An Economic and Environmental Comparison of Conventional and Controlled Environment Agriculture (CEA) Supply Chains for Leaf Lettuce to US Cities

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1 Introduction

Metropolitan agriculture, the production of food in urban and peri-urban areas, has captured the attention and excitement of municipalities and entrepreneurs as a means to improve fresh food access while contributing to environmental sustainability (Mougeot, 2000). What began as a community gardening movement has been transformed over the last five years with the emergence of larger-scale commercial Controlled

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Environment Agriculture (CEA) operations in metropolitan areas. These greenhouses and plant factories enable year-round intensive production of vegetables by creating controlled environments that supply an optimal balance of light, heat, CO_2 and water to optimise plant growth (Harbick & Albright, 2016). These systems have the potential to alter metropolitan food supply chains by decentralising vegetable production, reducing food waste and food miles, using less water than soil-based production, and creating new opportunities for entrepreneurs and workforce development.

A wide-range of CEA growing systems are being considered (Newbean Capital, 2015), but the three most commonly proposed for metropolitan areas are temperature-controlled greenhouses with supplemental lighting (GH-SL), plant factories (PF) with sole source lighting (SSL, i.e., no sunlight) and vertical farms (VF; multi-level buildings with windows and supplemental light (SL)[1]; Kozai, Niu, & Takagaki, 2015). CEA as an urban food production method, contributor to local food systems, and municipal investment strategy, however, is yet to be proven. Examples exist of commercially viable soil-based metro farms and apparently-successful metro-based GH operations, but neither the financial feasibility nor the scalability of metro-based CEA, particularly for plant factories, has been systematically addressed by previous research. The extent to which a city's demand for vegetables can be produced within its boundaries using CEA systems is yet unanswered. To fulfill the potential of metro CEA, a systems approach to analysis of the economic, social, and ecological footprint plus empirical information about the potential outcomes of its implementation is needed. Such efforts will deliver critical analysis and decision support tools to facilitate strategic investments in metro CEA as a key component of urban food supply chains. The potential benefits of metro CEA include lower transportation costs, reduced product waste, and job creation but must be assessed and also weighed against potentially higher land, labour, water, and energy costs and compared with field-based production methods. A supply-chain approach is useful to compare the economics and greenhouse gas emissions, energy use, and water use of representative conventional and metro-based CEA supply chains.

Our principal objective is to compare the economic and environmental performance for representative conventional (field-based) and CEA supply chains for leaf lettuce, which is a major vegetable crop with a production value of more than $850 million in 2015 (USDA, 2017) to two metropolitan areas in the US: New York City and Chicago. Although many CEA operations produce greens targeted to specialty markets, the comparison to conventional leaf lettuce is relevant because some CEA operations aspire to compete with supply chains using conventional production (Johnny Bowman, Edenworks, personal communication). We document and integrate information about production, processing, transportation and other marketing costs and input use for delivery to the ultimate consumers in these two metropolitan areas for both the conventional field production and representative configurations of two types of metropolitan-based CEA supply chains, greenhouses (GH) and plant factories (PF). This supply-chain analysis includes fixed costs, land, transportation, labour, energy, and other inputs required in production, processing, transportation and distribution. For the CEA production component, the analysis builds on energy-modeling analyses that incorporate relevant biological, lighting and other parameters for the specific locations (Harbick & Albright, 2016).

Although a number of previous studies have examined the environmental impacts of lettuce supply chains (e.g., Emery & Brown, 2016; Rothwell, Ridoutt, Page, & Bellotti, 2016), we are not aware of any previous study that has compared both landed costs and environmental outcomes of lettuce supply chains to major US urban areas. Thus, our analysis provides a much-needed comparative assessment of conventional and metropolitan-based agricultural supply chains for a key vegetable crop and provide a framework and example for future assessments of other food products. This information can lead to more informed decisions by potential investors, consumers and metropolitan policy makers with regard to the future configuration of urban food supply chains. We analyze "baseline" CEA supply chain performance based on current industry average performance and then assess a "best case" scenario with improved productivity and lower costs.

2 Literature Review

Few studies have evaluated the landed cost of lettuce from alternative supply chains to US metropolitan areas. Eaves and Eaves (2018) compared the profitability of producing lettuce in a greenhouse (GH) versus what they describe as a vertical farm (VF) but which operates similar to a multi-level plant factory (PF) to supply product to Québec City. They found that despite large differences in the composition of the investment (higher for the VF) and operating costs (higher for the GH), the overall production cost difference was small. Production of 1 kg of lettuce cost \$4.66 and \$4.51 (US dollars) in the GH and VF, respectively, a difference of about 3%. The authors did not examine the landed cost because they assumed that delivery processes and costs would be the same given their assumptions about the production location. This study utilised methods other than ASHRAE standard calculation methodologies for modeling energy consumption (a simplified spreadsheet model), which only approximates the complex energy flow dynamics.

A large number of studies have evaluated the environmental impacts of alternative lettuce production techniques and supply chain configurations. Most of these studies have used Life Cycle Assessment (LCA) methods that are commonly used to examine the environmental impacts of food supply chains (e.g., Notarnicola et al., 2017; Stoessel, Juraske, Pfister, & Hellweg, 2012). LCA methods typically account for resource use and outputs from production, but also those "embodied" in production inputs, equipment and structures. Although there are international standards for such studies (ISO 14040 and ISO 14044) their empirical implementation varies—often considerably—in terms of system boundaries, data inputs, computational methods and results.

A number of LCA studies exist for lettuce products with differing assumptions about the nature of production and the supply chain. Emery and Brown (2016) compared the production and delivery of lettuce from a commercial California-based field growing operation with a community garden approach to supply the Seattle, Washington market. They concluded that CO_2 emissions per unit for production and delivery were significantly lower (in fact, negative) for the community garden, although they did not consider the "embodied" costs of inputs. Hospido et al. (2009) examined field lettuce and greenhouse (GH) lettuce production systems supplying a retail distribution centre in the UK, using production locations in the UK and Spain. Emissions of CO_2 and cumulative energy demand from non-renewable sources were as much as 10 times larger for GH production systems, although water use per unit of production was only 40% of that for field production in the GH. These results suggest trade-offs between different production and distribution systems depending on the environmental indicators assessed. Rothwell et al. (2016) examined the CO_2 emissions and water use of lettuce production and distribution systems to supply the Sydney, Australia market. They compared three field production techniques and locations with two greenhouse production systems within 60 km of the central produce market. Large-scale field production located more than 900 km from Sydney had the lowest CO_2 emissions per unit for the *production* of 1 kg lettuce, but local lettuce had only 50% of *total* CO_2 emissions per unit including transportation for lettuce delivered to the central market. This was because emissions due to transportation were 2.5 times those for production for the large-scale production system. The large-scale field system also had the largest water use per kg lettuce. A GH production system located at 39 km from the central market had the lowest water use per kg lettuce produced, but the highest delivered CO_2 emissions.

