.

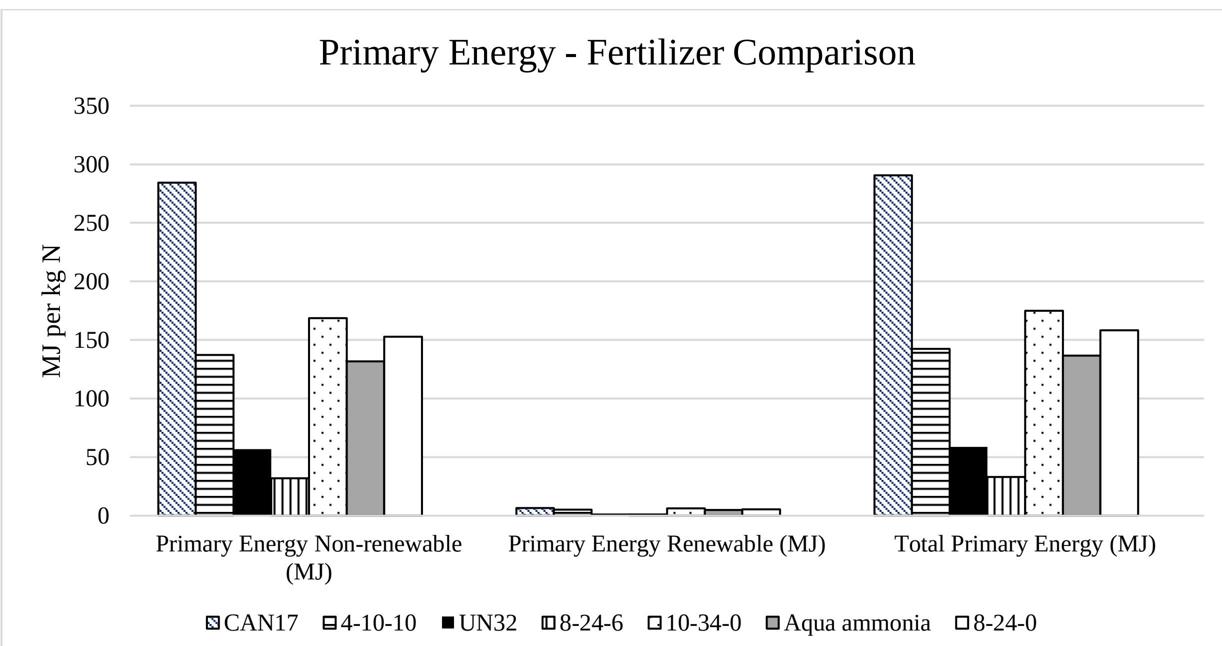

Figure 9 Primary Energy (non-renewable, renewable, and total) consumed in MJ of energy per kg of N per fertilizer type.

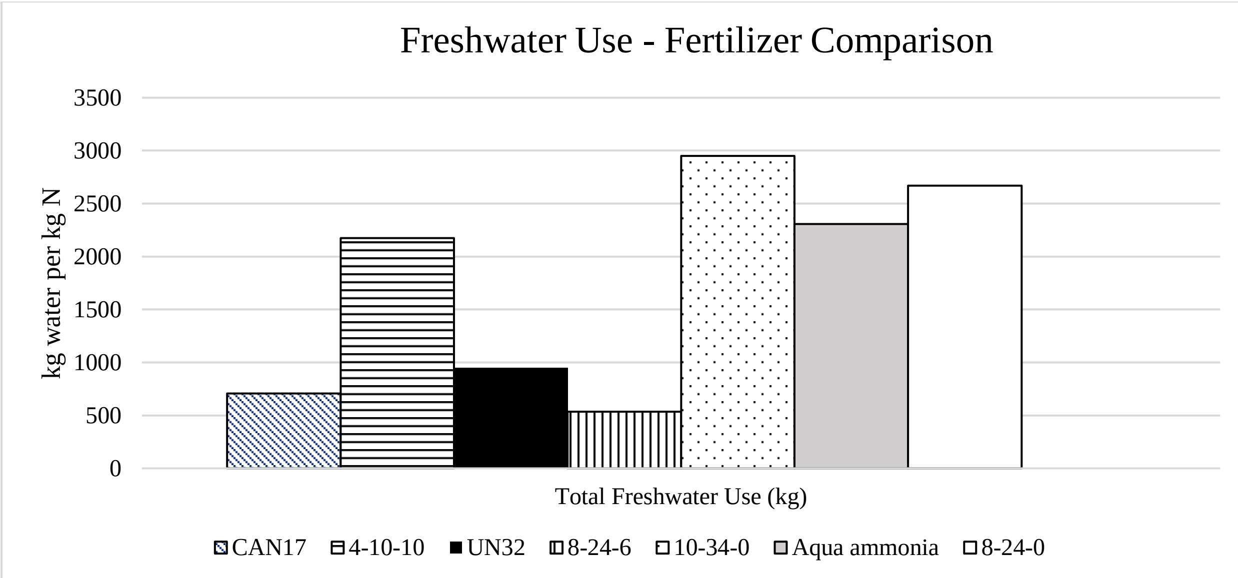

Figure 10 Total freshwater use in kg of water per kg of N per fertilizer type.

5. Comparison with other life cycle assessment studies

LCA has been used to assess environmental impacts of processing tomato cultivation in Italy (Del Borghi et al., 2014; De Marco et al., 2018), Greece (Ntinas et al., 2017), and Turkey (Karakaya and Ozilgen, 2011). Processing facility operations have been assessed in Italy (Del Borghi et al., 2014), California (Amon et al., 2015), and Turkey (Karakaya and Ozilgen, 2011). There is also extensive literature on LCA of greenhouse-based production of tomatoes for fresh market (not processsing tomato) as indicated and discussed below in the text.

Comparing the impact results between LCA studies is often a challenge due to variability in the system boundary, inputs (i.e. primary and secondary data) included in the assessment, and reporting format. To address this challenge, we focused on comparing the system inputs across studies and how they relate to results for selected impact categories. Most study authors indicate the hot spots or provide a qualitative overview linking the LCI primary data with the impact assessment results, often using impact categories such as carbon footprint or GWP or climate change (a midpoint category in the ReCiPe LCA methodology).

In general, at the cultivation phase, the main factors contributing to GWP (or climate change factors) include fossil fuels (diesel) (Del Borghi et al., 2014; De Marco et al., 2018) and electricity use for irrigation (De Marco et al., 2018; Ntinas et al., 2017), as well as fertilizer production and use (Ntinas et al., 2017). These findings are consistent with the current study, in which diesel production and combustion and electricity for irrigation are the main contributors to GWP in the cultivation phase. Del Borghi et al. (2014) report diesel use 0.069-0.078 MJ/kg cultivated tomato and De Marco et al. (2018) report 0.0071 kg diesel/kg cultivated tomato, compared to our study 0.036-0.047 MJ/kg cultivated tomato (0.0008-0.0010 kg diesel/kg cultivated tomato). De Marco et al. (2018) reported 0.014 kWh/kg cultivated tomato compared to our study (0.013-0.023 kWh/kg cultivated tomato). The GWP values ranged from 0.38-0.59 kg CO_2e per kg cultivated tomato (Del Borghi et al., 2014) to 1.36 kg CO_2e per kg packaged mashed tomato (De Marco et al., 2018) to 0.04-0.26 kg CO_2e per kg cultivated tomato in the current study. Although the main contributors to the GWP (and climate change) impact categories are similar, the input values for the identified main contributors vary, with De Marco reporting a much higher amount of diesel use in the cultivation phase, which may account for the higher GWP value. The variability in the resultant impact value may also be attributed to other factors, such as the reference LCIs used, and the weight of raw tomato ingredients considered in the final product, i.e. in this study, 1.3 kg and 6 kg to 1 kg of diced and paste product, respectively.

At the facility processing phase, the main factors contributing to the environmental impacts include packaging, energy and fuel use (Karakaya & Ozilgen, 2011; De Marco et al., 2018). Similar to our current study, De Marco et al. (2018) found that cultivation is the main contributor to ecotoxicity and human health impacts, includingozone depletion potential (in CML) and ionizing radiation (in ReCiPe), as well as fresh water use. Across the supply chain, facility processing is the main contributor to total primary energy use in the current study, which is consistent with previous studies (e.g., De Marco et al., 2018).

LCA has been used extensively to assess greenhouse operations, for fresh tomato, not processing tomato, in locations such as Spain (Martinez-Blanco et al., 2011; Torrellas et al., 2012), Ontario, Canada (Dias et al., 2017), Italy (Cellura et al., 2012), southern and central Europe (Ntinas et al., 2017), Iran (Pishgar-Komleh et al., 2017), and Australia (Page et al., 2012). In general, in greenhouse studies that do not use heating and use soil as a growth medium, the main factors contributing to environmental impacts include infrastructure and fertilizer emissions (Torrellas et al., 2012). In greenhouses that require heating and use a soil-less growth medium, fossil fuel use (for heating), packaging, and infrastructure are the main contributors to the overall environmental impacts (Cellura et al., 2012; Ntinas et al., 2016; Dias et al., 2017; De Marco et al., 2018). Anton et al. (2005) show that seasonal variability also contributed to different cultivation scenarios in the spring-summer months, not accounting for packaging, and estimated global warming impacts to equal ~0.0814 kg CO_2 eq per kg tomato. LCA studies (e.g., Munoz et al., 2008; Jones et al., 2012) that assessed open-field fresh tomato cultivation systems show 0.2–2.0 kg CO_2 eq per kg tomato, with the lower end of this range being similar to the results from the cultivation phase in the current study. As in the processing tomato cultivation systems, the main factors contributing to the environmental impacts of fresh tomato production include electricity use for irrigation and fertilizer production (Anton et al., 2005; Cellura et al., 2012). In general, greenhouse cultivation systems (e.g., in Germany or Canada) can result in as much as three times more energy use and ten times more GHG emissions than open-field cultivation systems, due to heating requirements during winter months in colder regions (Anton et al., 2005).

Scenarios tested for processing facilities as well as greenhouses that use fossil fuels for heating or other processes include use of solar or other renewable energy alternatives. As in the current study, use of solar at the processing facility phase indicates reduction in emissions affecting environmental and human health impacts by 9–12% in the current study and ~33% in De Marco et al. (2018). Regional- and national-scale production ranges that implicate variation in raw material use and transportation ranges has been addressed in few studies (Brodt et al., 2013; Theurl et al., 2014; Payen et al., 2015) and need to be assessed further.

6. 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 production and combustion, direct water use, and diesel production and combustion.

Direct use of energy and water resources on site per kg final product decreased at the cultivation phase by 45%. At the facility processing phase direct use of energy decreased by 27%

and 5% and of water decreased by 22% and 5% for diced and paste product, respectively, between 2005 and 2015. Accordingly, we observed reductions in the overall supply chain impacts including GWP_{100} by 27% (diced) and 13% (paste) and total primary energy consumption by 28% (diced) and 14% (paste). Upstream freshwater use decreased by 43% (diced) and 41% (paste). Also, the upstream CML impacts which account for toxicity and other adverse impacts decreased.

Several key areas of uncertainty remain. The downstream impact of pesticide applications needs to be more fully assessed to account for regional climate, soil, and application variables, and in relation to other studies that document these types of impacts for a related set of chemicals. The current analysis conducted with the USES-LCA model provides us with guidance on which active ingredients may need the most attention in future study, and it also suggests that chemicals escaping into the air, and secondary into freshwater bodies, may pose the greatest risks. However, it does not adequately address the level of actual risk posed to humans or the environment under actual California tomato production conditions. Waste materials from all phases, especially from packaging of inputs, need to be better characterized in terms of composition and ultimate fate, e.g., recycled, landfilled, etc. Depending on how they are handled, these materials have the potential to generate substantial impacts. Finally, access to primary data from 2005 for the greenhouse phase, and inclusion of more operations, would allow for an accounting of changes in impacts over time in this phase.

