Journal of Cleaner Production 140 (2017) 831–839

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Life cycle perspectives on the sustainability of Ontario greenhouse tomato production: Benchmarking and improvement opportunities

Goretty M. Dias [a,*], Nathan W. Ayer [b], Shalin Khosla [c], Rene Van Acker [d], Steven B. Young [a], Stephanie Whitney [a], Patrick Hendricks [d]

[a] *Faculty of Environment, University of Waterloo, 200 University Avenue West, Waterloo, Ontario, N2L 3G1, Canada*
[b] *School for Resource and Environmental Studies, Dalhousie University, 6100 University Ave. Suite 5010, Halifax, NS, B3H 4R2, Canada*
[c] *Ontario Ministry of Agriculture and Rural Affairs, Harrow, ON, Canada*
[d] *Plant Sciences, University of Guelph, 50 Stone Road West, Guelph, ON, Canada*

ARTICLE INFO

Article history:
Received 7 January 2016
Received in revised form
1 June 2016
Accepted 6 June 2016
Available online 8 June 2016

Keywords:
Life cycle assessment
Greenhouse tomatoes
Benchmarking
Sustainability
Biomass
Canada

ABSTRACT

Globally, there is a shortage of vegetables to meet the requirements of a healthy diet. Greenhouse production can help meet demand for vegetables, but under certain conditions it can be very energy intensive and unsustainable, particularly in cold climates, such as in Canada. Greenhouse producers in Ontario, Canada, which has the highest concentration of greenhouses in North America, have been actively improving the industry to reduce costs and address environmental concerns, but very little is known about the environmental sustainability of the industry. This study not only addresses the gap in life cycle environmental performance of Canadian greenhouse tomato production, it also provides a broader sustainability analysis that could be applied to other regions when considering improvements in the industry. Life cycle assessment (LCA) was used to benchmark Ontario greenhouse tomato production relative to other regions using data from 8 growers. Heating with fossil fuels contributed between 50 and 85% of the total impact for ozone depletion, global warming, smog, acidification, and respiratory effects. Using willow biomass produced in Ontario could reduce global warming impacts of tomato production by 72%. This solution requires approximately 50,000 ha of land to produce the biomass needed for the annual production of 165,000 t of tomatoes in this region, which is about 10 times more land than field tomato production. However, field tomatoes can be up to 50% more water intensive than greenhouse tomatoes. To mitigate these trade-offs, the industry needs to consider both growing biomass on degraded land and industrial symbiosis to recover wastes so that appropriate strategies are implemented to provide environmentally and economically sustainable vegetables. LCA combined with an evaluation of local factors, such as land resources and waste availability for industrial symbiosis, provides a stronger sustainability assessment of trade-offs and opportunities in greenhouse vegetable production.

1. Introduction

Population growth and the promotion of healthy diets are driving demand for more vegetables. Although it is increasingly recognized that high intake of vegetables are related to lower mortality, there are not enough vegetables globally to meet the required daily intake (Siegel et al., 2014). In Canada, a short growing season and cold climate, makes it challenging to meet vegetable demand year-round unless they are imported or produced in greenhouses. The province of Ontario is Canada's leader in greenhouse tomato production, with Leamington, Ontario having the highest concentration of greenhouses in North America, representing 64% of the total Canadian market in terms of production volume (Agriculture and Agricola Canada (AAFC), 2011).

Even though greenhouse vegetable production plays a role in meeting vegetable demand, this industry can have large environmental impacts. Life cycle assessment (LCA) has been used extensively to assess environmental impacts and trade-offs in field and greenhouse tomato production (Martínez-Blanco et al., 2011), and to identify issues in protected crops in various locations such as Spain (Torrellas et al., 2012a), France (Boulard et al., 2011), Italy (Cellura et al., 2012), Australia (Page et al., 2012), and Colombia

* Corresponding author.
E-mail address: gdias@uwaterloo.ca (G.M. Dias).

http://dx.doi.org/10.1016/j.jclepro.2016.06.039

(Bojacá et al., 2014). In general, most studies show that soil-based unheated tunnel or greenhouse production has better environmental performance than high-tech soil-less heated greenhouse production (e.g. Bojacá et al., 2014; Boulard et al., 2011; Cellura et al., 2012; Martínez-Blanco et al., 2011; Page et al., 2012; Russo and Mugnozza, 2005; Torrellas et al., 2012a, 2012b). Additionally, the hot spots in unheated, soil-based technologies tend to be the greenhouse structure and fertilizer production/emissions, while for heated, soil-less systems, the environmental hot-spots are the energy-intensive climate control systems (Torrellas et al., 2012a, 2012b).

Despite the number and geographical extent of LCA studies on greenhouse tomato production, many of these studies still do not account for a range of impacts such as toxicity and land and water use (Torrellas et al., 2012a), eutrophication and acidification (Almeida et al., 2014), and other local impacts (Martínez-Blanco et al., 2011). The need for multi-issue assessment of greenhouse production is being recognized (e.g. Almeida et al., 2014; Anton et al., 2014), and some researchers have started to do this by considering both economic and environmental assessment (Torrellas et al., 2012b) and local factors such as land use and water footprints (Page et al., 2014). Additionally, recent studies have shown opportunities to improve life cycle environmental performance of greenhouse production through the use of bio-based fuels and municipal solid waste for heating (Almeida et al., 2014), local recycling programs for waste materials and integrated pest management programs (Bojacá et al., 2014), and using photovoltaic systems (Page et al., 2014) in locations with high carbon intensity electricity.

There is a substantial number of studies on greenhouse production and improvement options in other regions, but very little is known about Canadian greenhouse production. Dyer et al. (2011) assessed the carbon emissions from greenhouses across Canada, but their study was based on energy modeling and average Canadian greenhouse vegetable production data. Additionally, Zhang et al. (2013) modeled integrated dairy farm-greenhouse systems in British Columbia, Canada, but were considering the disposal of organic waste as the main function of the product system.

Prior to 2008, the Ontario greenhouse industry was facing increasing energy costs due to heating requirements for maintaining an appropriate balance of light and temperature because of low winter light conditions and cold temperatures. Greenhouse producers have been responding to trends in the industry in Europe, and have been improving energy efficiency as a response to increasing energy costs. They have also been trying to minimize environmental impacts in response to concerns about climate change and water use (Mann, 2012), and yet there is no study that benchmarks the environmental performance of the industry in this region.

Not only is there a lack of environmental information on greenhouse tomato production in Ontario, it has been consistently pointed out that environmental performance of greenhouse production is highly influenced by technology and geographical location (Almeida et al., 2014; Brodt et al., 2013; Page et al., 2014). If Ontario producers are to address environmental issues, then LCA research needs to be focused on obtaining technologically and geographically relevant data. Other local factors, not captured by LCA, also need to be considered to identify potential trade-offs between impacts. It is crucial to have evidence-based information on the benefits and challenges of the greenhouse industry as more consumers demand sustainable and healthy food.