Because the technology is newer and there are fewer commercial operations, analyses of the environmental impacts of plant factories (PF) are limited. Shiina et al. (2011) reported high levels of CO_2 emissions per unit product for two PF configurations producing lettuce and spinach. Graamans et al. (2018) undertook detailed energy and water modeling of greenhouses and potential PF configurations located in the Netherlands, Sweden and the United Arab Emirates, noting that although there are regional differences, PF production required significantly more purchased energy per unit of product than production in greenhouses.

The limited coverage of previous studies is due in part to the challenges associated with compilation of data for the assessment of what are typically many possible production and supply chain configurations. In addition, we noted no previous studies have simultaneously evaluated the environmental and cost components, which will be key information to make informed judgments about which configurations are appropriate and(or) how existing configurations might be transitioned to reduce environmental impacts while maintaining profitability.

3 Methods

Our overall objective is to compare the Cumulative Energy Demand (CED), Global Warming Potential (GWP), Water Use (WU) and Total Landed Cost (TLC) of 1 kg of saleable leaf lettuce delivered to a representative wholesale market location in both New York City and Chicago from a conventional (field-based production) supply chain and two types of CEA-based supply chains. Using the terminology employed in Life Cycle Assessment studies, we adopt a cradle-to-wholesale system boundary (Fig. 1). We omit analysis of the processes after delivery to the wholesale market under the assumption that differences in costs and environmental outcomes for the different production systems would be small after wholesale delivery. The functional unit for comparison is 1 kg of saleable lettuce delivered to a major wholesale produce market in each of the two cities.

For the purposes of assessing cost and environmental impacts, we adopt a simplified version of a Life Cycle Inventory (LCI) approach, that is, the "detailed tracking of all the flows in and out of the product system,

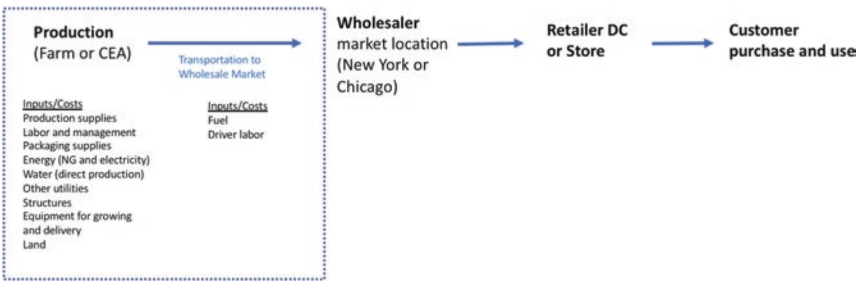

Fig. 1 System boundary for analysis of costs and environmental impacts of three lettuce supply chains. (Source: Authors)

including raw resources or materials, energy by type, water, and emissions to air, water and land by specific substance" (Athena Sustainable Materials Institute, 2017). Specifically, we account for inputs used in direct production but not those resources and impacts embodied in the production of the inputs. We define the lettuce production systems as follows. Conventional field-based leaf lettuce production is assumed to occur on 101 ha (250 acres) of an approximately 600-ha (1500-acre) farm in the Salinas Valley of California, which is the major lettuce-producing location for the US. The assumed yield is approximately 10,600 kg per acre per cropping cycle, about 900 cartons of lettuce packed for shipment. (Typically, there are two cropping cycles per year in the Salinas Valley.) We assume that 30% of the shipped production is not saleable upon arrival, based on industry estimates of shrink. The total production per acre per year is about 1800 cartons, considerably less than the quantities produced by GH and PF, which operate throughout the year. The GH production system assumes the use of a Nutrient Film Technique (NFT) growing system, a freestanding gable greenhouse with a total area of approximately 4460 m^2 (48,000 ft^2) and a net production area of 4000 m^2 (43,200 ft^2) with glass glazing material and artificial lights operated 2575 hours per year for NY, or 2856 hours per year for Chicago, based on 418 HPS luminaires of 1000 W. The PF system assumes an insulated warehouse-type structure with 10 production levels that result in the same total yield as the greenhouse, with a total area of 803 m^2 (8640 ft^2) based on one-tenth of the net production area of the greenhouse and 50% of total required space used for production. The GH and PF operations are non-automated systems assumed to be located in the relevant metro area at a location used by an existing CEA operation, although a peri-urban location is more consonant with the land requirements for GH and PF of the assumed production area. We choose a location for the New York CEA operations very close to the wholesale market and a location for the Chicago CEA operations farther away from the wholesale market to highlight the trade-offs in land versus transportation costs for urban and peri-urban production locations. Additional description of the production systems is provided in Table 1.

Table 1 Selected characteristics of field, CEA GH and CEA PF operations analysed

Production system	Field	GH	PF
Land area for production, ha	101.00	0.45	0.08
Land area for non-production,[a] ha	0.00	0.24	0.24
Total land area, ha	101.00	0.69	0.32
Cropping frequency analysed	1 crop (summer)	Continuous	Continuous
Production amount analysed,[b] kg	7144	454,685	454,685
Location of facility serving New York City	Salinas, CA	Bronx, New York	Bronx, New York
Location of facility serving Chicago	Salinas, CA	Northern Indiana	Northern Indiana
Distance from New York City wholesale market, km	4825	3.5	3.5
Distance from Chicago wholesale market, km	3570	75	75
Land value in New York area, $/ha	–	5,868,748	5,868,748
Land value in Northern Indiana, $/ha	–	753,282	753,282
Land rental cost in Salinas Valley, $/ha	3336	–	–

Source: Authors' own calculations and assumptions
[a]Non-production area is used for cooling, packing, office facilities and parking
[b]For Field production, this is calculated as harvested yield of 10,206 kg less 30% shrink in transit

3.1 Landed Costs

Production costs for field-based lettuce are based on Tourte, Smith, Murdock, and Sumner (2017), which provides detailed cost information for production supplies, packaging, labour, structures and equipment. Transportation cost calculations are based on diesel fuel costs for a tractor-trailer rig loaded with 900 cartons of lettuce achieving a fuel efficiency of 3 km/litre (7 miles per gallon) and requiring 33 hours of driver labour to travel 3570 km (2218 miles) from Salinas to the Chicago International Produce Market and 44 hours of driver labour to travel 4825 km (3000 miles) from Salinas to the Hunt's Point Produce Market in the New York City metropolitan area. Transportation costs assume that a backhaul to California is available for 75% of trips delivering lettuce from the field production operation. Transportation costs also include an estimate of overhead costs in addition to fuel and driver labour. Water use is reported as 1440 m^3 for production of 10,600 kg, or about 135 litres per kg of lettuce produced. (Additional details are provided in Tables 7, 8, and 9.)

