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

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USDA | NIFA

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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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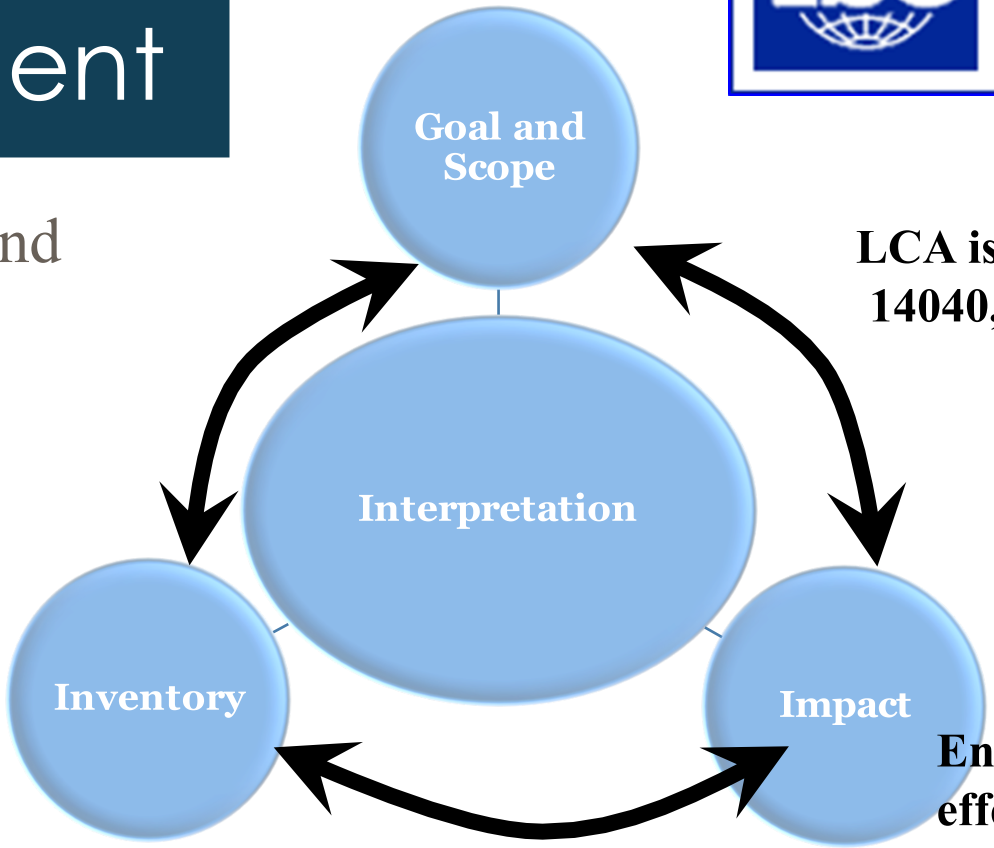
Introduction to Lifecycle assessment

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**

International Organization for Standardization

LCA is described in ISO 14040, 14044 and 14046 Standards



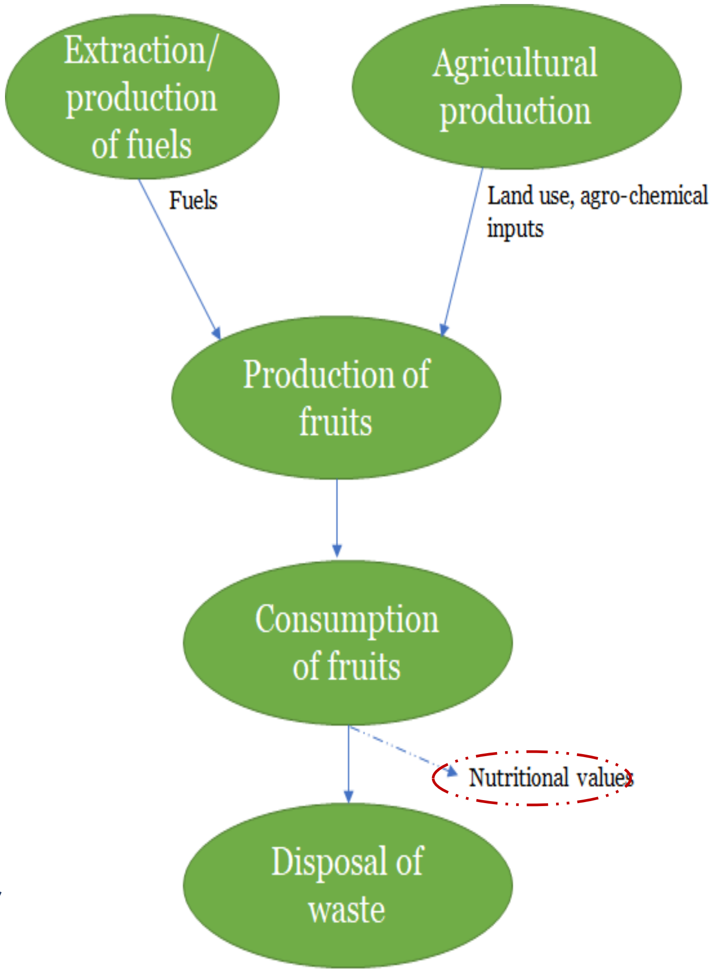
Attributes or characteristics of product or process

Environmental effects of product or process

LCA Modelling

- 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*.

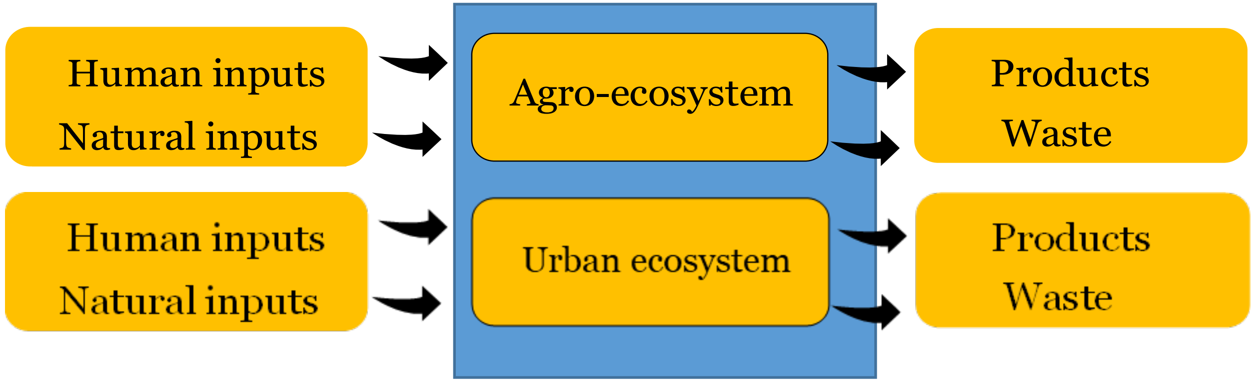
  - the FU should be consistent with the goal and scope of the study
- System boundaries: define the unit processes to be included in the system to be modelled.
- *- ideally, the product system should be modelled in such a manner that inputs and outputs at its boundary are elementary flows*



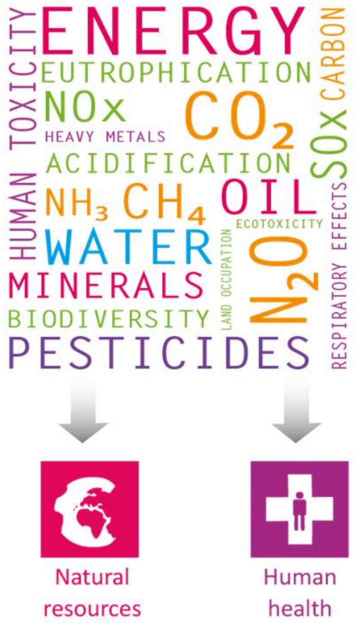
A simplified flow diagram for the life cycle of a fruits. Ellipses are unit processes, arrows are flows of products and services. The dashed arrow represents the function of the use process, which can be considered as the reference flow