This LCA study used an interdisciplinary approach and industry experts to provide Ontario-specific information on greenhouse production, which Torrellas et al. (2012b) suggested as being necessary to understanding the industry. Primary data collection was based on collaboration between academic experts (in plant agriculture, engineering, agricultural systems, and LCA), and government experts in tomato greenhouse production, to help collect and verify data from 8 growers in Leamington, Ontario. LCA was used to benchmark the environmental performance of Ontario greenhouse tomato production relative to other regions. This study not only addresses the gap in life cycle environmental performance of Canadian greenhouse tomato production, but also provides a broader approach to sustainability by considering resource use and availability in improvement scenarios, and the potential trade-offs. This contributes to a broader sustainability analysis that could be applied to other regions when considering improvements in the industry.

2. Methods

This study used attributional LCA to quantify the cradle-to- gate environmental impacts of average greenhouse tomato production in Ontario, so as to benchmark the industry and to suggest improvements to operations. Improvement analysis considered a broader assessment of resource use and availability. The analysis of the environmental and energy performance of average greenhouse tomato production followed the ISO 14044 (ISO, 2006) LCA framework as described in the following sections.

2.1. Goal and scope definition

The goal of this LCA study was to quantify the environmental and energy performance of greenhouse tomato production in the region of Leamington, Ontario. Since the study was focused on the greenhouse production of commercial tomatoes, the functional unit was 1 kg of packaged tomatoes at the greenhouse gate. This functional unit is commonly used in other greenhouse vegetable studies, and was the most appropriate for benchmarking and comparing to other studies.

This is a cradle-to-gate study and the system boundaries for the study include greenhouse infrastructure, seedling production, climate control (electricity generation for lighting and ventilation and the production and combustion of natural gas and bunker fuel for heating), tomato cultivation (pesticides, fertilizers, and growing medium), on-site packaging, and waste related to greenhouse operations (Fig. 1). The distribution, storage, and use of tomatoes was excluded from the analysis because the focus was on production activities.

The geographic boundaries of the study include all life cycle activities occurring in Ontario (including electricity generation specific to the Ontario grid mix) and the shipment of plastic greenhouse infrastructure to China for recycling.

2.2. Modeling average greenhouse production system

Primary data were collected through a survey administered to 8 Ontario greenhouse producers in Leamington, Ontario, and verified through follow-up communications. The survey was used to collect data on size of operation, yields, and operation and maintenance data (i.e. annual energy and water consumption based on utility bills, annual consumption of fertilizers, pesticides, growing medium, etc.). This study represents an average of various types of technologies (e.g. infrastructure materials and heating and irrigation technologies) and management systems (e.g. integrated and conventional pest management) from 2006 to 2010. Some producers grow specialty tomatoes in some years (e.g. cherry), but only data for larger tomatoes were used as they represented the majority of production.

A weighted average was calculated to represent typical Ontario tomato production in a greenhouse. The average size of the 8

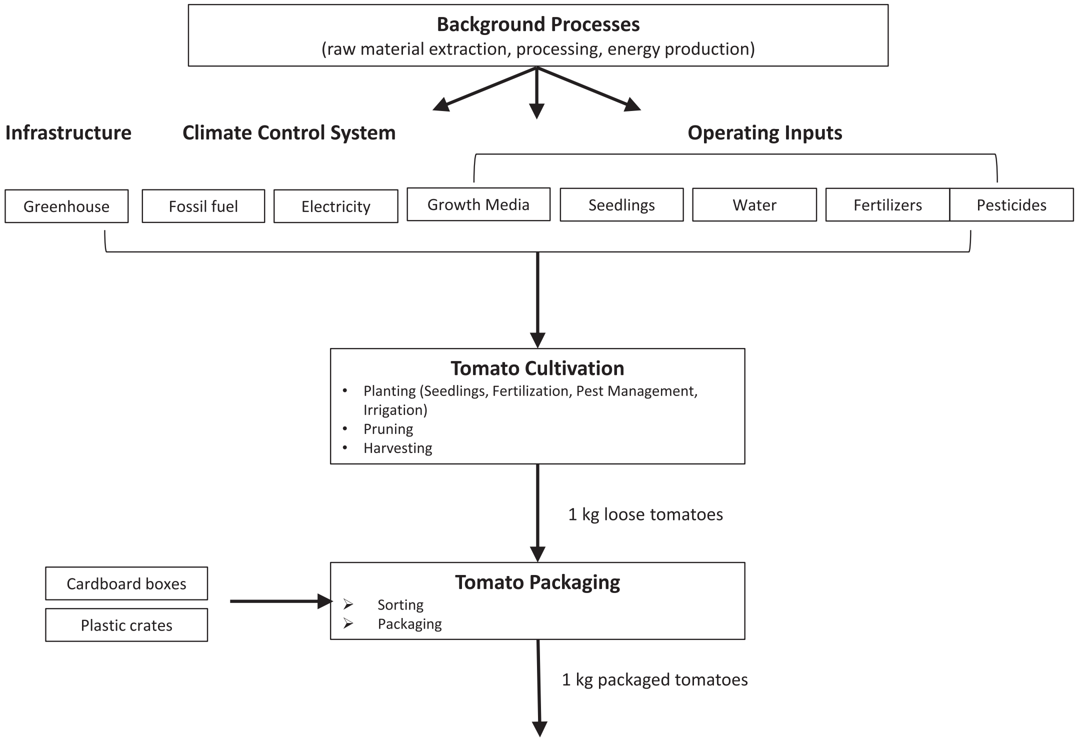

Fig. 1. System boundaries and processes used for the life cycle assessment of average Ontario greenhouse tomato production.

greenhouses is approximately 53,000 m^2 (range of 10,000 to 105,000 m^2) with an average annual yield of 55.5 kg/m^2 (range of 46–60 kg/m^2). The data collected represent a growing area of 427,000 m^2, or about 10% of the total tomato greenhouse area in the region. The results of the life cycle inventory for production of 1 kg of packaged tomatoes in an average Ontario greenhouse are summarized in Table 1.

The various stages of greenhouse tomato production were modeled as follows:

2.2.1. Greenhouse infrastructure

The greenhouse infrastructure includes the manufacturing of the major building materials and maintenance of components that wear down or are damaged during the lifetime of the greenhouse (e.g. plastic covering). The structure of the greenhouse is made from steel, aluminum, and plastic (polyethylene). For this study, a leading greenhouse manufacturer for the region provided information on the quantity of materials used in a 'typical' southwestern Ontario tomato greenhouse (DeCloet Greenhouse Manufacturing, Delhi, ON). It was assumed that the metals used in the structure of the greenhouse were made from virgin materials and that the greenhouse, excluding plastic, has a lifespan of 25 years.

2.2.2. Tomato seedlings

Tomato seedlings are produced in greenhouses and are transplanted in January. Their production was modeled based on the assumption that they are grown in greenhouses with similar characteristics as those used for production. Seeds are planted in plastic trays and fertilized and watered. Although actual data were not available from nurseries, a nursery operator (Personal communication, confidential) estimated the energy inputs of seedling production for a typical greenhouse to be 3% of total annual energy for the production of tomatoes. Based on this, it was assumed that all other inputs (e.g. fertilizer and water) were also 3% of annual consumption.

