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Title:

Cradle to farm gate life cycle assessment of strawberry production in the United States

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Abstract

The goal of this study was to develop a cradle to farm gate life cycle inventory and assess the environmental impacts of strawberry production in four major strawberry producing states of the United States: California, Florida, North Carolina and Oregon, representing 99% of the United States strawberry production. Life cycle environmental impacts depend strongly on geographic location and production practices. Data for California and North Carolina strawberry production were collected in collaboration with agricultural economists from those states using the “LCA Extended Enterprise Budget” Excel sheet (version 4.11). Data for Florida strawberry production were collected from the state’s existing enterprise budget (a detailed accounting of production costs and returns which estimates profitability of an enterprise). Data related to Oregon strawberry production were obtained through interviews with strawberry producers. OpenLCA software was used to conduct life cycle assessment for strawberry production. Missing unit processes for production of agricultural machinery, pesticides, fertilizers and materials were modeled based on existing literature. In order to better assess the sustainability of strawberry production, three metrics encompassing nitrogen productivity, phosphorous productivity and fossil energy productivity were introduced. Global warming potential for California, Florida, North Carolina and Oregon strawberry production was estimated to be 1.75, 2.50, 5.48 and 2.21 kg CO₂-eq per 1 kg of strawberry, respectively. The difference between LCA results was due to variation in yield and management practices which depend on geographic location. Plastics, fuels and fertilizers were the inputs with the highest contribution to environmental impact categories. California strawberry production scored the highest on three sustainability metrics mainly due to having the highest strawberry yield.

Keywords: enterprise budget, environmental impacts, life cycle assessment, openLCA, strawberry

1. Introduction

The total value of the United States (U.S.) strawberry production in 2014 was \$2.4 billion and surpassed that of the fresh apple industry for the first time in 2010 (AgMRC, 2013). Strawberries are the fourth most valuable fruit produced in the U.S. and the total production of strawberry has been reported by the United States Department of Agriculture (USDA) as 1.4 million tonne in 2014 (USDA, 2015). Increasingly, producers, food retailers and consumers are becoming conscious of the environmental impacts of the products they produce, sell and /or consume. Therefore, assessing environmental impacts of strawberry production is essential to enable more sustainable production practices and to inform consumers of their choices. Communicating environmental impact information to stakeholders in an easy-to-understand format is critical for the move towards more sustainable production practices (Peano et al., 2015).

There are two main types of strawberry plants, distinguished by the date that they begin to produce fruit: June-bearing and day-neutral. June-bearing strawberries produce fruit in the late spring and early summer, while day-neutral strawberries produce their fruits continuously from early summer to fall (Demchak et al., 2010). In the U.S. strawberry transplants are used for strawberry production purposes and they mostly come from California nurseries. Strawberry transplants are produced from meristem plants after they are propagated under controlled conditions and numbers are increased up to three generations in nursery fields. Transplants are used to prevent transfer of diseases and pests to fruit production fields (Murthy et al., 2014).

There are two main production systems for strawberries in the U.S.: matted-row and plasticulture. Matted-row production is an old and less expensive system in which strawberry plants are set out on cultivated lands at regularly spaced intervals within regularly spaced rows. This system allows strawberry runners to grow and establish daughter plants within the rows and it is also suitable for cooler regions. This system requires to be renovated each year. In the plasticulture system, strawberry plants are grown on raised beds covered with black plastic (plastic mulch). June-bearing and day-neutral strawberry plants can be cultivated under either system. The cultivated plants can be dormant plants or plug plants (plants grown from rooted runner tips) (Demchak et al., 2010). In recent years, plasticulture has become the main commercial growing system for strawberry production across most of the U.S. due to higher productivity and quality than the matted-row system (Fernandez et al., 2001; Poling, 2005).

