Life Cycle Assessment of Fruit and Vegetable Production, Including Protected Systems

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Innovating global fruit and vegetable food systems to help bring sustainable nutrition security
AGCI/Keystone Policy Institute
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#AGCIF&V
Introduction to Lifecycle assessment

LCA systematically quantifies inputs and outputs for a system in terms of a standardized unit of measure (FU).

- Product Development / Improvement
  - Selection of best materials or process options (e.g. conservation)
- Identification of ‘hotspots’ for innovation
- Benchmarking
- Product labels / marketing
- Inform public policy

LCA is described in ISO 14040, 14044 and 14046 Standards
Life cycle assessment (LCA) is a multi-step procedure for calculating the lifetime environmental impact of a product or service.

**Functional unit (FU):** defines the quantification of the identified functions.
- The FU should be consistent with the goal and scope of the study.

**System boundaries:** define the unit processes to be included in the system to be modelled.
- Ideally, the product system should be modelled in such a manner that inputs and outputs at its boundary are elementary flows.
Life Cycle Inventory is the stage of data collection

- inputs-outputs should include all the resource flows of the production system to provide the functional unit

- includes: extraction of raw resources, various primary and secondary production processes, emissions, and hundreds of tracked substances

- Life cycle impact assessment (LCIA) refers, the step to convey “what does it mean” after the inventory analysis: carbon/water footprint, etc

Hotspots in value chain, opportunities for improvement
LCA Modelling

- LCA approach-product and co-product handling
- ISO 14044 suggested, “when possible, allocation should be avoided by:
  - Sub-division of processes and collecting input/output data for the sub-processes
  - System expansion: of the product system to include the additional functions related to the co-products
  - Allocation: if avoiding allocation is not possible, use methods reflecting physical relationship, such as mass and energy content or using other relevant variables, such as economic value of the products (Guinée et al., 2004)
Authoritative definitions

- **Attributional approach**: System modelling approach in which inputs and outputs are attributed to the functional unit of a product system by linking and/or partitioning the unit processes of the system according to a normative rule.

- **Consequential approach**: System modelling approach in which activities in a product system are linked so that activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand for the functional unit.

UNEP/SETAC (2011). Shonan LCA database guidance principles
Attributional or consequential?

- **Purpose of attributional modelling:**
  - "how has this product been produced"
  - "analyse the current situation"
  - "historically tracking mass or energy flows"

- **Purpose of consequential modelling** is decision support:
  - "what is the consequence of buying this product"
  - "what is the consequence of choosing A instead of B"
  - "what is the consequence of implementing new technology"

- What information is relevant?
  - **Attributional:** how products *have been* produced. Focus is on attributing impacts (and not to predict impacts!)
  - **Consequential:** how the product *will be* produced as a consequence of our choice
Attributional or consequential?

An attributional product system is composed of:

- an allocated share of all the activities
- that have contributed to the production, consumption, and disposal of a product,
- that is, tracing the contributing activities backward in time,
- which is why data on specific or market average suppliers are relevant in such a system

A consequential product system is composed of:

- the full share of those activities
- that are expected to change when producing, consuming, and disposing of a product,
- that is, tracing the consequences forward in time,
- which is why data on marginal suppliers are relevant in such a system
An clear example from dairy: Intensification?

**Attributional model**

~80:20 split of impacts milk:meat
if intensification holds inputs ~ constant, increases milk production => lower intensity of (say) GHG emissions/kg milk.
Intensification always favored.

**Consequential model**

Demand for milk and meat both unchanged by intensification => meat must be provided to market from another source – beef sector
It is thus possible, if beef intensity is high, that increased production (replaced beef) necessary to maintain market demand could increase GHG emissions / kg milk.
LCA Modelling

Unit processes: LCA’s building blocks

Inputs from nature

Outputs to nature

Outputs to other processes

Inputs from other processes
LCA Modelling

Life Cycle Inventory Analysis

Extractions from environment

Releases to environment
Lifecycle impact assessment (LCIA)

Inventory results (LCI)

