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Testing the environmental performance of urban agriculture as a food supply in northern climates

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Abstract

The past decade has seen a renaissance of urban agriculture in the world's wealthy, northern cities. The practice of producing food in and around cities is championed as a method to reduce environmental impacts of urban food demands (reducing distance from farm to fork - 'food miles') whilst conferring a number of ancillary benefits to host cities (runoff attenuation, urban heat island mitigation) and ex-urban environments (carbon sequestration). Previous environmental assessments have found urban agriculture to be more sustainable than conventional agriculture when performed in mild climates, though opposite findings emerge when external energy inputs are significant. In this study we perform an environmental life cycle assessment of six urban farms in Boston, US producing lettuce and tomatoes, with conventional counterparts across six impact categories. Performance of urban agriculture was system dependent and no farm provided superior performance to conventional for all indicators. High-yield, heated, greenhouse production of tomatoes has potentially higher environmental burdens than conventional methods in terms of climate change (267-369%) and non-renewable resource depletion (108-239%), driven primarily by external energy inputs. Heated lettuce production systems showed similar trends. Low-tech, empty-lot farming appears to hold some advantages in terms of climate change burdens and resource use, though water and land usage was found to be elevated relative to conventional lettuce and tomatoes. Open rooftop farming apparently provides benefits if high yield crops (e.g. tomatoes) are cultivated, otherwise significant capital inputs detrimentally affect environmental performance. In general, the benefits of reduced food miles may be overwhelmed by energy inputs and inefficient use of production inputs. A comparison of urban agriculture and solar panels showed that the latter would confer greater benefits to mitigate climate change per unit area. Thus, urban agriculture may not be the optimal application of space in northern cities to improve urban environmental performance.

1. Introduction

Food consumption is a major driver of a city's total environmental burdens; often on par with mobility, building energy and construction activities (Goldstein et al., 2016a). By virtue of their majority shares of both population and wealth, cities consume the bulk of global food, the production of which is a leading cause of greenhouse gas (GHG) emissions, natural habitat appropriation, chemical pollution (nutrients and pesticides) and water consumption (Foley et al., 2011; Gliessman, 2015). Agriculture is also resource intensive; dependent on non-renewable fossil fuels and minerals for agrichemicals to meet growing food demands on approximately 36% of the globally available ice-free land, with scarce room for sustainable expansion (Foley et al., 2011; Steffen et al., 2015). For cities to become sustainable, environmental impacts from their food demands must be reduced, especially considering predicted urbanization, economic development and increasing consumption of environmentally-burdensome animal-proteins for an increasing share of humanity (Goldstein et al., 2016a; Tilman and Clark, 2014).

Urban agriculture (UA) *, the production of food in and adjacent to cities, leveraging pre-existing urban material energy flows as production factors* (Koc et al., 1999), is commonly touted as an urban design solution to the environmental impacts of urban food needs (IPCC, 2014; Pearson et al., 2010). A recent review by Goldstein et al. (2016c) found that UA is posited to have numerous advantages over conventional agriculture that will supposedly result in UA's superior environmental performance, grouped here into three categories:

1. Supply-chain efficiency; reduced distance from farm to consumer ('food miles'), attenuating overall environmental burdens from production and distribution;
2. Urban symbiosis potential; interacting with a city's material and energy fluxes, reducing a farm's operational inputs, absorbing urban waste flows (e.g. food waste), lowering building energy demand (i.e. through insulation or reducing the urban heat island effect) and other local environmental benefits (e.g. tempering stormwater runoff);

3. Ex-situ environmental benefits; supposed reductions in agricultural land occupation, carbon sequestration and other benefits to ecosystems beyond the city boundary.

Despite the fanfare, a paucity in evidence exists where literature reviews of UA been performed (Born and Purcell, 2006; Goldstein et al., 2016c; Specht et al., 2013).

Sanye-Mengual and colleagues' recent work on UA in Barcelona, ES has started addressing this, comparing the environmental performance of rooftop greenhouse tomatoes against conventional supply chains, finding that the former can have lower life-cycle GHG emissions and toxicity impacts (2015b, 2012). Rothwell and colleagues also found that lettuce from local farms could reduce GHG impacts compared to conventional produce in Sydney, AU (2015). Though promising, both studies considered UA in warm climes, more amenable to food production than many of the wealthy, northern cities where food related environmental impacts are typically highest and UA is often promoted to reduce these burdens.

Year-round UA in colder cities will likely rely heavily on controlled agriculture (i.e. greenhouses) to produce food to potentially negative environmental results. Leafy greens from a Japanese automated, conditioned, indoor farm ('plant factory') produced lettuce at 6.4 kg CO_2 equivalents per kg fresh lettuce, well above conventional production due to the system's energy demands (Shiina et al., 2011), due to the high energy requirements for 100% artificial lighting and temperature control. Kulak and colleagues found that low-tech greenhouse UA strawberries in London, UK , had a higher carbon footprint than conventional counterparts (2013) showing that embodied impacts in capital and equipment can also drive burdens.

Our contention here is that UA might not always have the intended positive effect on a city's environmental performance, particularly in a northern context. The generality of UA as an environmentally preferable urban food supply chain is questionable, since its three general environmental benefits may be largely contextual. UA's environmental efficacy is a pressing question in northern cities considering its renaissance at a grassroots level (Mok et al., 2014), active promotion by many northern cities through the Milan Urban Food Policy pact (City of

Milan, 2015) and codification in land use policies (City of Boston, 2014). Further consideration of UA's environmental performance could help balance what has hitherto been a pro-UA narrative and assuage data gaps in an evolving dialogue. In this study we test the performance of six UA systems, covering four distinct UA types, in Boston, US using environmental life cycle assessment (LCA), to see whether UA is a true environmental benefit to Boston, and by proxy, similar cities.

2. Methods

LCA is applied here to compare the potential environmental benefits of lettuce and tomato production with UA and conventional farming. Here we focus on the aspects most relevant to the study at hand. For a richer treatment of LCA methodology, see existing standards (ISO, 2006a, 2006b) and the European Commission's LCA handbook (European Union Joint Research Council, 2011).

2.1. Modelling Framework

Process-based LCA is applied here using detailed data for the processes throughout the life cycle (e.g. fertilizer application, freight transport, etc.), maximizing geographic, temporal and technological representativeness. A consequential LCA (CLCA) approach is used here as opposed to attributional-LCA (ALCA). CLCA models consumption as a mix of 'unconstrained suppliers' that respond to the next unit demand ('marginal producers'), not the average mix of historic suppliers as in ALCA (Weidema et al., 2013). In keeping with CLCA practice, we model multi-functional processes using system-expansion, and not the allocation approach of ALCA. For example, rooftop farms produce food and also minimize the energy consumption of the building on which they are situated; CLCA credits the farm for the avoided energy consumption, while ALCA uses economic value to allocate the environmental burdens between the energy savings (taken as the price of the energy that would have been consumed otherwise) and the value of the food. CLCA aligns best with ISO recommendations (ISO, 2006b) and is implemented here using the ecoinvent 3.1 database embedded within SimaPro 8 product system modelling software.