LCA Modelling

- 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

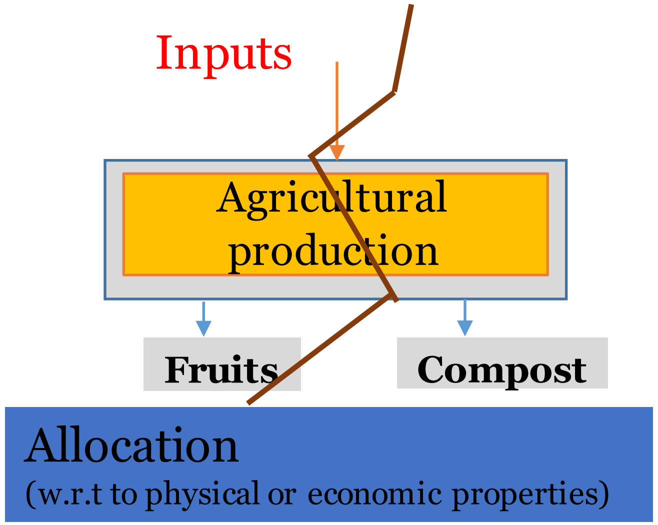


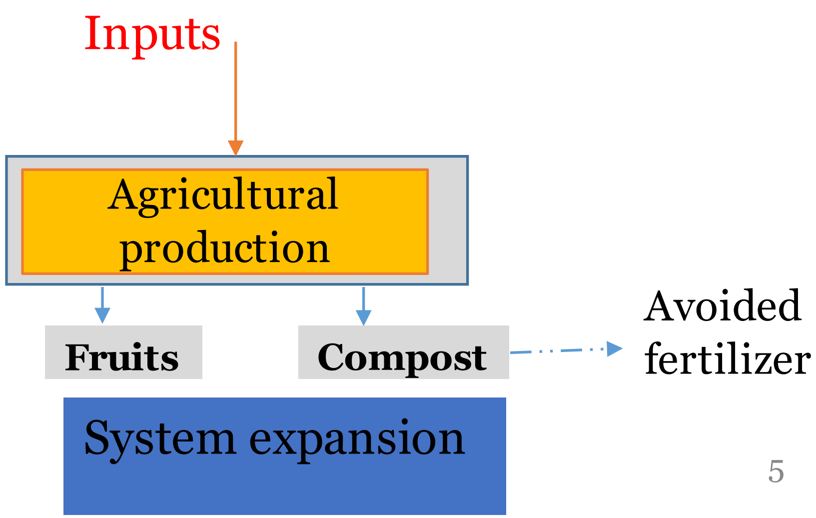
- includes: extraction of raw resources, various primary and secondary production processes, emissions, and hundreds of tracked substances
- Life cycle impact assessment (LCIA) refers, the step to convey "what does it mean" after the inventory analysis: carbon/water footprint, etc Hotspots in value chain, 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:

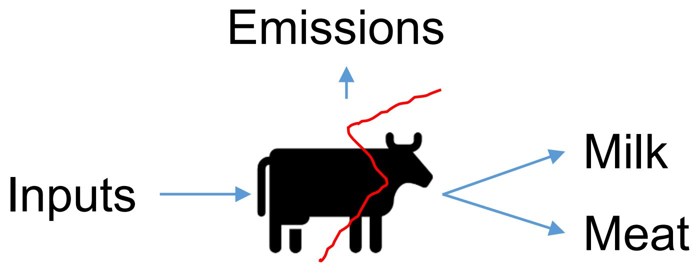
- an **allocated share** of all the activities
- that **have contributed** to the production, consumption, and disposal of a product,
- that is, tracing the contributing activities **backward** in time,
- which is why data on specific or market **average** suppliers are relevant in such a system

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?

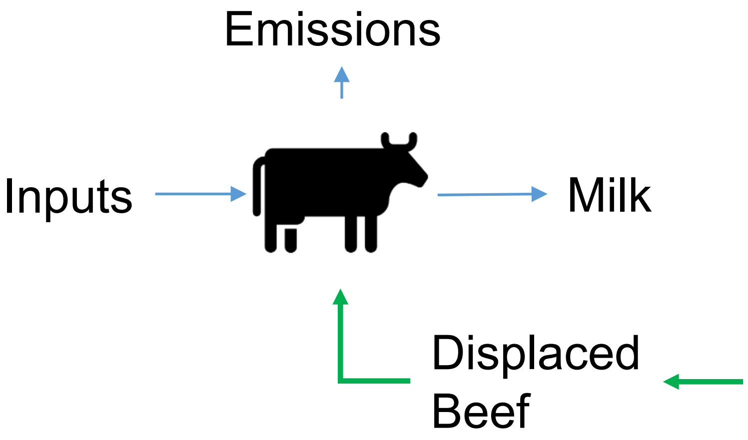
Attributional model



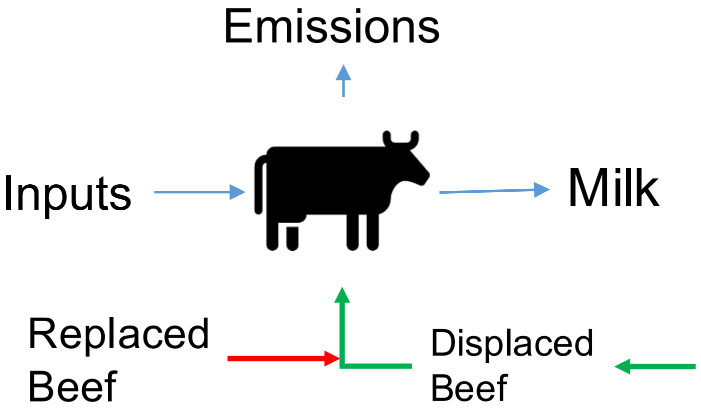
~80:20 split of impacts milk:meat
if intensification holds inputs ~ constant, increases milk production =>
lower intensity of (say) GHG emissions/kg milk.
Intensification always favored.

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.