<table>
<thead>
<tr>
<th>Substance</th>
<th>Compartment</th>
<th>Unit</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>Air</td>
<td>mg</td>
<td>27</td>
</tr>
<tr>
<td>Ammonia</td>
<td>Air</td>
<td>mg</td>
<td>776</td>
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<tr>
<td>Ammonium carbonate</td>
<td>Air</td>
<td>mg</td>
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<tr>
<td>Antimony</td>
<td>Air</td>
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<td>Antimony-124</td>
<td>Air</td>
<td>nBq</td>
<td>33</td>
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<tr>
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<td>nBq</td>
<td>344</td>
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<td>Arsenic-41</td>
<td>Air</td>
<td>Bq</td>
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<td>Arsenic</td>
<td>Air</td>
<td>µg</td>
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<tr>
<td>Barium</td>
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<tr>
<td>Benzaldehyde</td>
<td>Air</td>
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<tr>
<td>Benzene</td>
<td>Air</td>
<td>mg</td>
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<tr>
<td>Benzene, ethyl</td>
<td>Air</td>
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<tr>
<td>Benzene, hexachloro</td>
<td>Air</td>
<td>ng</td>
<td>55.2</td>
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<tr>
<td>Benzene, pentachloro</td>
<td>Air</td>
<td>ng</td>
<td>86.9</td>
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<tr>
<td>Benzo(a)pyrene</td>
<td>Air</td>
<td>µg</td>
<td>23.7</td>
</tr>
<tr>
<td>Beryllium</td>
<td>Air</td>
<td>ng</td>
<td>227</td>
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<tr>
<td>Beryllium</td>
<td>Air</td>
<td>mg</td>
<td>8.87</td>
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<tr>
<td>Bromine</td>
<td>Air</td>
<td>µg</td>
<td>686</td>
</tr>
<tr>
<td>Butadiene</td>
<td>Air</td>
<td>µg</td>
<td>23.4</td>
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<tr>
<td>Butene</td>
<td>Air</td>
<td>mg</td>
<td>15.7</td>
</tr>
<tr>
<td>Butene</td>
<td>Air</td>
<td>µg</td>
<td>146</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Air</td>
<td>µg</td>
<td>106</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Air</td>
<td>mg</td>
<td>1.36</td>
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<tr>
<td>Carbon-14</td>
<td>Air</td>
<td>Bq</td>
<td>28.8</td>
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<tr>
<td>Carbon dioxide, biogenic</td>
<td>Air</td>
<td>g</td>
<td>48.3</td>
</tr>
<tr>
<td>Carbon dioxide, fossil</td>
<td>Air</td>
<td>kg</td>
<td>28.8</td>
</tr>
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Impact assessment results

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carcinogens</td>
<td>2.36E-5</td>
</tr>
<tr>
<td>Respiratory organics</td>
<td>3.03E-6</td>
</tr>
<tr>
<td>Rasp. inorganics</td>
<td>0.0011</td>
</tr>
<tr>
<td>Climate change</td>
<td>0.000032</td>
</tr>
<tr>
<td>Radiation</td>
<td>1.21E-6</td>
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<tr>
<td>Ozone layer</td>
<td>5.16E-9</td>
</tr>
<tr>
<td>Ecotoxicity</td>
<td>1.15E-5</td>
</tr>
<tr>
<td>Acidification/Eutrophication</td>
<td>0.000128</td>
</tr>
<tr>
<td>Land use</td>
<td>1.85E-6</td>
</tr>
<tr>
<td>Minerals</td>
<td>1.3E-6</td>
</tr>
<tr>
<td>Fossil fuels</td>
<td>0.00624</td>
</tr>
</tbody>
</table>

Hundreds of individual emissions

Following environmental cause-effect chain
Fruit & Vegetable Supply Chains:
Climate Adaptation & Mitigation Opportunities

Enhancing the productivity, resilience, and sustainability of domestic produce food systems

NIFA Award #: 2017-68002-26789
Integrated (crop, economic, environmental) modeling to identify and test adaptation & mitigation strategies

Each crop reporting district and crop:
Current and future scenarios w/ & w/o adaptation (2030s, 2050s)

Land use change
Domestic F&V production & prices

Mitigation and Adaptation scenarios

Crop Model
Hydrology Model

Yield H₂O, N, P needs
H₂O avail.

CRD-Scale Econ. Model

Acres, Profitability

CRD Scale

International Econ. Model

LCA Model

C and H₂O footprints (for crop production)
Preliminary results

Impact assessments (Potato-fresh)

Fig. Environmental impacts per 1 kg potato production, until farm gate (CAL = California; WA = Washington; and ID = Idaho; US = ecoinvent database.

Results

Fig. Major contributions to the climate change (GWP_{100}) during potato production

Parajuli R. et al (2. On-progress)
Preliminary results

Impact assessments (Tomato-fresh)

Fig. Environmental impacts per 1 kg tomato production, until farm gate (CA= California; ROW = rest of the world, Ecoinvent.

Fig. Major contributions to the climate change (GWP100) during tomato production
Preliminary results

Impact assessments (Orange-fresh)

Fig. Environmental impacts per 1 kg orange production, until farm gate (FL = Florida; US = ecoinvent database).