2.2. System boundaries and functional unit

Our scope is cradle-to-shelf; cultivation, harvesting and distribution of food to market are modeled. This is justified given that these aspects of the product system are controlled by producers and the study aim of comparing relative environmental performance (post purchase transport and preparation are identical and can be excluded).

Tomato and lettuce production using UA and conventional methods are modeled here. The functional unit *is 1 kg of fresh food item delivered to the point of purchase in Boston*, for each item (tomato or lettuce). Tomatoes and lettuce were chosen as subjects of study due to their prominence in the North American farming system and diet. According to the FAO (2016), in the US tomatoes and lettuce account for 14% (2nd) and 10% (3rd) harvested vegetable area, respectively, and 37% (1st) and 10% (3rd) harvested vegetable mass, respectively. In the US diet they both the most consumed fresh vegetables by mass, with 21% a piece (Heller and Keoleian, 2015).

2.3. UA cases and life cycle inventory

Goldstein et al. (2016c) identified four overarching UA types based on material and energy regimes and expected disparate environmental performance: building-integrated-conditioned (BI-C), building-integrated-non-conditioned (BI-NC), ground-based-conditioned (GB-C) and ground-based-non-conditioned (GB-NC). Building-integrated identifies whether the farm is standalone or physically attached to a building, while conditioning refers to control of growing space variables (light, temperature, CO_2 levels, etc.) System particularities are outlined in Table 1, while detailed descriptions can be found in the aforementioned review.

Six urban farms were assessed; four in Boston, one in New York City (assumed to operate in Boston), and a single hypothetical rooftop greenhouse in Boston. Six examples were chosen to capture the potentially disparate environmental performances between architectures as hinted by Sanye-Mengual et al. (2015) results, allowing a richer discussion of UA’s environmental performance, departing from previous work on single UA types. Table 2 outlines the studied farms’ characteristics. Two of the UA cases (GB-NC1 and GB-C1) produce leafy greens

Attribute Example	**BI-C** Gotham Greens: www.gothamgreens.com	**BI-NC** Brooklyn Grange: http://brooklyngrangefarm.com	**GB-C** Bright Farms; http://www.brightfarms.com	**GB-NC** Edgemere farm: http://www.edgemerefarm.org
Capital inputs	High: greenhouse, supporting building buttressing, irrigation, HVAC	Medium: supporting building buttressing, irrigation, green roof membranes and media	High: same as BI-C minus structural buttressing	Low: irrigation, growing beds
Operational inputs	Low for water. Potentially high for nutrients and space conditioning (if heated)	Medium: can capture nutrients at parapet and rainwater	Same as BI-C	High: loss of nutrients and runoff
Urban symbiosis potential	Medium: interacts with host building energy system and can capture rainwater	High: same as BI-C, but can better utilize organic waste (compost)	Low: no building interaction, less likely to accept organic waste or harvest rainwater	Medium: accepts rainwater and compost, but no links to buildings
Urban environmental benefits	Medium: reduced urban heat island (UHI) and potentially runoff	High: reduced UHI and runoff. Potential biodiversity hotspot.	Same as BI-C	Same as BI-NC
Production efficiency	High	Medium	High	Low

Table 1 – Four predominant UA types based on predicted material and energy regimes as identified by Goldstein et al. (2016c) Examples of each are included in the current study (see Table 2).

UA Case	Farm Size (m^2)	Technology	Location	Growing Season	For Profit	Crop(s) assessed
GB-NC1	560	field	Boston	April to October	no	tomato, arugula
GB-NC2	1269	field	NYC	April to October	no	tomato, lettuce
GB-C1	558	soil media in greenhouse (heated)	Boston	All year	no	tomato, salad greens
GB-C2	30	modular hydroponic unit	-	All year	yes	lettuce
BI-NC	1469	soil media on green roof	Boston	April to October	yes	tomato, lettuce
BI-C	3493	hydroponic greenhouse (heated)	Boston	All year	yes	tomato

Table 2 – General attributes of the UA cases assessed in this study. The GB-C2 is a portable unit and therefore has no fixed location, though the LCI is for east coast US operation. All farms are operational with the exception of the hypothetical BI-C. See appendices A-F for system descriptions.

(arugula) instead of lettuce. We assume here that leafy greens are directly substitutable for lettuce, fulfilling the same function (salad or sandwich topping), despite potential nutritional mismatches in terms of calories, micronutrients, macronutrients, etc. This is acceptable since the assessment is performed on a mass basis, but future studies could look into the environmental impacts per unit of nutritional value generated, as has been recommended by Heller et al. (2013).

The LCIs for the studied UA operations were based on primary data collected through site visits, interviews, financial records and, where necessary, estimation. For the BI-C, a rooftop greenhouse designer was consulted to develop a reasonable facsimile of the operation, complimenting this with publically available data from an operating rooftop greenhouse in Montreal, Canada. For detailed case descriptions and LCIs see appendices A-F. There were some important data gaps that could not be filled. Information for structural buttressing of the supporting buildings for both BI systems was not available. A licensed structural engineer was employed to make reasonable estimates of these inputs based on site photos (see appendix A), but the findings should be viewed with this caveat in mind. The lack of a participating BI-C farm in the project also meant that the LCI for this system was built using expert input from a greenhouse designer and publically available information. Finally, data was not available for irrigation in many instances, which meant this information was estimated.

The UA produce are compared to conventional tomato and iceberg lettuce production. Tomatoes and lettuce were modeled from the ‘Tomato {GLO}’ and ‘Lettuce {GLO}’ unit processes in the ecoinvent 3.1 database, respectively. These processes represent LCIs for current conventional farming technologies in Europe which will result in an overestimation of heating inputs, it is assumed that they are technologically representative of North American production (Stoessel et al., 2012). Of note is that the conventional tomato used here was modeled on a heated greenhouse. An unheated greenhouse would improve the relative performance for energy related impacts, though the countering effect of the lower yields remains unknown. In the same vain, field tomatoes have significantly lower yields than their greenhouse counterparts, which would have an impact on land use related indicators. Nonetheless, keeping these study limitations in mind, the conventional cases should provide robust enough yardstick of comparison to test UA's environmental performance.

Distances from conventional farms are taken as weighted average source distances for US tomatoes (2550 km) and lettuce (2962 km) to Iowa (Pirog and Benjamin, 2003), since food miles for the Northeast US are unknown. These values represent intermediate estimates considering the coast to coast distance of United States (~5000 km). Post-harvest, pre-consumer losses of 11% are assumed for both products (USDA, 2014). For more information on the conventional produce see appendix G.

