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Comparative environmental footprints of lettuce supplied by hydroponic controlled-environment agriculture and field-based supply chains

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ABSTRACT

Attributional life cycle assessment was applied to determine environmental footprints of lettuce produced across ten supply chain configurations, based on either hydroponic closed-environment agriculture (CEA) with six different electricity sources, or field supply chains involving regional, continental or inter-continental transport. Hydroponic CEA systems use circa 15 kWh of electricity for lighting, cooling, ventilation and pumping per kg of lettuce supplied. Based on typical current national grid electricity generation mixes with significant fossil fuel dependence, this results in large environmental footprints, e.g. up to 17.8 kg CO_2 eq. and 33 g N eq. per kg lettuce – compared with 10 kg CO_2 eq. and 16 g N eq. per kg lettuce air-freighted across continents. However, hydroponic CEA can produce orders of magnitude more produce per m^2.yr and can be integrated into existing buildings (e.g. on roof tops, in basements and disused warehouses, etc). Factoring in the carbon opportunity costs of land use, and meeting electricity requirements exclusively through renewable generation, could result in closed hydroponic CEA delivering produce with a smaller carbon footprint than most field-based supply chains, at 0.48 kg CO_2 eq. per kg lettuce. However, this would only be the case where renewable electricity originates from genuinely additional capacity, and where a land use policy or other mechanisms ensure that modest areas of land spared from horticultural production are used for "nature based solutions" such as afforestation. Hydroponic CEA uses orders of magnitude less direct water than field-based systems, and could help to mitigate water stress and associated soil degradation in arid and semi-arid regions used for horticulture – so long as upstream water stress associated with electricity generation is mitigated. CEA could be one of the least sustainable forms of food production if poorly implemented, and has numerous environmental hotspots. But with careful design and scaling, in appropriate contexts of high demand and low agro-climatic potential for production of horticultural produce, CEA deployment could play a role in sustainable food system transformation, potentially helping to reconnect consumers with (urban) producers. There may be opportunities to link building air handling systems with rooftop or basement CEA requiring inputs of cooling, CO_2 and water.

1. Introduction

1.1. Environmental impacts of food supply chains

Approximately 21–37% of global anthropogenic greenhouse gas (GHG) emissions are attributable to the food system, inclusive of 5–10% from supply chain activities (IPCC, 2019b). Global food demand is steadily increasing in response to population growth, rising incomes, dietary trends and food waste (IPCC, 2015; Vågsholm et al., 2020). To meet this increasing demand, over 1.6 billion ha of the world's land is used for crop production (FAOStat, 2021), and global cropping area has expanded by 5 million ha annually for the last 30 years, contributing to deforestation and associated land degradation and greenhouse gas (GHG) emissions (Searchinger et al., 2018). Globalisation of food systems has resulted in geographical and psychological disconnections between production and consumption, with food commodities traded

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over long distances (Albrecht and Smithers, 2017) meaning that food consumption is no longer constrained by seasonality or local availability. Fader et al. (2013) indicate that 16% of the world's population rely on internationally transported agricultural products. Long food supply chains enable food to be grown efficiently in well-suited agro-climatic zones (Webb et al., 2013), but can also incur large environmental costs. Transport distance and mode are important factors in supply chain sustainability (Coley et al., 2011). Food transport to and within the UK emits 19 million tonnes of CO_2 equivalent annually (Smith et al., 2005). Previous studies have shown that foods imported into the UK, including tomatoes from Spain and lamb from New Zealand, can have a smaller carbon footprint than foods produced within the UK (Webb et al., 2013). Airfreight may be used to transport high-value, perishable foods constrained by seasonality, accounting for 0.1% of food vehicle-kilometres but contributing 11% of food transport GHG emissions (Smith et al., 2005). Frankowska et al. (2019) found that food products transported by airfreight can have carbon footprints five times larger than for domestically produced food crops. The European Environment Agency recommends shorter supply chains coupled with prevention of food loss as important measures to reduce the environmental cost of food production (EEA, 2014). However, the productivity of field crop production varies across regions and farm production systems, and is subject to biophysical constraints including seasonality (Oglethorpe and Heron, 2013) and adverse weather conditions that may increase in frequency due to climate change (Barlow et al., 2015; Beillouin et al., 2020). Alongside priority actions such as moderating demand for livestock products and reducing food waste (Springmann et al., 2018; Willett et al., 2019), improving the sustainability of horticultural supply chains will be integral to driving sustainable transformation of food systems.