Process-level within facility variability in energy and water use have already been discussed briefly in sections 4.3 and 4.4 above, and more thoroughly in Karakaya and Özilgen (2011) and Amon and Simmons (2016). Based on the current study results, it is evident that a process-level, within facility assessment would help to decipher some of this variability.

Finally, more site-specific field research is needed to elucidate the trade-offs between impacts generated during the production of specific types of fertilizer products versus emissions such as ammonia and nitrous oxide emissions generated after application of different products.

These results suggest two key avenues for continued improvement in environmental performance of processed tomato products in California. One avenue is to continue to reduce total use and increase efficiency of the most impactful resources, including fossil energy sources, water, and fertilizers (especially nitrogen-based fertilizers). Careful monitoring of the use and targeted, precision application strategies may help to further increase use efficiency as well as total per acre use of these inputs. Second, in some cases, switching to different products may reduce impacts, such as fertilizers with lower global warming potential in their production and post-application use, and pesticides with lower toxicity potentials. In the case of processing facilities, increased onsite energy generation from sources such as solar energy could also allow for a reduction in impacts. For example, in a scenario of 100% solar replacement for current imported energy use (2005 and 2015) the overall supply-chain GWP_{20} and GWP_{100} impacts reduce by 9–12%.

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8. Appendices

Appendix A: Operations Tables 2005 & 2015

Year: 2005	**OCT**	**NOV**	**DEC**	**JAN**	**FEB**	**MARCH**	**APRIL**	**MAY**	**JUNE**	**JULY**	**AUG**	**SEPT**
Operation												
bed shaper												
chisel		**N, S**										
cultivator							**N, S**					
disc & roller		**N, S**										
landplane												
laser leveler												
lister			**N, S**									
medium-duty discern												
mulcher						**N, S**						
performer		**N, S**										
triplane												
Fertilizer Application												
CAN-17									**S**	**N, S**	**N**	
Gypsum		**N, S**										
N, P, K						**S**	**N**					
UN-32							**S**	**N, S**	**N**			
Zinc												
Pesticide Application												
Bravo-Weather-strip									**S**		**N**	
Confirm												
kocide												
sulfur									**S**	**N**		
warrior												
zinc phosphide												
Dimethoate									**S**	**N**		
Asana									**S**	**N**		
Rally									**S**	**N**		
Herbicide Application												
glyphosate		**S**										
oxyfluorfen												
rimsulfuron							**S**	**N**				
trifluralin						**S**	**N**					
Fruit Ripening Agent												
ethrel												
Irrigation						**S**	**N, S**	**N, S**	**N, S**	**N, S**	**N**	
Planting				**S**	**S**	**N, S**	**N, S**	**N**				
Harvest										**S**		**N**

Abbreviated counties: N = Northern region (Butte, Glenn, Colusa, Sutter, Yolo, Solano, San Joaquin, and Stanislaus); S = Southern region (Merced, Fresno, Kings, Kern, and Madera

Year: 2015	OCT	NOV	DEC	JAN	FEB	MARCH	APRIL	MAY	JUNE	JULY	AUG	SEPT
Operation												
bed shaper												
chisel		**N, S**										
cultivator							**N, S**					
disc & roller		**N, S**										
landplaner												
laser leveler												
lister			**N, S**									
medium-duty disc												
mulcher												
performer		**N, S**										
triplane												
Fertilizer Application												
CAN-17									**S**	**N, S**	**N**	
Gypsum		**N, S**										
N, P, K						**S**	**N**					
UN-32							**S**	**N, S**	**N**			
Zinc												
Pesticide Application												
Bravo-Weather-strip									**S**		**N**	
Confirm												
kocide												
sulfur									**S**	**N**		
warrior												
zinc phosphide												
Dimethoate									**S**	**N**		
Asana									**S**	**N**		
Rally												
Herbicide Application												
glyphosate		**S**										
oxyfluorfen												
rimsulfuron							**S**	**N**				
trifluralin						**S**	**N**					
Fruit Ripening Agent												
ethrel												
Irrigation						**S**	**N, S**	**N, S**	**N, S**	**N, S**	**N, S**	
Planting				**S**	**S**	**N, S**	**N, S**	**N**				
Harvest										**S**		**N**

Abbreviated counties: N = Northern region (Butte, Glenn, Colusa, Sutter, Yolo, Solano, San Joaquin, and Stanislaus); S = Southern region (Merced, Fresno, Kings, Kern, and Madera

Appendix B: Fertilizer & Pesticide Use – Greenhouse - 2015

Greenhouse Fertilizers Use Table – 2015[1]

Product Ingredient	Unit	Amount
Manganese EDTA 13.0% Mn	kg/ha	56
Iron EDTA 13.2% Fe	kg/ha	174
Nitric acid, calcium ammonium salt 15.5-0-0	kg/ha	2242
Potassium phosphate 0-52-34	kg/ha	19054
Magnesium nitrate 11-0-0 Mg 9.5%	kg/ha	728
Potassium nitrate 13-0-46	kg/ha	8967
Potassium sulfate 50 0-0-52	kg/ha	13618

Greenhouse Pesticides Use Table - 2015[1]

Active Ingredient	Unit	Amount
Lactic Acid	kg/ha	45
Boscalid	kg/ha	175
Copper Hydroxide	kg/ha	1569
Mono- and dipotassium salts of Phosphorous acid	kg/ha	404
Mancozeb	kg/ha	376
Esterquat	kg/ha	146
Propamocarb	kg/ha	90
Cyprodinil, Fludioxonil	kg/ha	216
Cymoxanil, Famoxadone	kg/ha	123
Spinetoram	kg/ha	18
Chlorothalonil	kg/ha	174

[1] Note: product names are withheld to honor non-disclosure agreements.

Appendix C: Fertilizer Use – Cultivation – 2005 & 2015 – MODEL VALUES

Averaged fertilizer values for 2005 and 2015 per material (lbs/ac of element, e.g., nitrogen (N) applied) and total average lbs N /ac, phosphorus (lbs P_2O_5 /ac), potassium (lbs K_2O /ac), and calcium (lbs Ca /ac) applied.

	Average amount of N, P, K, Ca applied per material in 2005												**Total average amount of N, P, K, Ca applied in 2005**			
	CAN17 (lbs N/ac)	UN32 (lbs N/ac)	4-10-10 (lbs N/ac)	8-24-6 (lbs N/ac)	10-34-0 (lbs N/ac)	Aqua ammonia (lbs N/ac)	4-10-10 (lbs P_2O_5/ac)	8-24-6 (lbs P_2O_5/ac)	10-34-0 (lbs P_2O_5/ac)	4-10-10 (lbs K_2O /ac)	8-24-6 (lbs K_2O /ac)	CAN17 (lbs Ca/ac)	lbs N/ac	lbs P2O5/ac	lbs K_2O/ac	lbs Ca/ac
Avg	41.63	105.72	6.83	3.92	1.45	43.62	17.17	11.76	2.15	17.17	2.94	21.03	175.28	31.08	20.11	19.27
Stnd	43.23	100.06	10.09	9.42	5.02	79.06	25.36	28.25	7.45	25.36	7.06	23.35	90.57	30.33	24.14	23.07
	Average amount of N, P, K, Ca applied per material in 2015												**Total average amount of N, P, K, Ca applied in 2015**			
	CAN17 (lbs N/ac)	UN32 (lbs N/ac)	4-10-10 (lbs N/ac)	8-24-6 (lbs N/ac)	10-34-0 (lbs N/ac)	Aqua ammonia (lbs N/ac)	4-10-10 (lbs P_2O_5/ac)	8-24-6 (lbs P_2O_5/ac)	10-34-0 (lbs P_2O_5/ac)	4-10-10 (lbs K_2O /ac)	8-24-6 (lbs K_2O /ac)	CAN17 (lbs Ca/ac)	lbs N/ac	lbs P2O5/ac	lbs K_2O/ac	lbs Ca/ac
Avg	61.52	166.42	6.83	5.32	1.93	0.00	17.17	15.96	2.87	17.17	1.79	31.76	242.02	27.20	27.29	31.62
Stnd	65.22	121.05	10.09	10.00	6.70	0.00	25.36	30.01	9.93	25.36	6.20	33.67	94.54	30.61	33.21	35.31

A subsample of the grower data for 2005 and 2015 was used for direct, consistent comparison of grower practices over the study duration (n=8). Values for 8-26-0 and 8-26-6 are combined per element, N, P, K averages.

Averaged fertilizer values for 2015 per material (lbs/ac of element, e.g., nitrogen (N) applied) and total average lbs N /ac, phosphorus (lbs P_2O_5 /ac), potassium (lbs K_2O /ac), and calcium (lbs Ca /ac) applied.

	Average amount of N, P, K, Ca applied per material in 2015												Total average amount of N, P, K, Ca applied in 2015			
	CAN17 (lbs N/ac)	UN32 (lbs N/ac)	4-10-10 (lbs N/ac)	8-24-6 (lbs N/ac)	10-34-0 (lbs N/ac)	Aqua ammonia (lbs N/ac)	4-10-10 (lbs P_2O_5/ac)	8-24-6 (lbs P_2O_5/ac)	10-34-0 (lbs P_2O_5/ac)	4-10-10 (lbs K_2O /ac)	8-24-6 (lbs K_2O /ac)	CAN17 (lbs Ca/ac)	lbs N/ac	lbs P2O5/ac	lbs K_2O/ac	lbs Ca/ac
Avg	66.71	163.96	6.31	4.91	3.12	0.00	15.85	14.74	2.65	15.85	1.65	29.32	245.01	33.23	17.50	29.32
Stnd	65.18	116.24	9.85	9.69	7.71	0.00	24.74	29.07	9.54	24.74	5.96	33.42	91.16	29.45	24.31	33.42

A subsample of the grower data for was used. Any incomplete datasets for 2015 were excluded from the analysis (n=13). Values for 8-26-0 and 8-26-6 are combined per element, N, P, K averages.

Appendix D: Pesticide Use – Cultivation – 2005 & 2015 – MODEL VALUES

Averaged pesticide values for 2005 and 2015 per material (lbs/ac of active ingredient, e.g., trifluralin applied)

	Herbicides					Insect, disease, vertebrate pests				Additive
2005	**Glyphosate (lbs/ac)**	**Trifluralin (lbs/ac)**	**Metolachlor (lbs/ac)**	**Oxyfluorfen (lbs/ac)**	**Rimsulfuron (lbs/ac)**	**Lambda Cyhalothrin (lbs/ac)**	**Copper Hydroxide (lbs/ac)**	**Sulfur (lbs/ac)**	**Chlorothalonil (lbs/ac)**	**Adjuvant (lbs/ac)**
Avg	2.12	0.44	0.45	0.05	0.04	0.31	0.41	13.63	0.69	0.06
Stnd	1.74	0.27	0.64	0.15	0.06	1.05	0.92	14.56	1.08	0.14
	Herbicides					**Insect, disease, vertebrate pests**				**Additive**
2015	**Glyphosate (lbs/ac)**	**Trifluralin (lbs/ac)**	**Metolachlor (lbs/ac)**	**Oxyfluorfen (lbs/ac)**	**Rimsulfuron (lbs/ac)**	**Lambda Cyhalothrin (lbs/ac)**	**Copper Hydroxide (lbs/ac)**	**Sulfur (lbs/ac)**	**Chlorothalonil (lbs/ac)**	**Adjuvant (lbs/ac)**
Avg	3.38	0.43	0.86	0.07	0.02	0.15	0.08	18.68	0.38	0.06
Stnd	2.04	0.36	0.75	0.15	0.02	0.53	0.23	25.58	0.72	0.14

A subsample of the grower data for 2005 and 2015 was used for direct, consistent comparison of grower practices over the study duration (n=13).