Table 1
Average material and energy inputs and outputs for the cultivation of 1 kg of packaged tomatoes in Ontario greenhouses.

Infrastructure	
Steel (g)	61.0
Glass (g)	3.20
Aluminum (g)	0.240
Plastic (HDPE) (g)	0.270
Heating fuel	
Natural gas (MJ)	28.9
Bunker fuel or #2 oil (MJ)	4.06
Electricity consumption (kWh)	0.278
Fertilizers	
Calcium nitrate – $Ca(NO_3)_2$ (g)	11.0
Potassium nitrate – KNO_3 (g)	10.7
Monopotassium phosphate – KH_2PO_4 (g)	1.28
Potassium sulphate – K_2SO_4 (g)	1.02
Potassium chloride – KCl (g)	1.30
Magnesium sulphate – $MgSO_4$ (g)	2.71
Ammonium nitrate – $(NH_4)(NO_3)$ (g)	0.338
Micronutrients (g)	0.298
Pesticides	
Insecticides (insect and mite pests) (g)	0.130
Fungicide (diseases) (g)	0.100
Water	
Irrigation water consumption (L)	18.4
Growing Media	
Rockwool (g)	9.4
Packaging material	
Corrugated cardboard (kg)	0.105
Plastic (baskets, crates, clips) (kg)	0.0
Waste	
Plastic film roof (LDPE) (g)	2.35
Waste (inorganic, landfill) (g)	63.2
Waste (organic, landfill) (g)	89.7
Compost (g)	71.5
Plastic sleeve rockwool (LDPE) (g)	0.444

2.2.3. Climate control

This aspect of greenhouse production includes electricity for ventilation and lighting (but excludes infrastructure related to ventilation and lighting system) and fuels for heating (i.e. Greenhouses in southwestern Ontario commonly use a fossil fuel-based central heating system (either hot water, steam, or a combination)). Natural gas combustion is the most used heating system, but some growers use bunker fuel, and some used both fuels during the 5 year period of data collection. The annual volume of each fuel used by the 8 growers was averaged and used to represent all growers. In addition to providing heat, newer boiler technology uses flue gas for carbon dioxide enrichment.

2.2.4. Tomato cultivation

Tomato cultivation includes the following operations and maintenance: consumption of rock wool substrate, replacement of greenhouse structure plastic, closed-loop fertigation (fertilizer and water consumption), pest and disease control, and pruning and harvesting activities (tomatoes are pruned and hand-harvested, using carts on electric tracks). Material and energy inputs for the manufacturing of all material inputs (i.e. rockwool, fertilizer, pesticides, etc.) are also included. Nitrous oxide emissions to air from N fertilizer application were not included since this is a soil-less system and nitrous oxide emissions are either considered negligible or there is no consensus on whether emissions occur from these substrates (Almeida et al., 2014). Additionally, it is assumed that there are no other fertilizer emissions to the environment as the fertilizer is delivered through a closed-loop fertigation system.

Although only 3 growers provided details on pesticide use, it was assumed that their practice was representative of all grower operations. Some producers use Integrated Pest Management (use of insects to manage other pests), but data were not available to quantify this, so it was excluded. The life span for rockwool substrate and the plastic covering the greenhouse structure was assumed to be 1 and 4 years, respectively. Transportation of material inputs from a supplier to the greenhouse was included and estimated at 50 km.

2.2.5. Packaging

Tomatoes are packaged on-site using a series of conveyor belts to deliver the tomatoes to the packagers. This process includes the production of cardboard boxes and plastic packaging material. Steps comprise cutting, extrusion, folding and printing. In addition to the input of cardboard and plastic, the electricity consumption and emissions from production are included.

2.2.6. Waste

Waste products include used rockwool, damaged and worn-out plastic from infrastructure, plastic packaging, and organic waste from pruning activities. It was assumed that all waste from the greenhouse operations was landfilled, with the exception of the plastic infrastructure, which was assumed to be recycled. During the period for which data were collected, plastic was being shipped to China. It was assumed that the plastic was shipped 4000 km by train to the west coast of Canada, and then an additional 9000 km by ship to China.

2.3. Alternative scenarios description

Some producers use only natural gas for heating, while others have started using biomass to provide greenhouse heating in the Leamington area, therefore two alternative heating scenarios were modeled based on 1) 100% natural gas; and 2) willow biomass combustion. Data from a study on pelletized willow biomass produced in southern Ontario were used to model the latter scenario (Dias et al., 2015). It was assumed that the willow pellets were combusted in an industrial furnace using average technology.

2.4. Life cycle inventory and impact assessment

The Ecoinvent 3.1 database was used to characterize background processes such as the production and combustion of energy feedstocks, the manufacture and disposal of infrastructure components, the manufacture of chemical inputs to the process, and emissions and fuel consumption for various modes of transportation. Electricity use was modeled based on the average Ontario mix of electricity feedstocks between January and July of 2015: 60.4% nuclear, 23.9% hydro, 9.9% natural gas, 5.3% wind, 0.3% biofuel, and 0.1% solar (IESO, 2015). Electricity generation processes for these six feedstocks were modeled using Ecoinvent average unit processes, including material and energy inputs, air emissions and disposal of solid wastes.

SimaPro 7.3 (Pre Consultants B.V.) was used for the LCA modeling, and the TRACI 2.1 (version 1.00) LCIA (life cycle impact assessment) method was used for the accounting and analysis of the emissions and midpoint level impacts. TRACI 2.1 (v. 1.00), employs Canada 2005 normalization/weighting sets and is the only LCIA method available that is based on North American characterization factors (Bare et al., 2003). Furthermore, a subset of TRACI impact categories were chosen to reflect impacts on health, ecosystems, and non-renewable resources, in a way that addresses the most pertinent environmental concerns in Ontario, namely climate change, smog and air quality concerns, and eutrophication and acidification of water bodies (e.g. the Great Lakes). Therefore the impact assessment focused on global warming potential (GWP), smog potential (SP), respiratory effects (RE), eutrophication potential (EP), and acidification potential (AP). In addition to the set of TRACI indicators, life cycle energy use was quantified using the Cumulative Energy Demand (CED) method v. 1.08, while the water footprint was calculated using the water depletion characterization method from ReCiPe 1.07. This method accounts for water consumption across the life cycle, but does not account for water availability and contributions to water scarcity.

2.5. Benchmarking and resource sustainability analysis

LCA studies of tomato greenhouse production from other parts of the world, with similar study boundaries were used to benchmark the performance of Ontario greenhouse production. Only GWP was considered in the benchmarking since it was quantified across all studies. Because greenhouse heating with fossil fuels drives environmental impacts, monthly temperature data were obtained from various websites and were averaged to provide context on the effect of temperature on environmental impacts due to heating.