Results

Parajuli R. et al (2. On-progress)
Mitigation and Adaptation Scenarios

- Conservation tillage
- Cover crops
- Advanced irrigation (drip, etc.)
- Advanced crops
- Tree-based mixed farming systems
- Protected agriculture

Future Constraints:
- Climate change (weather, CO₂)
- Nitrogen limitations
- Irrigation water limitations

Low cost, movable high tunnel.
Photo credit: Tim Coolong
Protected tomato production systems

110 ft row, Plastic-string and stake system
## Protected tomato production systems

### Tunnel system (sizing for Gothic style-high tunnels)

<table>
<thead>
<tr>
<th>Assumptions on the greenhouse size (tunnels)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sides</td>
<td>2: numbers</td>
</tr>
<tr>
<td>Height</td>
<td>6: ft</td>
</tr>
<tr>
<td>Length of row</td>
<td>100: ft</td>
</tr>
<tr>
<td>Roof (side, inclined)</td>
<td>5.5: ft</td>
</tr>
<tr>
<td>Ends (front view)</td>
<td>10: ft</td>
</tr>
<tr>
<td>Length (from upper side to the inclined roof)</td>
<td>2.25: ft</td>
</tr>
<tr>
<td>Sides (area)</td>
<td>1200: sq. ft</td>
</tr>
<tr>
<td>Roof (Area)</td>
<td>1100: sq. ft</td>
</tr>
<tr>
<td>Ends (area)</td>
<td>165: sq. ft</td>
</tr>
<tr>
<td>Total surface area</td>
<td>2465: sq. ft</td>
</tr>
<tr>
<td>Total surface area for 50-100 ft rows green house</td>
<td>229: sq m2</td>
</tr>
<tr>
<td>Total surface area</td>
<td>11450: sq m2</td>
</tr>
</tbody>
</table>

High tunnel (hothic style) for tomato production

High tunnel (hoop type) system used for tomato production in western Washington

http://blogs.cornell.edu/hightunnels/structures/
## Protected tomato production systems

<table>
<thead>
<tr>
<th>Farm types</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open field</td>
<td>78-95 (ton per ha)(^a)</td>
</tr>
<tr>
<td>100 ft row, plastic string and stake types</td>
<td>196 (ton per ha)(^b)</td>
</tr>
<tr>
<td>High tunnel system (unheated)</td>
<td>484 (ton per ha)(^c)</td>
</tr>
</tbody>
</table>

### Assumptions:

\(^a\) Yield = 0.70 lb / sq.ft

\(^b\) Yield = 1.6-3 lb / sq.ft. Total estimated area of planting per row = 3000 sq ft. No of beds per row = 2. Total number of rows for 1 ha = 25 (for 2 bed system). Calculated after: UGA extension, 2013; Hochmuth G., 2006; Gazula A., 2009 and CAES, UGA.


Checked with: Plants per greenhouse = 800 plants. Yield per plant = 20 lb, or, Yield = 9 lbs / sq.ft (Fenneman D., et al., 1990 (revised 2015).)

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# Preliminary results

## Environmental impacts (per 1 kg tomato)

<table>
<thead>
<tr>
<th>Impacts</th>
<th>Units</th>
<th>Open-field</th>
<th>Plastic strings and stakes</th>
<th>Greenhouse (Plastic roof, walls, and tubes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate change</td>
<td>kg CO₂ eq</td>
<td>1.25E-01</td>
<td>2.13E-01</td>
<td>1.32E-01</td>
</tr>
<tr>
<td>Freshwater eutrophication</td>
<td>g P eq</td>
<td>5.11E-05</td>
<td>1.66E-04</td>
<td>9.08E-05</td>
</tr>
<tr>
<td>Terrestrial ecotoxicity</td>
<td>kg 1,4-DB eq</td>
<td>9.07E-05</td>
<td>3.38E-03</td>
<td>4.01E-03</td>
</tr>
<tr>
<td>Water depletion</td>
<td>m³</td>
<td>6.16E-02</td>
<td>3.52E-02</td>
<td>1.31E-02</td>
</tr>
<tr>
<td>Fossil depletion</td>
<td>kg oil eq</td>
<td>3.18E-02</td>
<td>7.92E-02</td>
<td>5.15E-02</td>
</tr>
</tbody>
</table>

![Graph showing environmental impacts](image.png)
Preliminary results: Contribution Analysis: GHG

Plastic Greenhouse

- Greenhouse structure (including accessories + ferti-irrigation): 33%
- Field emissions: 1%
- Transport: 3%
- Irrigation and energy use: 6%
- Strings and Stakes: 0%