Averaged pesticide values for 2015 per material (lbs/ac of active ingredient, e.g., trifluralin applied)

	Herbicides					Insect, disease, vertebrate pests				Additive
2015	**Glyphosate (lbs/ac)**	**Trifluralin (lbs/ac)**	**Metolachlor (lbs/ac)**	**Oxyfluorfen (lbs/ac)**	**Rimsulfuron (lbs/ac)**	**Lambda Cyhalothrin (lbs/ac)**	**Copper Hydroxide (lbs/ac)**	**Sulfur (lbs/ac)**	**Chlorothalonil (lbs/ac)**	**Adjuvant (lbs/ac)**
Avg	2.01	0.49	0.45	0.10	0.02	0.02	0.16	22.71	1.04	0.25
Stnd	2.08	0.33	0.77	0.17	0.03	0.03	0.36	29.08	1.24	0.52

A subsample of the grower data for 2015 was used. Any incomplete datasets for 2015 were excluded from the analysis (n=42).

Cultivation Pesticide Use Table – 2005 -ALL DATA

Class	Product name(s)	Active ingredients	Survey County	Average amount (AI kg/ha)	Stndv (AI kg/ha)	EPA 'signal word'[3]	% of 2005 sample
Non-fumigants							
Insecticide	Var. (Cymate 267, Dimate 4e, Dimethoate 25 wp)	Dimethoate[1]	Fresno, Merced, Stanislaus, San Joaquin, Colusa, Yolo, Glenn	0.39	0.05	W	67
	Asana	Esfenvalerate	Fresno, Merced, San Joaquin, Stanislaus	0.28	0.00	W	33
	Warrior	Lambda Cyhalothrin	Colusa, Glenn, Merced, Solano, Yolo	0.78	1.59	W; RU	50
	Intrepid	Methoxyfenozide	Merced	0.21	0.00	C	17
	Diazinon AG500	Diazinon[1]	Sutter, Yolo	2.61	0.37	C; RU	17
Herbicide	Matrix	Rimsulfuron	Merced, Yolo, Stanislaus, Fresno, San Joaquin	0.009	0.009	C; RU	50
	Goal 2XL	Oxyfluorfen	Merced, Sutter, Yolo	0.24	0.24	W	25
	Various Products (Tenkoz, Trifluralin E.C., Drexel Trifluralin)	Trifluralin[1]	Colusa, Fresno, Merced, San Joaquin, Solano, Stanislaus, Yolo	0.64	0.12	C	83
	Dual Magnum	S-Metolachlor/Metolachlor	Colusa, Glenn, Merced, Yolo	1.31	0.43	C	42
	Round Up or GLY-4 or Makaze	Glyphosate	Fresno, Glenn, Merced, San Joaquin, Solano, Stanislaus, Sutter	1.71	0.60	C	75
	Devrinol	Napropamide	Sutter	0.60	0.00	C	8
Fungicide	Thiolux	Sulfur	Colusa, Fresno, Merced, San Joaquin, Solano, Stanislaus, Yolo	24.82	12.75	C	58
	Bravo weather stick	Chlorothalonil[1]	Fresno, Merced, San Joaquin, Stanislaus	2.52	0.00	C	25
	Rally	Myclobutanil[1]	Fresno, Merced, San Joaquin, Stanislaus	0.24	0.08	C	42
	Kocide 3000	Copper hydroxide	Colusa, Merced, Yolo	1.98	1.09	C	8
	Quadris	Azoxystrobin	Colusa, Yolo	0.11	0.00	C	8
	Manzate or Dithane-M45	Mancozeb	Yolo, Merced	0.81	0.36	C	17
	Vapam[2]	Sodium Methyldithiocarbamate	Merced, Sutter	66.20	29.29	D; RU	17
Growth Regulator	Ethrel	Ethephon	N/A	N/A	N/A		0

[1]Listed in CalEnviroScreen as highly toxic and volatile; [2]Vapam is used as a fungicide as well as a herbicide. It includes the active ingredient methyldithiocarbamate/metam sodium, which is a fumigant; and [3]The EPA signal word is based on 4 categories of acute toxicity in order of increasing toxicity: caution (C), Warning (W), Danger (D); RU indicates restricted use.

Cultivation Pesticide Use Table – 2015 – ALL DATA

Class	Product name(s)	Active ingredients	Survey County	Average amount (AI kg/ha)	Stndv (AI kg/ha)	EPA 'signal word'[3]	% of 2015 sample
Non-fumigants							
Insecticide	Various Products (Cymate 267, Dimate 4e, Dimethoate 25 wp)	Dimethoate[1]	Colusa, Glenn, Yolo, Fresno, San Joaquin, Stanislaus, Merced	0.52	0.16	W	31
	Asana	Esfenvalerate	Fresno, Merced, San Joaquin, Stanislaus	0.28	0.00	W	10
	Warrior	Lambda Cyhalothrin	Colusa, Fresno, Kings, Madera, Solano, Sutter, Yolo	0.20	0.52	W; RU	36
	Radiant	Spinetoram[2]	Butte, Colusa, Fresno, Merced, Sutter, Yolo	0.07	0.02	C	31
	Belay Insecticide	Clothianidin	Colusa, Fresno, Sutter, Yolo	0.11	0.04	C	14
	Macho2.0FL, Macho4.0, Admire Pro or LeveragePlus, Montana4F	Imidacloprid	Colusa, Fresno, Kern, Madera, Merced, San Joaquin, Solano, Yolo, Sutter, Glenn	0.31	0.16	C	48
	Intrepid	Methoxyfenozide	Fresno, Madera, San Joaquin	0.28	0.19	C	14
	Sevin 5 Bait, Carbary 5% Bait	Cabaryl[1]	Colusa, Fresno, Merced, Solano, Sutter, Yolo	1.00	1.13	C	26
	Agri-Mek, Zoro, Epi_MEK0.15EC, Abba Ultra, Timestin	Abamectin	Butte, Colusa, Fresno, Madera, San Joaquin, Solano, Sutter, Yolo, Glenn	0.02	0.01	W; RU	38
	Belt SC	Flubendiamide	Colusa, Fresno, Madera, Merced, San Joaquin, Sutter, Yolo	0.07	0.02	C	33
	Coragen	Chlorantraniliprole	Colusa, Sutter, Fresno, Kern, Kings, Merced	0.07	0.01	C	19
	Bifenture10DF, Bifen 2AG Gold, BifentureEC, Capture2EC, Sniper	Bifenthrin	Butte, Colusa, Fresno, San Joaquin, Solano, Sutter, Yolo, Glenn	0.14	0.04	C; RU	38
	Diazinon AG500	Diazinon[1]	Colusa, Glenn, Sutter, Yolo	4.19	1.17	C; RU	12
	Actara, Platinum 75 SG	Thiamethoxam	Colusa, Fresno, Kern, Merced	0.16	0.05	C	24
	Surround-WP	Kaolin[2]	Colusa, Fresno, Sutter	44.36	6.63	C	7

[1]Listed in CalEnviroScreen as highly toxic and volatile; [2]Kaolin and spinetoram are biopesticides (subset: microbial pesticides); and [3]the EPA signal word is based on 4 categories of acute toxicity in order of increasing toxicity: caution (C), Warning (W), Danger (D); RU indicates restricted use. [4]Other refers to crops such as almond, pepper, cotton, etc.

Cultivation Pesticide Use Table – 2015 (Cont.)

Class	Product name(s)	Active ingredients	County	Avg (AI kg/ha)	Stndv (AI kg/ha)	EPA 'signal word'[3]	% of 2015 sample
Non-fumigants							
Herbicide	Matrix	Rimsulfuron	Colusa, Fresno, Glenn, Madera, Merced, San Joaquin, Solano, Yolo	0.04	0.02	C	55
	Goal 2XL	Oxyfluorfen	Colusa, Fresno, Merced, San Joaquin, Solano, Sutter, Yolo	0.29	0.20	W	40
	Var. (Tenkoz, Trifluralin E.C.)	Trifluralin[1]	Butte, Colusa, Fresno, Glenn, Kern, Kings, Merced, San Joaquin, Solano, Sutter, Yolo	0.74	0.26	C	76
	Shark EW	Carfentrazone	Colusa, Fresno, Madera, San Joaquin, Solano, Sutter, Yolo	0.02	0.01	C	24
	Dual Magnum	S-Metolachlor/Metolachlor	Butte, Colusa, Sutter, Fresno, Glenn, Kern, Madera, Merced, San Joaquin, Solano, Yolo	2.12	0.87	C	26
	Prowl	Pendimethalin	Colusa, Fresno, Madera, Sutter, Yolo	0.87	0.35	C	14
	Round Up or GLY-4 or Makaze	Glyphosate	Colusa, Fresno, Glenn, Kings, Madera, Merced, San Joaquin, Solano, Stanislaus, Sutter, Yolo	2.96	2.19	C	76
Fungicide	Thiolux	Sulfur	Colusa, Fresno, Madera, Merced, San Joaquin, Solano, Stanislaus, Sutter, Yolo, Glenn	49.95	56.68	C	62
	Bravo weather stick	Chlorothalonil[1]	Colusa, Sutter, Fresno, Kings, Madera, Merced, San Joaquin, Solano, Yolo, Glenn	2.40	0.90	C	48
	Quadris	Azoxystrobin	Butte, Colusa, Sutter, Fresno, Kern, Merced, San Joaquin, Solano, Stanislaus, Yolo, Glenn	0.30	0.36	C	40
	Rally	Myclobutanil[1]	Fresno, Madera, Merced, Yolo	0.12	0.02	C	10
	Kocide 3000	Copper hydroxide	Colusa, Fresno, Kern, Kings, Madera, Yolo	1.80	2.55	C	17
	Priaxor	Fluxapyroxad+Pyraclostrobin	Butte, Colusa, Sutter, Fresno, Yolo, Glenn	0.69	0.01	C	24
	Quadris Top	Azoxystrobin+Difenoconazole	Colusa, Fresno, Merced, San Joaquin, Solano, Sutter, Yolo	0.24	0.22	C	40
	Dithane-M45	Mancozeb	Colusa, Fresno, Madera, Yolo, Glenn	1.59	0.68	C	19
	Famoxate or Tanos	Famoxadone	Fresno	0.84	0.00	C	2
Growth Regulator	Ethrel	Ethephon	Fresno, Merced, San Joaquin, Sutter, Yolo	0.84	0.18	D	14
	Adjuvant		Colusa, Sutter, Fresno, Kern, Madera, Merced, San Joaquin, Solano, Yolo, Glenn	0.72	0.72	NA	3

[1]Listed in CalEnviroScreen as highly toxic and volatile; [2]Kaolin and spinetoram are biopesticides (subset: microbial pesticides); and [3]the EPA signal word is based on 4 categories of acute toxicity in order of increasing toxicity: caution (C), Warning (W), Danger (D); RU indicates restricted use. [4]Other refers to crops such as almond, pepper, cotton, etc. [5]'RR' refers to round-up ready.

Appendix E: Pesticides Unaccounted for in the LCA Note: These pesticides were excluded from the LCA because fewer than 5 of the 49 growers sampled applied them to their fields.