2.4. Impact categories included

Six metrics that are broadly representative of agriculture's environmental impacts were included: climate change (CC) from agricultural land expansion, energy inputs, enteric fermentation; freshwater ecotoxicity (FE) from fertilizer and biocide application; marine eutrophication (ME) from fertilizer application; water resource depletion (WRD) from irrigation; land use (LU) from agricultural land expansion and degradation; and mineral, fossil and renewable resource depletion (RD) from agrochemical consumption. There exists numerous methodologies to convert LCIs to impact categories of potential impacts (herein 'impact potentials' or 'IPs'), opting here for the ILCD method.

It should be noted that the study boundary of the point of purchase ignores potential contamination in the UA from local pollution and its adverse effects on human health. Though human health IPs were not assessed here, precluding contamination impacts from showing up in the results, it is important to note that UA is susceptible to local contamination, either in soil or from aerial deposition (Säumel et al., 2012; Wortman and Lovell, 2013), hinting that this may be an important factor in future LCAs of UA.

3. Results

Table 3 shows the results for the UA and conventional product systems for tomatoes and lettuce across all impact categories, while appendix H situates these relative to previous studies. No UA system is superior to conventional production across all impact categories, although select UA systems may appear preferable (based on equal weighting of considered impact categories) in that they have lower IPs for a majority of impact categories. The reasons for the disparate performance vary by system, but trends exist. For conditioned UA systems, energy consumption for space conditioning drives most IPs; CC (> 90%), FE (> 70%), ME (> 80%) and RD (> 70%) for both tomato and lettuce UA systems. Capital inputs seldom mattered with the exception of the BI-NC system's structural steel which was more than half of the IPs for CC, FE, ME, LU and RD impact categories. GB-NC systems are inefficient in land and water use, but low intensity for other aspects. Between tomatoes and lettuce, UA generally performs better when producing the former, as the greater yield of tomatoes per unit area ensures that capital and energy inputs, which are applied evenly across the case farms, are best utilized, reducing IPs. The following sections detail the findings for the food products.

3.1. Tomatoes

Figure 1 outlines findings for tomatoes. UA IPs are classified as related to capital inputs (equipment and structures), operational inputs (supplies and distribution) and urban symbiosis (interaction between farm and built environment's material and energy fluxes). IPs for conventional tomatoes are classified as related to cultivation or distribution.

UA was found to be ubiquitously superior for freshwater ecotoxicity, FE and marine eutrophication, ME (Figures 1b and c), a consequence of the use of inorganic fertilizers for nutrients and pesticides during conventional tomato production. All the UA cases generally avoid pesticides using beneficial insects for pest control, though GB-C1 was applying small doses of natural pesticides to combat aphids (this was not modeled, decreasing this IP). Fertilization levels were generally low for the UA cases (typically with fish emulsion),

	Tomato						Lettuce					
	BI-C	**BI-NC**	**GB-C1**	**GB-NC1**	**GB-NC2**	**Conventional**	**BI-NC**	**GB-C1**	**GB-C2**	**GB-NC1**	**GB-NC2**	**Conventional**
CC (kg CO_2 eq)	2.15	0.26	1.58	0.08	0.07	0.59	0.40	26.51	8.65	0.23	0.08	0.92
FE (CTU eq)	1.30	1.35	0.86	0.15	0.13	9.09	4.55	8.83	6.08	0.38	0.27	1.97
ME (kg N eq)	$1.0*10^{-3}$	$4.3*10^{-4}$	$6.3*10^{-4}$	$8.9*10^{-5}$	$8.1*10^{-5}$	$1.4*10^{-3}$	$1.4*10^{-3}$	$7.9*10^{-3}$	$3.8*10^{-3}$	$3.9*10^{-4}$	$1.4*10^{-4}$	$2.9*10^{-3}$
WRD (m^3 H_2O eq)	$9.0*10^{-3}$	$6.8*10^{-2}$	$6.6*10^{-2}$	$5.1*10^{-2}$	$7.4*10^{-2}$	$3.0*10^{-3}$	0.20	0.18	0.02	0.17	0.22	0.02
LU (kg C deficit)	2.03	1.25	2.43	5.10	3.63	3.35	4.23	30.23	8.78	30.48	18.73	6.55
RD (kg Sb eq)	$1.4*10^{-5}$	$1.1*10^{-4}$	$3.1*10^{-5}$	$1.3*10^{-5}$	$1.0*10^{-5}$	$1.3*10^{-5}$	$3.6*10^{-4}$	$2.3*10^{-4}$	$4.3*10^{-4}$	$3.6*10^{-4}$	$2.4*10^{-5}$	$2.3*10^{-5}$

Table 3 – Results per functional unit of tomato and lettuce for CC in kilogram CO_2 equivalents (kg CO_2 eq), FE in comparative toxicity units for ecotoxicity (CTU_e), ME in kilogram nitrogen equivalents (kg N eq), WRD in m^3 H_2O equivalents (m^3 H_2O eq), LU in kilogram carbon deficit (kg C deficit) and RD in kilogram antimony equivalent (kg Sb eq). Color spectrum traverses white (lowest IP) to dark grey (highest IP).