Consequential model

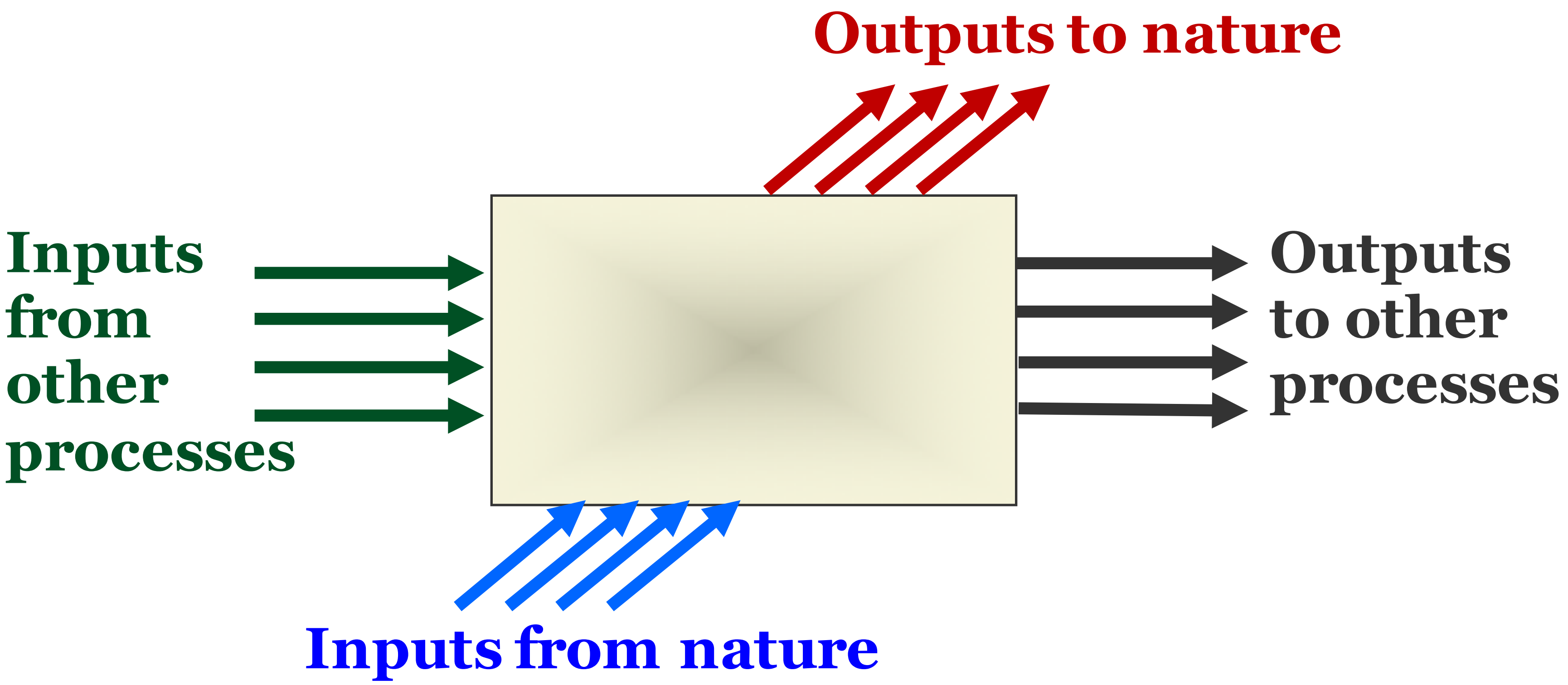


Intensification of dairy =>



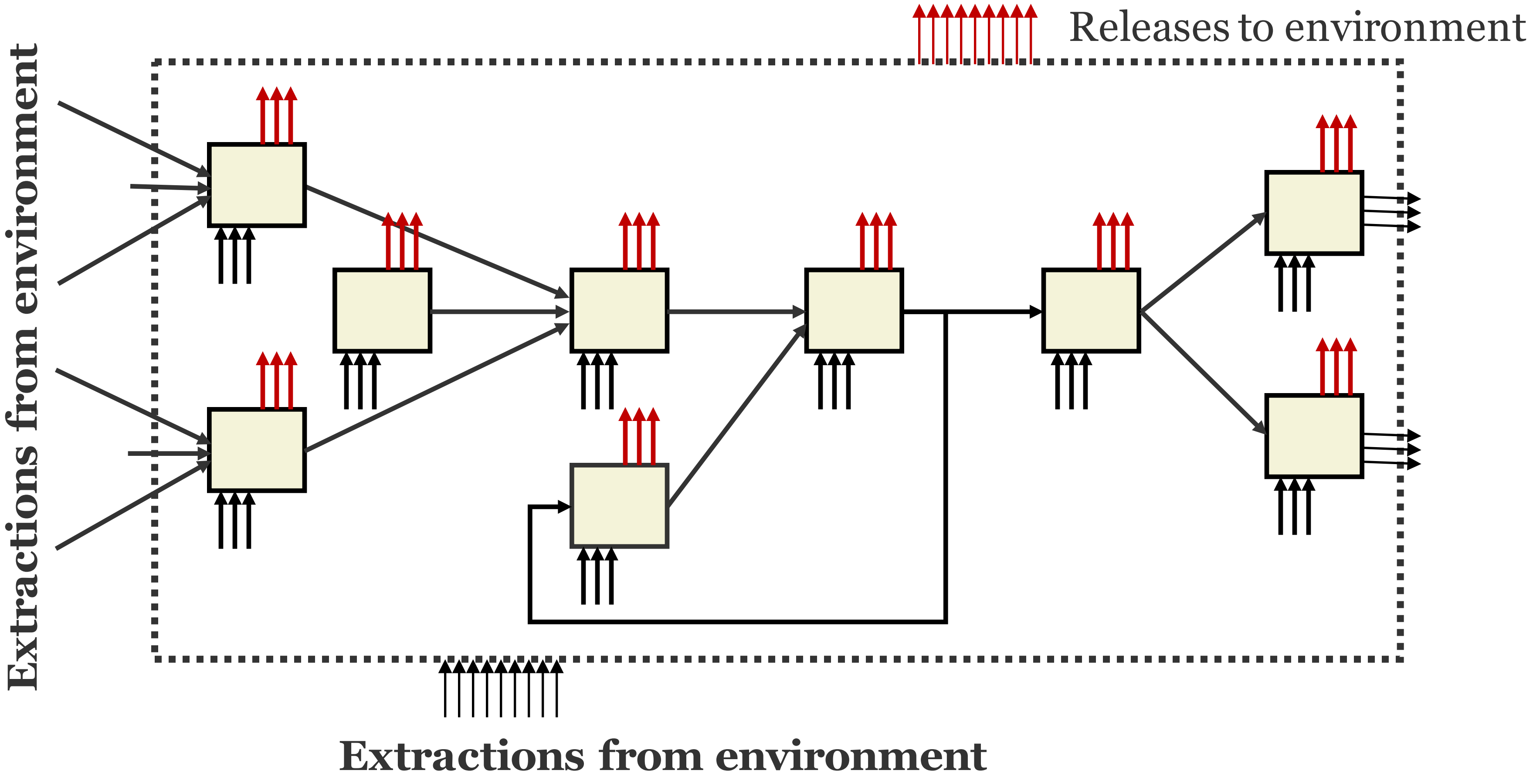
LCA Modelling

Unit processes: LCA's building blocks



LCA Modelling

Life Cycle Inventory Analysis

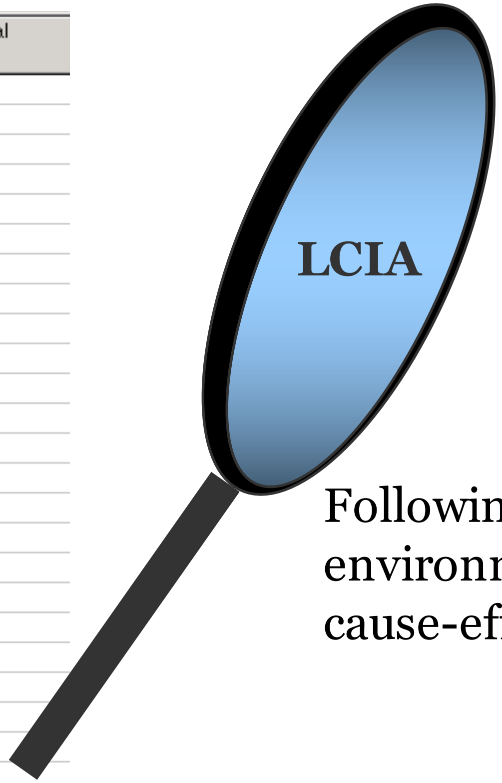


Lifecycle impact assessment (LCIA)

Inventory results (LCI)

Substance	Compartment	Unit	Total
Aluminum	Air	mg	27
Ammonia	Air	mg	776
Ammonium carbonate	Air	ng	441
Antimony	Air	µg	9.52
Antimony-124	Air	nBq	33
Antimony-125	Air	nBq	344
Argon-41	Air	Bq	7.34
Arsenic	Air	µg	97
Barium	Air	µg	100
Barium-140	Air	µBq	22.3
Benzaldehyde	Air	ng	17.5
Benzene	Air	mg	5.74
Benzene, ethyl-	Air	µg	149
Benzene, hexachloro-	Air	ng	56.2
Benzene, pentachloro-	Air	ng	80.9
Benzo(a)pyrene	Air	µg	23.7
Beryllium	Air	ng	227
Boron	Air	mg	9.87
Bromine	Air	µg	606
Butadiene	Air	pg	23.4
Butane	Air	mg	10.7
Butene	Air	µg	146
Cadmium	Air	µg	106
Calcium	Air	mg	1.36
Carbon-14	Air	Bq	28.6
Carbon dioxide, biogenic	Air	g	46.3
Carbon dioxide, fossil	Air	kg	20.8

Hundreds of individual emissions



Following environmental cause-effect chain

Impact assessment results

Impact category	Total
Carcinogens	2.35E-5
Resp. organics	3.03E-6
Resp. inorganics	0.0011
Climate change	0.000432
Radiation	1.21E-6
Ozone layer	5.16E-9
Ecotoxicity	1.15E-5
Acidification/ Eutrophication	0.000128
Land use	1.85E-6
Minerals	1.3E-6
Fossil fuels	0.00624

Fruit & Vegetable Supply Chains:
Climate Adaptation & Mitigation Opportunities

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

USDA | NIFA

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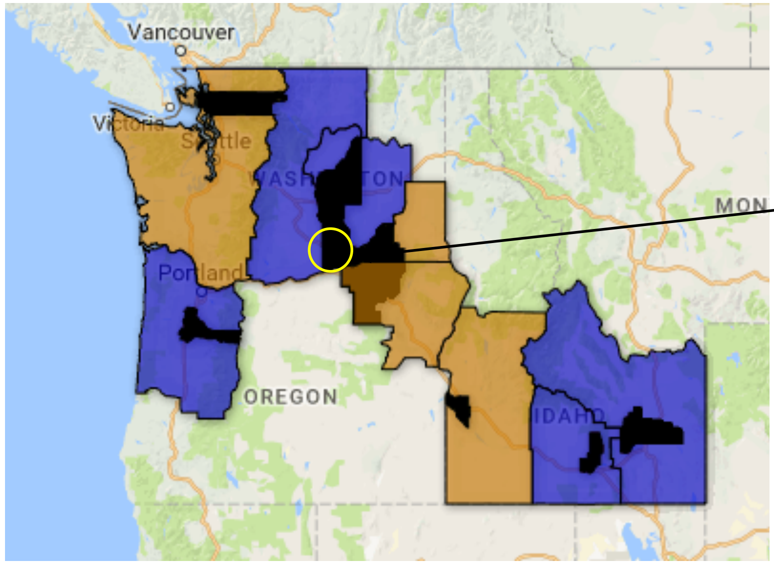
Model Integration

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

Yield
H_2O, N, P needs

Hydrology Model

H_2O avail.