Production costs for the CEA GH and PF are derived from information in the Lettuce Interactive Business Tool (Gómez, Mattson, & Nishi, 2017) and Eaves and Eaves (2018), both of which also include costs of production supplies, packaging, labour, structures and equipment. Production supplies include seeds, propagation cubes, beneficial insects, fertilisers, and sanitisers used in direct production. For the GH operation, costs for bio-based fungicides and pesticides and biological control of insects are also included, although they are not in the case of the PF because this system operates without direct access to the outside. Production labour includes that for seeding, transplanting, harvesting and packaging. Additional labour is required for delivery to markets. Production management includes a production manager and administrative support, and a single sales manager is responsible for marketing. A salaried executive position is assumed to oversee all operations. Packaging costs are assumed to be similar for the three systems, using wax cardboard cartons with a capacity of approximately 11 kg. Utilities other than energy and water include sewer, landline telephones and cell phones. Miscellaneous costs include those for advertising and promotions, office supplies laboratory testing, postage, software, professional services (legal and accounting) and participation in trade shows. Water use is assumed to be about 21 litres per kg for the operation of the growing systems (Harbick & Albright, 2016), which does not include the additional water required for evaporative cooling. (Additional details are provided in Table 10.)

Energy costs often account for more than one-third of the total costs for a CEA operation, and likely constitute a main cost difference between field, GH and PF operations (Eaves & Eaves, 2018). In contrast to many previous studies, we used detailed energy modeling simulations specific to the assumed GH and PF structures to determine energy use and related costs for the both operations. EnergyPlus (Crawley et al., 2001) is an energy modeling simulation engine that implements the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) heat balance method (ASHRAE, 2017). It is commonly used for buildings in the commercial sector but was modified to facilitate the modeling of CEA buildings (Harbick & Albright, 2016). To estimate the annual energy use, EnergyPlus calculates loads and system response on sub-hourly time steps using building parameters and Typical Meteorological Year (TMY3; Wilcox & Marion, 2008) hourly weather data. Warehouse building parameters reflect the warehouse type of Department of Energy (DOE) commercial reference buildings, which follow ASHRAE 90.1–2004 standards (ASHRAE, 2004). Heating is assumed to use a natural gas boiler. Cooling the GH is assumed to require evaporative pads, whereas a chiller unit is required for the PF. The required amounts of natural gas (m^3) and electricity (kWh) are calculated for each month based on changes in climate during the course of a year. Electricity use includes lighting and ventilation but not water pumping. The GH CED and GWP values assume DLI control using LASSI (Albright, Both, & Chiu, 2010), which is close to day-wise optimal. Threshold or timer-based lighting control, such as available from greenhouse controls companies, would incur higher CED/GWP for the same yield. The same value of efficacy of supplemental lighting was used for both the GH and PF. Costs for natural gas are calculated based on the reported unit costs per m^3 of natural gas for commercial use from the US Energy Information Administration. Electricity costs are based on a per state-specific average industrial rates (for New York and Indiana) per kWh used, plus a “demand charge” based on the peak number of kW used across all months in the year. Additional assumptions related to energy modeling are presented in Table 6.

The transportation costs for the metro-based GH and PF assume production in locations currently used by CEA operations in both Chicago and New York City, located at distances of 75 km and 3.5 km from the wholesale markets of these two cities, respectively. The difference in distances traveled within the metropolitan area can provide insights regarding the intra-metropolitan-area location decision for CEA operations. We assume 10 round-trip deliveries per week to the wholesale market with a refrigerated reefer truck. (Additional details are provided in Table 12.)

Individual cost components for CEA structures and equipment are difficult to obtain and extant information shows considerable variation among these components. We use a simplified industry rule of thumb of \$538.3/m^2 (\$50/ft^2) for the production-related area of the GH and PF to calculate structure and equipment costs. Our assumed value is a commonly-used average unit cost, although this this can vary based on location and GH or PF configuration. We subsequently evaluate the impact of this assumption with scenario analysis using an industry-indicated minimum value, to represent a scenario for this cost component.

Another major cost is for the land required for the CEA operation, for non-production space (e.g., restrooms, administrative offices and parking). Following Eaves and Eaves (2018), we assume that non-production land area is equal to 0.56 times the area of the production facility. Overall, the PF require about half the land area required for a GH for the production levels assumed. The lower land requirement (and therefore cost) and higher energy use (for both lighting and cooling) for the PF are the key cost components for comparison with GH operations. We calculated the cost of purchasing the land required for operating the two types of CEA operations based on per-acre values of commercial land parcels offered for sale in the two focal metropolitan regions.

To calculate the annualised cost of investment in CEA operations, we summed the total value of investment in structures, equipment and land and then assumed that this entire amount would be financed with a ten-year loan at an annual interest rate of 6.2%, which is the weighted average cost of capital (WACC) for US farming or agriculture operations reported by Damodaran (2018) for January 2018. Although this assumes no equity investment in the operation, this is roughly equivalent to charging a 6.2% opportunity cost per year for equity invested in the business. (Additional details are in Table 11.)

3.2 Cumulative Energy Demand (CED)

CED is expressed in MJ of total energy per kg of functional unit (e.g., 1 kg saleable lettuce delivered to the wholesale market). This comprises the energy used for the production, transport, and the use of production inputs including structures and equipment. For field production, this includes the energy in diesel and gasoline used in farm equipment and the electricity used in pumping water used in production. Diesel and gasoline use are reported directly in Tourte et al. (2017) but because gasoline use is quite small (less than 8 litres) we converted only the diesel fuel use to its energy equivalent using the standard factors of Btu per litre and MJ per Btu. Electricity for water pumping is calculated based on the diesel equivalent required to pump an acre-inch of water and the equivalent number of kWh per unit of diesel fuel. Energy use for GH and PF operations was calculated based on the energy modeling approach discussed above and includes energy in natural gas used for heating and electricity for lighting and cooling. Energy used in transportation is calculated based on the estimated amount of diesel fuel required to transport lettuce from the production location to the wholesale markets in New York and Chicago. (Additional details are in Tables 13 and 14.)

3.3 Global Warming Potential (GWP)

GWP is expressed in terms of kg CO_2 equivalent per kg of functional unit (e.g., 1 kg lettuce delivered to the wholesale market). This comprises the CO_2 generated for the production, transport, and the use of production inputs including structures and equipment. Similar to a number of previous studies, we ignore the potential impacts of changes in soil carbon for the field production operation. Natural gas (NG) use is converted to CO_2 equivalent using a fixed conversion factor of 0.0503 MT CO_2 per GJ energy in NG. Electricity CO_2 is based on total kWh used in production multiplied by state-specific emissions factors for California (Field), New York and Indiana obtained from the US Energy Information Agency. Emissions from transportation are calculated based on the diesel fuel required to transport lettuce from the production site to the wholesale markets, using a standard diesel conversion factor of 2.7 kg CO_2/litre (10.21 kg CO_2/gallon). (Additional details are in Table 15.)

3.4 Water Use (WU)

Water use is expressed in terms of litres water per functional unit (e.g., 1 kg lettuce delivered to the wholesale market). This comprises only the water used for the production process, not water for evaporative cooling or in transportation. As noted above, water use is estimated as 20.9 litres/kg for both the GH and PF operations (Harbick & Albright, 2016) and a 135.4 litres/kg for field-based operations in California (Tourte et al., 2017).