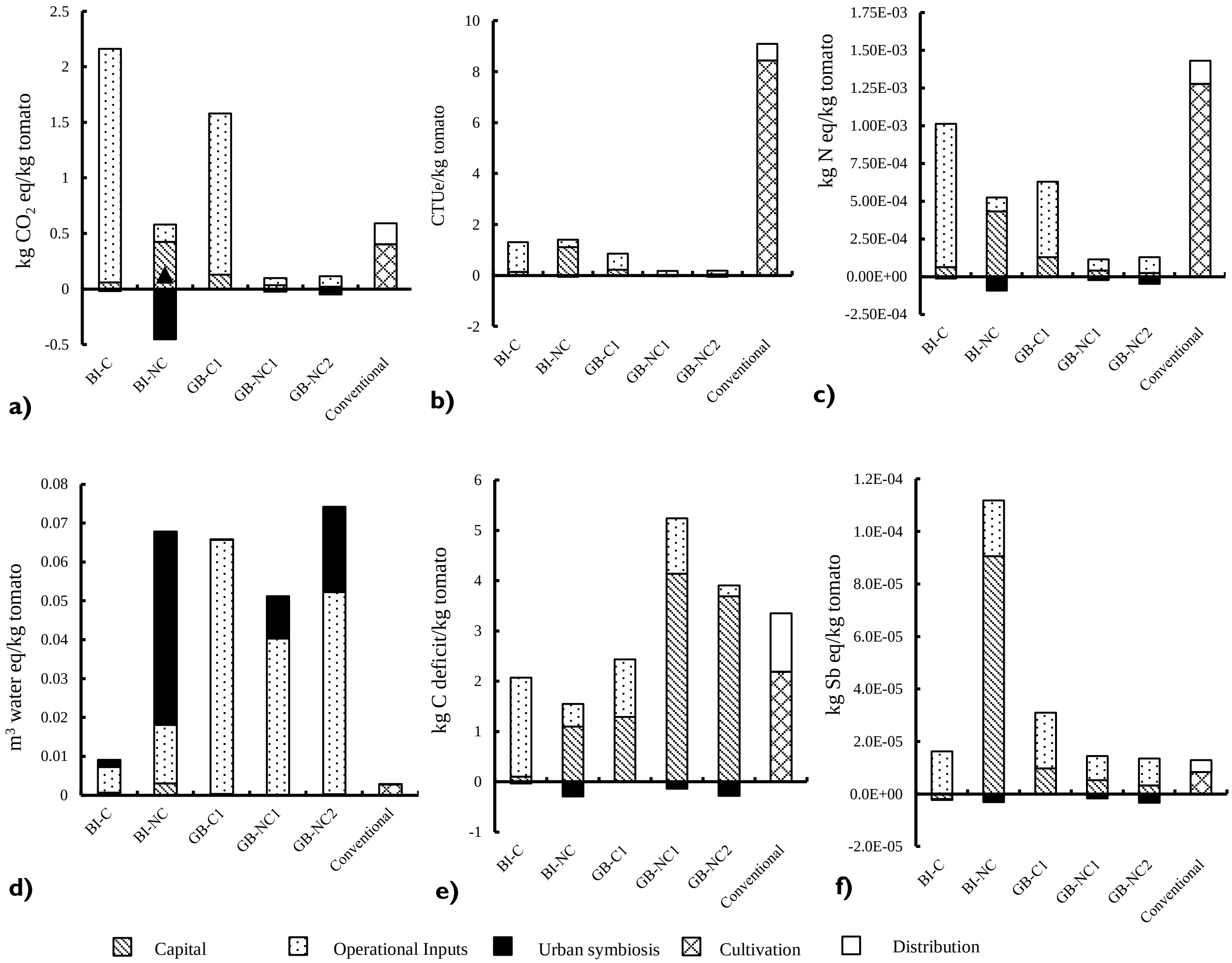

Figure 1) IPs for production of 1 kg fresh tomatoes with the studied UA systems and a conventional system for CC (a), FE (b), ME (c), WRD (d), LU (e) and RD (f). Black triangle is the aggregate BI-NC CC IP.

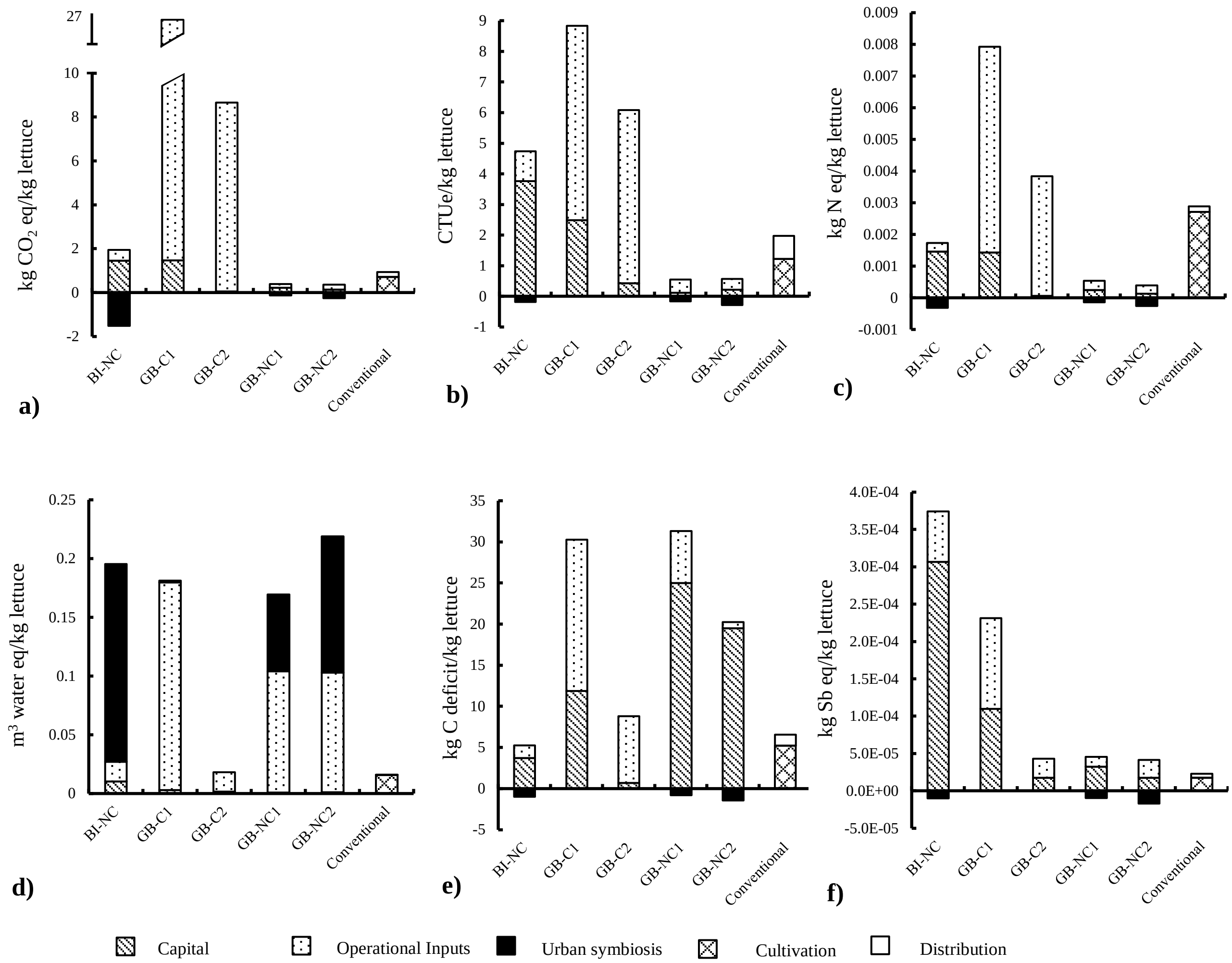

Figure 2) IPs for production of 1 kg fresh tomatoes with the studied UA systems and a conventional system for CC (a), FE (b), ME (c), WRD (d), LU (e) and RD (f).

recycled in closed hydroponic systems (BI-C) or even zero (GB-NC1), though natural gas for operational energy elevates the conditioned urban farms above their counterparts for ME due to NOx emissions. Notably, BI-NC's FE and ME IPs deviate from most agricultural LCAs, driven not by operations, but capital; structural steel affects FE while natural gas to produce expanded shale/clay growth medium drives ME.