Estimates of biomass and land needed to produce pelletized willow biomass for use in tomato greenhouse production were based on a study of Ontario-grown willow biomass (Dias et al., 2015). The yields used were 7 oven dry t/ha and the energy content was 16.9 MJ/kg willow pellets. Estimates of biomass needed were extrapolated to 165,000 t annual tomato production in Leamington for 2010, assuming that all growers had a similar energy use per mass of tomatoes produced.

3. Results

The results are presented as follows: overall LCA results and contribution analysis; alternative heating improvement analysis; benchmarking to other studies.

3.1. Environmental contribution of greenhouse stages

One of the primary objectives of the study was to understand the contribution of specific life cycle activities to the overall environmental performance of Ontario greenhouse tomato production. The life cycle environmental impacts of producing 1 kg of packaged tomatoes in an average Ontario greenhouse are dominated by fossil fuel use Fig. 2 and Table 2. Fuel combustion for greenhouse heating (natural gas and bunker fuel) accounted for between 50 and 85% of the total impact for ozone depletion, global warming, smog, acidification, and respiratory effects, a finding similar to other studies showing that the climate control systems account for more than 75% of impacts (Page et al., 2012, 2014) Torrellas et al., 2012a). The secondary hot spot for all impact categories was the manufacturing of cardboard packaging, contributing from 8 to 28% of the same impacts; packaging also contributed to almost 61% of the eutrophication impacts, with natural gas and bunker fuel contributing 20 and 17%, respectively. This finding was consistent with that of Cellura et al. (2012).

The CED of the tomato production system was also dominated by fuel use, which accounted for almost 70% of the total when including both natural gas and bunker fuel (Fig. 3). The manufacturing of cardboard packaging accounted for 17% of the CED. Water consumption at the greenhouse accounted for 65% of the total life cycle water depletion, with water use in the supply chain of cardboard manufacturing accounting for 27% of water depletion. It is also notable that despite the significant transport distance involved, the impacts of transporting greenhouse plastic to China for recycling are generally negligible, accounting for less than 5% of impacts in all categories with the exception of contributions to smog. This small contribution is due in part to the relatively high efficiency of rail and ocean transport.

3.2. Alternative heating scenario analysis

Combustion of natural gas and bunker fuel is the biggest contributor to most life cycle impacts in greenhouse production. Some Ontario greenhouse producers are beginning to use biomass for heating their greenhouses. Substituting natural gas for bunker fuel results in small improvements (<10%) for global warming potential, ozone depletion, and eutrophication, with larger improvements (between 13% and 30%) in smog, acidification and respiratory effects (Fig. 4). Substituting willow pellets for natural gas and bunker fuel reduces GWP and ozone depletion substantially, by 72 and 78%, respectively Fig. 4). However, willow pellet combustion could potentially increase other impacts by 40% for eutrophication, 45% for acidification, 65% for smog, and 126% for respiratory effects. These potential impacts are due to increased particulates and NOx that are common in biomass combustion, and reflect older average technology represented in the industrial furnace process used to model combustion.

Assuming that all tomato greenhouses in Southern Ontario have similar heat production requirements for tomato production (approximately 33 MJ/kg, Table 1), substituting willow pellets for fossil fuels would result in annual GWP reductions of 380 Mt of CO_2, based on the annual tomato production of 165,000 t in the Leamington region. Currently, Ontario field tomato yields are 31 t/ha, thus to produce 165,000 t of greenhouse tomatoes under field conditions would require about 5300 ha of land. In comparison, producing willow biomass for heating greenhouses would require about 50,000 ha of land, or about 10 times more land.

3.3. Benchmarking of Ontario greenhouse tomato production

Energy use largely depends on the climate and technology. The CED was 60.3 MJ/kg packaged tomatoes in this study. Other studies

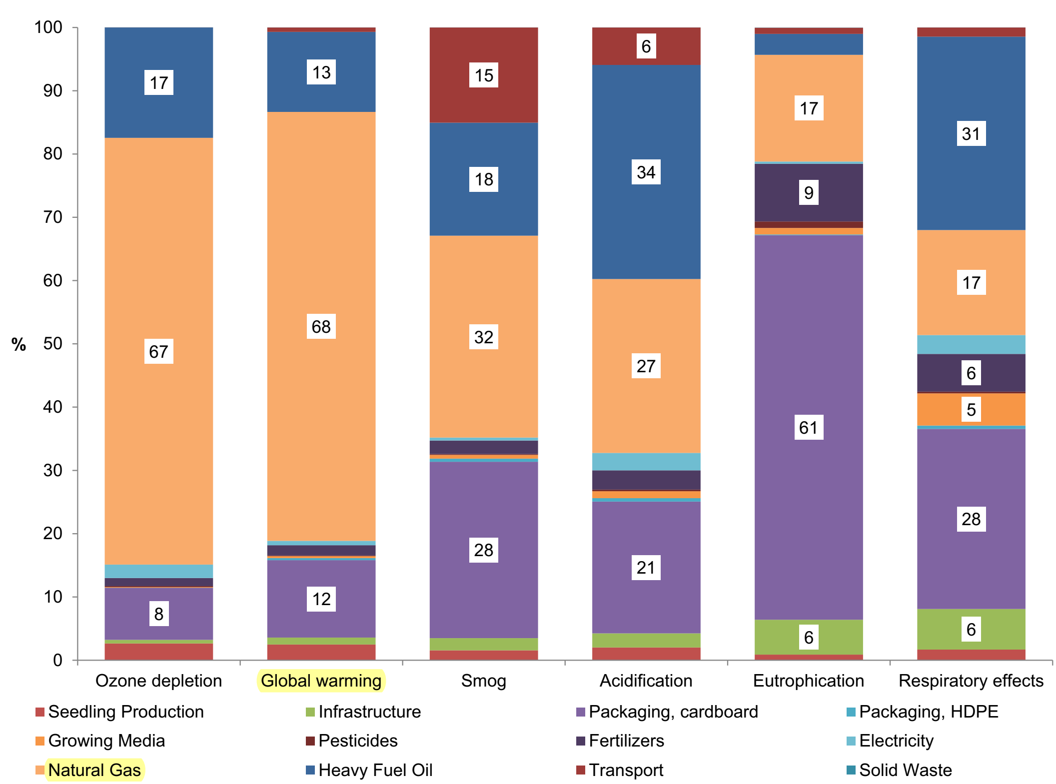

Fig. 2. Contribution analysis of the life cycle impacts of producing 1 kg of packaged tomatoes in an average Ontario greenhouse. Numbered labels indicate percentage of total impact.

Table 2
Contribution analysis of the cradle-to-gate life cycle impacts of producing 1 kg of packaged tomatoes in an average Ontario greenhouse.

	Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Respiratory effects
	(kg CFC-11 eq)	(kg CO_2 eq)	(kg O_3 eq)	(kg SO_2 eq)	(kg N eq)	(kg PM2.5 eq)
Seedling Production	1.6E-08	7.9E-02	1.4E-03	1.3E-04	2.3E-05	8.9E-06
Infrastructure	3.4E-09	3.5E-02	1.7E-03	1.5E-04	1.4E-04	3.4E-05
Growing Media	5.9E-10	1.0E-02	5.2E-04	7.2E-05	2.6E-05	2.7E-05
Transport	1.7E-12	4.5E-02	2.7E-02	7.8E-04	5.0E-05	1.5E-05
Pesticides	9.2E-10	3.0E-03	1.3E-04	1.8E-05	2.6E-05	1.4E-06
Fertilizers	7.5E-09	5.2E-02	1.9E-03	2.0E-04	2.3E-04	3.2E-05
Electricity	1.2E-08	2.2E-02	4.1E-04	1.8E-04	8.9E-06	1.6E-05
Natural Gas	4.0E-07	2.2E+00	2.9E-02	1.8E-03	4.3E-04	8.8E-05
Bunker Fuel	1.0E-07	4.0E-01	1.6E-02	2.2E-03	8.5E-05	1.6E-04
Packaging, cardboard	4.9E-08	3.9E-01	2.5E-02	1.4E-03	1.6E-03	1.5E-04
Packaging, HDPE	4.4E-12	1.1E-02	4.5E-04	3.6E-05	2.5E-06	2.8E-06
Solid Waste	1.6E-13	7.5E-05	2.6E-07	1.7E-08	1.0E-06	1.6E-09
Total	5.9E-07	3.2E+00	9.0E-02	6.6E-03	2.6E-03	5.3E-04

have found CEDs as low as 5.2 MJ/kg and 31.6 MJ/kg for cold tunnel and unheated multi-span greenhouse technologies, respectively, and as high as 95.5 MJ/kg for conventional heated greenhouses (Almeida et al., 2014). Similarly, this study showed a GWP of 3.2 kg CO_{2e}/kg of packaged tomatoes, which is within the range of values (0.24–5.1 kg CO_{2e}/kg of tomatoes) found in other greenhouse tomato production studies for a variety of technologies (Table 3). As expected, when fossil-fuel heated greenhouses are considered, there is a higher GWP for regions with lower annual temperatures (Fig. 5). Nonetheless, Ontario greenhouse production is relatively efficient given the lower temperatures considering that in northern Italy and Hungary, where natural gas was used for heating, the GWP is higher than in this study, even though average annual temperatures are higher.

The water footprint for Ontario greenhouse production was 28.3 L/kg, with 18.4 L due to water consumption from the greenhouse operations. Other studies have found the water footprint to range from 31 L/kg for the tomato cultivation process to 122.6 L/kg of fresh tomatoes when including indirect water use in heating and CO_2 fertilization (Almeida et al., 2014). Page et al. (2011) report water footprints ranging from 1.5 to 16 L/kg of fresh tomatoes, depending on the technology used (e.g. rainwater harvesting) and location. Cellura et al. (2012) found water consumption to be 88.9 L/kg of tomatoes. The range of water footprints are a function of several factors. First, the water footprint methods vary in terms of how they account for water consumption and withdrawals, thus variability is largely a result of the footprint method used. However, there are also technological (e.g. closed-loop fertigation vs. tunnel and soil systems) and geographical factors that affect water use efficiency and water demand. Thus, a consistent method needs to be applied to understand the differences in water footprint due to technological and geographical factors.

Finally, there was 0.23 kg solid waste production per kg packaged tomatoes based only on solid waste produced at the greenhouses Boulard et al. (2011) found 17 kg of waste per m^2 (yield = 50 kg/m^2) or 0.30 kg/kg loose tomatoes. Although waste management did not make a significant contribution to any impact category that was assessed, it represents an inefficiency in resource use that greenhouse operators may be able to address.

4. Discussion

Ontario greenhouses provide fresh market tomatoes year-round for household consumers and commercial needs across North America. However, if the industry is to remain sustainable, it needs to address challenges related to rising energy costs, and water consumption and supply issues (Hill, 2015), as well as environmental impacts. This study found that fossil fuel use for climate control in greenhouse tomato production is the greatest contributor to all impact categories considered, which is not surprising given the climate of southern Ontario. Nevertheless, technology improvements in the last 10 years, along with a lower carbon

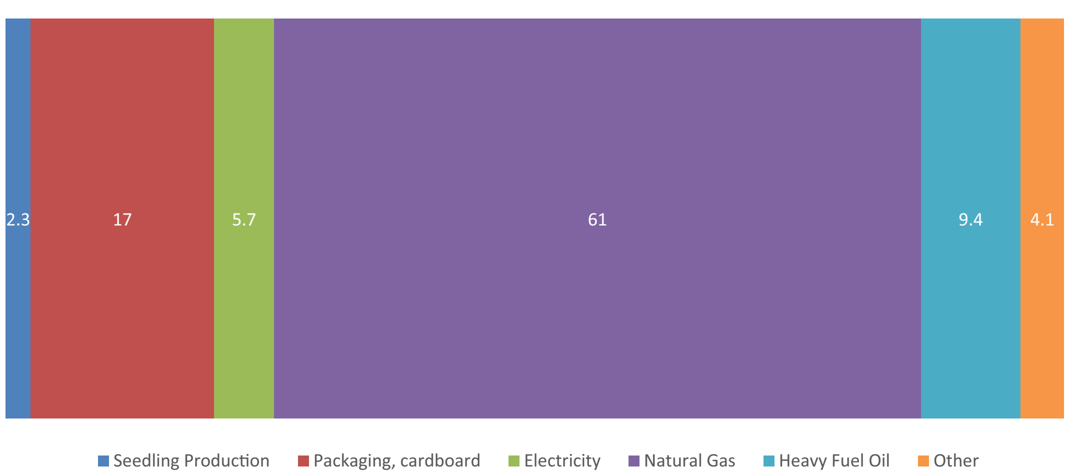

Fig. 3. Cumulative energy demand contribution analysis for producing 1 kg of packaged tomatoes in an average Ontario greenhouse. Numbered labels indicate percentage of total impact. The category of "Other" consists of CED related to infrastructure, fertilizers, plastic packaging, growing media, and pesticides.