3.5 Scenario Analysis

Many assumptions are required to assess the comparative economic and environmental assessment of the three systems under study. Key assumptions used in our study are based on published data or industry sources that are specific to the supply chains analyzed, such as product yields, input use (especially energy), labor costs and land costs. Although comprehensive sensitivity analysis is often recommended for LCA studies (Bjorklund, 2002; Beccali et al., 2010), we undertake a less broad *scenario analysis* to assess whether our findings for the landed costs are robust. We compare our estimate of average landed costs for the CEA supply chains as described above to a "best case" scenario that assumes the best currently feasible productivity and lowest costs based on published literature and industry contacts. Specifically, for both the CEA operations in both cities, we assume 20% increase in yields per growing area, and a 40% lower cost for structures and equipment ($322.9/m^2 rather than $538.2/m^2), based on information from industry contacts. For New York, we assess a lower land value in New York City, using the value for the Chicago-area operation, which is consistent with locating further from the New York wholesale market (which also implies higher transportation costs for the "best case"). We also assume lower per-kWh electricity costs in New York by assuming the lower value reported for

Indiana. As noted above, we assumed energy-optimizing for the GH lighting in the average performance case and this assumption is applied in the “best case” scenario also. Although this approach does not allow us to assess the distribution of costs or for any possible (e.g., optimal) configuration of a CEA operation, it provides substantive evidence about the likely comparative performance with field-based production for many configurations of CEA operations.

4 Findings

4.1 Landed Costs Findings

Our analysis indicates that the total landed costs for CEA supply chains to provide lettuce to the Chicago and New York City metro areas are markedly larger than those with field-based production in the Salinas Valley of California (Table 2). Lettuce produced and delivered from the GH has a landed cost 158% to 163% higher than that of field lettuce from California, despite much higher transportation costs for the field-produced lettuce. Lettuce produced in a PF has a landed cost 153% to 157% higher than field produced lettuce. The differences between CEA supply chains and field production are smaller in the Chicago market (despite lower transportation costs from California) due to lower land values and lower rates per kWh for electricity. Similar to Eaves and Eaves (2018), we find that GH and PF can have similar landed costs in both locations; higher energy costs for PF are offset by lower land requirements.

In addition to the overall cost differences, the structure of costs for these supply chains are quite different. Field production costs are quite low and packaging (including harvesting) and shipment costs account for 67 to 70% of landed costs, whereas they comprise less than 12% of landed cost for GH and PF operations. For the CEA GH, labour and management, energy and structures account for more than 80% of landed costs, and transportation costs are minimal. Labour costs are notably higher for CEA supply chains, in part due to additional labor required for

Table 2 Total landed cost for delivery of 1 kg lettuce to wholesale produce markets in New York City and Chicago from field-based production, a CEA greenhouse (GH) and a CEA plant factory (PF)

	New York City wholesale market, Hunt's point			Chicago international produce market		
Cost category	Field	GH	PF	Field	GH	PF
	$/kg delivered saleable lettuce					
Production supplies	0.17	0.29	0.27	0.17	0.29	0.27
Labour and management	*0.09*	*4.31*	*4.31*	*0.09*	*4.31*	*4.31*
Packaging	0.98	0.76	0.76	0.98	0.76	0.76
Utilities other than water and energy	0.00	0.03	0.03	0.00	0.03	0.03
Miscellaneous	0.50	0.10	0.10	0.50	0.10	0.10
Water (direct production only, not evaporative cooling)	0.02	0.08	0.08	0.00	0.08	0.08
Energy for operations	*0.04*	*0.46*	*1.36*	*0.04*	*0.41*	*0.89*
Structure, equipment, land, growing and delivery equipment	*0.08*	*2.05*	*0.90*	*0.08*	*1.00*	*0.40*
Transportation from production to market (fuel)	*1.17*	*0.00*	*0.00*	*0.87*	*0.04*	*0.04*
Total landed cost	3.04	8.09	7.82	2.72	7.03	6.89

Source: Authors' own calculations

Note: *Field* indicates field-based production in Salinas Valley, California, *GH* indicates a CEA greenhouse located in the same metropolitan area as the wholesale market, and *PF* indicates a CEA Plant Factory located in the same metropolitan area as the wholesale market production, but also due to the administrative staff required for management and marketing that are typically lower and spread over much larger volumes for field-based operations. These results suggest that greater productivity of CEA GH labour and utilities—as well as locations that optimise trade-offs between land and transportation costs—will be necessary for costs to be more comparable between field and CEA lettuce supply chains.[2]

4.2 Environmental Impacts Findings

The environmental impacts analysis indicates that CEA supply chains have larger energy use and greenhouse gas emissions than those based on field production (Table 3). GH supply chains have markedly lower energy demand and GWP than PF supply chains in both studied locations, primarily due to the energy required for lighting and cooling. GH supply chains delivering to New York have estimated GWP only 3% larger than field-based supply chains, but the difference is much larger in Chicago due to higher energy use in production and longer transportation distances. More generally, CED and GWP per kg lettuce for the GH and

Table 3 Environmental impacts for the delivery of 1 kg lettuce to wholesale produce markets in New York City and Chicago from field-based production, a CEA greenhouse and a CEA plant factory

	New York City wholesale market, Hunt's point			Chicago international produce market		
	Field	GH	PF	Field	GH	PF
CED (MJ/kg lettuce)	18.52	23.83	42.52	14.24	29.19	44.74
GWP (kg CO_2-eq/kg lettuce)	1.29	1.33	2.72	0.99	2.07	4.62
WU (liters/kg lettuce)	201.43	20.86	20.86	201.43	20.86	20.86

Source: Authors' own calculations

Note: *Field* indicates field-based production in Salinas Valley, California, *GH* indicates a CEA greenhouse in the same metropolitan area as the wholesale market, and *PF* indicates a CEA Plant Factory in the same metropolitan area as the wholesale market the PF for New York are lower than for the same supply chains serving Chicago due to the assumed shorter transportation distance and lower energy use for heating, cooling and lighting. The model results show that the average CED and GWP values are lower for field-based production than for CEA. However, during the months of June, July, and August, the CED and GWP values for CEA are only 28 to 33% of the average values, bringing them well below the field-based values. CED and GWP values for CEA in non-summer months are high, but this is also during a period of the year when field-based product is much less available. Water use for production (but not cooling) is significantly larger per kg lettuce for the field-based production system. Overall, these results suggest that no one production system and location will always be preferred for all environmental outcomes.

4.3 Comparison to Previous Results

A number of previous studies have assessed the environmental impacts of lettuce supply chains, often using LCA methods. Our results can usefully be compared to the results of the previous studies, although the basic method, system boundaries and data sources often differ (Table 4). In general, our assessed values for the three production systems are consistent with those reported in previous studies. Our field production system reports higher CED than previous studies, in part because of the long distances the product is transported. Our GWP values are consistent with previous study values, despite that fact that most previous studies accounted for the embodied effects of inputs, structures and equipment. Similarly, our CED values for GH production appear to be lower than those of previous studies because those studies considered embodied energy. We report values of GWP for the PF consistent with previous studies.