1.2. Controlled environment agriculture

In recent decades there has been increasing interest in various forms of "controlled environment agriculture" (CEA), which in essence refers to indoor, soil-less systems where light, temperature, humidity, water and nutrient availability are carefully controlled (Brechner and Both, 2013; Goodman and Minner, 2019). Often they are hydroponic (i.e. using recirculated water to deliver nutrients to plant roots) and vertical (i.e. multi-level cultivation), and have been touted as a modern approach to produce leafy greens and vegetables within cities via short, local supply chains (Benke and Tomkins, 2017). CEA systems typically use artificial LED lighting that can be tailored to selected crops, including cucumbers, leafy greens, tomatoes, strawberries, eggplants, and peppers (Grewal et al., 2011; Barbosa et al., 2015; Yang and Kim, 2020). CEA avoids problems such as soil degradation, including erosion, salinization and compaction (Atmadja et al., 2017; KHAN, 2018), crop losses from extreme weather and various pests and diseases (Yuvaraj and Subramanian, 2020), and soil-derived emissions of nitrous oxide (N_2O) and nutrient leaching (Oertel et al., 2016). CEA based on hydroponic systems can use 90% less water to produce 20 times more food than conventional agricultural methods (Barbosa et al., 2015), providing optimum growing conditions to maximise crop productivity and potentially sparing land for carbon dioxide removal (CDR) via, *inter alia*, forestry (Searchinger et al., 2018) and soil improvement (IPCC, 2019b). CEA are touted as a disruptive technology with potential to reconfigure food supply chains by enabling continuous local production (Nakandala and Lau, 2019), including in urban settings (Brechner and Both, 2013; Albrecht and Smithers, 2017). Urban agriculture (Goldstein et al., 2016; Martin and Molin, 2018; Farhangi et al., 2020; Yang and Kim, 2020) could reconnect the 68% of global population housed within cities occupying just 1% of global land (Flörke et al., 2018) with food production. But CEA can also be deployed in rural settings, e.g. in disused farm buildings, providing an opportunity for farmers to diversify income.

However, CEA systems are energy intensive, and the environmental footprint of food produced in such systems requires careful evaluation to determine what, if any, role they could play sustainable food system transformation. Life Cycle Assessment (LCA) is a holistic approach that can be used to assess the environmental efficiency (Rebitzer et al., 2004) of food value chains (Notarnicola et al., 2017). Hydroponic CEA systems have been environmentally assessed in Sweden (Martin and Molin, 2018), Arizona (Barbosa et al., 2015) and France (Romeo et al., 2018). Romeo et al. (2018) found hydroponic CEA systems to be more efficient than open-field and heated greenhouse systems and all these studies found that energy use is the main environmental hotspot that could be mitigated through use of renewable energy. However, these studies applied local grid mix electricity emission factors, and benchmarked against local counterpart systems (rather than long-distance supply chains). There is a gap in the literature for a comprehensive LCA comparison of hydroponic CEA with large-scale open field horticulture, considering multiple supply chain configurations. Our study addresses this knowledge gap by benchmarking the environmental performance of hydroponic systems under different energy source scenarios with a range of regional and international supply chains based on field production across different agri-climatic zones. This study was undertaken as part of a project evaluating the potential for novel metal-organic material sorbents (Mukherjee et al., 2019) to supply water and CO_2 enrichment to CEA systems. Results presented here are intended as a benchmark of baseline CEA performance against which the introduction of these sorbents can be benchmarked (future research).