CRD Scale

CRD-Scale Econ. Model

Acres, Profitability

International Econ. Model

LCA Model

C and H_2O footprints (for crop production)

Preliminary results

Impact assessments (Potato-fresh)

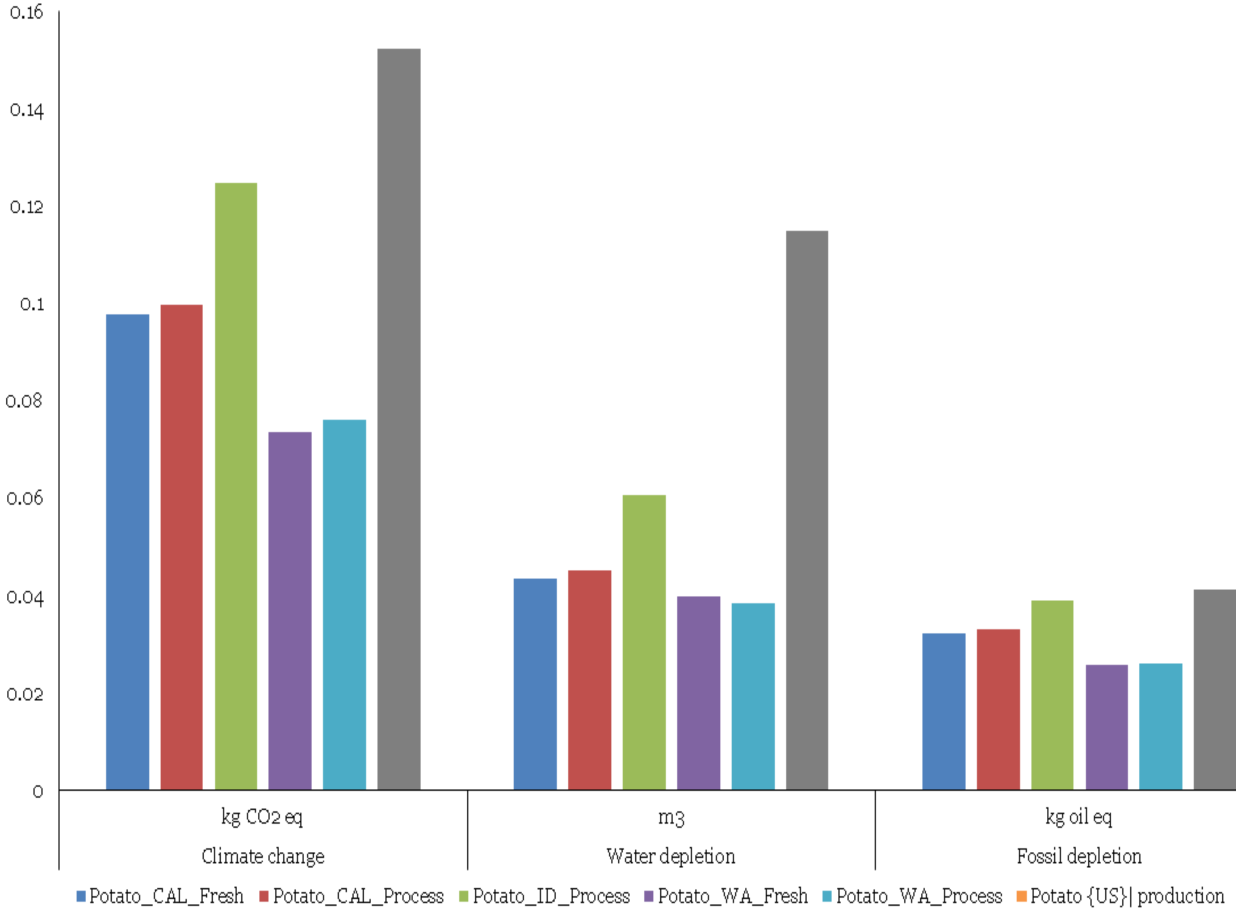


Fig. Environmental impacts per 1 kg potato production, until farm gate (CAL= California; WA = Washington; and ID = Idaho; US = ecoinvent database.

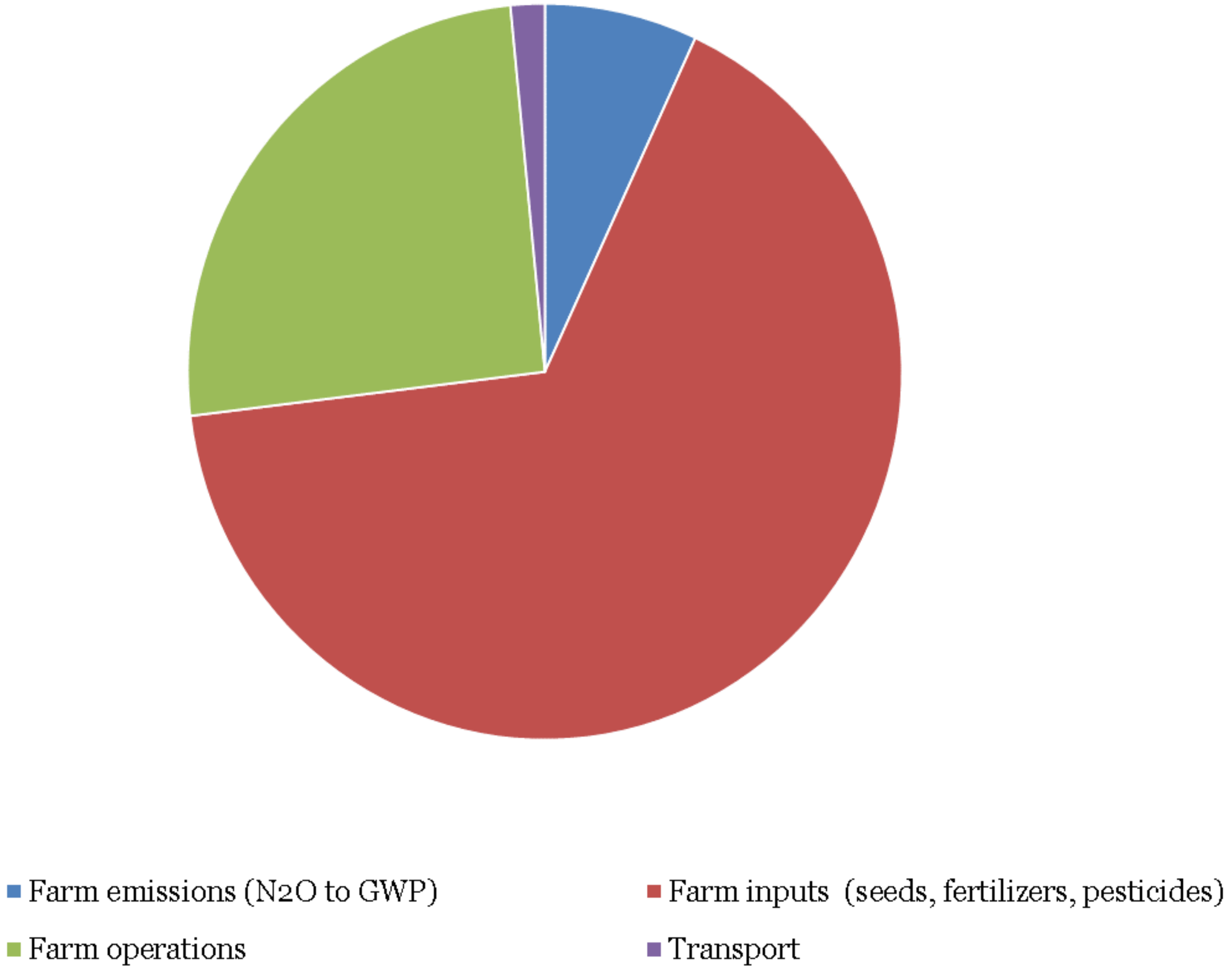


Fig. Major contributions to the climate change (GWP_{100}) during potato production

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

Preliminary results

Impact assessments (Tomato-fresh)