Table 4 Comparison of environmental outcomes from current and previous studies of lettuce production and supply chains

Production setting	CED (MJ/kg)	GWP (kg CO_2-eq/kg)	WU (liters/kg)	References
Field	*14.24–18.52*	*0.99–1.29*	*135.4*	*Author calculations*
Literature field, including post-farm	5.67–7.00[a]	0.25–3.75	42–97	Bartzas, Zaharaki, and Komnitsas (2015), Emery and Brown (2016), Gunady, Biswas, Solah, and James (2012), Rothwell et al. (2016), Stoessel et al. (2012)
Literature field, production only	2.98	0.14–2.30	83–160	Bartzas et al. (2015), Emery and Brown (2016), Gunady et al. (2012), Foteinis and Chatzisymeon (2016), Hospido et al. (2009), Romero-Gámez, Audsley, and Suárez-Rey (2014), Rothwell et al. (2016)
Greenhouse (GH)	*23.83–29.19*	*1.33–2.07*	*20.9*	*Author calculations*
Literature GH, including post-farm	38.67	0.52–2.62	20–36	Hospido et al. (2009), Rothwell et al. (2016)
Literature GH, production only	3.15–3.47	0.21–2.46	–	Bartzas et al. (2015), Hospido et al. (2009), Rothwell et al. (2016)
Plant Factory (PF)	*42.52–44.74*	*2.72–4.62*	*20.9*	*Author calculations*
Literature PF, production only	–	2.30–6.20	–	Shiina et al. (2011)

Source: Authors' own calculations and cited references
[a]Non-renewable energy only for maximum value

4.4 Scenario Analysis Findings

As is the case with most studies comparing the costs and environmental outcomes of alternative supply chain configurations, the nature of these configurations (size, location, and production technology) can vary considerably. Our "best case" scenario represents likely lowest cost values for both GH and PF in the two locations. Assuming the productivity and costs for the "best case" scenario considerably lowers landed costs for both GH (20 to 31%) and PF (17 to 27%) but this does not change the basic result that field production in California is far less costly (Table 5). This suggests that our findings with regard to the average assumed costs and productivity are likely to be robust. However, lower cost for land purchase do affect the relative costs of GH and PF (Table 5). The best case scenario would reverse the cost rankings, with GH operations indicating lower costs than PF. This shift occurs because the larger land footprint for the GH makes its landed cost more sensitive to assumptions regarding land values.

Table 5 Comparisons of the baseline and best case total landed cost of 1 kg lettuce delivered to wholesale markets in New York and Chicago metropolitan areas

Location, CEA operation	Baseline scenario	Best case scenario	Best case less baseline scenario	Field production to indicated location	Best case less field production
	$/kg delivered lettuce				
New York				3.04	
GH	8.09	5.59	−2.50		2.55
PF	7.82	5.69	−2.13		2.65
Chicago				2.72	
GH	7.03	5.63	−1.39		2.91
PF	6.89	5.69	−1.20		2.97

Source: Authors' own calculations

Note: All values in $/kg lettuce delivered to wholesale market in each metropolitan area. The Baseline Scenario represents average CEA performance in the two metropolitan areas, as reported in Table 2. The Best Case Scenario modifies assumptions to represent current best possible performance. For New York, the Best Case Scenario assumes the land value, electricity rates and transportation costs for Chicago. For both locations, the unit costs for structure and equipment is assumed to be 40% lower than in the Baseline and productivity per unit production area is assumed to be 20% higher

5 Discussion

Our analyses are broadly consistent with evidence available from the limited previous work on similar topics. Field-based lettuce supply chains have lower landed costs because of lower per kg land, equipment, structure, labour, and energy inputs costs, despite much higher transportation costs due to the distance from wholesale market customers. Thus, the underlying cost structures for field-based and CEA supply chains are quite different, and within relevant potential ranges for improvement, it appears that at present there are limited management options for CEA operations to achieve costs approaching those of field-based operations. Labour is a substantial cost in CEA production and opportunities to lower costs with as automation technologies are further developed should be included in future analyses. However, we acknowledge that comparable or lower landed costs alone are not required for a successful CEA business, especially if consumers are willing to pay price premiums either because of the "local" nature of the food or its perceived environmental friendliness. Current CEA businesses producing lettuce exist in many US metropolitan areas, and although there has been no formal study of their financial performance, there is continued interest in CEA investment, which suggests the potential for profitability despite much higher costs.

Our analyses also shed light on the relative costs of the two types of CEA operations. Similar to Eaves and Eaves (2018), we found that under our baseline conditions, PF can have comparable or lower costs compared to GH. The underlying rationale is that higher energy costs are offset by lower land costs due to the smaller footprint required in a PF to achieve the same level of production. However, this means the decision to invest in GH versus PF is sensitive to the costs of both energy and land, as well as the cost per unit area for structures and equipment.

Combining the analysis of economic and environmental outcomes is not common in previous LCA-based studies comparing the performance of different production systems. However, our analysis suggests that informed decision making on the part of supply chain actors and consumers can benefit from information about both of these dimensions because the two sets of indicators will not result in the same rank for the alternatives. On a cost basis—i.e., assuming that buyers consider the product of different systems as essentially identical—field-based supply chains are preferred. From an environmental perspective, CEA have considerably higher CED and somewhat higher GWP, but these are much smaller for GH operations than for PF despite roughly similar landed costs. Locating the CEA operation further from urban customers tends to reduce costs (due particularly to lower land values) but increases transportation costs and negative environmental impacts. However, both CEA systems use far less water per unit than field-based production. Thus, buyers and ultimate consumers may face relevant trade-offs between cost and environmental outcomes, and the environmental outcomes themselves can be sensitive to factors such as location within a metropolitan area for CEA operations. The mix of fuels used to generate electricity can also affect the nature of GWP, although in our study such differences were of limited importance.

Although our findings are a substantive contribution to the knowledge of the potential role and impacts of CEA supply chains serving metropolitan areas, our work could be extended in five principal ways. First, consideration of the embodied energy and environmental effects through LCA would allow more direct comparisons with similar studies using that approach and provide a more comprehensive estimate of environmental impacts. Second, additional scenario analysis would help to identify more specifically the importance of individual assumptions about costs and environmental impacts. Third, further work could usefully identify the scale, configuration and location of operations that minimise total cost within a given metropolitan area. Costs appear particularly sensitive to land values, so analysis of the location within a metropolitan area and of rooftop greenhouse operations (e.g., Nadal et al., 2017) would be of particular relevance. Fourth, additional cities could be analysed, because the climate conditions were relatively similar in New York and Chicago (New York is ASHRAE climate zone 4A, and Chicago is 5A), and the equipment configurations and energy use would be quite different in drier and hotter climate zones. Finally, additional assessment of profitability (rather than just cost) through consideration of product selling prices, consumer perceptions of, and preferences for, field and CEA lettuce, and revenue streams would provide an improved context for assessing the potential of CEA operations to provide lettuce (and other leafy greens) to metropolitan areas of the US.