A previous life cycle assessment (LCA) study for strawberry production in Italy indicated that most of the GHG emissions could be attributed to the plastics used in production (Girgenti et al., 2014). Similar studies were performed to assess life cycle impacts of strawberry production in Australia (Gunady et al., 2012), the United Kingdom (U.K.) and Spain (Williams et al., 2008). However, to date, there is no LCA for strawberry production in the U.S. to the best of our knowledge. This study represents the first LCA for strawberry production in the U.S. in multiple geographic locations. Life cycle environmental impacts depend strongly on geographic location and production practices. The main goal of this study was to perform LCA for strawberry production using the plasticulture method in four states across the U.S. A second goal of this paper was to propose simple producer/consumer friendly metrics that indicate the overall efficiency of nitrogen, phosphorous and fossil energy use during strawberry production.

2. Material and methods

2.1. Goal and scope definition

The primary goal of this study was to develop a cradle-to-farm-gate life cycle inventory (LCI) and assess the environmental impacts of the plasticulture method of non-organic strawberry production in four major strawberry producing states in the U.S.: California, Florida, North Carolina and Oregon. These four states produced 99% of strawberry in the U.S. from 2012 to 2014 (USDA, 2015). Obtaining high-quality LCI data is critical for a reliable LCA. Since such data do not as yet exist for strawberry production, a modified enterprise-budget tool that collects necessary LCI data in the background while performing economic analysis for production was developed. The scope of this study was intended to provide a preliminary data-set for conducting strawberry LCAs in four geographic regions of the U.S. Moreover, an uncertainty analysis was performed to evaluate the impact of variations in inputs on LCA results. Since the strawberry is a fresh market product, the functional unit of 1 kg at farm gate (before transporting to point of sale) was chosen for the LCA.

2.2. System boundaries

System boundaries define which unit processes and inputs are included in the LCA (Fig. 1). Strawberry production has several inputs such as fertilizers, pesticides, fuels and materials. Plastic mulch, drip tubes, floating row covers and packaging baskets were considered as materials. In addition to these material inputs, field operations require using agricultural machinery for land preparation, planting, application of fertilizer and pesticides. These inputs, including the fuel used for operation of agricultural machinery, were considered in the LCI. N₂O emissions due to applied nitrogen fertilizer and flows associated with harvesting and packaging processes were included in the LCI. Due to lack of information, the strawberry nursery phase was excluded from the LCI.

<Figure 1>

2.3. *Life cycle inventory*

Farmers, agricultural economists and other stakeholders commonly use enterprise budgets for planning purposes. Enterprise budget is a detailed accounting of production costs and returns which provides an estimate of profitability. In this study the “LCA Extended Enterprise Budget Tool” was developed to capture LCI data in conjunction with the enterprise budget analysis. The LCI was necessary to evaluate variations in both the format and content of the various enterprise budgets and to capture the most common strawberry management practices currently used. Plasticulture and matted-row practices were represented in enterprise budgets for each state. Enterprise budgets for each state also provided quantity and cost estimates for materials and activities associated with strawberry production, based on surveys of growers, retailers, extension agents, crop advisors, and other market participants. In addition, the enterprise budgets provided the baseline format for the LCA Extended Enterprise Budget tool (v. 4.11). The first version of this tool was distributed to an internal advisory group for an “in-process” review and was updated based on the advisory group’s comments. Details of tool development, reviewer comments and user tutorials can be found in Murthy et al. (2014). The updated tool was distributed to five state economists, four horticulturalists, and three extension agents from California, North Carolina, Florida, Washington, Oregon, New York, and Pennsylvania to test its usability and collect data about current strawberry production (41% response rate: 5 out of 12). Data for California and North Carolina strawberry production were collected in collaboration with agricultural economists from these states using the LCA Extended Enterprise Budget Tool. Data for Florida strawberry production were collected from the state’s existing enterprise budget, while those for Oregon were obtained through interviews with