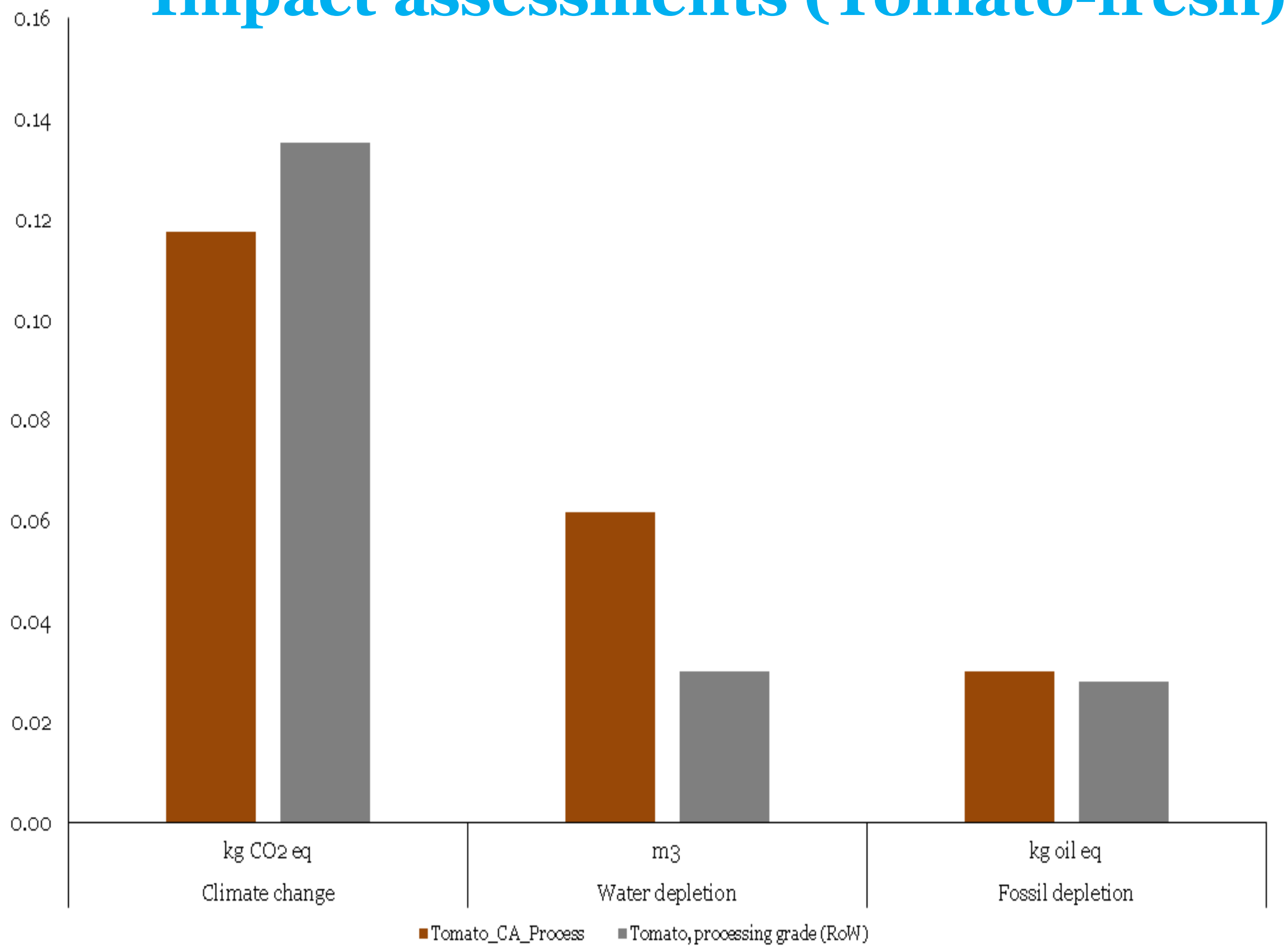


Fig. Environmental impacts per 1 kg tomato production, until farm gate (CA= California; ROW = rest of the world, Ecoinvent.

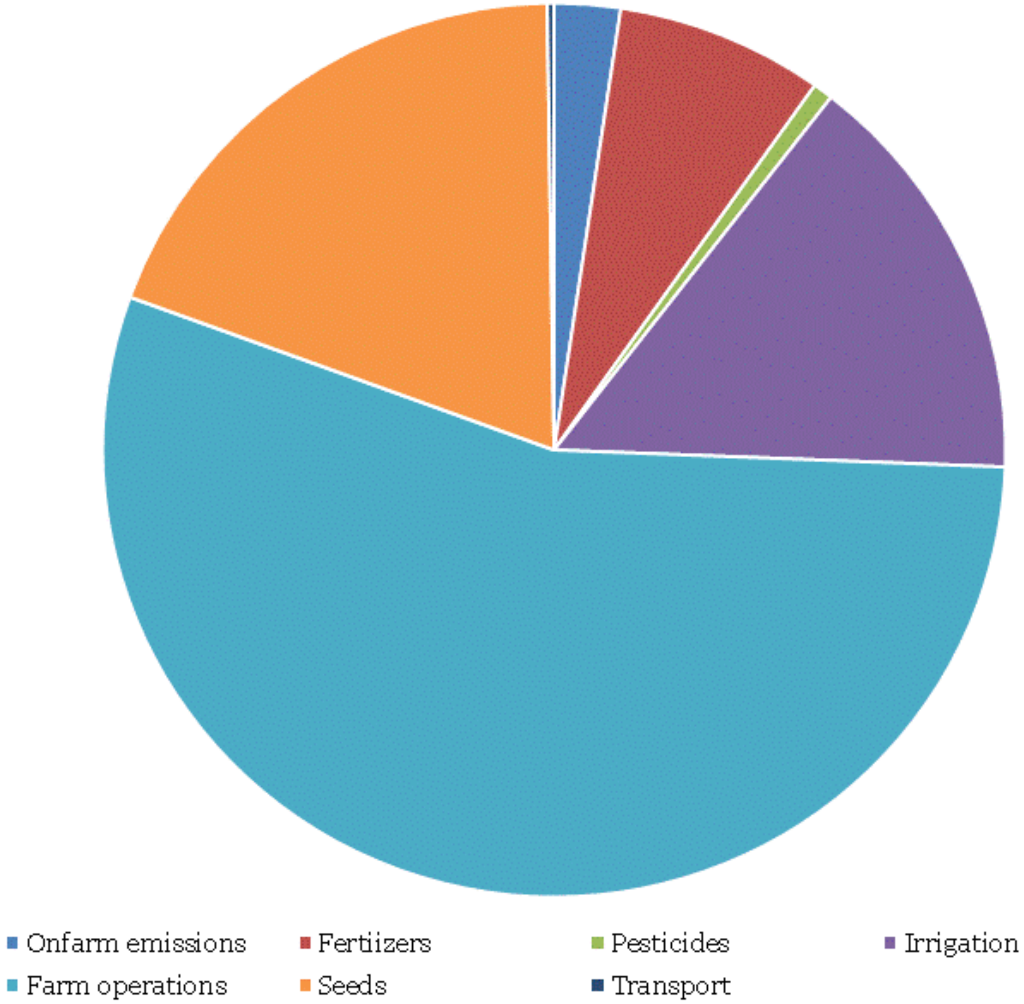


Fig. Major contributions to the climate change (GWP_{100}) during tomato production

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

Preliminary results

Impact assessments (Orange-fresh)

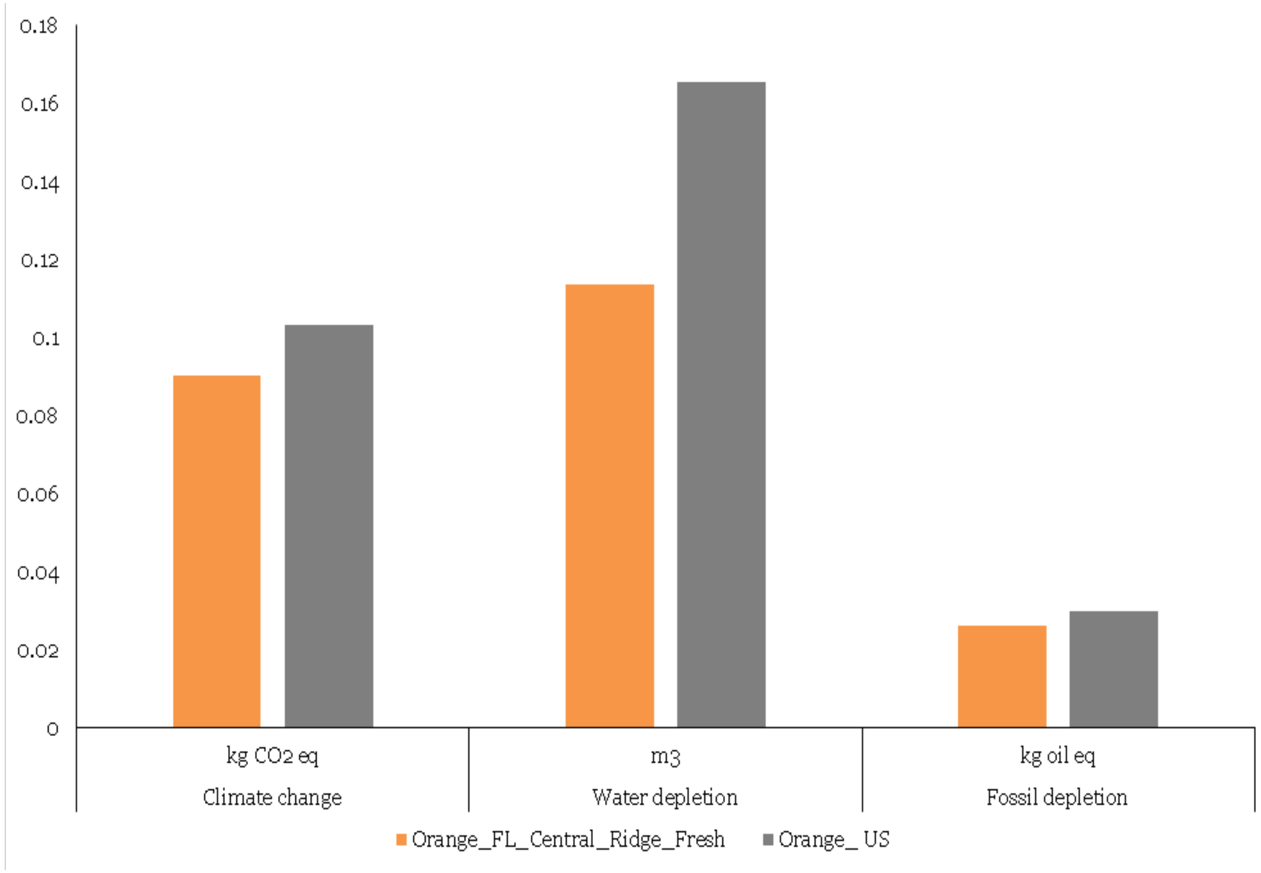


Fig. Environmental impacts per 1 kg orange production, until farm gate (FL = Florida; US = ecoinvent database.