6 Conclusions

Our analysis of three supply chains to provide lettuce to two US metropolitan areas indicates that at present the lowest landed-cost option is a supply chain based on field production rather than non-automated GH or PF in urban locations. Because the landed cost differences are larger (nearly double even in the "best case" scenario) this suggests that modifications to reduce the costs of non-automated, urban CEA systems to the level of field production will present major challenges. In addition, the studied configurations and locations of CEA supply chains operating within metropolitan urban areas may have higher energy use and GWP, although all the CEA operations analysed used less water per kg of lettuce than field production. Thus, the rankings based on costs and environmental outcomes do not always align. Although the configuration of a CEA supply chain affects environmental impacts, it is inappropriate to claim that "local" CEA supply chains for lettuce are broadly more environmentally friendly than field-based production, even when field lettuce is shipped long distances. Additional analyses of alternative scales, locations and more automated CEA configurations as well as seasonal field-based production closer to metropolitan areas could provide further insights to supply chain actors.

The future development of CEA supply chains is likely to continue despite higher costs, due to the ability of CEA systems to control selected quality aspects for leafy greens (e.g., production of micro-greens for the high-end restaurant segment) and their flexibility as suppliers to certain market segments. Although it is beyond the scope of our analysis, differentiation of CEA-produced leafy greens from those produced by more conventional field-based methods to receive substantially higher prices would seem necessary for business success given much higher costs. As the number of CEA operations increases, additional evidence will become available about their role and status in supplying metropolitan food needs. Further analysis of the scaling-up effects (potentially both positive through agglomeration economies and negative through competition for scarce resources) will be appropriate as growth proceeds.

Appendix

Table 6 Characteristics and assumptions for energy modeling of GH and PF production systems

Energy system characteristic or assumption	Value	Units	Comment or value
GH production area	4460	m^2	
GH growing area	90%		% of total GH production area
PF production area	802	m^2	
PF layers	10		
PF growing area	50%		% of total PF production area
New York TMY3 station			LaGuardia airport
Chicago TMY3 station			Midway airport
Day temp set point	24	°C	
Night temp set point	19	°C	
RH low set point	50%		
RH high set point	70%		
GH transmittance (frame/glazing)	70%		
Shade cloth reduction	60%		
Supplemental light efficacy[a]	2.1	µmol/J	
Infiltration rate	0.5	ACH	
DLI target	17	$Mol/m^2/day$	
Heating system			Natural gas boiler
GH cooling system			Evaporative pads
PF cooling system			Chiller
Heating efficiency	80%		
Evaporative pad effectiveness	80%		
Chiller COP	5.5		
Average crop spacing	48	$Head/m^2$	

Source: Authors' own calculations and assumptions

[a]The same efficacy value is assumed for both the GH and PF. The specified value is the best efficacy value for High Pressure Sodium (HPS) lighting often used in GH and among the higher efficacy values for broad-spectrum LED lighting used in PF

Table 7 Detailed calculations for field-based lettuce production operating costs per acre

Category	Quantity used	Units of quantity	Price/unit	Units of price	Cost/acre, $
Production supplies					*1234*
Seed (package)	157.50	Thousand	1.4	/thousand	221
Herbicide	1.00	Acre	92	/acre	92
Insecticide	1.00	Acre	282	/acre	282
Fertiliser					
Compost	2.00	Ton	55	/ton	110
Potassium sulphate	150.00	Lb	0.86	/lb	129
7-7-0-7	30.00	Gal	2.03	/lb	61
28-0-0-5	20.00	Gal	2.28	/lb	46
20-0-0-5	37.00	Gal	1.73	/lb	64
Fungicide	1	Acre	230	/acre	230
Packaging costs					*6975*
Harvest-field pack	900	Carton	6	/carton	5400
Cool/palletise	900	Carton	1	/carton	900
Market/sales fee	900	Carton	0.75	/carton	675
Miscellaneous costs					*1173*
Soil sample	1	Acre	8	/acre	8
Laser level	0.5	Acre	165	/acre	82.5
Haul/spread compost	1	Acre	20	/acre	20
List bed 3-row 80″	1	Acre	23	/acre	23
Ground application	1	Acre	15	/acre	15
Plant thinning—automated	1	Acre	115	/acre	115
Air application	3	Acre	20	/acre	60
Pest control advisor/ certified crop advisor	1	Acre	30	/acre	30
Machinery repair	1	Acre	165	/acre	165.0
Liability insurance	1	Acre	20	/acre	20.0
Food safety program	1	Acre	40	/acre	40.0
Regulatory program	1	Acre	40	/acre	40.0
Office expense	1	Acre	350	/acre	350.0
Field sanitation	1	Acre	12	/acre	12.0
Property taxes	1	Acre	28	/acre	28.0
Property insurance	1	Acre	2	/acre	2.0
Investment repairs	1	Acre	96	/acre	96.0
Interest on operating costs @ 4.5%	1.00	Acre	66	/acre	66
Production labour					*622*
Equipment operator labour	10.51	Hours	21.85	/hour	229.6
Irrigation labour	13	Hours	17.8	/hour	231.4
Non-machine labour	9.52	Hours	16.9	/hour	160.9
Utilities					*532*

(*continued*)

Table 7 (continued)

Category	Quantity used	Units of quantity	Price/unit	Units of price	Cost/acre, $
Water—pumped	14.00	Acre-inch	18	/acre-inch	252.00
Fuel—gas	2	Gal	3.25	/gal	6.5
Fuel—diesel	87.861	Gal	2.7	/gal	237.2
Lube	1	Acre	36	/acre	36.0
Miscellaneous costs					*2430*
Land rent	1.80	Acre	1350	/acre	2430

Source: Authors' own calculations and assumptions and Tourte et al. (2017)
Note: Yield per acre is assumed to be 900 cartons each weighing 11.4 kg (25 lbs), for a total weight of 10,631 kg less 30% shrink for 7144 saleable yield. One acre equals 0.4046 hectare

Table 8 Detailed calculations for field-based lettuce production structure and equipment costs per acre

Category	Investment cost, $	Annualised costs $/acre[a]
Structures	72,000	3
Shop building 2400 ft^2	72,000	3
Production equipment	559	3,059,790
Fuel tanks—overhead	1	**3,059,790**
Shop tools	1	10,975
Drip system	89	20,000
Sprinkler system	48	341,884
Sprinkler pipe	131	370,495
205HP crawler	74	1,139,000
Disc—offset 25′	19	350,000
Subsoiler—16′	15	48,769
Triplane—16′	9	42,454
Chisel—heavy 26′	18	38,000
Ring roller—heavy 18′	6	51,218
Lilliston rolling 3-row	4	15,552
Bed shaper 3-row	8	18,000
150HP 4WD tractor	48	44,412
Row crop planter	13	225,000
Cultivator 3-row	2	54,887
Fertiliser Bar 20′	2	9500
Drip tape laying machine 3-row	4	13,000
Pickup 3/4 ton	15	16,117
Saddle tanks 300 gallons	1	50,000
Spray boom 20′	1	1660
Ring-roller 25′	11	2900
Drip tape extraction sled	10	29,000
120HP 2WD tractor	29	30,000

Source: Authors' own calculations and assumptions and Tourte et al. (2017)
[a]Calculated using an assumption of 20% capital recovery per year, divided by 250 acres for two crops per year