Conversely, for both water resource depletion, WRD and mineral and fossil resource depletion, RD (Figures 1d and f) the UA systems generally perform equally or worse than the conventional tomato cultivation. WRD, driven by irrigation, puts inefficient soil based systems at a handicap compared to the BI-C and market hydroponic systems. Of note is that rainwater irrigation, reducing municipal water demands, nonetheless deprives the surrounding catchment of water; depleting local water resources. This captured rainwater is called 'green water' in the water footprint method of embodied water impacts (Mekonnen and Hoekstra, 2011), its presence here highlighting that harvesting flows from the built-environment can come at a price, potentially reducing ecosystem quality or redirecting potentially potable water. For RD, the main driver of the UA systems' poorer performances varies. For the BI-C it is the natural gas for operational energy. For the BI-NC system it is the capital inputs that drive RD IPs, particularly additional steel for structural buttressing. The GB-C1 is influenced strongly by produce distribution, which despite the short distance, is done in small batches by pickup truck resulting in high capital inputs for the vehicle, contradicting claims that reducing 'food miles' is a universal environmental good (Born and Purcell, 2006; Sanyé-Mengual et al., 2012). Contributions from the greenhouse structure (steel) and irrigation (piping in municipal water system) also hamper the GB-C1 system. Similar to the GB-C1 the GB-NC1 RD IP is driven by distribution, and less so, the plastics for the irrigation system. The GB-NC2 performs on par with the conventional tomato, having minor impacts for nutrient demands.

For climate change (CC) IPs (Figure 1a), no general pattern between UA and conventional production is seen. Energy space heating leads to discouraging CC results for the conditioned UA types. Clearly heating greenhouses to grow tomatoes over winter in a northern clime has a high energy cost, with commensurate CC IPs if fossil fuels are relied on, as in Boston (natural gas as marginal fuel for heat and electricity). Comparing these greenhouse tomatoes to those from earlier LCAs in appendix H shows that our results align well with previous findings (1.27-1.97 kg CO_2 eq/kg tomato in heated greenhouses). Moreover, the BI-C is modeled as procuring half of its heat through symbiosis with its host building (in the same manner as Montreal farm on which selected system aspects were taken), hinting at the true unsuitability of this UA practice in Boston where free, dissipative energy is lacking. Alternatively, both GB-NC farms are markedly superior to conventional practices for CC IPs, a consequence of their minimal capital and energy inputs. Once again the BI-NC stands out: embodied carbon in the structural steel has significant CC IPs, but these are offset by energy savings at the host building (assumed 3% of heating and 5% of cooling), elucidating UA's potentially meaningful mutualisms with the urban system. The land use (LU) IPs in Figure 1e unexpectedly showed that BI UA, though ostensibly devoid of direct land use, nonetheless has substantial indirect land use. For the BI-C, land occupation for natural gas extraction is substantial, while the BI-NC is affected by structural steel (mine infrastructure, energy inputs) and natural gas used in producing expanded clay media. The conventional tomato, also reliant on natural gas as heating source, has similar LU IPs for the production stage as the BI-C, while also having burdens for road area and diesel during distribution. The GB-C1 LU is a mix of natural gas demands, direct urban LU and greenhouse capital (wood and steel). Lastly, for the GB-NC farms, the combination of direct land occupation and low yields lead to elevated LU IPs above conventional tomatoes.

3.2. Lettuce

Figure 2 shows the IPs in the six impact categories for the production systems broken down in the same manner as in Figure 1. The lettuce results diverge markedly from the tomato results in that across the different sites UA does not perform consistently better than conventional agriculture for any single indicator. For CC IPs the conditioned systems are again hampered by heating demands and accompanying natural gas inputs (GB-C2 incurs additional penalties for 100% artificial light demands), which when combined with the low yields of lettuce, result in CC IP levels similar to red meat (Nijdam et al., 2012). Non-conditioned ground-based farms perform slightly better than the conventionally cultivated market lettuce for the same reasons as the tomatoes.

Lettuce results in FE and ME mirror each other. Energy inputs to the conditioned systems results in high IPs, while the capital inputs for the BI-NC farm mar its performance. The GB-NC farms perform better than conventional lettuce cultivation due to the latter's fertilizer and biocide use. For WRD only the GB-C2's closed-loop hydroponics performs comparably to market lettuce, with all of the others consuming significant irrigation volumes, as municipal water or 'green water'. All of the ground-based UA farms' LU IPs are elevated above conventional lettuce; with GB-C1, GB-NC1 and GB-NC2 all driven by the same inputs as the tomato production. GB-C2 occupies very little land directly, but its high electricity consumption makes it a prohibitively costly for LU. Lastly, none of the UA systems provide an attractive alternative to conventional lettuce for RD where the same pattern as for the tomatoes continues for the BI-NC, GB-C1, GB-NC1 and GB-NC2 systems, while the GB-C2 performs poorly due to space conditioning and equipment.

4. Discussion

The results confirm the intimations of a number of earlier reviews of UA (Goldstein et al., 2016c; Mok et al., 2014; Specht et al., 2013) that UA has the potential, in certain contexts, to be a far more environmentally damaging food source than conventional agriculture. Furthermore, the performance of UA is as varied as the types that exist, hinting at the need for a more nuanced discussion of UA, one that departs from the pro UA bias that has heretofore dominated the discourse. In the following sections we re-visit the three themes raised in the introduction (supply-chain efficiency; urban symbiosis potential; ex-situ environmental benefits) to see how our results align with these claims. To balance the discussion we also touch on some of the non-environmental considerations of UA.

4.1. UA and supply-chain efficiency

A primary argument for UA is reduced 'food miles' and the belief that this makes food more environmentally sustainable (Born and Purcell, 2006; Weber and Matthews, 2008). Here we have shown that in Boston's case, this is not a defensible claim. Firstly, the food miles argument overestimates the importance of transport from a life-cycle perspective, which was never a dominant driver for either conventional case here, as supported by other LCAs and reviews of the topic (Born and Purcell, 2006; Garnett, 2011), although expanding the scope to a full life-cycle, including consumer transport, might affect this. Bulk-freight by ground over long distances, though certainly imparting environmental burdens, is relatively efficient on a per mass basis. The RD IP for the BI-C1 displays this through the significant contribution from distribution using a pickup truck, despite the short intra-city distances.

By overemphasizing the importance of transport, UA advocates underestimate the environmental impacts of producing food (Garnett, 2011; Weber and Matthews, 2008), which is where the majority of burdens lie. Efficient use of agricultural inputs is intricately related to system performance, and in this regard the conventional cases appear to make for leaner supply chains than many of the UA alternatives in Boston. Table 4 explores this, showing per square-meter performance for the different production systems for CC and WRD IPs, as well as cumulative energy demand (sum of all direct and indirect energy during production).