Year	Product	Active Ingredient	No of growers
2005	Metribuzin	Metribuzin	1
	Cabrio	Pyraclostrobin	1
	Induce	Alkyl Aryl Polyoxylkane Ether	1
	Latron	Modified phthalic glycerol alkyd resin	1
	Ridomil	Mefenoxam	1
	Endosulfan 3 E.C.	Endosulfan	1
	Manex	maneb	2
	Nordox 75 WG	Cuprous oxide	1
	Magnify	Ammonium sulfate + Alkyl Polyglucoside + Ammonium Nitrate	1
	RNA Si 100	Polyetherpolymethylsiloxane-Copolymer	1
	Nudrin or Lannate	Methomyl	3
2015	Assail 30 or 70	Acetamiprid	4
	Beleaf50SG	Flonicamid	1
	Movento	Spirotetramat	2
	2,4-D dimethyline salt, 2, 4-D dimethylamine salt	2,4-D dimethyline salt, 2, 4-D dimethylamine salt	2
	K-PAM	Metam Potassium	5
	Metribuzin	Metribuzin	4
	Paraquat	Paraquat	2
	Copper Oxychloride+Copper Hydroxide	Copper Oxychloride+Copper Hydroxide	2
	Quinoxyfen	Quinoxyfen	2
	Cabrio	Pyraclostrobin	4
	Penthiopyrad	Penthiopyrad	5
	Basic Copper Sulfate	Basic Copper Sulfate	2
	Ridomil	Mefenoxam	4
	Kaligreen	Potassium bicarbonate	1
	Mustang 1.5 EW	S Zeta cypermethrin	2
	Spinosad	Methyl eugenol + spinosad	1
	NEEM oil	NEEM oil	1
	Pyrethrum	Pyrethrum	2
	Clethodim	Clethodim	2
	Dicamba	Dimethylamine salt	1
	Dinotefuran	Dinotefuran	1
	Cyfluthrin	Cyfluthrin	2
	Emamectin benzoate	Emamectin benzoate	2
	Malathion	Malathion	2
	Nudrin or Lannate	Methomyl	1
	Indoxacarb	Indoxacarb	5

Appendix F: OFFROAD Data – Tractor Use – Cultivation – 2005

Cultivation Tractor Details - 2005

2005

County	Make	Model	Tier	Year - Equip	HP	AVG Gal/Hr	Equip Type (OFFROAD)
Yolo	JD	4020	1	1968	95	5.20	Tractors/Loaders/Backhoes
Yolo	JD	4000	1	1972	97	5.10	Tractors/Loaders/Backhoes
Yolo	JD	4620	1	1972	132	6.55	Tractors/Loaders/Backhoes
Colusa, Glenn	JD	4430	1	1973	120	6.05	Tractors/Loaders/Backhoes
Yolo	JD	7630	1	1974	155	6.20	Tractors/Loaders/Backhoes
Yolo	JD	4240	1	1978	105	5.85	Tractors/Loaders/Backhoes
Colusa, Glenn	Caterpillar	D5	1	1978	100	5.00	Crawler Tractor
Yolo	JD	4840	1	1980	180	7.65	Tractors/Loaders/Backhoes
Colusa, Glenn	Versatile	800	1	1981	220	11.6	Tractors/Loaders/Backhoes
Colusa, Glenn	Versatile	835	1	1981	235	9.35	Tractors/Loaders/Backhoes
Yolo	JD	6400 mudder	1	1982	85	4.37	Tractors/Loaders/Backhoes
Colusa, Glenn	JD	4050	1	1987	110	5.35	Tractors/Loaders/Backhoes
Colusa, Glenn	JD	2955	1	1991	80	4.45	Tractors/Loaders/Backhoes
Colusa, Glenn	JD	3055	1	1991	90	4.75	Tractors/Loaders/Backhoes
Yolo	Cat Challenger	45	1	1995	200	9.95	Crawler Tractor
Yolo	Cat Challenger	85	1	1996	355	10.65	Crawler Tractor
Colusa, Glenn	JD	8300	1	1998	225	8.75	Tractors/Loaders/Backhoes
Fresno	JD	7405	1	2002	125	5.10	Tractors/Loaders/Backhoes
Merced	JD	7405	1	2002	125	5.10	Tractors/Loaders/Backhoes
San Joaquin	JD	7405	1	2002	125	5.10	Tractors/Loaders/Backhoes
Stanislaus	JD	7405	1	2002	125	5.10	Tractors/Loaders/Backhoes
Fresno	CAT	MT765	2	2002	300	11.95	Crawler Tractor
Merced	CAT	MT765	2	2002	300	11.95	Crawler Tractor
San Joaquin	CAT	MT765	2	2002	300	11.95	Crawler Tractor
Stanislaus	CAT	MT765	2	2002	300	11.95	Crawler Tractor
Fresno	CTM	Tomato Harvester	1	2003	175	8.95	Tractors/Loaders/Backhoes
Merced	CTM	Tomato Harvester	1	2003	175	8.95	Tractors/Loaders/Backhoes
San Joaquin	CTM	Tomato Harvester	1	2003	175	8.95	Tractors/Loaders/Backhoes
Stanislaus	CTM	Tomato Harvester	1	2003	175	8.95	Tractors/Loaders/Backhoes

Cultivation OFFROAD Data – 2005 (Cont.)

2005								OFFROAD data						
County	**Make**	**Model**	**Tier**	**Year - Equip**	**HP**	**Avg (gal/hr)**	**Activity (hrs / ha)**	**Year - Equip**	**HP**	**ROG**	**CO**	**Nox**	**PM**	**Assumptions**
Yolo	JD	4020	1	1968	95	5	0.99	1968	95	1.44	4.80	13.00	0.84	1968 not avail; 1987 used
Yolo	JD	4000	1	1972	97	5	0.99	1972	97	1.44	4.80	13.00	0.84	1972 not avail; 1987 used
Yolo	JD	4620	1	1972	132	7	0.99	1972	132	1.10	4.40	13.00	0.66	1972 not avail; 1971 used
Colusa, Glenn	JD	4430	1	1973	120	6	0.99	1973	120	1.44	4.80	13.00	0.84	1973 not avail; 1987 used
Yolo	JD	7630	1	1974	155	6	0.99	1974	155	1.10	4.40	13.00	0.66	1974 not avail; 1971 used
Yolo	JD	4240	1	1978	105	6	0.99	1978	105	1.44	4.80	13.00	0.84	1978 not avail; 1987 used
Colusa, Glenn	Caterpillar	D5	1	1978	100	5	0.99	1978	100	1.44	4.80	13.00	0.84	1978 not avail; 1987 used
Yolo	JD	4840	1	1980	180	8	0.99	1980	180	1.00	4.40	12.00	0.55	1980 not avail; 1979 used
Colusa, Glenn	Versatile	800	1	1981	220	12	0.99	1981	220	1.00	4.40	12.00	0.55	1981 not avail; 1979 used
Colusa, Glenn	Versatile	835	1	1981	235	9	0.99	1981	235	1.00	4.40	12.00	0.55	1981 not avail; 1979 used
Yolo	JD	6400 mudder	1	1982	85	4	0.99	1982	85	1.44	4.80	13.00	0.84	1982 not avail; 1987 used
Colusa, Glenn	JD	4050	1	1987	110	5	0.99	1987	110	1.44	4.80	13.00	0.84	NA
Colusa, Glenn	JD	2955	1	1991	80	4	0.99	1991	80	1.44	4.80	13.00	0.84	1991 not avail; 1987 used
Colusa, Glenn	JD	3055	1	1991	90	5	0.99	1991	90	1.44	4.80	13.00	0.84	1991 not avail; 1987 used
Yolo	Cat Challenger	45	1	1995	200	10	0.99	1995	200	0.68	2.70	8.17	0.38	NA
Yolo	Cat Challenger	85	1	1996	355	11	0.99	1996	355	0.68	2.70	8.17	0.38	1996 not avail; 1995 used
Colusa, Glenn	JD	8300	1	1998	225	9	0.99	1998	225	0.68	2.70	8.17	0.38	1998 not avail; 1995 used
Fresno	JD	7405	1	2002	125	5.1	0.82	2002	125	0.68	2.70	6.90	0.38	NA
Merced	JD	7405	1	2002	125	5.1	0.82	2002	125	0.68	2.70	6.90	0.38	NA
San Joaquin	JD	7405	1	2002	125	5.1	0.82	2002	125	0.68	2.70	6.90	0.38	NA
Stanislaus	JD	7405	1	2002	125	5.1	0.82	2002	125	0.68	2.70	6.90	0.38	NA
Fresno	CAT	MT765	2	2002	300	11.95	0.49	2002	300	0.14	0.92	4.51	0.11	NA
Merced	CAT	MT765	2	2002	300	11.95	0.49	2002	300	0.14	0.92	4.51	0.11	NA
San Joaquin	CAT	MT765	2	2002	300	12	0.49	2002	300	0.14	0.92	4.51	0.11	NA
Stanislaus	CAT	MT765	2	2002	300	11.95	0.49	2002	300	0.14	0.92	4.51	0.11	NA
Fresno	CTM	Tomato Harvester	1	2003	175	8.95	2.47	2003	175	0.33	2.70	5.26	0.24	NA
Merced	CTM	Tomato Harvester	1	2003	175	8.95	2.47	2003	175	0.33	2.70	5.26	0.24	NA
San Joaquin	CTM	Tomato Harvester	1	2003	175	8.95	2.47	2003	175	0.33	2.70	5.26	0.24	NA
Stanislaus	CTM	Tomato Harvester	1	2003	175	8.95	2.47	2003	175	0.33	2.70	5.26	0.24	NA

Tractor Emission Data – 2005- Calculated based on OFFROAD Data (Cont.)

County	Make	Model	Tier	Year - Equip	ROG (t/dy)	ROG/ha	CO (t/dy)	CO/ha	Nox (t/dy)	Nox/ha	PM (t/dy)	PM/ha	N20 (g/hp-hr)	N20/ha	THC (g/hp-hr)	THC/ha	CH4 (g/hp-hr)	CH4/ha
Yolo	JD	4020	1	1968	1505	74	5016	247	13585	672	878	44	73	2	1188	59	70	2
Yolo	JD	4000	1	1972	1536	77	5122	252	13871	684	896	44	74	2	1213	59	71	2
Yolo	JD	4620	1	1972	1597	79	6389	316	18876	934	958	47	87	5	1261	62	74	2
Colusa, Glenn	JD	4430	1	1973	5246	94	17487	314	47362	848	3060	54	142	2	4143	74	244	5
Yolo	JD	7630	1	1974	1876	509	7502	2039	22165	6024	1125	306	95	25	1481	403	87	25
Yolo	JD	4240	1	1978	1663	82	5544	274	15015	741	970	47	77	5	1313	64	77	5
Colusa, Glenn	Caterpillar	D5	1	1978	5087	91	16957	304	45926	823	2968	54	140	2	4017	72	236	5
Yolo	JD	4840	1	1980	1980	99	8712	430	23760	1174	1089	54	99	5	1563	77	92	5
Colusa, Glenn	Versatile	800	1	1981	6679	119	29388	526	80150	1436	3674	67	189	2	5274	94	310	5
Colusa, Glenn	Versatile	835	1	1981	7135	128	31392	561	85615	1532	3924	69	195	2	5634	101	331	5
Yolo	JD	6400 mudder	1	1982	1346	67	4488	222	12155	600	785	40	69	2	1063	52	63	2
Colusa, Glenn	JD	4050	1	1987	4809	776	16030	2582	43415	6996	2805	452	136	22	3797	613	223	37
Colusa, Glenn	JD	2955	1	1991	3497	62	11658	208	31574	566	2040	37	115	2	2762	49	162	2
Colusa, Glenn	JD	3055	1	1991	3935	72	13116	235	35521	635	2295	42	122	2	3107	57	183	2

Cultivation Tractor Emission Data – 2005- Calculated based on OFFROAD Data (Cont.)