Table 9 Detailed calculations for field-based lettuce transportation costs

Wholesale market area and cost category	Quantity	Units of quantity	Price/ unit	Units of price	Cost/ shipment
New York City area					*8329*
Fuel (diesel)	800	Gallons	2.96	$/gallon	2368
Driver labour	44	Hours	21.90	$/hour	964
Overhead and other costs			150%	% of direct	4997
Chicago area					*6184*
Fuel (diesel)	800	Gallons	591	Gals fuel	1751
Driver labour	44	Hours	33	Hours	723
Overhead and other costs			150%	% of direct	3710

Source: Authors' own calculations and assumptions
Note: One-way distance to New York is 3000 miles and to Chicago 2218 miles. Assumes a backhaul proportion of 75%, and fuel use of 5 miles per gallon of diesel fuel

Table 10 Annual operations costs for greenhouse and plant factory operations

Cost category	Units of quantity	Quantity used		Cost/year, $	
		GH	PF	GH	PF
Production supplies				*130,707*	*124,257*
Seed (package)	Packages	637	637	70,070	70,070
Horticubes	Cases	550	550	35,750	35,750
Beneficial insects	Packages	83	83	3320	3320
Fertiliser					
Blended mix	Pounds	7813	7813	7813	7813
$CaNO_3$	Pounds	7813	7813	3594	3594
Additions	Pounds	105	105	105	105
Fungicide/ pesticide	Gallons	105	0	6300	0
Sanitiser	Gallons	103	103	3605	3605
Sticky traps	Packages	5	0	150	0
Packaging costs				*346,105*	*346,105*
Box	Box	126,302	126,302	315,755	315,755
Labels	Roll	607	607	30,350	30,350
Miscellaneous costs				*46,900*	*46,900*
Advertising, mailings, flyers	Campaigns	1	1	200	200

(*continued*)

Table 10 (continued)

Cost category	Units of quantity	Quantity used GH	Quantity used PF	Cost/year, $ GH	Cost/year, $ PF
Continuing education	Meetings	40	40	10,000	10,000
Internet service	Months	12	12	2400	2400
Laboratory fees	Tests	1000	1000	20,000	20,000
Office supplies	Months	12	12	2400	2400
Postage	Months	12	12	2400	2400
Marketing materials & promotions	Promos	2	2	2000	2000
Record keeping	Months	12	12	3000	3000
Software	Programs	5	5	2500	2500
Subscriptions	Subscriptions	10	10	1000	1000
Marketing & trade shows	Trade show	2	2	1000	1000
Utilities other the energy and water				*12,960*	*12,960*
Mobile phones	Months	240	240	12,000	12,000
Telephone	Months	24	24	960	960
Labour and management				*1,961,041*	*1,961,041*
Seed/transplant/harvest/package	Hours	78,812	78,812	1,024,558	1,024,558
Delivering to market	Hours	9094	9094	109,124	109,124
Production management	Hours	6062	6062	78,812	78,812
Sales manager	Positions	1	1	75,000	75,000
Admin assistant	Positions	1	1	45,000	45,000
Executive level	Positions	1	1	100,000	100,000
Outside services	$	1	1	75,999	75,999
Fringe benefits	%	30%	30%	452,548	452,548
Water cost				*32,578*	*32,578*
Water for production (not cooling)	Gallons	6,031,727	6,031,727	32,578	32,578

Source: Authors' own calculations and assumptions

Note: Assumes that unit costs are not location specific (i.e., are the same for New York and Chicago). Yields for both GH and PF operations are 454,685 kg per year

Table 11 Total investment costs for structures, land and equipment for greenhouse and plant factory operations

	New York		Chicago	
Cost category	GH	PF	GH	PF
Structures	2400,000	632,160	2400,000	632,160
Production area, ft^2	43,200	4320	43,200	4320
Production levels	1	10	1	10
Non-production grow area, ft^2	4800	4320	4800	4320
Total production-related area, ft^2	48,000	8640	48,000	8640
Cost of structures & equipment, $\$/ft^2$	50	50	50	50
Ratio PF to GH Costs[a]	1.00	1.46	1.00	1.46
Land	4,077,410	1,931,405	523,355	247,905
Production area, ft^2	48,000	8640	48,000	8640
Factor for packing, parking and bathrooms	0.558	0.558	0.558	0.558
Parking, packing, bathrooms, ft^2	26,784	26,784	26,784	26,784
Total land area required, ft^2	74,784	35,424	74,784	35,424
Ft^2/acre	43,560	43,560	43,560	43,560
Acres required	1.72	0.81	1.72	0.81
Value of land, $/acres	2,375,000	2,375,000	304,843	304,843
Growing and delivery equipment costs	466,800	466,800	466,800	466,800
Back pack sprayer	1600	1600	1600	1600
Carbon dioxide generator	7680	7680	7680	7680
Cooler	20,000	20,000	20,000	20,000
Delivery truck with AC	110,000	110,000	110,000	110,000
Fertiliser mixing pump	480	480	480	480
Meters and sensors				
EC	2560	2560	2560	2560
pH	800	800	800	800
Thermometer	400	400	400	400
Monitors				
Humidity	480	480	480	480
CO_2	2000	2000	2000	2000
Growing system	320,000	320,000	320,000	320,000
Scale	800	800	800	800
Total structures, land and equipment	6,477,410	2,563,565	2,923,355	880,065
Annual cost, $/year	933,531	407,381	455,749	181,063

Source: Authors' own calculations and assumptions

Note: Annual cost assumes a 6.2% interest rate for 10 years based on Weighted Average Cost of Capital in farming and agriculture from Damodaran (2018)

[a]Assumes the ratio between GH and PF reported by Eaves and Eaves (2018)

Table 12 Detailed calculations for CEA lettuce transportation costs

Wholesale market area and cost category	Quantity	Units of quantity	Price/ unit	Units of price	Cost/ shipment
New York City area					*777*
Fuel (diesel)	312	Gallons	2.49	$/gallon	777
Chicago area					*20,449*
Fuel (diesel)	6909	Gallons	2.96	$/gallon	20,449

Source: Authors' own calculations and assumptions

Note: Labour costs are included in other operations costs, Table 10. One-way distance to New York is 2.1 miles (3.5 km) and to Chicago 46.5 miles (74.8 km). Deliveries are assumed to be made 10 times per week with a refrigerated reefer truck with diesel fuel use of 7 miles per gallon

Table 13 Energy use and cost calculations for New York metropolitan area greenhouse and plant factory operations