Agro-chemicals: 57%

Open Field

- Agro-chemicals: 90%
- Farm operations: 6%
- Transport: 2%
- Field emissions: 2%
- Plastics (Black plastic rolls, stakes): 6%

Partial Protection

- Farm operations + seedlings: 85%
- Transport: 3%
- Field emissions: 3%
- Agro-chemicals: 9%

Inventory data incomplete; LCA results will change
Preliminary results: trade-offs

Global Average Environmental Impacts (per 1 kg tomato)

- Land use
- Water consumption
- Non-carcinogenic toxicity
- Carcinogenic toxicity
- Terrestrial ecotoxicity
- Mineral resource scarcity
- Terrestrial acidification
- Freshwater eutrophication
- Fine particulate matter formation
- Marine ecotoxicity
- Fossil resource scarcity
- Global warming

0.35 m²/kg
0.12 m³/kg
1 kg/kg
Table 3.7 Impact assessment absolute and percentage values for greenhouse tomato production in southwestern Ontario per functional unit (F.U. – 1 kg tomato) based on a Life Cycle Assessment using base data from eight growers in the Leamington, Ontario region. GW = Global Warming; AD = Acidification; EU = Eutrophication; OD = Ozone Depletion; SM = Smog; CED = Cumulative Energy Demand.

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Unit</th>
<th>GW</th>
<th>AD</th>
<th>EU</th>
<th>OD</th>
<th>SM</th>
<th>CED</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg CO₂ eq (x10^3)</td>
<td>H⁺ moles eq (x10^3)</td>
<td>kg N eq (x10^3)</td>
<td>kg CFC-11 eq (x10^3)</td>
<td>g NOₓ eq (x10^3)</td>
<td>MJ eq (x10^3)</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>2881(100%)</td>
<td>273(100%)</td>
<td>1252(100%)</td>
<td>4205(100%)</td>
<td>270(100%)</td>
<td>5276(100%)</td>
<td></td>
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<tr>
<td>Greenhouse Structure</td>
<td>32(1%)</td>
<td>7(2%)</td>
<td>38(3%)</td>
<td>11(&lt;1%)</td>
<td>6(2%)</td>
<td>51(&lt;1%)</td>
<td></td>
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<tr>
<td>Electricity</td>
<td>83(3%)</td>
<td>30(11%)</td>
<td>270(22%)</td>
<td>98(2%)</td>
<td>16(6%)</td>
<td>340(6%)</td>
<td></td>
</tr>
<tr>
<td>Fertilization</td>
<td>279(10%)</td>
<td>55(20%)</td>
<td>256(20%)</td>
<td>141(3%)</td>
<td>42(16%)</td>
<td>196(4%)</td>
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<tr>
<td>Heating</td>
<td>2460(85%)</td>
<td>171(63%)</td>
<td>613(49%)</td>
<td>3940(94%)</td>
<td>197(73%)</td>
<td>4643(88%)</td>
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<tr>
<td>Rockwool</td>
<td>14(&lt;1%)</td>
<td>5(2%)</td>
<td>38(3%)</td>
<td>5(&lt;1%)</td>
<td>3(1%)</td>
<td>24(&lt;1%)</td>
<td></td>
</tr>
<tr>
<td>Water Use</td>
<td>8(&lt;1%)</td>
<td>3(1%)</td>
<td>28(2%)</td>
<td>3(&lt;1%)</td>
<td>2(&lt;1%)</td>
<td>13(&lt;1%)</td>
<td></td>
</tr>
<tr>
<td>Waste</td>
<td>5(&lt;1%)</td>
<td>2(&lt;1%)</td>
<td>9(&lt;1%)</td>
<td>7(&lt;1%)</td>
<td>4(1%)</td>
<td>9(&lt;1%)</td>
<td></td>
</tr>
</tbody>
</table>

Impact per 1 ton tomato.

Impact per 1 kg tomato
Hendricks P. 2012

2.88 kg/kg; 85% heating Ontario

0.78 kg/kg
83% heating
Mediterranean
Limitations

• Incomplete assessment of:
  • Biodiversity
  • Soil health
  • Land use / Land use change (especially with regard to urban/peri-urban locations)
  • Social factors
• Continually improving input data/system descriptions
Summary & Conclusions

- LCA is a valuable tool for system assessment: hotspots and tradeoffs can be identified and quantified
- Fruit/Vegetable systems are complex and highly variable
  - Consistent and high quality data are necessary (GIGO)
- Trade-offs readily apparent between open field and greenhouse production of tomatoes
  - GHG emissions vs. Land use (and others). Possible seasonal differences.
  - Additional gains in greenhouse yield needed to reduce GHG intensity
- Continued evaluation of systems is ongoing in the project.
Questions ?

Thank you