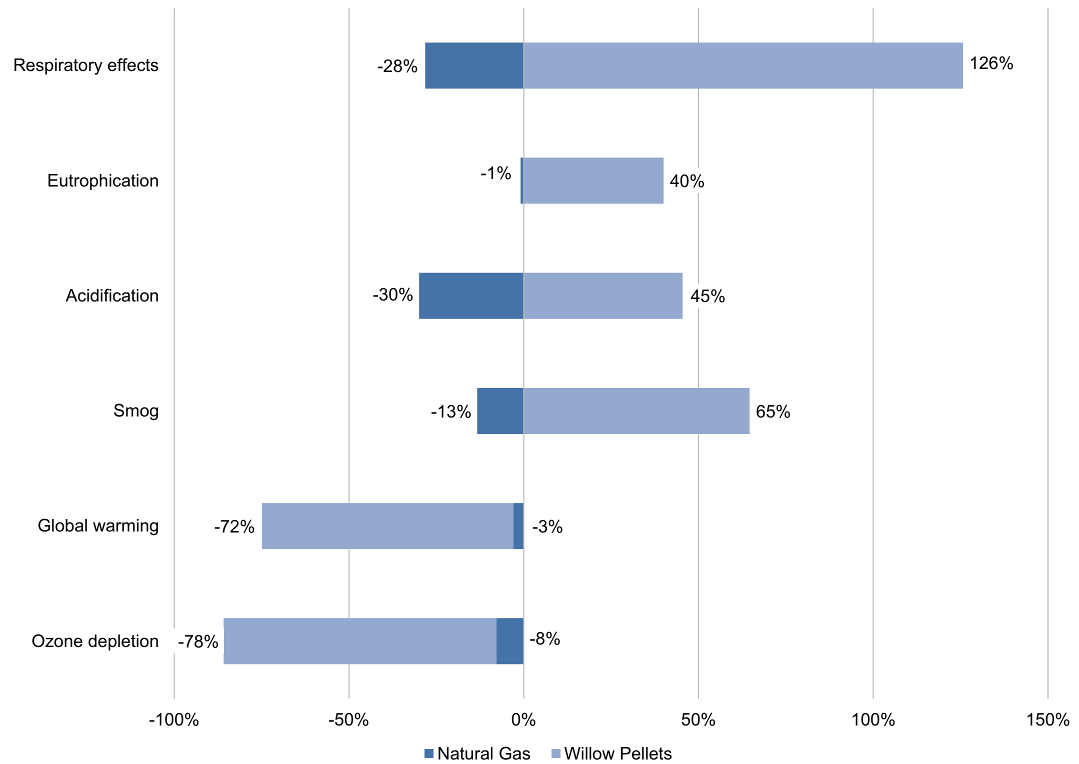

Fig. 4. Comparison of the life cycle impacts of substituting "Natural gas only" and "Willow pellets" for the Reference case heat supply (i.e. natural gas and bunker fuel). Comparison is based on 1 kg of packaged tomatoes in an average Ontario greenhouse.

intensity electricity grid, have resulted in efficiency benefits that result in lower GWP than other greenhouse production systems in similar climates that require heating and electricity.

The Ontario provincial government is committed to implementing a form of cap and trade and there will be incentives to reduce emissions from capped sectors, of which greenhouse growers may be one. Using willow pellets to substitute fossil fuels has substantial potential to reduce GWP and ODP, but could increase smog. Since the highest demand for heat is in the winter, and particulates are responsible for a large portion of the impacts, this could pose a problem in terms of increased contributions to winter smog. There are technologies being developed for combustion of woody biomass that reduce air emissions that contribute to these impact categories (Lefsrud, 2016), but data are needed to support claims of these improvements. With appropriate technology to control particulate emissions from biomass, other impact categories might be improved as well.

Table 3
Comparison of GWP for different studies using heated and unheated technologies.

Country	GWP ($kg\ CO_{2e}/FU$)	Heat type
Spain[f]	0.24	Unheated
France[b]	0.51	Unheated
Hungary[e]	0.53	Thermal water
Italy[c]	0.74	Unspecified
Australia[d]	1.7	Coal, medium technology
Australia[d]	1.9	Natural gas, coal, high technology
Netherlands[e]	2.0	Combined heat and power
France[b]	2.0	Natural gas, oil
Northern Italy[a]	2.3	Natural gas
This study, Canada	3.2	Natural gas, bunker fuel
Hungary[e]	5.1	Natural gas

[a] Almeida et al. (2014).
[b] Boulard et al. (2011).
[c] Cellura et al. (2012).
[d] Page et al. (2012).
[e] Torrellas et al. (2012a).
[f] Torrellas et al. (2012b).

The Leamington region produces about 165,000 t of greenhouse tomatoes annually. Substituting willow biomass pellets for fossil fuels would result in annual greenhouse gas reductions of 380 Mt of CO_2. There are trade-offs in using willow biomass in terms of land use, as growing biomass would require about 10 times more land than growing field tomatoes. Currently, there are 170,000 ha of degraded or marginal land within 100 km of Leamington, including old tobacco land, which is not suitable for agriculture, where farmers could use much of the existing infrastructure to grow willow, or other dedicated bioenergy crops (Thevathasan, 2015). For example, some greenhouses have started to use Miscanthus crops for energy or bioplastics in their operations (Harrison, 2013). Currently, biomass production is costly, but growing biomass could create other economic benefits in the region and provide opportunities for rural development. These benefits, along with carbon pricing, could make this solution more sustainable. Nevertheless, as the appeal of bioenergy grows, biomass availability and demand could drive up costs and make it unattractive for use in greenhouse heating. Demand for biomass could also result in prime agricultural land in Ontario being used for producing biomass to increase yields and make it more cost effective (Sanscartier et al., 2013), which would then potentially create trade-offs with food security.

Other technology options for greenhouses that could be considered include: cogeneration (Almeida et al., 2014); biomass gasification (Beach, 2013); integration of pyrolysis technologies to produce bio-oils and bio-char that can be used to enhance productivity in hydroponic systems (Nichols et al., 2010); biogas from