County	Make	Model	Tier	Year - Equip	ROG (t/dy)	ROG/ha	CO (t/dy)	CO/ha	Nox (t/dy)	Nox/ha	PM (t/dy)	PM/ha	N20 (g/hp-hr)	N20/ha	THC (g/hp-hr)	THC/ha	CH4 (g/hp-hr)	CH4/ha
Yolo	Cat Challenger	45	1	1995	1741	689	6912	2733	20915	8268	973	385	92	37	1375	544	81	32
Yolo	Cat Challenger	85	1	1996	3090	153	12269	605	37124	1834	1727	86	125	7	2440	121	144	7
Colusa, Glenn	JD	8300	1	1998	4645	84	18444	331	55809	998	2596	47	156	2	3668	67	216	5
Fresno	JD	7405	1	2002	1697	37	6738	151	17220	388	948	22	83	2	1340	30	79	2
Merced	JD	7405	1	2002	2006	37	7963	151	20351	388	1121	22	91	2	1584	30	93	2
San Joaquin	JD	7405	1	2002	1620	37	6432	151	16437	388	905	22	81	2	1279	30	75	2
Stanislaus	JD	7405	1	2002	2468	37	9801	151	25047	388	1379	22	101	2	1949	30	115	2
Fresno	CAT	MT765	2	2002	591	12	3886	86	19050	427	465	10	88	2	467	10	27	0
Merced	CAT	MT765	2	2002	699	12	4593	86	22514	427	549	10	96	2	552	10	32	0
San Joaquin	CAT	MT765	2	2002	564	12	3709	86	18184	427	444	10	86	2	446	10	26	0
Stanislaus	CAT	MT765	2	2002	860	12	5652	86	27709	427	676	10	107	2	679	10	40	0
Fresno	CTM	Tomato Harvester	1	2003	3494	79	28586	642	55690	1250	2541	57	155	2	2759	62	162	2
Merced	CTM	Tomato Harvester	1	2003	4129	79	33784	642	65816	1250	3003	57	170	2	3261	62	192	2
San Joaquin	CTM	Tomato Harvester	1	2003	3335	79	27287	642	53159	1250	2426	57	152	2	2634	62	155	2
Stanislaus	CTM	Tomato Harvester	1	2003	5082	79	41580	642	81004	1250	3696	57	190	2	4013	62	236	2

Appendix G: OFFROAD Data – Tractor Use – Cultivation – 2015

2015

County	Make	Model	Tier	Year - Equip	HP	AVG Gal/Hr	Equip Type (OFFROAD)
Yolo	JD	4020	1	1968	95	5.20	Tractors/Loaders/Backhoes
Colusa, Glenn	Versatile	835	1	1981	235	9.35	Tractors/Loaders/Backhoes
Colusa, Glenn	JD	4050	1	1987	110	5.35	Tractors/Loaders/Backhoes
Colusa, Glenn	JD	2955	1	1991	80	4.45	Tractors/Loaders/Backhoes
Colusa, Glenn	JD	3055	1	1991	90	4.75	Tractors/Loaders/Backhoes
Colusa, Glenn	JD	8400	1	1995	250	10.25	Tractors/Loaders/Backhoes
Yolo	Cat Challenger	85	1	1996	355	10.65	Crawler Tractor
Colusa, Glenn	JD	8300	1	1998	225	8.75	Tractors/Loaders/Backhoes
Fresno	CAT	MT 765	2	2002	300	11.95	Crawler Tractor
Merced	CAT	MT 765	2	2002	300	11.95	Crawler Tractor
San Joaquin	CAT	MT 765	2	2002	300	11.95	Crawler Tractor
Stanislaus	CAT	MT 765	2	2002	300	11.95	Crawler Tractor
Yolo	JD	7130	3	2010	100	5.35	Tractors/Loaders/Backhoes
Yolo	JD	7330	3	2010	125	6.00	Tractors/Loaders/Backhoes
Yolo	JD	7830	3	2010	165	6.85	Tractors/Loaders/Backhoes
Yolo	JD	8260R	4	2011	260	8.60	Tractors/Loaders/Backhoes
Colusa, Glenn	JD	6150R	4	2014	150	6.95	Tractors/Loaders/Backhoes
Fresno	JD	6150R	4	2015	150	6.45	Tractors/Loaders/Backhoes
Merced	JD	6150R	4	2015	150	6.45	Tractors/Loaders/Backhoes
San Joaquin	JD	6150R	4	2015	150	6.45	Tractors/Loaders/Backhoes
Stanislaus	JD	6150R	4	2015	150	6.45	Tractors/Loaders/Backhoes
Fresno	JD	7215R	4	2015	215	7.95	Tractors/Loaders/Backhoes
Merced	JD	7215R	4	2015	215	7.95	Tractors/Loaders/Backhoes
San Joaquin	JD	7215R	4	2015	215	7.95	Tractors/Loaders/Backhoes
Stanislaus	JD	7215R	4	2015	215	7.95	Tractors/Loaders/Backhoes
Colusa, Glenn	JD	8270R	4	2015	270	9.20	Tractors/Loaders/Backhoes
Fresno	CTM	Tomato Harvester	3	2015	225	8.95	Tractors/Loaders/Backhoes
Merced	CTM	Tomato Harvester	3	2015	225	8.95	Tractors/Loaders/Backhoes
San Joaquin	CTM	Tomato Harvester	3	2015	225	8.95	Tractors/Loaders/Backhoes
Stanislaus	CTM	Tomato Harvester	3	2015	225	8.95	Tractors/Loaders/Backhoes
Yolo	JD	8245R	4	2016	245	7.65	Tractors/Loaders/Backhoes

Cultivation Tractor Details - 2015

Cultivation OFFROAD Data – 2015 (Cont.)

2015								OFFROAD Data						
County	**Make**	**Model**	**Tier**	**Year - Equip**	**HP**	**Avg Gal/Hr**	**Activity (CM HRS per Yr)**	**Year - Equip**	**HP**	**ROG**	**CO**	**Nox**	**PM**	**Assumptions**
Yolo	JD	4020	1	1968	95	5.20	239	1968	95	1.44	4.8	13.0	0.84	1968 not avail; 1987 used
Colusa	Versatile	835	1	1981	235	9.35	55	1981	235	1.00	4.4	12.0	0.55	1981 not avail; 1979 used
Colusa	JD	4050	1	1987	110	5.35	55	1987	110	1.44	4.8	13.0	0.84	NA
Colusa	JD	2955	1	1991	80	4.45	55	1991	80	1.44	4.8	13.0	0.84	1991 not avail; 1987 used
Colusa	JD	3055	1	1991	90	4.75	55	1991	90	1.44	4.8	13.0	0.84	1991 not avail; 1987 used
Colusa	JD	8400	1	1995	250	10.25	55	1995	250	0.68	2.7	8.2	0.38	NA
Yolo	Cat Challenger	85	1	1996	355	10.65	239	1996	355	0.68	2.7	8.2	0.38	1996 not avail; 1995 used
Colusa	JD	8300	1	1998	225	8.75	55	1998	225	0.68	2.7	8.2	0.38	1998 not avail; 1995 used
Fresno	CAT	MT 765	2	2002	300	11.95	22	2002	300	0.14	0.9	4.5	0.11	NA
Merced	CAT	MT 765	2	2002	300	11.95	26	2002	300	0.14	0.9	4.5	0.11	NA
San Joaquin	CAT	MT 765	2	2002	300	11.95	21	2002	300	0.14	0.9	4.5	0.11	NA
Stanislaus	CAT	MT 765	2	2002	300	11.95	32	2002	300	0.14	0.9	4.5	0.11	NA
Yolo	JD	7130	3	2010	100	5.35	239	2010	100	0.19	3.1	5.0	0.24	2010 not avail; 2007 used
Yolo	JD	7330	3	2010	125	6.00	239	2010	125	0.16	2.7	4.4	0.16	2010 not avail; 2006 used
Yolo	JD	7830	3	2010	165	6.85	239	2010	165	0.16	2.7	4.4	0.16	2010 not avail; 2006 used
Yolo	JD	8260R	4	2011	260	8.60	239	2011	260	0.10	0.9	4.0	0.11	2011 not avail; 2005 used
Colusa	JD	6150R	4	2014	150	6.95	55	2014	150	0.10	2.7	2.4	0.14	2014 not avail; 2020 used
Fresno	JD	6150R	4	2015	150	6.45	27	2015	150	0.10	2.7	2.4	0.14	2015 not avail; 2020 used
Merced	JD	6150R	4	2015	150	6.45	32	2015	150	0.10	2.7	2.4	0.14	2015 not avail; 2020 used
San Joaquin	JD	6150R	4	2015	150	6.45	26	2015	150	0.10	2.7	2.4	0.14	2015 not avail; 2020 used
Stanislaus	JD	6150R	4	2015	150	6.45	40	2015	150	0.10	2.7	2.4	0.14	2015 not avail; 2020 used
Fresno	JD	7215R	4	2015	215	7.95	27	2015	215	0.10	0.9	2.4	0.11	2015 not avail; 2020 used
Merced	JD	7215R	4	2015	215	7.95	32	2015	215	0.10	0.9	2.4	0.11	2015 not avail; 2020 used
San Joaquin	JD	7215R	4	2015	215	7.95	26	2015	215	0.10	0.9	2.4	0.11	2015 not avail; 2020 used
Stanislaus	JD	7215R	4	2015	215	7.95	40	2015	215	0.10	0.9	2.4	0.11	2015 not avail; 2020 used
Colusa	JD	8270R	4	2015	270	9.20	55	2015	270	0.10	0.9	2.4	0.11	2015 not avail; 2020 used
Fresno	CTM	Tomato Harvester	3	2015	225	8.95	110	2015	225	0.10	0.9	2.4	0.11	2015 not avail; 2020 used
Merced	CTM	Tomato Harvester	3	2015	225	8.95	130	2015	225	0.10	0.9	2.4	0.11	2015 not avail; 2020 used
San Joaquin	CTM	Tomato Harvester	3	2015	225	8.95	105	2015	225	0.10	0.9	2.4	0.11	2015 not avail; 2020 used
Stanislaus	CTM	Tomato Harvester	3	2015	225	8.95	160	2015	225	0.10	0.9	2.4	0.11	2015 not avail; 2020 used
Yolo	JD	8245R	4	2016	245	7.65	239	2016	245	0.10	0.9	2.4	0.11	2016 not avail; 2020 used

Cultivation Tractor Emissions – 2015- Calculated based on OFFROAD Data (Cont.)