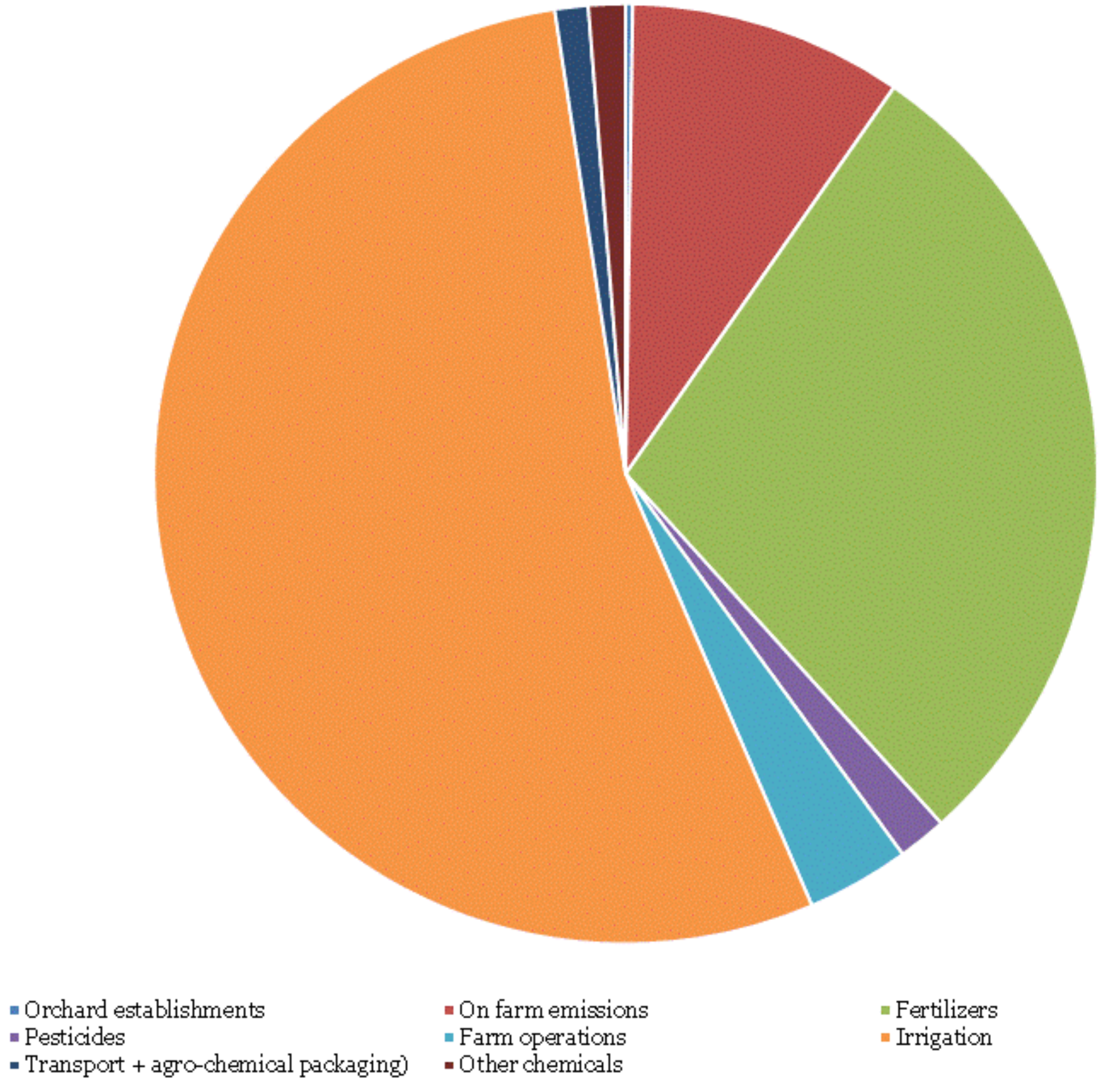


Fig. Major contributions to the climate change (GWP_{100}) during orange production

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**

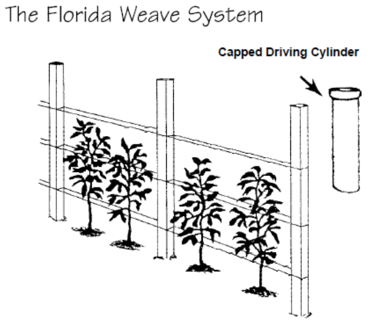
Low cost, movable high tunnel.
Photo credit: Tim Coolong

Future Constraints:
Climate change (weather, CO_2)
Nitrogen limitations
Irrigation water limitations

Protected tomato production systems

Beds (dimensions: 100' x 30' ft*ft)	numbers	2	Length	100	ft
Number of twin rows (beds) =	numbers	5	Area of planting in 1 row	3000	ft2
Spacing between plants	inch	15	ft-m conversions	0.8	ft
Plants/twin row	numbers/row	160	sq. ft to sq m, conversions	0.0929	m2
Total plants (in 1 GH)	numbers	800	Plants per 1 sq. m	2.8704	no. per m2
Total plants	plants per 1 sq. ft	0.2666667	Plants per m2 per kg	4E-05	no. per m2 per kg
100 ft rows platic greenhouse, tomato to acre		50	numbers of 100 ft rows to form 1 acre		
Black plastic 1 roll		2000	sq. ft per acre		

110 ft row, Plastic-string and stake system



The Florida Weave: Two plants between stakes. The first string is app. 10 inches high. Stringing is repeated every 8 inches.

Materials	Units	Amount per production in Plastic-mulch Florida North: acre	per ton	per kg	Remarks/Source
Inputs					
Fertilizers	kg				Crop budget (CB)
Tomato, seedlings for planting	numbers	4000.00	51.12	5.1E-02	
Planting area	p				
N	kg	68.55	0.88	8.8E-04	
P_2O_5	kg	92.17	1.18	1.2E-03	
K_2O	kg	104.84	1.34	1.3E-03	
Sulphur	kg		0.00	0.0E+00	
Gypsum	kg		0.00	0.0E+00	
Lime	kg	226.80	2.90	2.9E-03	
Pesticides	kg	1456.00	18.61	1.9E-02	CB
Metribuzin	kg	8.50	0.11	1.1E-04	
Paraquat dichloride	kg	14.17	0.18	1.8E-04	
Flumioxazin	kg	1.45	0.02	1.8E-05	
Esfenvalerate	kg	89.81	1.15	1.1E-03	
Spinosad	kg	19.39	0.25	2.5E-04	
Mancozeb	kg	714.41	9.13	9.1E-03	
Copper Hydroxide	kg	424.56	5.43	5.4E-03	
Chlorothalonil	kg	183.70	2.35	2.3E-03	
Greenhouse construction materials					Calculated, assumption tables below
Black Plastic (4K Roll)	m2	371.61	4.75	4.7E-03	
UV Plastic Strips	m2	11450.29	146.34	1.5E-01	
Stakes	m3	6.81	0.09	8.7E-05	
Twine	kg	13.61	0.17	1.7E-04	
Drip irrigation tube/tapes	m	2655.42	33.94	3.4E-02	
Irrigation Water	m3	2312.78	29.56	3.0E-02	
Outputs					
Yield	ton	78.24	1.00	1.0E-03	CB + Florida productions reports
Emissions					Calculated, IPCC and N-balance methods
SOC change		x	x	x	
Total N_2O-N		1.04	0.01	1.3E-05	
Total NH_3-N		1.37	0.02	1.8E-05	
Total Nox-N		0.48	0.01	6.1E-06	
Total NO_3-N		44.43	0.57	5.7E-04	

Protected tomato production systems

Tunnel system (sizing for Gothic style-high tunnels)

Assmptions on the greenhouse size (tunnels)		
Sides	2	numbers
Height	6	ft
Length of row	100	ft
Roof (side, inclined)	5.5	ft
Ends (front view)	10	ft
Length (from upper ede to the inclined roof)	2.25	ft
Sides (area)	1200	sq. ft
Roof (Area)	1100	sq. ft
Ends (area)	165	sq. ft
Total surface area	2465	sq. ft
Total surface area	229	sq m2
Total surface area for 50-100 ft rows greenhouse	11450	sq m2