From this perspective one can see that the conventional systems, despite their considerable cumulative energy (heating, agrochemicals and capital) and irrigation demands relative to the UA options produce in substantial volumes to make for environmentally superior systems across a number of IPs. Where UA does provide a more sustainable substitute for the conventional cases, the UA system falls within one of two scenarios; very low inputs or high inputs matched by high yields. The GB-C2 system producing lettuce provides an example of the high input-high yields nexus for WRD IPs. Looking at the system it is clear that per unit growing space, the GB-C2 operation has the highest WRD IPs relative to other UA systems. Countering the substantial irrigation demand is a high yield with the end result that it is the only UA system out of the five that competes with conventional lettuce by this metric as visible in Table 3. Conversely, the cumulative energy demand, driven by heating and lighting, is too great to be offset by the system's efficiency, resulting in the system's elevated CC IPs.

Indicator	BI-C	BI-NC	GB-C1	GB-C2	GB-NC1	GB-NC2	Conventional
Tomato							
CC (kg CO_2/m^2)	150	2.1	15.5	-	0.3	0.5	14.7
Cumulative Energy Demand (kWh/m^2)	1090	15	90	-	8	5	114
WRD (m^3/m^2)	0.63	1.11	0.64	-	0.23	0.51	0.099
Yields (kg/m^2)	70.0	16.3	9.8	-	4.4	6.9	40.6
Lettuce							
CC (kg CO_2/m^2)	-	1.9	19.2	250.6	0.2	0.11	11.0
Cumulative Energy Demand (kWh/m^2)	-	14	104	1830	7	3	94.2
WRD (m^3/m^2)	-	0.94	0.13	0.52	0.12	0.29	0.3
Yields (kg/m^2)	-	4.8	0.7	53.6	0.7	1.3	15.8

Table 4 – CC, cumulative energy demand, WRD and yields per unit growing area for the different UA systems and crops.

The GB-NC systems both display the benefits of having low inputs. For instance, the GB-C1 and GB-NC1 have the same yield of lettuce, but the high energy inputs of the former result in a CC IP that is orders of magnitude larger than the latter, since GB-NC1 has almost minimal direct energy requirements over its lifetime. Therefore, it might appear that UA in northern climates is best suited for summer production, where heating needs are negated, in line with previous studies in mild climates (Rothwell et al., 2015; Sanyé-Mengual et al., 2015b). Despite their positive performance in a number of areas low-input UA systems have very high LU IPs, exacerbated by the lengthy cold periods of the year where the land is unused. Boston land is amongst the priciest in the United States (Davis and Palumbo, 2008), while the percentage of income spent on food by Americans is amongst the lowest globally (FAO, 2016), hampering the economic tractability of these systems in Boston, or similar markets. The low efficiency of GB-NC UA hints at why it is primarily applied on patches of underutilized municipal land, as a usufruct exercise between private owner and community-members prior to development or as a food source in shrinking cities with abundant space (e.g. Detroit) (Smit et al., 2001).

4.1.1. **Different Energy Scenarios**

Given that UA will likely have to produce in large quantities in order to compete with other uses of space in the city, it is worth investigating whether high yield UA systems, despite their relative inefficiency, could provide a sustainable alternative to conventional systems in Boston or other northern cities using alternative energy sources. We re-performed our analysis on the high-yield cases (BI-C and GB-C2), comparing the conventional lettuce and tomato to these systems with the existing marginal energy source (natural gas) replaced by photovoltaic, on-shore wind and hydroelectric power. The conventional production system was not altered since electricity is not a major input. We only show results for the CC, LU and RD IPs since these are most tied to the energy consumption in the previous assessment. Results are shown in table 5.

Grid changes profoundly affect the results. For the BI-C tomato the wind and hydro power options clear preferences over the conventional tomato. The photovoltaic powered BI-C, though an improvement in terms of

	NPCC grid	Photovoltaic	On-shore Wind	Hydro	Conventional	NPCC grid	Photovoltaic	On-shore Wind	Hydro	Conventional
	Tomato (BI-C)					Lettuce (GB-C2)				
CC (kg CO_2 eq.)	2.15	0.478	0.323	0.241	0.591	8.65	1.65	0.903	0.515	0.925
LU (kg C deficit)	2.03	28.9	0.735	0.379	3.35	8.78	136	3.63	1.95	6.55
RD (kg Sb eq.)	$1.4*10^{-4}$	$1.9*10^{-4}$	$4.0*10^{-6}$	$1.9*10^{-6}$	$1.3*10^{-5}$	$4.3*10^{-5}$	$8.8*10^{-4}$	$2.4*10^{-5}$	$1.4*10^{-5}$	$2.3*10^{-5}$

Table 5 – LCA results for BI-C producing 1 kg tomatoes and GB-C2 producing 1 kg lettuce using different marginal electricity sources. Northeast Power Coordinating Council (NPCC) grid is the default scenario from the earlier results.

CC IPs, is a step backwards for RD (metals in PV-panels), and unsurprisingly considering the energy demands, LU; once again calling into question the claim of UA's ability to lower the land usage of agriculture. Despite the hydro tomatoes' strong performance, hydro power in the Northeast Power Coordinating Council (NPCC) region is not expected to grow within the operational lifetime of the BI-C project (U.S. Energy Information Administration, 2015), with natural gas remaining the marginal fuel for the foreseeable future. Electricity generation from wind and solar power in the Northeast US are likely to grow in coming decades, plausibly supporting UA production of tomatoes that is preferable to the status quo.

The analysis for the lettuce deviates from the tomato. Although hydro is clearly the best choice amongst the energy sources, as mentioned above it is not a realistic marginal power source for Boston. Photovoltaic, though a marked improvement from the original analysis is still worse than conventional lettuce, while a farm utilizing wind power appears to match conventional lettuce for CC and RD, and performing slightly better for LU, offering the potential for this design to reduce the burdens of urban food demand within this constrained context. Since only energy intensive forms are really competitive in terms of yields (and hence LU), the marginal electricity source is crucial. If we have a future with unrestricted access to renewable energy, intensive UA may compete with conventional, though this is currently hypothetical.