strawberry producers. The process of data collection was mentioned in detail by Murthy et al. (2014). Both datasets were manually entered into the LCA Extended Enterprise Budget Excel sheet. The lists of all inputs used and outputs produced in strawberry production for four states were tabulated (Appendix A, Supplementary Materials). After extraction of LCI data, the UWDFE (University of Washington Design for Environment) lab Excel-to-ILCD (International Life Cycle Database) File Generator (LCA Commons, 2014) was used to create intermediate flows for strawberry production. Generated intermediate flows were imported into openLCA v. 1.4.2 software to perform a LCA for strawberry production. The U.S. LCI Database (2014) contained processes for the production of fuels and nitrogen fertilizer but not for some specific inputs including materials, other fertilizers, pesticides and agricultural machinery. Therefore, these processes were created using existing raw material and energy flows in the U.S. LCI Database (see next paragraph). Mass allocation method was used to allocate the emissions to co-products in upstream processes. Direct N₂O emissions from agricultural soils from applied nitrogenous fertilizers were estimated as 1.25 % of applied nitrogen (IPCC, 2006).

2.4. Flows and processes

Production processes for agricultural machinery (e.g. tractor, disc, plow, leveler, chisel plow, cultivator) consisted of manufacturing, assembly, repair and maintenance stages. In the manufacturing process, steel and rubber were the main raw materials. For steel, the existing process flow (“steel billet” production) from the U.S. LCI Database was used, however, there were no processes for rubber, machine assembly, repair and maintenance in the U.S. LCI Database. Therefore, emissions (e.g. volatile organic compound (VOC), carbon monoxide (CO), carbon dioxide (CO₂), nitrogen monoxide (NO), nitrogen dioxide (NO₂), nitrous oxide (N₂O), particulate matter (PM₁₀), particulate matter (PM_{2.5}), sulfur dioxide (SO₂), sulfur trioxide

(SO₃), methane (CH₄) associated with those processes were created using Greenhouse gases, Regulated Emissions and Energy use in Transportation (GREET, 2012) data and input as cutoff processes.

Production processes for pesticides (e.g. herbicides, insecticides, fungicides, fumigants, miticides) were also created. The resources used to produce each pesticide were calculated based on the mass of its active ingredient(s). The amounts of naphtha, gas, coke, fuel oil, electricity and steam used to produce pesticides were obtained from Audsley et al. (2009). Existing U.S. LCI Database's flows for these energy sources were used as inputs for production process of pesticides. Overall, 43 pesticide processes were created (Appendix A, Supplementary Materials).

Regarding the processes for materials, especially plastic mulch, the main component of each material was considered as input. For example, polyethylene was considered as the main component of plastic mulch and accordingly the only input used in production of plastic mulch. In addition, production processes of all fertilizers except nitrogen fertilizer were created using GREET (2012) data.

Irrigation is necessary for strawberry production, and drip irrigation is one of the most popular methods because it provides ideal soil moisture for plant growth. In this study, drip irrigation using 7200 m³/ha/year of water was assumed for strawberry production in all regions. It was assumed that water was pumped from a depth of 37 m using a pump with 70% energy efficiency, pressurized to 207 kPa, and sent through drip tubes using a second pump with 70% efficiency (Dara et al., 2011).

2.5. Life cycle impact assessment (LCIA)

The Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI 2.1), developed by U.S. Environmental Protection Agency (EPA), was used as

an impact assessment method in this study (Bare, 2002; Ryberg et al., 2014). TRACI 2.1 has seven environment-related impact categories (acidification, ecotoxicity, eutrophication, global warming potential (GWP), ozone depletion, photochemical ozone formation and resource depletion) and three human-health-related impact categories (carcinogenics, non-carcinogenics and respiratory effects). Compared to the previous version of TRACI (TRACI 1.0), TRACI 2.1 has characterization factors (CFs) for most agricultural chemicals, and its CFs have been updated. However, the method for calculating these CFs is not clear, and some chemicals still have no CF; thus, it was concluded that the ecotoxicity could not be estimated reliably (Ryberg et al., 2014). Hence, flows of agricultural chemicals in the inventory were reported as environmental releases. This approach was inspired by the USDA LCA Commons Database (LCA Commons, 2014), which distinguishes environmental releases (inventory outflows without impact assessment) from environmental emissions (includes impact assessment using a specified method). Also, since fossil energy consumption was assessed as a sustainability metric in this study, the resource depletion category was not calculated.