High tunnel (gothic 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

Farm types	Yield
Open field	78-95 (ton per ha)[a]
100 ft row, plastic string and stake types	196 (ton per ha)[b]
High tunnel system (unheated)	484 (ton per ha)[c]

Assumptions:

[a] Yield = 0.70 lb / sq.ft

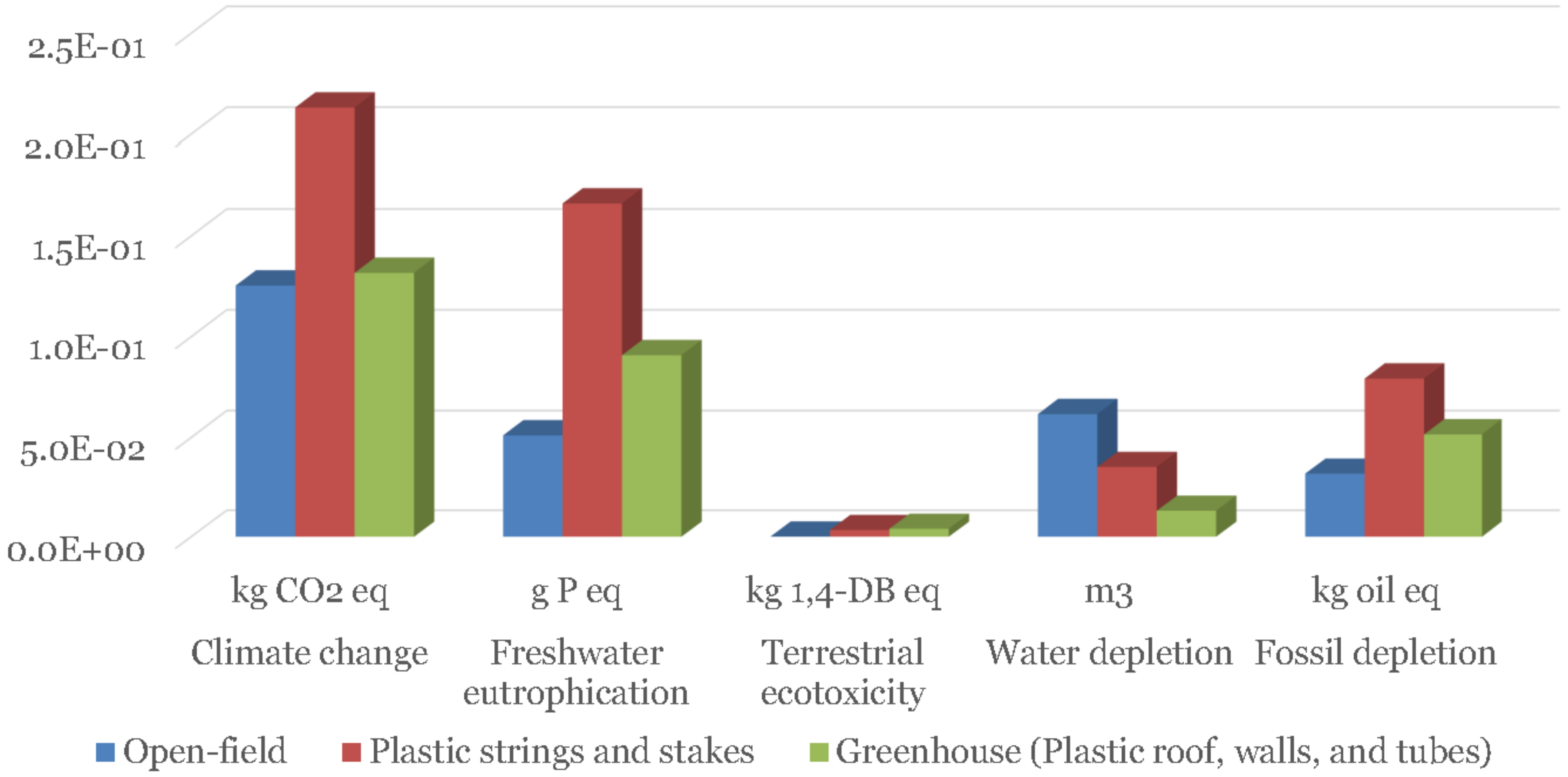
[b] Yield = 1.6-3 lb / sq.ft. Total estimated area of planting per row = 3000 sq ft. No of beds per row =2. Total number of rows for 1 ha = 25 (for 2 bed system). Calculated after: UGA extension, 2013; Hochmuth G., 2006; Gazula A., 2009 and CAES, UGA.

[c] Calculated as: US production (159,664 ton from 330 ha) http://ucce.ucdavis.edu/files/datastore/234-447.pdf 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).

More permanent, quonset-style high tunnel. Photo credit: Linda Naeve, Iowa State University Extension

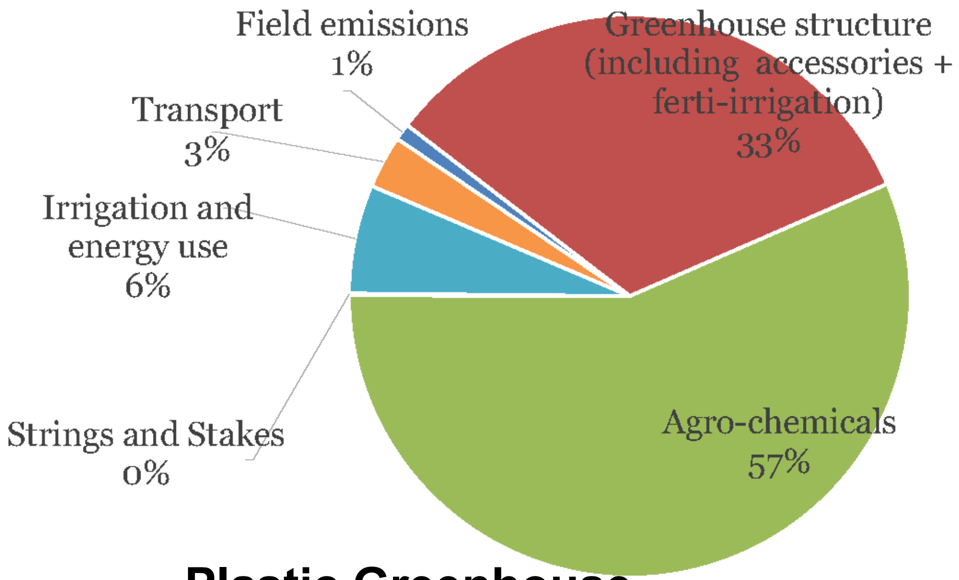
Preliminary results

Environmental impacts (per 1 kg tomato)



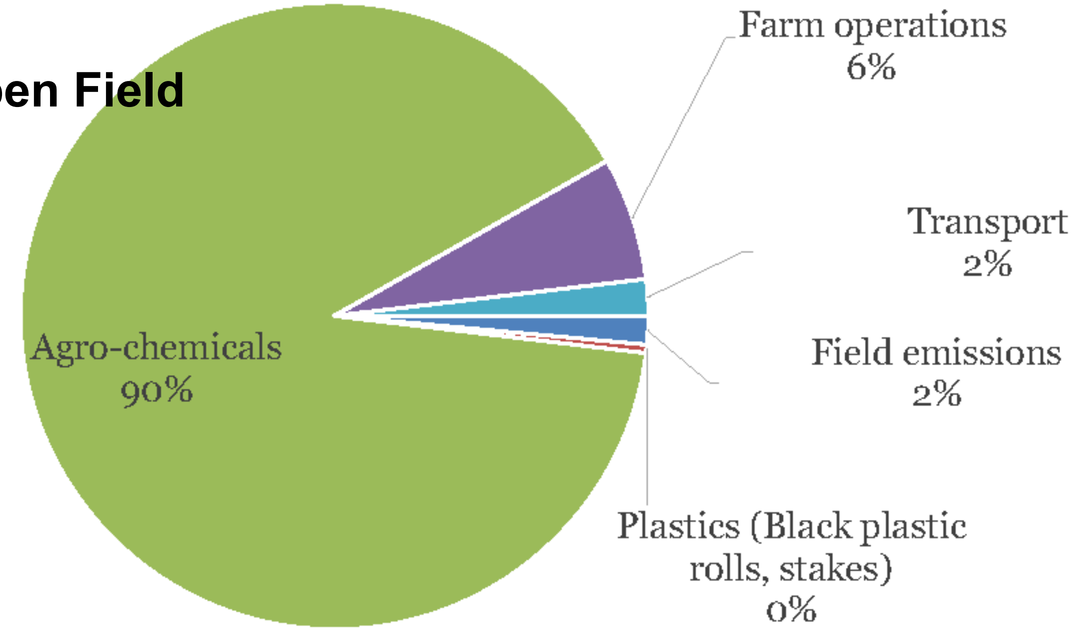
Impacts	Units	Open-field	Plastic strings and stakes	Greenhouse (Plastic roof, walls, and tubes)
Climate change	kg CO2 eq	1.25E-01	2.13E-01	1.32E-01
Freshwater eutrophication	kg P eq	5.11E-05	1.66E-04	9.08E-05
Terrestrial ecotoxicity	kg 1,4-DB eq	9.07E-05	3.38E-03	4.01E-03
Water depletion	m3	6.16E-02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