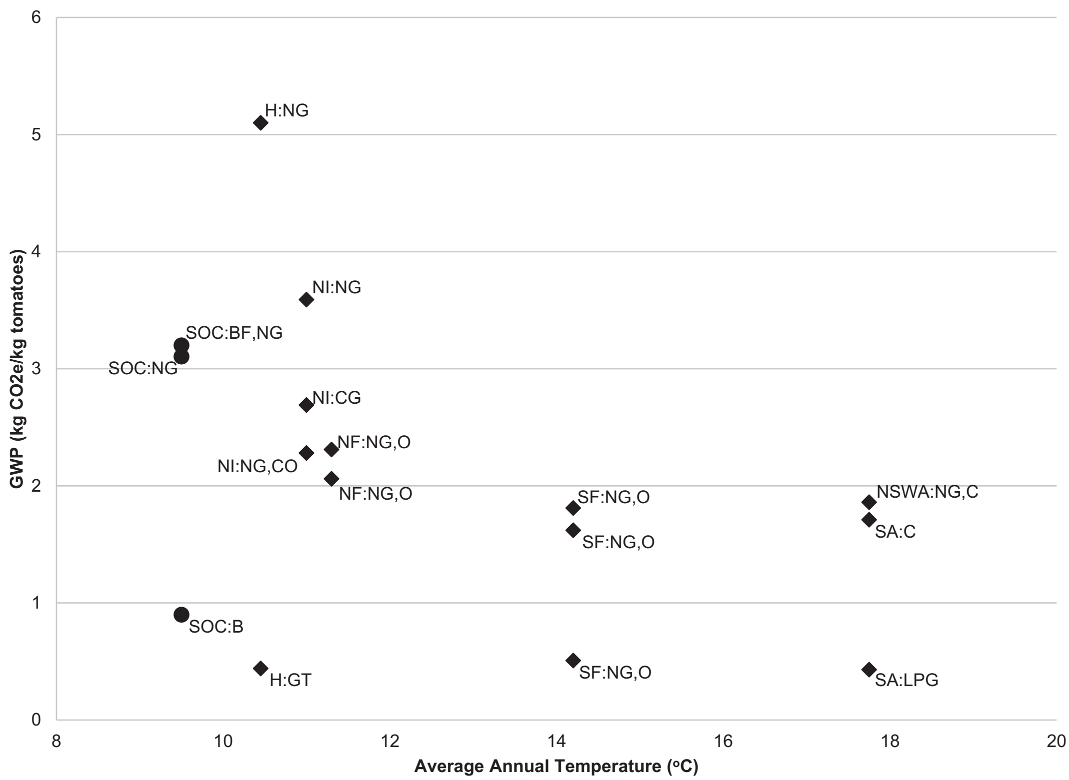

Fig. 5. Relationship between GWP and average annual temperature for various studies showing that Ontario greenhouse production is relatively efficient given the low temperatures and high heating requirements for this region. Labels indicate location or region, and type of fuel used. SOC = Southern Ontario, Canada (this study); NI = Northern Italy; NF = Northern France, SF = Southern France; H = Hungary; NSWA = New South Wales, Australia; SA = Sydney, Australia. NG = Natural gas, BF = Bunker fuel; GT = Geothermal heat; CO = canola oil; CG = Cogeneration, O = Oil; LPG = Liquid propane gas; B = biomass. All studies are cradle-to-gate including waste and packaging, except for Hungary.

waste (Zhang et al., 2013); and even ground-source heat pumps, particularly for future greenhouse development. Combined heat and power systems could increase energy efficiencies, reduce greenhouse gas emissions, and provide electricity at the local level to address issues of supply. There are also energy-efficiency options (Van Alstine, 2013) and technological options being implemented such as grow pipes (Hein, 2012). Finally, as costs of production increase, greenhouse producers could implement LED lights to save on costs, which would also help to reduce electricity consumption. Because Ontario currently has an electricity grid with low carbon intensity, and the impacts due to electricity are minor in this study, this will not reduce GWP substantially; however, it does provide other sustainability benefits, such as avoiding additional electricity infrastructure to meet demand (Hill, 2015).

Although there is an abundance of water in Ontario from the Great Lakes, the industry is being scrutinized for large water withdrawals for greenhouse production. This study found water consumption of 28 L/kg packaged tomatoes at Ontario greenhouses, which is reasonable given that other researchers have found water requirements of 39 and 50 L/kg tomatoes (unpackaged) for hi-tech and field tomatoes, respectively (Page et al., 2012). However, consistent and meaningful assessments of water withdrawal impacts by the industry require further development of water footprinting methods for Ontario conditions.

Ontario has recently announced a strategy to create positive economic and environmental impacts by using resource efficiency and recovery to achieve a circular economy, where no waste is produced (Government of Ontario, 2015). One potential opportunity to contribute to the circular economy and reduce trade-offs is to apply industrial symbiosis to use resources and wastes in the vicinity of the greenhouses more effectively. Recent studies show that industrial symbiosis networks have benefits or reduced impacts compared to reference systems (Martin, 2015). These networks are particularly beneficial if the industries involved are required to meet environmental regulations (Martin et al., 2015). This approach has been applied in Sweden where waste heat from pulp mills is used to heat greenhouses (Advantage Environment, 2016). These opportunities have also been modeled to show how wastes can be used to provide bioenergy, such as using agricultural wastes for greenhouse heating (Zhang et al., 2013) and incorporating wastewater treatment and land remediation options to produce biomass in a cost effective way (Gopalakrishnan et al., 2009). In Ontario there is great potential for these approaches, as there are storm water and wastewater ponds associated with greenhouses (Mann, 2012) and the region has many food processing plants and farms producing animal waste. Already there is an anaerobic digestion facility that uses vegetable and animal waste from local farms and greenhouses to generate heat, electricity and natural fertilizer (Anon, 2012).

Food security, including a shortage of vegetables to meet requirements for healthy diets, along with the high environmental impacts related to the food production system requires a more sustainable use of energy, water, and land. There are environmental trade-offs in both field and greenhouse vegetable production, and approaches that address local factors are needed that identify opportunities to reduce impacts and maximize benefits. For all these opportunities discussed, economic considerations would need to be evaluated along with potential environmental benefits.

5. Conclusions

Globally, there is a need for more vegetables to meet needs of a growing population and to meet the requirements of healthy diets. Meeting this demand will likely require increasing both field and greenhouse vegetable production, both of which have sustainability trade-offs. This study showed that the highest environmental impacts in Ontario greenhouse tomato production are related to heating with fossil fuels. Using willow biomass for heating could reduce many of these impacts, but would require much more land to grow the biomass required than is needed for field tomato production.

As food security, climate change, water scarcity and energy security become more important, greenhouse producers globally need to look at continually improving management and technologies to maximize resource use and feed a growing population. LCA combined with an evaluation of local factors, such as land resources and waste availability for industrial symbiosis, could provide a stronger sustainability assessment of trade-offs and opportunities in vegetable production, but further research will be needed to identify and evaluate these opportunities.

Acknowledgements

This work was possible through the assistance of the Ontario Greenhouse Vegetable Growers in obtaining collaboration from the greenhouse producers for data collection. The authors deeply appreciate the time and effort by the producers in providing the data required for this study. Finally, the authors acknowledge Gudmundur Johannesson for helping with manuscript formatting.

References

Advantage Environment, 2016. Industrial Symbiosis Grows Tomatoes. At: advantage-environment.com/food/industrial-symbiosis-grows-tomatoes/ (Published: March 27 2013, accessed 20.04.16).

Agriculture and Agrifood Canada (AAFC), 2011. Crop Profile for Greenhouse Tomato in Canada, 2011. At: www.agr.gc.ca/eng/?id=1288878630273 (accessed 10.04.16).

Almeida, J., Achten, W.M.J., Verbist, B., Heuts, R.F., Schrevens, E., Muys, B., 2014. Carbon and water footprints and energy use of greenhouse tomato production in northern Italy. J. Ind. Ecol. 18, 898–908.

Anon, 2012. Canada: biogas from AD a winner for Ontario greenhouse grower. Waste Manag. World. At: https://waste-management-world.com/a/biogas-from-ad-a-winner-for-ontario-greenhouse-grower (Published: 29.06.2012, accessed 10.04.16).

Anton, A., Torrellas, M., Nunez, M., Sevigne, E., Amores, M.J., Munoz, P., Montero, J.I., 2014. Improvement of agricultural life cycle assessment studies through spatial differentiation and new impact categories: case study on greenhouse tomato production. Environ. Sci. Technol. 48, 9454–9462.

Bare, J.C., Norris, G.A., Pennington, D.W., McKone, T., 2003. TRACI: the tool for the reduction and assessment of chemical and other environmental impacts. J. Ind. Ecol. 6, 49–78.