	Greenhouse				Plant factory			
Month, cost category	Heating (GJ)	Lighting (GJ)	Cooling (GJ)	Total energy (GJ)	Heating (GJ)	Lighting (GJ)	Cooling (GJ)	Total energy (GJ)
Jan	1006	648	14	1668	113	1119	457	1689
Feb	1258	425	13	1696	99	1011	411	1521
Mar	1017	310	14	1340	80	1119	459	1658
Apr	626	193	14	833	47	1083	445	1575
May	445	111	14	570	27	1119	461	1608
Jun	157	162	14	332	19	1083	453	1555
Jul	85	130	14	230	16	1119	480	1615
Aug	85	103	14	202	16	1119	474	1609
Sep	239	229	14	482	30	1083	452	1565
Oct	506	282	14	802	44	1119	462	1625
Nov	495	601	14	1109	66	1083	446	1595
Dec	830	681	14	1525	99	1119	458	1676
Total	6748	3876	165	10,789	657	13,177	5456	19,290
Natural gas (NG) cost								
GJ per MMBtu	0.948				0.948			
MMBtu	6396				622			
Mcf per MMBtu	0.964				0.964			
Mcf NG	6168				600			
NG cost, $/Mcf	6.79				6.79			
NG cost, $/year	41,878				4075			
Electricity cost								

(*continued*)

Table 13 (continued)

	Greenhouse				Plant factory			
Month, cost category	Heating (GJ)	Lighting (GJ)	Cooling (GJ)	Total energy (GJ)	Heating (GJ)	Lighting (GJ)	Cooling (GJ)	Total energy (GJ)
kWh per GJ		277.8	277.8	277.8		277.8	277.8	277.8
kWh used		1,076,534	45,841	1,122,375		3,660,208	1,515,586	5,175,794
Electricity cost, $/kWh		0.1060	0.1060	0.1060		0.1060	0.1060	0.1060
Electricity cost, $/year		114,113	4859	118,972		387,982	160,652	548,634

Source: Authors' own calculations and assumptions

Note: Costs for electricity will also include a "demand charge" for the GH calculated as 379 kW times 12 times $10.77 per kW, equal to $48,982 per year. The "demand charge" for the PF is calculated as 516 kW times 12 times $10.77 per kW, equal to $66,688 per year

Table 14 Energy use and cost calculations for Chicago metropolitan area greenhouse and plant factory operations

	Greenhouse				Plant factory			
Month, cost category	Heating (GJ)	Lighting (GJ)	Cooling (GJ)	Total energy (GJ)	Heating (GJ)	Lighting (GJ)	Cooling (GJ)	Total energy (GJ)
Jan	1451	685	16	2152	137	1119	459	1715
Feb	1264	492	15	1770	104	1011	417	1532
Mar	1039	391	16	1445	74	1119	464	1657
Apr	629	354	16	999	38	1083	451	1573
May	558	156	16	730	27	1119	467	1614
Jun	228	148	16	391	14	1083	459	1556
Jul	93	120	16	230	8	1119	478	1605
Aug	107	156	16	279	11	1119	478	1608
Sep	214	165	16	395	16	1083	459	1558
Oct	467	437	16	920	41	1119	468	1628
Nov	657	501	16	1174	60	1083	450	1594
Dec	1063	695	16	1774	110	1119	462	1691
Total	7770	4298	189	12,257	643	13,177	5512	19,332
Natural gas (NG) cost								
GJ per MMBtu	0.948				0.948			
MMBtu	7365				609			
Mcf per MMBtu	0.964				0.964			
Mcf NG	7102				588			
NG cost, $/Mcf	7.80				7.80			
NG cost, $/year	55,394				4584			

(*continued*)

Table 14 (continued)

	Greenhouse				Plant factory			
Month, cost category	Heating (GJ)	Lighting (GJ)	Cooling (GJ)	Total energy (GJ)	Heating (GJ)	Lighting (GJ)	Cooling (GJ)	Total energy (GJ)
Electricity cost								
kWh per GJ		277.8	277.8	277.8		277.8	277.8	277.8
kWh used		1,193,857	52,589	1,246,445		3,660,208	1,531,089	5,191,297
Electricity cost, $/kWh		0.0637	0.0637	0.0637		0.0637	0.0637	0.0637
Electricity cost, $/year		76,049	3350	79,399		233,155	97,530	330,686

Source: Authors' own calculations and assumptions

Note: Costs for electricity will also include a "demand charge" for the GH calculated as 379 kW times 12 times $11.19 per kW, equal to $50,892 per year. The "demand charge" for the PF is calculated as 520 kW times 12 times $11.19 per kW, equal to $69,826 per year

Table 15 Detailed calculations of CO_2 equivalent emissions, field, greenhouse and plant factory operations

Emissions category and calculation information	New York			Chicago		
	Field	GH	PF	Field	GH	PF
Emissions from natural gas						
GJ from NG	0	6748	657	0	7770	643
CO_2 per GJ from NG, MT/GJ	0.0503	0.0503	0.0503	0.0503	0.0503	0.0503
CO_2 from NG, MT/year	0.0	339.4	33.0	0.0	390.8	32.3
Emissions from electricity						
GJ from electricity	1.87	4041	18,633	1.87	4487	18,689
CO_2 per GJ from electricity, MT/GJ	0.0662	0.0645	0.0645	0.0662	0.1069	0.1069
CO_2 from electricity, MT/year	0.1238	260.7	1202.4	0.1238	479.6	1997.4
Emissions from diesel						
Diesel used, gallons/year	888	312	312	679	6909	6909
CO_2 from diesel, kg/gallon	10.21	10.21	10.21	10.21	10.21	10.21
CO_2 from diesel, kg/year	9065	3186	3186	6936	70,537	70,537
Miles traveled per year	3750	2184	2184	2773	48,360	48,360
CH_4 emissions, g/mile	0.0051	0.0051	0.0051	0.0051	0.0051	0.0051
CH_4 emissions, g/year	19.1	11.1	11.1	14.1	246.6	246.6
CH_4 to CO_2 conversion	25	25	25	25	25	25
CO_2 equivalents emissions as CH_4, kg/year	0.5	0.3	0.3	0.4	6.2	6.2
N_20 emissions factor, g/mile	0.0048	0.0048	0.0048	0.0048	0.0048	0.0048
N_20 emissions, g/year	18.0	10.5	10.5	13.3	232.1	232.1
N_20 to CO_2 conversion	298	298	298	298	298	298
CO_2 equivalent emissions as N_20, kg/year	5.4	3.1	3.1	4.0	69.2	69.2
CO_2 equivalent from diesel, MT/year	9.0709	3.1889	3.1889	6.9403	70.6119	70.6119
Total CO_2 emissions, MT/year	*9.1*	*603.3*	*1238.6*	*7.1*	*941.0*	*2100.3*
Production, kg lettuce per year	7144	454,685	454,685	7144	454,685	454,685
CO_2 emissions, kg CO_2/kg lettuce	1.29	1.33	2.72	0.99	2.07	4.62

Source: Authors' own calculations and assumptions

Note: Diesel emissions are for field production and transportation for all three operations. Calculations ignore a small amount of gasoline used in field production (2 gallons, 7.5 litres)

Notes

1. At present, we estimate that at least 90% of the light in VF would need to come from supplemental light, so in practice most light in a vertical farm would probably need to come from supplemental sources.
2. Note that we have not accounted for potential differences in prices that wholesalers (or consumers) are willing to pay for lettuce produced in the same metropolitan area. This may make the profitability differences smaller than the landed cost differences that are our focus here.

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