Preliminary results: Contribution Analysis: GHG

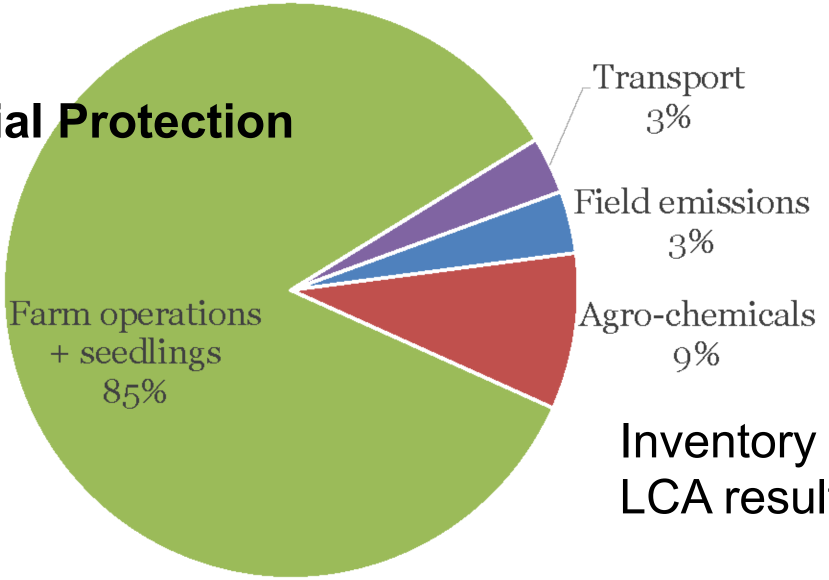


Plastic Greenhouse

Open Field



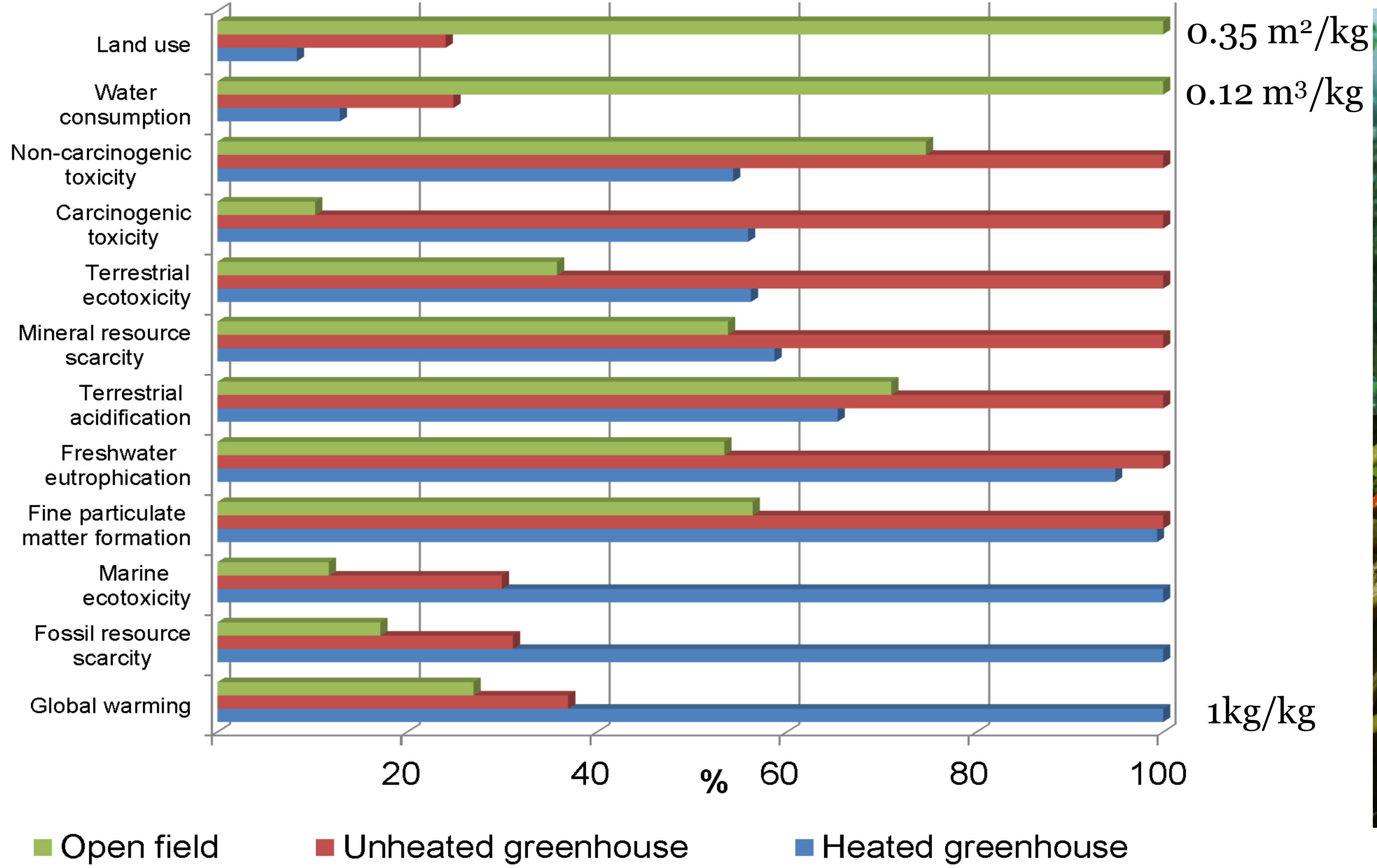
Partial Protection



Inventory data incomplete;
LCA results will change

Preliminary results: trade-offs

Global Average Environmental Impacts (per 1 kg tomato)



Similar studies (in different agro-climates)

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.

Impact category	GW	AD	EU	OD	SM	CED
Unit	kg CO_2 eq ($x10^{-3}$)	H^+ moles eq ($x10^{-3}$)	kg N eq ($x10^{-6}$)	kg CFC-11 eq ($x10^{-10}$)	g NO_x eq ($x10^{-5}$)	MJ eq ($x10^{-2}$)
Total	2881(100%)	273(100%)	1252(100%)	4205(100%)	270(100%)	5276(100%)
Greenhouse Structure	32(1%)	7(2%)	38(3%)	11(<1%)	6(2%)	51(<1%)
Electricity	83(3%)	30(11%)	270(22%)	98(2%)	16(6%)	340(6%)
Fertilization	279(10%)	55(20%)	256(20%)	141(3%)	42(16%)	196(4%)
Heating	2460(85%)	171(63%)	613(49%)	3940(94%)	197(73%)	4643(88%)
Rockwool	14(<1%)	5(2%)	38(3%)	5(<1%)	3(1%)	24(<1%)
Water Use	8(<1%)	3 (1%)	28(2%)	3(<1%)	2(<1%)	13(<1%)
Waste	5(<1%)	2 (<1%)	9(<1%)	7(<1%)	4(1%)	9(<1%)

2.88 kg/kg;
85% heating
Ontario

Impact per 1 ton tomato.
Antón A. et al. 2012. Proc.

Impact per 1 kg tomato
Hendricks P. 2012

IC	Unit	Total	Structure	Climate system	Auxiliary equipment	Fertilizers	Pesticides	Waste
AD	kg Sb eq	**5.6E+00**	3.4E-01	**5.0E+00**	1.4E-01	9.9E-02	1.6E-03	3.3E-03
AA	kg SO_2 eq	**1.2E+00**	3.0E-01	**6.6E-01**	8.8E-02	1.1E-01	1.8E-03	2.3E-03
EU	kg PO_4^{-3} eq	**-1.1E+00**	**9.7E-02**	-1.3E+00	2.1E-02	1.6E-02	6.1E-04	9.1E-04
GW	kg CO_2 eq	**7.8E+02**	.3E+01	**6.6E+02**	1.4E+01	4.8+01	2.0E-01	2.1E+00
PO	kg C_2H_4	**1.9E-01**	1.4E-02	**1.6E-01**	6.5E-03	2.2E-03	1.1E-04	7.6E-05
CED	MJ	**1.2E+04**	8.2E+02	**1.1E+04**	3.1E+02	2.0E+02	3.9E+00	7.9E+00

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 green house 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