County	Make	Model	Tier	Year - Equip	ROG (t/dy)	ROG/ha	CO (t/dy)	CO/ha	Nox (t/dy)	Nox/ha	PM (t/dy)	PM/ha	N20 (g/hp-hr)	N20/ha	THC (g/hp-hr)	THC/ha	CH4 (g/hp-hr)	CH4/ha
Yolo	JD	4020	1	1968	18028	74	60092	247	162748	672	10516	44	275	0	14235	59	837	2
Colusa	Versatile	835	1	1981	7135	128	31392	561	85615	1532	3924	69	195	2	5634	101	331	5
Colusa	JD	4050	1	1987	4809	430	16030	1436	43415	3887	2805	252	136	12	3797	341	223	20
Colusa	JD	2955	1	1991	3497	62	11658	208	31574	566	2040	37	115	2	2762	49	162	2
Colusa	JD	3055	1	1991	3935	72	13116	235	35521	635	2295	42	122	2	3107	57	183	2
Colusa	JD	8400	1	1995	5161	91	20493	368	62010	1110	2884	52	165	2	4076	74	240	5
Yolo	Cat Challenger	85	1	1996	37017	153	146980	605	444751	1834	20686	86	470	2	29231	121	1719	7
Colusa	JD	8300	1	1998	4645	84	18444	331	55809	998	2596	47	156	2	3668	67	216	5
Fresno	CAT	MT 765	2	2002	591	12	3886	86	19050	427	465	10	88	2	467	10	27	0
Merced	CAT	MT 765	2	2002	699	12	4593	86	22514	427	549	10	96	2	552	10	32	0
San Joaquin	CAT	MT 765	2	2002	564	12	3709	86	18184	427	444	10	86	2	446	10	26	0
Stanislaus	CAT	MT 765	2	2002	860	12	5652	86	27709	427	676	10	107	2	679	10	40	0
Yolo	JD	7130	3	2010	2504	10	40720	168	66022	272	3163	12	170	0	1977	7	116	0
Yolo	JD	7330	3	2010	2636	10	44476	183	73138	301	2636	10	180	0	2081	7	122	0

Cultivation Tractor Emissions – 2015- Calculated based on OFFROAD Data (Cont.)

County	Make	Model	Tier	Year - Equip	ROG (t/dy)	ROG/ha	CO (t/dy)	CO/ha	Nox (t/dy)	Nox/ha	PM (t/dy)	PM/ha	N20 (g/hp-hr)	N20/ha	THC (g/hp-hr)	THC/ha	CH4 (g/hp-hr)	CH4/ha
Yolo	JD	7830	3	2010	3479	15	58708	242	96542	398	3479	15	208	0	2747	12	162	0
Yolo	JD	8260R	4	2011	3426	15	31522	131	137051	566	3769	15	251	0	2706	12	159	0
Colusa	JD	6150R	4	2014	455	7	12296	220	11157	200	638	12	66	0	360	7	21	0
Fresno	JD	6150R	4	2015	227	5	6126	138	5558	126	318	7	45	0	179	5	11	0
Merced	JD	6150R	4	2015	268	5	7239	138	6569	126	375	7	50	0	212	5	12	0
San Joaquin	JD	6150R	4	2015	217	5	5847	138	5306	126	303	7	44	0	171	5	10	0
Stanislaus	JD	6150R	4	2015	330	5	8910	138	8085	126	462	7	56	0	261	5	15	0
Fresno	JD	7215R	4	2015	325	7	2992	67	7967	178	358	7	55	2	257	5	15	0
Merced	JD	7215R	4	2015	384	7	3536	67	9416	178	423	7	60	0	303	5	18	0
San Joaquin	JD	7215R	4	2015	310	7	2856	67	7605	178	341	7	54	2	245	5	14	0
Stanislaus	JD	7215R	4	2015	473	7	4352	67	11589	178	520	7	67	0	374	5	22	0
Colusa	JD	8270R	4	2015	820	15	7541	136	20083	361	902	17	90	2	647	12	38	0
Fresno	CTM	Tomato Harvester	3	2015	1361	30	12524	282	33351	749	1497	35	118	2	1075	25	63	2
Merced	CTM	Tomato Harvester	3	2015	1609	30	14801	282	39414	749	1770	35	129	2	1270	25	75	2
San Joaquin	CTM	Tomato Harvester	3	2015	1299	30	11954	282	31835	749	1429	35	115	2	1026	25	60	2
Stanislaus	CTM	Tomato Harvester	3	2015	1980	30	18216	282	48510	749	2178	35	144	2	1563	25	92	2
Yolo	JD	8245R	4	2016	3229	12	29703	124	79101	326	3551	15	187	0	2549	10	150	0

Appendix H: Transportation Distances

Transport distances for materials used in each phase of tomato processing

Greenhouse[1]			Cultivation			Facility	
Material	**Use**	**Distance (miles)**	**Material**	**Use**	**Distance (miles)**	**Material**	**Distance (miles)**
Vermiculite	growing medium	1867	Potash Corp[2] (e.g., UN-32, zinc, kocide)	fertilizer, pesticides	2599	60% Sodium Hydroxide	1124
Peat moss	growing medium	8687	[Thiolux] Sulfur	pesticide	1182	40% Potassium hydroxide	2325
Peat moss	growing medium	5496	[Goal 2XL] Oxyfluorfen	pesticide	2214	35% HCl	2148
Various (Potassium nitrate, Streptomycin, etc.)	fertilizer, pesticides	1661	[Var brands] Dimethoate	pesticide	2044	37% Calcium chloride	2419
Iron EDTA	fertiliser	2024	Bravo weather stick	pesticide	1661	50% Citric acid	2478
Nitric acid, ammonium calcium salt	fertiliser	2618	[Matrix] Rimsulfuron	pesticide	2813	50% Sodium hydrochloride	2197
Potassium phosphate	fertiliser	1202	Diazinon	pesticide	2794	Plastic drums	69
Magnesium nitrate	fertiliser	7515	[Trifluralin 4 E.C.] Trifluralin	pesticide	1998	Metal drums	76
Potassium nitrate	fertiliser	7515	[Warrior] Lambda cynalothirin	pesticide	2709	Plastic bins	2258
			Gypsum	soil amendment	2091	Wooden bins	77
			Glyphosate	herbicide	2015	Glass containers	145
			Adjuvant	additive	728	Fiber drums	197
						300 gal bags	2159
						5 gal bags	2159
						102 oz pouches	2904
						Plastic containers	156

[1]Method of transport distance estimation: ArcGIS and Google were used to estimate the total road miles between material manufacturer and its respective use phase. [2]The distance between Potash Corp. and each phase varies, as the location of each phase (greenhouse, cultivation, and facility) differs depending on the use phase or site (e.g., facility or field) location. [1]Greenhouse results are based on 2015 data only.

Appendix I: Life Cycle Inventories

Greenhouse-LCI Documentation

Source	Region	Years Valid	LCI Name	Inputs	Formula/Notes
-	-	-	-	Water withdrawal	LCI*(3.79 kg/gal) for 1 kg water withdrawal
G	US	2013-2019	natural gas production + combustion	Natural gas	LCI*(1.9787kg/therm) natural gas per year
G	US-CA	2015-2018	Electricity grid mix - CAMX	Electricity	Used as is
G	US	2009-2016	1 kg Diesel [Refinery products]	Diesel	LCI*(3.24 kg/gal) for 1 kg diesel
G	US	2009-2016	1 m^3 US: Diesel, combusted in industrial equipment [Products and Intermediates]	Diesel	LCI*(0.0038 m3/gal) for 1 kg diesel
G	US	2012 - 2018	Propane at refinery	Propane	LCI*(4.22 kg/gal) for 1 kg propane
E	CH	2015-0	Vermiculite Expanded	Vermiculite	Used as is
E	NORDEL	2015-0	peat production	Peat moss	Used as is
E	CA-QC	2015-0	peat moss production, horticulture use	Peat moss	Used as is
G	US	2012 - 2018	Gasoline mix (regular) at filling station	Gasoline	LCI*(2.805 kg/gal) for 1 kg gasoline
E	GLO	2015-0	market for EDTA, ethylenediaminetetraacetic acid	Manganese EDTA 13% Mn	LCI*(1/2.2 kg/lb) for 1 kg product 13% Mn
E	GLO	2015-0	market for DTPA, diethylenetriaminepentaacetic acid	Iron EDTA 13.2% Fe	LCI*(1/2.2 kg/lb) for 1 kg product 13.2% Fe
G	US	2015-2018	Calcium ammonium nitrate (CAN, solid)	Nitric acid, ammonium calcium salt 15.5-0-0	LCI*(1/2.2 kg/lb) for 1 kg product
G	US	2015-2018	Phosphoric acid (54% P_2O_5, agrarian)	Potassium phosphate 0-52-34	LCI*(1/2.2 kg/lb) for 1 kg product 0-52-34
E	GLO	2015-0	market for magnesium	Magnesium nitrate 11-0- Mg 9.4791%	LCI*(9.4791%*1/2.2 kg/lb) for 1 kg product 11-0- Mg 9.4791%
G	US	2015-2018	Nitric acid (60%)	Magnesium nitrate 11-0- Mg 9.4791%	LCI*(1/2.2 kg/lb) for 1 kg product 11-0- Mg 9.4791%
G	US	2012-2018	Hydrogen at refinery	Magnesium nitrate 11-0- Mg 9.4791%	LCI*((4.7172%-0.96%)*1/2.2 kg/lb) for 1 kg product 11-0-Mg 9.4791%
E	GLO	2015-0	Field application of potassium nitrate	Potassium nitrate 13-0-46	LCI*(1/2.2 kg/lb) for 1 kg product 13-0-46
E	GLO	2015-0	Field application of potassium nitrate	Potassium nitrate 13-0-46	LCI*(1/2.2 kg/lb) for 1 kg Potassium product13-0-46

Greenhouse-LCI Documentation cont.

Source	Region	Years Valid	LCI Name	Inputs	Formula/Notes
E	GLO	2015-0	market for potassium sulfate, as K_2O	Potassium sulfate 50 0-0-52	LCI*(1/2.2 kg/lb) for 1 kg product50 0-0-52
G	US	2015-2018	Lactic acid (fermentative)	Streptomycin	LCI*(1/2.2 kg/lb) for 1 kg product
E	GLO	2015-0	market for chlorothalonil	Chlorothalonil	LCI*(2.73 kg/gal) for 1 kg product
G	US	2015-2018	Chlorobenzene (by product chlorobenzene, hydrochloric acid)	Boscalid	LCI*(1/2.2 kg/lb) for 1 kg product
G	US	2015-2018	Nitric acid (60%)	Boscalid	LCI*(14.066%*1/2.2 kg/lb) for 1 kg product
G	US	2015-2018	Oxygen (liquid)	Bosalid	LCI*(71.5104%*1/2.2 kg/lb) for 1 kg product
G	US	2012-2018	Hydrogen at refinery	Boscalid	LCI*(2.5529%*1/2.2 kg/lb) for 1 kg product
E	RNA	2015-2018	copper production, primary	Copper hydroxide	LCI*(65.134%*1/2.2 kg/lb) for 1 kg product
G	US	2015-2018	Oxygen (liquid)	Copper hydroxide	LCI*(32.7989%*1/2.2 kg/lb) for 1 kg product
G	US	2012-2018	Hydrogen at refinery	Copper hydroxide	LCI*(2.0663%*1/2.2 kg/lb) for 1 kg product
G	US	2015-2018	Phosphoric acid (75%)	Phosphoric acid	LCI*(3.2 kg/gal) for 1 kg product
E	GLO	2015-0	market for mancozeb	Mancozeb	LCI*(2.2 kg/gal) for 1 kg product
E	GLO	2015-0	market for esterquat	Ammonium chloride	LCI*(3.73 kg/gal) for 1 kg product
E	GLO	2015-0	market for trimethylamine	Propamocarb hydrochloride	LCI*(2.73 kg/gal) for 1 kg product
G	US	2015-2018	Oxygen (liquid)	Propamocarb hydrochloride	LCI*(14.2389%*2.73 kg/gal) for 1 kg product
G	US	2015-2018	Chlorine mix	Propamocarb hydrochloride	LCI*(15.7759%*2.73 kg/gal) for 1 kg product
E	GLO	2015-0	market for esterquat	Ammonium chloride	LCI*(3.73 kg/gal) for 1 kg product
E	GLO	2015-0	market for trimethylamine	Propamocarb hydrochloride	LCI*(2.73 kg/gal) for 1 kg product

Greenhouse-LCI Documentation cont.