4.2. Urban symbiosis of UA and scaling up

Another frequent claim in UA literature is the practice's ability to be weaved within the urban fabric and affect pre-existing material and energy flows to reduce inputs to the farm and positively affect the urban environment (Goldstein et al., 2016c). Examples include solid (food) and liquid (toilet and kitchen water) waste assimilation, energy exchanges between farm and host building, runoff attenuation and mitigating the urban heat island effect (IBID). Where they were present in this study, these mutualisms seldom resulted in large benefits for the UA systems. Energy exchanges with the host building was one exception; BI-NC energy savings to the host building, meager as they are, counteracted the embodied burdens of the structural steel. For instance, the CC

IP for tomato production was reduced by 77% from a no-energy-savings scenario, while ME and LU were both reduced by about 20%. Bootstrapping on the dissipative energy of the host building, the BI-C reduces heating needs by 50%, essentially halving the CC IP for this system (2.14 instead of 4.11 kg CO_2 eq./kg tomato), while also showing that such synergies cannot overcome the system's low energy efficiency, thought shifts towards renewable energy systems in the future would reduce these advantages. Rainwater capture and subsequent runoff avoidance, though beneficial to the systems employing it, does not translate into significant environmental savings in this study, evidenced by the small, negative, black bars in Figures 1 and 2 (less than 1% across all IPs for BI-C and GB-C variants). The rainwater capture did have significant affect some IPs for the GB-NC farms (CC: 32-72%, FE: 18-43%, ME: 27-60%, RD: 13-32% reductions), but in an absolute sense the actual reductions of the IPs are small since the environmental burdens of these systems are very low for these impact categories. Moreover, this rainwater capture did nothing to ameliorate the water stress caused by irrigation since UA diverts water from other anthropogenic or ecosystems uses.

The use of compost by the farms, though a potentially meaningful synergy between the city and farm, does not affect the results. This is because composting benefits (avoided landfilling, avoided fertilizer production) are given to the original waste generator who decided to forego landfilling. In other words, the mere presence of UA in Boston was not a driver of compost production, and hence, from consequential LCA thinking is not credited with related benefits. However, if UA were scale up within cities, inducing a market, allocating the benefits of composting to an UA operation would be justified. An existing example is the use of sewage sludge in UA in developing countries, where the production systems are prevalent enough to act as continual repositories for the waste, providing a disposal route where other options are absent (Qadir et al., 2010), though challenges of pathogenic contamination posed by low-tech nutrient capture techniques cannot be downplayed (Srikanth and Naik, 2004).

Looking at single UA sites it is difficult to gauge the UA's latent ability to affect large scale change. If densely applied throughout a city, scaling effects could manifest, whereby some of the espoused UA's benefits, such as urban heat island mitigation (Pearson et al., 2010), attenuation of runoff from rain events (Ackerman, 2012) and local biodiversity increases (Havaligi, 2011) result in substantial changes to city's environmental performance. Most salient is whether a city-wide food production system would produce in appreciable volumes to satisfy a substantial proportion of urban food demands. Studies have been varied in their findings in this arena. An assessment of Oakland, US found that intensive utilization of suitable open space in the city by UA would only supply ~1% of the city's fruit and vegetable needs (McClintock et al., 2013) – in consonance with the nominal yields found in this study for the GB-NC systems. Conversely, Orsini et al. (2014) estimated that rooftop UA could supply 77% of the fruit and vegetable demands in Bologna, IT. Future work could involve modelling the changes in a city's total environmental burdens through the application of the UA systems that are preferential to conventional supply chains, answering the question about UA's true ability to contribute to sustainable urban consumption regimes.

The antagonisms of scaled up UA also require further exploration. If GB-NC UA is to be employed as an efficient food production means and an economically competitive land use, the application of both fertilizer and pesticides will likely increase, with a potential for adverse local environmental changes (eutrophication and contamination) and human health impacts (ambient pesticide exposure in densely populated urban settings). Moreover, the ability for plants to release toxic chemicals when stressed is also a consideration when scaling up to city-wide UA (Pataki et al., 2011). Ambient pollution uptake during cultivation is both a real risk and of primary concern to the purchasing public, requiring further exploration to help UA gain traction and support responsible application (Wortman and Lovell, 2013).

4.3. Ex-situ environmental benefits and urban land use

It is often espoused that UA could have a number of environmental benefits beyond the city boundary (Goldstein et al., 2016c), two of which, reduction of agricultural land occupation and sequestration of carbon we explore here. Results show that UA in Boston can actually have larger LU IPs than conventional agriculture for the GB-NC tomatoes where low yields mixed with direct land occupation. UA lettuce also had greater LU IPs than conventional lettuce since GB-NCs suffered from low yields, heating fuels exacerbated the conditioned farms, while capital inputs (mainly steel) elevated the BI-NC results. This finding casts doubt on the generality of the claim that UA could reduce net land occupation. The direct carbon uptake potential of the case farms is likely limited, since the bulk of the atmospheric CO_2 converted to biomass is harvested for human consumption, digestion and subsequent release to the atmosphere, as opposed to long term storage in biomass or soil (Gliessman, 2015). Low-tillage UA would increase the amount of GHG sequestration in soil, but given that globally the application of such agricultural systems would only sequester 3-6% of anthropogenic GHGs (Hutchinson et al., 2007), the contribution from UA appears meager. Moreover, the fact that conventional farming occurs directly on land, it is hypothetically better able to accumulate biomass in the soil than systems limited by growing medium mass (rooftop farms) or hydroponic systems.

Nonetheless, it is worthwhile considering if Boston UA, under the best scenarios, could lead to significant reductions in farmland and carbon sequestration. Here we assume that BI-C is operating with solar power sources and that their production allows farmland in Massachusetts to return to forest, sequestering carbon. Yields for field tomatoes in Massachusetts are 1.4 kg/m^2(USDA, 2013). Subtracting the space occupied by solar panels, every square meter of BI-C frees 48.5 m^2 of farmland, with each square meter free farmland sequestering 0.95 kg CO_2 annually (30 year timeframe) (Schmidinger and Stehfest, 2012). The BI-C is 3492.8 m^2, producing 244.5 tons of tomatoes annually, resulting in 187 tonnes of CO_2 eq avoided annually; 27.8 by replacing conventional tomatoes, the remainder through off-site carbon sequestration. A similar assessment with the GB-C2 shows a net GHG reduction of 11.4 kg CO_2 eq/year through UA substitution of conventional produce and carbon sequestration. Appendix I outlines the underlying calculations.

These hypothetical outcomes must be viewed skeptically, since US agricultural land (cropland and pasture) with little room for expansion (USDA, 2011; World Bank, 2015) will probably continue operating at full capacity to accommodate a growing US population (FAO, 2016). Thus it is unlikely to see prime agricultural land in Massachusetts (or any other part of the US) returning to forest on account of UA production. A conservative appraisal, until contrary evidence can be found, is that it is improbably that UA result in these types of land use changes outside the city.