2.6. Uncertainty analysis

Since management practices for strawberry production differ across the U.S., inputs such as fertilizers and chemicals vary from region to region. To evaluate effects of variation in inputs on LCA results, uncertainty analysis was performed using Monte Carlo simulation (Tu and McDonnell, 2016) (10% variation in each input using normal distribution, all inputs varied simultaneously, 1000 iterations).

2.7. Sustainability metrics for strawberry production

While the LCA estimates environmental impacts in several categories, not all categories are useful to non-experts. Therefore, three additional metrics were included that may be more

accessible to the general public and convey important information about the sustainability of strawberry production. These metrics were inspired by the energy return on energy invested (EROEI), the Net Energy concept, and the indicator of Mulder et al. (2010) for water-use intensity of energy production technologies by defining energy return on water invested (EROWI). A metric, Net EROWI, was developed as a function of EROWI and EROEI to estimate water use in fuel production systems (Mulder et al. 2010):

$$\omega = \frac{EROEI}{EROEI-1} \quad (1)$$

$$Net\ EROWI = \frac{Gross\ EROWI}{\omega} \quad (2)$$

The metrics for nitrogen and phosphorous use and fossil energy consumption are similar to the EROWI concept described above: nitrogen productivity (NP), phosphorous productivity (PP) and fossil-energy productivity (FEP). These metrics indicate nitrogen-, phosphorous-, and energy-use efficiencies of strawberry production, which influence its sustainability. NP, PP, and FEP are defined as follows:

$$NP = \frac{Productivity\ (\frac{kg}{ha.season})}{Nitrogen\ input\ (\frac{kg}{ha.season})} \quad (3)$$

$$PP = \frac{Productivity\ (\frac{kg}{ha.season})}{Phosphorous\ input\ (\frac{kg}{ha.season})} \quad (4)$$

$$FEP = \frac{Productivity\ (\frac{kg}{ha.season})}{Fossil\ Energy\ input\ (\frac{MJ}{ha.season})} \quad (5)$$

To calculate FEP, the fossil energy consumed to produce each input was calculated based on fossil-energy life cycle factors (Table 1).

<Table 1>

3. Results and Discussion

Higher strawberry yields per ha generally corresponded to lower environmental impacts per kg of strawberry (Table 2). Strawberry yield and quality can be affected by day length, temperature, soil characteristics, altitude, latitude, cultivation system and management practices (Kruger et al., 2004) and the variation in strawberry yield among four states can be attributed to these factors. One of the most important factors was the climate (Palencia et al., 2013) which was totally different among these four states. California's unique climate (moderate temperature year round) is a perfect condition for growing strawberry which result in high yield (1.25 million tons strawberry production in 2014 (90% of the U.S. strawberry production) (USDA, 2015)). Strawberry production in Oregon and North Carolina had the highest acidification due mainly to low productivity of potassium sulfate fertilizer which releases sulfur dioxide and sulfur trioxide. Farmers in these two states produced less strawberry using the same amount of potassium sulfate fertilizer as farmers in other states. Triple superphosphate fertilizer also contributed to acidification. North Carolina had the highest eutrophication (Table 2) due to the use of potassium sulfate, which releases nitrogen oxide and nitrogen dioxide. In addition, the production of crude oil, used to produce diesel and polyethylene, can cause eutrophication. Besides NO_x and SO_x , potassium sulfate also releases methane, CO and VOC, which are primary factors in photochemical ozone formation. Therefore, farmers in states that used more potassium sulfate in strawberry production (Oregon and North Carolina) had the highest photochemical ozone formation. The high respiratory effect impact in Oregon came from the use of potassium sulfate, while that in North Carolina came from the use of fuels and polyethylene-based materials. Because potassium sulfate was the primary contributor to most impacts, it should be used cautiously (i.e. considering the facts that how much increase in yield will occur by using one