Beach, C., 2013. Greenhouse nears energy independence. The Packer. At: www.thepacker.com/fruit-vegetable-news/Greenhouse-nears-energy-independence-201657161.html (Published: 5.4.2013, accessed 10.04.16).

Bojacá, C.R., Wyckhuys, K.A.G., Schrevens, E., 2014. Life cycle assessment of Colombian greenhouse tomato production based on farmer-level survey data. J. Clean. Prod. 69, 26–33.

Boulard, T., Raeppel, C., Brun, R., Lecompte, F., Hayer, F., Carmassi, G., Gaillard, G., 2011. Environmental impact of greenhouse tomato production in France. Agron. Sustain. Dev. 31, 757–777.

Brodt, S., Kramer, K.J., Kendall, A., Feenstra, G., 2013. Comparing environmental impacts of regional and national-scale food supply chains: a case study of processed tomatoes. Food Policy 42, 106–114.

Cellura, M., Longo, S., Mistretta, M., 2012. Life cycle assessment (LCA) of protected crops: an Italian case study. J. Clean. Prod. 28, 56–62.

Dias, G., Ayer, N., Kariyapperuma, K., Thevathasan, N., Gordon, A., 2015. Life cycle assessment of thermal energy production from short-rotation willow biomass in southern Ontario, Canada. Appl. Energy.

Dyer, J.A., Desjardins, R.L., Karimi-Zindashty, Y., McConkey, B.G., 2011. Comparing fossil CO_2 emissions from vegetable greenhouses in Canada with CO_2 emissions from importing vegetables from the southern USA. Energy Sustain. Dev. 15, 451–459.

Gopalakrishnan, G., Negri, M.C., Wang, M., Wu, M., Snyder, S.W., LaFreniere, L., 2009. Biofuels, land, and water: a systems approach to sustainability. Environ. Sci. Technol. 43, 6094–6100.

Government of Ontario, 2015. Strategy for a waste free Ontario: building the circular economy. Minist. Environ. Clim. Change Draft. At: www.downloads.ene.gov.on.ca/envision/env_reg/er/documents/2015/012-5834_DraftStrategy.pdf (accessed 10.04.16).

Harrison, D., 2013. First Miscanthus-based bio-plastics debut. Greenh. Can. At: www.greenhousecanada.com/news/first-miscanthus-based-bio-plastics-debut-3672#sthash.O8yDS2IL.dpuf (Published: 28.6.2013, accessed 10.04.16).

Hein, T., 2012. Energy Edge: an energy advantage. Greenh. Can. At: www.greenhousecanada.com/energy/management/energy-edge-an-energy-advantage-3420 (Published: 19.12.2012, accessed 10.04.16).

Hill, S., 2015. $500M of greenhouse expansion depends on more hydro to Leamington. Windsor Star. At: windsorstar.com/news/500m-of-greenhouse-expansion-depends-on-more-hydro-to-leamington (January 12, 2015. Windsor Star. Published: 12.1. 2015, accessed 10.04.16).

IESO, 2015. Generator Output by Fuel Type Monthly Report. At: www.ieso.ca/Pages/Ontario's-Power-System/Supply-Mix/default.aspx (accessed 18.04.16).

ISO, 2006. ISO 14044:2006. Environmental Management – Life Cycle Assessment – Requirements and Guidelines. International Organization for Standardization, Geneva, Switzerland.

Lefsrud, M., 2016. Personal Communication. Associate Professor Bioresource Engineering. McGill University, Macdonald Campus, Ste-Anne-de-Bellevue, Quebec, Canada. mark.lefsrud@mcgill.ca.

Mann, H., 2012. Greenhouse wastewater discharges provoke legislation debate. Better Farming. At: www.betterfarming.com/online-news/greenhouse-wastewater-discharges-provoke-legislation-debate-5435 (Published: 18.5.2012, accessed 10.94.16).

Martin, M., 2015. Quantifying the environmental performance of an industrial symbiosis network of biofuel producers. J. Clean. Prod. 102, 202–212.

Martin, M., Svensson, N., Eklund, M., 2015. Who gets the benefits? An approach for assessing the environmental performance of industrial symbiosis. J. Clean. Prod. 98, 263–271.

Martínez-Blanco, J., Muñoz, P., Antón, A., Rieradevall, J., 2011. Assessment of tomato Mediterranean production in open-field and standard multi-tunnel greenhouse, with compost or mineral fertilizers, from an agricultural and environmental standpoint. J. Clean. Prod. 19, 985–997.

Nichols, M., Savidov, N., Aschim, K., 2010. Biochar as a hydroponic growing medium. Pract. Hydroponics Greenh. 112, 39–42.

Page, G., Ridoutt, B., Bellotti, B., 2011. Fresh tomato production for the Sydney market: an evaluation of options to reduce freshwater scarcity from agricultural water use. Agric. Water Manag. 100, 18–24.

Page, G., Ridoutt, B., Bellotti, B., 2012. Carbon and water footprint tradeoffs in fresh tomato production. J. Clean. Prod. 32, 219–226.

Page, G., Ridoutt, B., Bellotti, B., 2014. Location and technology options to reduce environmental impacts from agriculture. J. Clean. Prod. 81, 130–136.

Russo, G., Mugnozza, G.S., 2005. LCA methodology applied to various typology of greenhouses. In: VanStraten, G., Bot, G.P.A., VanMeurs, W.T.M., Marcelis, L.M.F. (Eds.), Proceedings of the International Conference on Sustainable Greenhouse Systems, vols. 1 and 2, pp. 837–843.

Sanscartier, D., Deen, B., Dias, G., MacLean, H.L., Dadfar, H., McDonald, I., Kludze, H., 2013. Implications of land class and environmental factors on life cycle GHG emissions of Miscanthus as a bioenergy feedstock. GCB Bioenergy 6, 401–413.

Siegel, K.R., Ali, M.K., Srinivasiah, A., Nugent, R.A., Narayan, K.M., 2014. Do we produce enough fruits and vegetables to meet global health need? PloS One 9, e104059.

Thevathasan, N., 2015. Personal Communication. Adjunct Faculty, School of Environmental Sciences. University of Guelph, Guelph, Ontario, Canada. nthevath@uoguelph.ca.

Torrellas, M., Antón, A., López, J.C., Baeza, E.J., Parra, J.P., Muñoz, P., Montero, J.I., 2012a. LCA of a tomato crop in a multi-tunnel greenhouse in Almeria. Int. J. Life Cycle Assess. 17, 863–875.

Torrellas, M., Antón, A., Ruijs, M., García Victoria, N., Stanghellini, C., Montero, J.I., 2012b. Environmental and economic assessment of protected crops in four European scenarios. J. Clean. Prod. 28, 45–55.

Van Alstine, D., 2013. Optimizing energy use. Greenh. Can. At: www.greenhousecanada.com/energy/management/optimizing-energy-use-3614 (Published: 17.5.2013, accessed 10.04.16).

Zhang, S., Bi, X.T., Clift, R., 2013. A life cycle assessment of integrated dairy farm-greenhouse systems in British Columbia. Bioresour. Technol. 150, 496–505.