4.3.1. Urban land use

If uncertainties preclude making solid assessments of the effects of UA on land use beyond the city boundary, LCA does allow us to evaluate the efficacy of UA compared to other uses of the space within the city. Figure 3 compares the amount of GHGs reduced annually for different application of a square meter in Boston. Here land either generates solar power which replaces electricity from the NPCC grid or substitutes conventional produce with UA production (high yield UA forms are assessed using NPCC grid and ‘clean’ electricity). Generation of solar power turns out to be far superior in terms of GHG reductions compared to both lettuce and tomato production. Thus if Boston is looking to enact land use policies that result in optimal GHG reductions per unit area, then promotion of solar generating capacity appears to be the superior choice over UA. This finding can likely be extrapolated to other northern cities with fossil fuel dominated energy grids. Appendix I outlines the calculations supporting Figure 3. However, façade integrated solar power (Quesada et al., 2012) combined with BI UA, could provide double dividends of conventional produce and electricity substitutions making for a more efficient use of urban space than either technology on its own.

4.4. Profit vs. non-profit UA

One dichotomy that emerged in this LCA was the divergence between for- and non-profit UA. Non-profit UA is typically part of a larger exercise, be it community building, nutritional literacy, food-desert amelioration, parks and recreation, after-school programs, or any other number of intangibles (Sanyé-Mengual et al., 2015a). These benefits should be considered when one compares the tradeoffs of 26.5 kg CO_2 eq/kg lettuce from a GB-C operation running natural gas heaters in winter to a 0.92 kg CO_2 eq/kg lettuce from the prevailing supply-chain. Providing urbanites the experience to produce food (potentially stymieing food waste) or fostering alternative

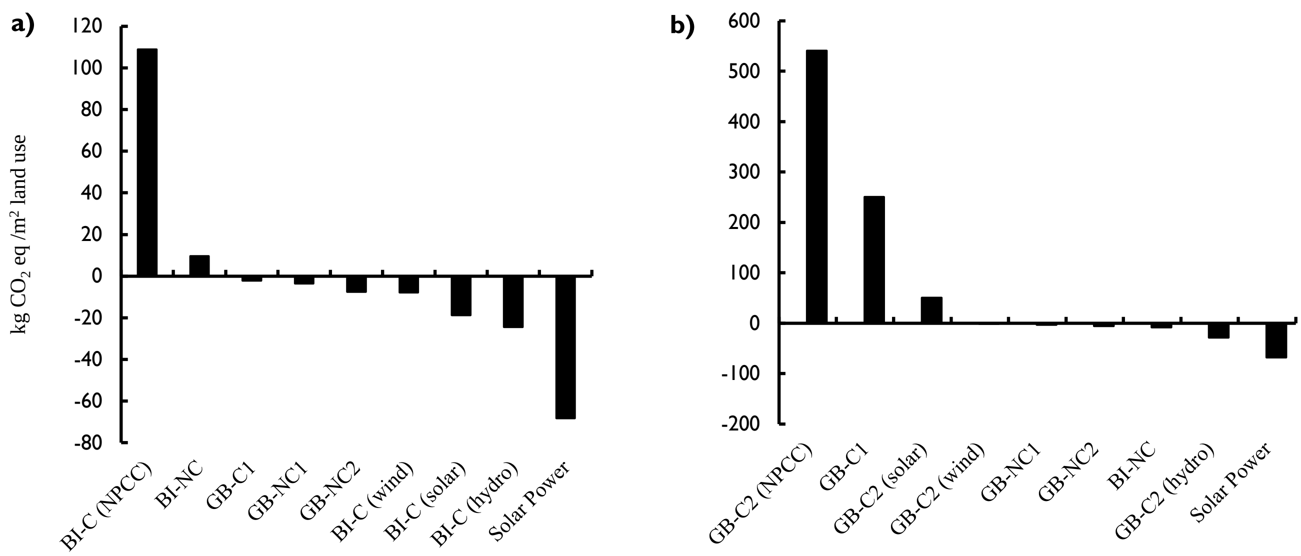

Figure 3 – CC impacts per m² of different farms assuming a substitution of conventional tomato (a) and lettuce (b) for UA produce. Net impact of 1 m² solar panel installation is also shown.

spaces in low-income neighborhoods for inner-city youth are vital activities. Moreover, though less common in Boston than cities in the emerging economies, the ability to provide income and nutrition to locals cannot be discounted.

Transparency in motives is essential. If a farmer partakes in UA for reasons aside from environmental sustainability, as all of the non-profit systems in this study do, then there is no contradiction between their motives and the environmental performance of their systems. However, if UA is done under the auspices of providing an environmentally preferable alternative to the status quo food system, as is often the case with for-profit UA, then it should operate in a way that aligns with this goal, such as tomato production for the BI-NC case. Contrarily, when these environmental goals are not met and no ancillary services are provided (e.g. lettuce from GB-C2), different objectives should be evoked; quality-control, freshness, etc.

5. Conclusions

This study has tested the urban environmental legend that UA provides environmentally superior food to conventional agriculture. We have used LCA to show that three of the common claims of UA advocates appear to be largely questionable: reducing food miles does not lead to more efficient supply-chains and reduced environmental impacts; the potential for symbiosis between farm and urban environment seem overstated at the farm scale; UA does not necessarily lead to reductions in land use and carbon sequestration. Though some of the UA systems do perform well against their conventional counterparts for certain IPs, a general recommendation for UA over conventional would be premature at this point. The UA systems that performed best are generally low-input systems with low yields, which cannot realistically compete with other land uses in the competitive markets of Boston and of most other large cities in northern climates. The conditioned UA forms with high yields, though ostensibly more financially tractable, are hampered by energy demands of year-round production in a northern climate and are environmentally deleterious given the underlying energy grid. Moreover, even when UA performs better than conventional agriculture, it turns out that an equivalent amount of space producing solar power would better combat GHGs, though tradeoffs in other IPs should then also be considered. Though this study was performed on UA in Boston, the conclusions likely apply to UA in other northern cities with cold winters and fossil fuel energy sources.

Ultimately, shifting towards a well-fed world that respects the finite carrying capacity of the planet will require a manifold agenda, including a reduction in the consumption of high-intensity foods (meat and dairy) (Goldstein et al., 2016b; Tilman and Clark, 2014) and a reduction of the 1/3 of global edibles discarded annually (FAO, 2013). Perhaps the agency of cities would be better applied towards these ends than towards UA in combating their food-borne environmental impacts. Even if UA's gross environmental benefits may be limited, there is still a place for it in cities as a constructive, social enterprise, as the non-profit cases in this study have shown.

One unanswered question is whether a city that fully utilizes UA will actually make a dent in their food related environmental impacts. An assessment at the urban level which looks at available space and production capacity given different UA forms, and then assesses the amount of conventional food displaced by the urban production system would serve as a good starting point to understand if UA is a meaningful design intervention to combat the environmental challenges of prevailing urban food supply chains, whilst also testing scaling effects on some of the purported environmental benefits to the city at large. However, in light of the reality that the meat and dairy are the dominant drivers of food related environmental impacts (Foley et al., 2011; Tilman and Clark, 2014), the ability of UA to significantly alter a city's environmental burdens, even given potential urban symbiosis, appears limited.

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