additional kg of potassium sulfate and there are some alternatives for potassium sulfate such as composts, kelp meal, wood ash and etc.). Strawberry production in North Carolina had the most adverse effect on human health in the form of carcinogenics, non-carcinogenics and ozone depletion, due primarily to ethylene production, used in materials such as plastic mulch and floating covers.

GWP_s for California, Florida, North Carolina and Oregon strawberries were 1.75, 2.50, 5.48 and 2.21 kg CO₂-eq per 1 kg, respectively. California had the lowest GWP because it had the highest strawberry yield (74 t/ha) (Table 2). The large variation in GWP due to differences in production practices and yields is not unusual. Mordini et al. (2009) reported that the GWP for strawberries among several countries (e.g. Spain, U.K., Japan) varied from 0.27-3.99 kg CO₂-eq/kg. Production system, yield, climate, soil, fertilizer production and application, machinery and irrigation system are the key factors that affect the GWP of strawberry production (Mordini et al., 2009). LCA studies of strawberry production with similar production systems in Italy (Peano et al., 2015), Australia (Gunady et al., 2012), Spain (Williams et al., 2008) and the U.K. (Lillywhite, 2008) were chosen to compare the results of this study with their results. GWP_s for California, Florida, North Carolina and Oregon strawberries were compared to those of other countries (Fig. 2) and as it can be seen, North Carolina strawberry has the highest GWP compared to other states as well as other countries.

From the uncertainty analysis, variability in impact was lowest for California (coefficient of variation = 6-7%) because it had the highest strawberry yield, and variability decreased as yield increased. Coefficients of variation of impacts were 10-12% for the other 3 states, showing a near 1:1 relation between variations in inputs and variations in LCA results.

<Table 2>

<Figure 2>

Materials contributed most to GWP of strawberry production in all the states (Fig. 3). Plastic mulch, drip tubes, floating row covers and packaging baskets mainly consist of polyethylene and polyethylene terephthalate (PETE). PETE is used to produce plastic trays for strawberry packaging. Production of one of the materials used to produce polyethylene and PETE –paraxylene– is energy intensive and consequently has high GWP. Production of fuel for machines was the second largest contributor to GWP. Similar to the results of this study, the REWE Group (2009) found that the main contributors to GWP of strawberry production were polytunnel and plastic mulch production. More chemicals were used for strawberry production in Florida than the other states, resulting in a higher contribution to GWP. Agricultural machinery had the lowest contribution to GWP (and to acidification) in all the states due to its long useful life (10-15 years) and operation hours (up to 1000 h/year) (Fig. 3).

<Figure 3>

Although the use of toxic pesticides to manage pest problems is considered a quick, easy, and inexpensive solution and has become a common practice around the world, it has several adverse effects on human health as well as on the environment (Aktar et al., 2009). Releases of active ingredients in pesticides to environment ranged from 16 kg/ha in Oregon to 290 kg/ha in Florida (Appendix A, Supplementary Materials). Florida has the highest use of pesticides even though heavy use of pesticides is not always the only solution to manage pest problems. A safer and usually less costly alternative for effective control of pests is Integrated Pest Management recommended by EPA and Florida Department of Health (EPA, 2015).

Increasing strawberry yield without increasing input use would reduce environmental impacts per kg of strawberry production. California strawberry production had the highest

sustainability metrics due mainly to having the highest yield (74 t/ha) (Table 3). While North Carolina strawberry production used fertilizers efficiently (ranked second in both nitrogen productivity and phosphorous productivity), it did not use materials efficiently (lowest fossil-energy productivity).