Source	Region	Years Valid	LCI Name	Inputs	Formula/Notes
G	US	2015-2018	Oxygen (liquid)	Propamocarb hydrochloride	LCI*(14.2389%*2.73 kg/gal) for 1 kg product
G	US	2015-2018	Chlorine mix	Propamocarb hydrochloride	LCI*(15.7759%*2.73 kg/gal) for 1 kg product
G	US	2015-2018	Aniline (Phenyl amine, Amino benzene)	Cypronil + Fludioxonil	LCI*(2.2 kg/lb) for 1 kg product
E	RoW	2015-0	fluorine production, liquid	Cypronil + Fludioxonil	LCI*(8.0251%*2.2 kg/lb) for 1 kg product
G	US	2015-2018	Oxygen (liquid)	Cypronil + Fludioxonil	LCI*(6.7583%*2.2 kg/lb) for 1 kg product
E	GLO	2015-0	market for N-methyl-2-pyrrolidone	Famoxadone+Cymoxanil	LCI*(1/2.2 kg/lb) for 1 kg product
G	US	2015-2018	Acetone (from cumene)	Famoxadone+Cymoxanil	LCI*(1/2.2 kg/lb) for 1 kg product
E	GLO	2015-0	market for pesticide, unspecified	Spinetoram	LCI*(0.45 kg/gal) for 1 kg product
G	US	2009-2016	US: Transport, combination truck, average fuel mix [Products and Intermediates]	Average Material Transport	Used as is

Cultivation-LCI Documentation

Source	Region	Years Valid	LCI Name	Inputs	Formula/Notes
G	US	2009-2016	1 kg Diesel [Refinery products]	Diesel	LCI*(3.24 kg/gal) for 1 kg diesel
G	US	2009-2016	1 m3 US: Diesel, combusted in industrial equipment [Products and Intermediates]	Diesel	LCI*(0.0038 m3/gal) for 1 kg diesel
G	US-CA	2015-2018	Electricity grid mix - CAMX	Water for irrigation	LCI*((1/380.6)*0.00026 kWh/gal/Ac
-	-	-	-	Water withdrawal	Accounted for in model
E	GLO	2015-0	market for zinc	Zinc	LCI*(1/2.2 kg/lb) for 1 kg zinc
E	GLO	2015-0	market for gypsum, mineral	Gypsum	LCI*(1/2.2 kg/lb) for 1 kg gypsum
G	US-CA	2015-2018	Urea (agrarian)	UN-32	LCI*(34.8%*1.55 kg/gal) for 1 kg UN-32
G	US-CA	2015-2018	Ammonium nitrate (AN, solution) 52% N	UN-32	LCI*(45.2%*(100/52)*1.55 kg/gal) for 1 kg UN-32
G	US	2015-2018	Calcium ammonium nitrate (CAN, solid)	CAN17	LCI*(17%) for 1 kg product
-	-	-	-	N_2O in field	Accounted for in model
G	US	2015-2018	Ammonia (liquid, agriculture)	Aq ammonia	Used as is
G	US	2012-2018	Sulphur (elemental) at refinery	[Thiolux] Sulfur	LCI*(1/2.2 kg/lb) for 1 kg Sulfur
E	GLO	2015-0	market for dinitroaniline-compound	[Trifluralin 4 E.C.] Trifluralin	LCI*(1/2.2 kg/lb) for 1 kg Trifluralin
E	GLO	2015-0	market for pyrethroid-compound	[Warrior] Lambda cyhalothrin	LCI*(1/2.2 kg/lb) for 1 kg Lambda cyhalothrin
E	GLO	2015-0	market for benzoic acid	[Intrepid] Methoxyfenozide	LCI*(1/2.2 kg/lb) for 1 kg Methoxyfenozide
G	US	2015-2018	Nitrogen (liquid)	[Intrepid] Methoxyfenozide	LCI*(7.6026%*1/2.2 kg/lb) for 1 kg Methoxyfenozide
E	GLO	2015-0	market for organophosphorous-compound, unspecified	[DiazinonAG500] Diazinon	LCI*(1/2.2 kg/lb) for 1 kg Diazinon
E	GLO	2015-0	glyphosate production	[Round Up or GLY-4 or Makaze] Glyphosate	LCI*(1/2.2 kg/lb) for 1 kg Glyphosate
E	GLO	2015-0	market for chlorothalonil	[BRAVO] Chlorothalonil	LCI*(2.73 kg/gal) for 1 kg Bravo Weather Stik
E	GLO	2015-0	market for [sulfonyl]urea-compound	[Matrix] Rimsulfuron	LCI*(1/2.2 kg/lb) for 1 kg Rimsulfuron
E	GLO	2015-0	Diphenylether (sub. for Oxyflurefen)	Oxyflurefen	Used as is
E	GLO	2015-0	market for paraffin	Adjuvant	LCI*(1/2.2 kg/lb) for 1 kg Adjuvant
E	GLO	2015-0	market for metolachlor	[Dual Magnum] Metolachlor	LCI*(1/2.2 kg/lb) for 1 kg Metolachlor
G	US	2009-2016	US: Transport, combination truck, average fuel mix [Products and Intermediates]	Average Material Transport	Used as is

Facility-LCI Documentation

Source	Region	Years Valid	LCI Name	Inputs	Formula/Notes
G	US-CA	2015-2018	Electricity grid mix - CAMX	Electricity	Used as is
G	US	2010-2018	Electricity from natural gas (West)	Natural gas	LCI*(11.63 kg/kWh) for 1 kg Natural gas burned
G	US	2009-2016	1 kg Diesel [Refinery products]	Diesel	LCI*(3.24 kg/gal) for 1 kg diesel
G	US	2009-2016	1 m3 US: Diesel, combusted in industrial equipment [Products and Intermediates]	Diesel	LCI*(0.0038 m3/gal) for 1 kg diesel
G	US	2012-2018	Propane at refinery	Propane	LCI*(1.92 kg/gal) for 1 kg Propane
G	US	2015-2018	Sodium hydroxide (caustic soda) mix (100%)	Sodium Hydroxide 50%	LCI*(5.77 kg/gal) for 1 kg NaOH
E	GLO	2015-0	market for calcium chloride	Calcium Chloride 37%	LCI*(5.21 kg/gal) for 1 kg CaCl
G	US	2015-2018	Citric acid (from starch)	Citric Acid 50%	LCI*(1.2205/264.172 kg/gal) for 1 kg Citric acid
G	US	2009-2016	US: Transport, combination truck, average fuel mix [Products and Intermediates]	Average Material Transport	Used as is

Appendix J: Downstream potential environmental impacts from pesticides

Substance	CAS No.	Type	Initial emission compartment				
Name			**Air**	**Fresh water**	**Sea water**	**Agricultural soil**	**Industrial soil**
Diazinon	333-41-5	FAETP[1]	3.24E+00	4.35E+02	2.07E-03	1.63E+01	1.02E+02
		MAETP	3.01E+00	2.41E+01	6.07E+01	9.57E-01	5.69E+00
		TETP	1.44E+03	3.18E+01	2.13E+00	2.73E+01	2.07E+01
		HTP[2]	1.52E+02	5.99E+02	2.16E+00	3.80E+01	1.42E+02
		Carc.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		Non-Carc.	1.52E+02	5.99E+02	2.16E+00	3.80E+01	1.42E+02
Chlorothalonil	1897-45-6	FAETP	1.87E+01	6.73E+02	1.02E+00	2.65E+01	1.58E+02
		MAETP	1.85E+02	1.93E+02	2.66E+02	8.08E+01	1.08E+02
		TETP	2.23E+04	8.82E+03	1.36E+03	9.33E+03	9.77E+03
		HTP	5.31E+00	1.01E+01	3.46E-01	2.20E+00	3.75E+00
		Carc.	5.13E-02	9.70E-02	3.32E-03	2.12E-02	3.61E-02
		Non-Carc.	5.26E+00	1.00E+01	3.42E-01	2.18E+00	3.72E+00
Mancozeb	8018-01-7	FAETP	7.92E+00	7.80E+01	7.70E-12	1.07E+01	5.67E+01
		MAETP	3.85E+00	4.31E+00	1.04E+01	5.89E-01	3.13E+00
		TETP	4.23E+04	9.45E-06	6.22E-08	8.45E-04	3.59E-05
		HTP	4.95E+01	2.43E+00	6.02E-04	2.75E+00	1.77E+00
		Carc.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		Non-Carc.	4.95E+01	2.43E+00	6.02E-04	2.75E+00	1.77E+00
Propamocarb HCL	25606-41-1	FAETP	1.63E-02	3.44E-01	8.49E-12	3.02E-02	1.82E-01
		MAETP	8.39E-03	1.90E-02	4.60E-02	1.67E-03	1.01E-02
		TETP	2.39E+01	4.28E-07	2.75E-08	4.05E-06	2.92E-06
		HTP	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		Carc.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		Non-Carc.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cyprodinil	121552-61-2	FAETP	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		MAETP	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		TETP	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		HTP	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		Carc.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		Non-Carc.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

[1]Freshwater aquatic ecotoxicity potential (FAETP), marine aquatic ecotoxicity potential (MAETP), terrestrial ecotoxicity potential (TETP), and human toxicity potential (HTP) are estimated in 1.4-DCB equivalents. [2]HTP is the sum of the carcinogenic (Carc.) and the noncarcinogenic (Non-Carc.) human toxicity potentials.

Downstream potential environmental impacts from pesticides, cont.

Substance	CAS No.	Type	Initial emission compartment				
Name			Air	Fresh water	Sea water	Agricultural soil	Industrial soil
Fludioxonil	131341-86-1	FAETP	1.22E+01	2.75E+02	6.95E-05	9.31E+00	6.98E+01
		MAETP	1.53E+01	2.28E+01	4.46E+01	7.74E-01	5.80E+00
		TETP	1.16E+04	1.45E+00	1.10E-01	1.06E+00	1.15E+00
		HTP	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		Carc.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		Non-Carc.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cymoxanil	57966-95-7	FAETP	2.24E-02	1.90E+00	1.63E-09	4.89E-03	4.14E-02
		MAETP	1.39E-01	1.06E-01	4.26E-01	2.73E-04	2.31E-03
		TETP	8.04E+00	7.50E-07	6.42E-07	4.12E-08	5.49E-08
		HTP	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		Carc.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		Non-Carc.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Trifluralin	1582-09-8	FAETP	3.54E-02	3.54E+01	2.11E-02	4.38E-01	3.61E+00
		MAETP	1.52E+00	4.61E+00	4.72E+01	6.14E-01	9.79E-01
		TETP	2.95E+01	3.18E+01	1.82E+01	1.13E+01	1.32E+01
		HTP	4.58E+00	1.32E+02	6.44E+00	5.31E+00	1.41E+01
		Carc.	1.34E-01	3.80E+00	1.86E-01	1.53E-01	4.07E-01
		Non-Carc.	4.44E+00	1.28E+02	6.25E+00	5.16E+00	1.37E+01
Glyphosate	38641-94-0	FAETP	2.43E-01	2.45E+00	1.15E-16	3.65E-01	1.67E+00
		MAETP	9.19E-02	5.83E-02	2.62E-01	8.68E-03	3.97E-02
		TETP	1.26E+03	1.64E-10	8.87E-13	1.57E-05	6.26E-10
		HTP	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		Carc.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		Non-Carc.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Rimsulfuron	122931-48-0	FAETP	2.29E+00	2.72E+01	1.15E-05	3.87E+00	2.05E+01
		MAETP	1.05E+00	2.26E+00	4.23E+00	3.22E-01	1.70E+00
		TETP	8.30E+03	1.12E+00	8.10E-02	1.43E+01	4.47E+00
		HTP	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		Carc.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		Non-Carc.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

[1]Freshwater aquatic ecotoxicity potential (FAETP), marine aquatic ecotoxicity potential (MAETP), terrestrial ecotoxicity potential (TETP), and human toxicity potential (HTP) are estimated in 1.4-DCB equivalents. [2]HTP is the sum of the carcinogenic (Carc.) and the noncarcinogenic (Non-Carc.) human toxicity potentials.