<Table 3>

The intention of developing the LCA Extended Enterprise Budget tool was to standardize production-practice data collection and transformation into unit processes for strawberry production. After testing, it became clear that, while a worthy concept, the tool's design and nomenclature were not intuitive for agricultural economists and horticulturalists, making it difficult to accurately gather cost-of-production and production-practice data. Because the underlying methods that stakeholders use vary by state, it was difficult to create a standardized tool that accommodated this variety.

One issue encountered during testing was that language and terms used in the tool differed from those that state economists used. For example, the term 'Prime Movers', initially used to describe farm machinery, was later renamed 'Self-Propelled Farm Machinery,' a more common term in state enterprise crop budgets. Users were not familiar with requests for additional information that used terminology from LCA instead of agriculture. For example, field emissions of greenhouse gases (GHGs) are important in agricultural LCAs, and the tool required user estimates for field emission factors due to degradation of applied nitrogen fertilizers. User responses and comments indicated that it is generally not realistic to ask agricultural economists for these types of data.

The data collected through the enterprise crop budgets revealed that the nursery production cycle is not captured by state enterprise crop budgets. Transplants listed in enterprise

budgets can be 3-4 years old when they arrive at the strawberry production farms. Transplants are grown in low-elevation nurseries in the Sacramento and San Joaquin Valleys of California or high-elevation nurseries in northern California and southern Oregon mountains. Currently, public nursery production data do not exist beyond what was collected in this study or reported previously (Murthy et al., 2014). The first attempt to describe strawberry nursery practices for LCA in the U.S. (Murthy et al., 2014) was based on a personal interview with one industry expert. They reported that GWP of the nursery phase is approximately 7% of the total strawberry production in California. However, they stated that their estimates did not fully capture the complexity or variation of the nursery phase in different regions. Girgenti et al. (2014) reported that the GWP of strawberry nursery is about 6% of GWP of strawberry production up to the farm gate. The nursery phase was excluded from the LCI in this study due to lack of reliable data; however, to have a complete LCA, data from the nursery phase are critical.

While using the LCA Extended Enterprise Budget tool to transform budget data into unit processes for LCA was feasible, LCA results indicate that variability in collection methods of crop budget data presents challenges for LCA. Therefore, budgets must be examined individually to determine if they are reliable for comparative LCA. If state enterprise crop budgets as a whole are to be reliable data sources for LCA, data collection methods must be standardized beyond their format. The intent of the LCA Extended Enterprise Budget tool was to collect cost-of-production data systematically to standardize data across states. In the absence of standard methods among states, the analyst must understand and reconcile variability among states before making comparisons.

4. Conclusions

The use of modified enterprise budget sheets for collecting LCI data, while a worthy concept, was not very effective due to differences in production methods, which is reflected in differences in the format of enterprise budgets in different regions. Strawberry production varies greatly among geographic regions, and reliable LCAs for strawberry production can be performed only using datasets that are specific to a particular location. GWPs for strawberry production in California, Florida, North California and Oregon were 1.75, 2.50, 5.48 and 2.21 kg CO₂-eq/kg, respectively. GWP for North Carolina strawberry was the highest even in comparison with GWPs for strawberry production in other countries. Materials and fuels were the main contributors to GWP in strawberry production in all the states. Additionally, potassium sulfate was the primary contributor to most environmental burdens. Incorporating characterization factors for agricultural chemicals into existing life cycle impact-assessment methods is necessary to perform objective LCIA for agricultural commodities.

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467 **Table 1**

468 Fossil-energy life cycle factors for agricultural inputs.

Input	Unit	Fossil energy	Ref.
Nitrogen	MJ/kg	47.70	Wang (2009)
Phosphorous	MJ/kg	13.35	Wang (2009)
Potassium	MJ/kg	8.09	Wang (2009)
Lime	MJ/kg	0.42	Wang (2009)
Sulfur	MJ/kg	1.12	Mohammadi et al. (2010)
Micronutrients	MJ/kg	120	Canakci and Akinci (2006)
Cover crop seed	MJ/kg	2.35	Krohn and Fripp (2012)
Herbicide	MJ/kg	274.63	Wang (2009)
Insecticide	MJ/kg	313.46	Wang (2009)
Fungicide	MJ/kg	115.00	Beheshti Tabar et al. (2010)
Gasoline	MJ/L	39.52	Wang (2009)
Diesel	MJ/L	45.30	Wang (2009)
Plastic	MJ/kg	90.00	Canakci and Akinci (2006)
Agriculture machinery	MJ/h	62.70	Cetin and Vardar (2008)
Electricity	MJ/kWh	7.98	Wang (2009)

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470 **Table 2**

471 Mean (± 1 standard deviation) environmental impacts for 1 kg of strawberry produced in each of four U.S. states. Standard deviations
472 come from 1000 Monte Carlo simulations, all inputs varying simultaneously.

Impact category	Unit	California	Florida	North Carolina	Oregon
Acidification	kg SO ₂ -eq	0.03 $\pm$ 0.002	0.02 $\pm$ 0.002	0.07 $\pm$ 0.008	0.07 $\pm$ 0.008
Eutrophication	kg N-eq	2.02E-3 $\pm$ 1.28E-4	1.36E-3 $\pm$ 1.62E-4	4.58E-3 $\pm$ 5.32E-4	4.16E-3 $\pm$ 5.06E-4
Global warming	kg CO ₂ -eq	1.75 $\pm$ 0.12	2.50 $\pm$ 0.29	5.48 $\pm$ 0.65	2.21 $\pm$ 0.26
Carcinogenics	CTUh	2.66E-9 $\pm$ 1.96E-10	3.57E-9 $\pm$ 4.28E-10	7.86E-9 $\pm$ 9.49E-10	3.23E-9 $\pm$ 3.89E-10
Non-carcinogenics	CTUh	0.96E-7 $\pm$ 7.06E-9	1.38E-7 $\pm$ 1.63E-8	2.84E-7 $\pm$ 3.43E-8	1.17E-7 $\pm$ 1.41E-8
Ozone depletion	kg CFC-11-eq	5.21E-10 $\pm$ 3.93E-11	6.78E-10 $\pm$ 8.20E-11	14.4E-10 $\pm$ 1.74E-10	6.28E-10 $\pm$ 7.61E-11
POF	kg O ₃ -eq	0.66 $\pm$ 0.04	0.37 $\pm$ 0.04	1.42 $\pm$ 0.17	1.44 $\pm$ 0.18
Respiratory effects	kg PM2.5-eq	6.53E-4 $\pm$ 3.87E-5	6.88E-4 $\pm$ 8.08E-5	18.24E-4 $\pm$ 2.13E-4	11.11E-4 $\pm$ 1.27E-4

473 **POF: photochemical ozone formation**

Table 3

Sustainability metrics for strawberry production in four U.S. states.

Unit		California	Florida	North Carolina	Oregon
NP	kg strawberry/kg N	409	213	251	111
PP	kg strawberry/kg P	2362	654	1209	1768
FEP	kg strawberry/MJ	0.17	0.13	0.06	0.13

NP: nitrogen productivity

PP: Phosphorous productivity

FEP: fossil-energy productivity

Figure captions

Fig. 1. System boundaries for the life cycle assessment of strawberry production (dotted line).

Fig. 2. Greenhouse gas emissions per 1 kg of strawberries.

Fig. 3. Contributions of inputs to global warming potential of 1 kg of strawberries.

Fig. 1.

Fig. 2.

Fig. 3.