Downstream potential environmental impacts from pesticides, cont.

Substance	CAS No.	Type	Initial emission compartment				
Name			Air	Fresh water	Sea water	Agricultural soil	Industrial soil
Oxyfluorfen	42874-03-3	FAETP	1.30E+00	1.77E+02	2.81E-02	3.29E-01	2.36E+00
		MAETP	3.59E+01	3.61E+01	1.60E+02	7.52E-01	1.16E+00
		TETP	5.01E+02	3.18E+01	1.15E+01	9.68E+00	1.00E+01
		HTP	5.97E+02	4.17E+03	1.25E+02	2.24E+01	6.56E+01
		Carc.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		Non-Carc.	5.97E+02	4.17E+03	1.25E+02	2.24E+01	6.56E+01
Metolachlor	87392-12-9	FAETP	4.87E+00	1.47E+02	3.69E-04	9.37E+00	6.18E+01
		MAETP	3.56E+00	1.22E+01	2.33E+01	7.89E-01	5.14E+00
		TETP	5.07E+03	1.13E+01	8.30E-01	1.84E+01	1.57E+01
		HTP	5.61E+00	3.37E+00	1.21E-02	3.42E-01	1.43E+00
		Carc.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		Non-Carc.	5.61E+00	3.37E+00	1.21E-02	3.42E-01	1.43E+00

[1]Freshwater aquatic ecotoxicity potential (FAETP), marine aquatic ecotoxicity potential (MAETP), terrestrial ecotoxicity potential (TETP), and human toxicity potential (HTP) are estimated in 1.4-DCB equivalents. [2]HTP is the sum of the carcinogenic (Carc.) and the noncarcinogenic (Non-Carc.) human toxicity potentials.

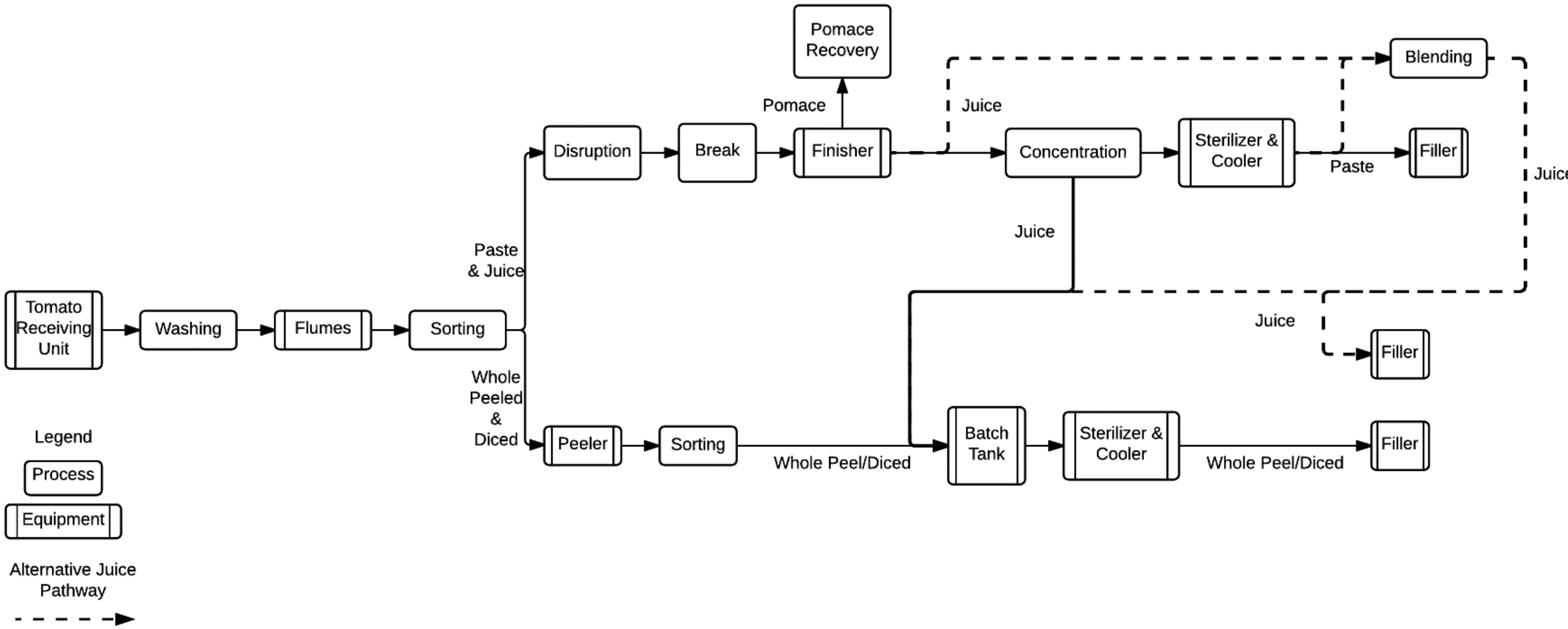
Appendix K: California Tomato Processing Facility Process-level Practices

Generally, thermal processes tend to be more energy intensive than mechanical processes, whereas the evaporation process uses more energy (by an OOM) per ton of product produced compared with the mechanical processes (see table below in the text). The table **(below in the text)** is adapted from tables 3 & 6 of Karakaya & Özilgen (2011). Note this study does not address the 'break' step in the paste production line. However, the 'break' step is an important step and a thermal process and therefore it is assumed to use more energy than a mechanical process.

Energy consumption (MJ/ton product) associated with the production of the tomato paste, juice, whole peel & diced tomato.

Processing step and equipment details	**MJ/ton of product**	**Thermal (T)/ Mechanical (M)**
Evaporator (Paste)	1,894.7	T
Bottle Pasteurizer (Juice)	1,198.0	T
Evaporator (Juice)	237.8	T
Can filler (Paste)	96.1	M
Pulping to 0.8 mm mesh size (Paste)	48.3	M
Blender (Juice)	14.3	M
Crushing (Paste)	11.4	M
Pulping to 0.5 mm mesh size (Juice)	8.4	M
Deaerator(Juice)	7.9	M
Pasteurizer (Whole Peel & Diced)	6.7	T
Peeler/Skin Eliminator (Whole Peel & Diced)	5.9	M
Pasteurizer (Paste)	5.1	T
Crushing (Juice)	5.1	M
Washing (Paste)	4.0	M
Sorting (Paste)	4.0	M
Dicer (Whole Peel & Diced)	4.0	M
Conveying (Paste)	2.8	M
Washing (Juice)	1.8	M
Sorting (Juice)	1.8	M
Manual Sorting Machine (Whole Peel & Diced)	1.6	M
Bottle hot filler and capper (Juice)	1.5	M
Conveying (Juice)	1.3	M
Washing (Whole Peel & Diced)	1.0	M
Sorting (Whole Peel & Diced)	1.0	M
Conveying (Whole Peel & Diced)	0.7	M

Adapted from tables 3 & 6 of Karakaya & Özilgen (2011). It is important to note that this table should not be considered as a benchmark for processors, as it is solely included here to illustrate the order of magnitude difference in energy usage between thermal processing and mechanical processing.



Generalized process-level processing tomato for diced and paste tomato production facility diagram. ‘Disruption’ refers to mechanical disruption of the intact fruit to form a slurry, which can be achieved through a hammer mill or chopper pump.

The ‘break’ step or breaking is the process of heating the tomatoes to prepare them for the finisher. Cold breaking is done at 65° C which is low enough to allow enzymatic activity. Enzymes naturally present in tomatoes will break up long chain molecules, lowering the viscosity of concentrated tomato products (facility engineer, May 2017). Hot breaking occurs at 95° C which deactivates the enzymes in the tomatoes, leaving long chain molecules intact and thus increasing viscosity (anonymous, May 2017). Because heat transfer is generally performed using steam, due to its antiseptic qualities and the fact that the temperature of steam can be controlled directly and precisely by changing the temperature, the water requirements will vary as well depending on whether the paste is hot break or cold break and depending on the concentration (°Bx) of the tomato paste.

Evaporation is used to concentrate the sugars in the paste and evaporation progress is measured in Brix (1°Bx = 1 g sucrose/100 g solution). All facilities use evaporation for paste or juice production; whereas juice is added to diced tomato products. Evaporation is performed under a vacuum so that the temperature required to vaporize water from the tomato juice is below the caramelization point of the sugars found in tomato paste. The degree to which the paste is evaporated depends on what the product will be used for, e.g., raw tomatoes vs. grade ‘A’ ketchup. When producing paste specifically, processors generally choose between managing viscosity, managing color and taste, or managing °Bx and Color (anonymous, May 2017).

Evaporation can be achieved through several methods. The most common is a multi-effect evaporator system, although some operators only use a single effect. An alternative style of evaporator, called a falling film evaporator is also sometimes employed. Falling film evaporators can be used in conjunction with standard evaporators or by themselves. Falling film evaporators can also have multiple effects. A more recent design is to incorporate mechanical vapor recompression (MVR). MVR must always be used in conjunction with either a standard evaporator system or in conjunction with a falling film evaporator system.

Appendix L: Results for CML Characterization Factors, for Diced and Paste Product in 2005 and 2015

The CML baseline characterization factors are used for impact categories ozone-depleting potential (ODP), in kg CFC 11-equivalents, acidifying potential (AP), in kg SO_2, photochemical ozone-creating potential (POCP), in kg C_2H_4 equivalents, and eutrophication potential (EP), in kg PO_4^{3-} equivalents (Guinée et al. 2001). Human Toxicity Potential (HTP), Marine Aquatic Toxicity Potential (MAETP), Terrestrial Ecotoxicity Potential (TETP) and Freshwater Aquatic Ecotoxicity Potential (FAEP) are accounted for in DCB equivalents. Elemental Abiotic Depletion (elements ADP) is accounted for in units of kg Sb (antimony).

Description of CML baseline characterization factor units:
CFC-11 is trichlorofluoromethane which contributes to ozone depletion potential. SO_2 is sulfur dioxide, a gas that contributes to the formation of aerosols, which can cause respiratory and other breathing problems among other human health problems, and directly and indirectly interacts with the earth's atmosphere warming and cooling (Satein 2009). C_2H_4 is ethylene which is a volatile organic compound that can contribute to ground-level ozone. PO_4^{3-} is phosphate and can contribute to eutrophication (or overfertilization) of aquatic and terrestrial systems. DCB is 1, 4-Dichlorobenzene, a compound that is poorly soluble in water, not easily broken down by soil microorganisms, and is a carcinogen (OEHHA, 1986). Antimony is an indication of the extraction of the earth's non-renewable resources and fossil abiotic depletion (fossil ADP) accounted for in megajoules (MJ) as an indication of the total amount of fossil energy in a kg of antimony equivalent.