2. Materials and methods

2.1. Goal and scope definition

The LCA method in this study adheres to the relevant ISO LCA standards: ISO 14040–14044 (Finkbeiner et al., 2006), and consists of four main phases: goal scope and definition; life cycle inventory analysis; life cycle impact assessment and life cycle interpretation. The goal of this work is to compare the environmental efficiency of lettuce production, packaging and transport across different supply chain configurations for hydroponic CEA and conventional field production. An attributional cradle-to-gate LCA is conducted to calculate the environmental footprint of 1 kg of "delivered" lettuce (functional unit), on a fresh matter basis, at regional distribution centres (RDC). For field cultivation, Great Britain (GB) is considered as the destination country. Primary foreground activity data were obtained from a commercial provider of CEA systems (Freight Farms, 2021), whilst a combination of primary and secondary foreground data were used to model various field systems, as described in the inventory sections, below. Data quality and representativeness are used to inform uncertainty analyses (section 2.6). Economic allocation is applied, using the "allocation at point of substitution" Ecoinvent v3.6 inventory database. All identified inputs or emission sources accounting for at least 1% of product impacts were included in the inventory.

2.2. Supply chain scenarios & system boundaries

Ten indicative supply chain configurations are evaluated to indicate the range of footprints associated with local CEA production supplied by different electricity sources, and regional (GB), continental (ES) and intercontinental (US) supply of lettuce to GB, with inclusion of arid cultivation in the US desert to represent potential water scarcity effects (Table 1). Previous studies have suggested the use of renewable energy to reduce the environmental footprint of CEA systems (Molin and Martin, 2018; Barbosa et al., 2015; Romeo et al., 2018). Three renewable and three grid electricity source options were modelled. In addition to using 100% wind and solar PV renewable electricity inputs, the CEA system is also coupled with GB grid electricity (to compare with field-grown lettuce supply chains terminating in GB RDCs) and with Norwegian and South African grid electricity to demonstrate the influence of relatively clean and polluting grid electricity generation,

Table 1
Summary of evaluated lettuce supply chain configurations, comprising six hydroponic CEA systems with different energy sources, plus four field systems across three agro-climatic zones and with differing transport burdens.

Supply chain	Hydroponic, solar (off-grid)	Hydroponic, wind (off-grid)	Hydroponic, wind (on grid)	Hydroponic, GB	Hydroponic, Norway	Hydroponic, South Africa	Field, GB	Field, Spain	Field, US Coast	Field, US Desert
Name	H-RE$_{Solar}$	H-RE$_{Wind}$	H-RE$_{WindG}$	H-GB	H–NO	H-ZA	F-GB	F-ES	F-US$_{coast}$	F-US$_{desert}$
Climate	N/A	N/A	N/A	N/A	N/A	N/A	Temperate	Semi-arid	Mediterranean	Arid
Grid	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Electricity source	Solar PV cells & 85 kWh battery	Onshore <1 MW wind turbine & 85 kWh battery	Onshore <1 MW wind turbine &	GB grid (natural gas, renewables & nuclear)	Norway grid (hydro dominated)	South Africa grid (coal-dominated)	GB grid (natural gas, renewables & nuclear)	Spanish grid (fossil fuels, renewables & nuclear)	US grid (natural gas, coal, nuclear & renewables)	US grid (natural gas, coal, nuclear & renewables)
Transport	NA	NA	NA	NA	NA	NA	HGV	HGV	Air-freight & HGV	Air-freight & HGV

respectively, on CEA lettuce footprints (Table 1). Although transport to GB is considered to indicate different transport distances for field lettuce systems, it is assumed that CEA systems (hydroponic containers) are always located in close proximity to final consumers, resulting in negligible waste and transport requirements (Fig. 1). "Hyper-local" production is one of the main justifications for investment in CEA systems, and therefore the scenarios presented here provide a comparison of these systems with different energy inputs, to benchmark against conventional supply chains using GB as an example country for final consumption. Transport modes are primarily refrigerated heavy goods vehicle (HGV) and airfreight. Comparing lettuce from CEA directly with lettuce from RDCs (still requiring onward distribution) is thus regarded as a conservative approach.

The system boundary (Fig. 1) includes all processes relevant to cultivation and primary distribution of products, from raw material extraction to manufacturing of infrastructure, up to the point of a GB RDC for field systems, as an example of seasonal supply to a temperate country, congruent with the CEA systems.

2.3. Controlled environment agriculture inventories

Inventory data for the CEA systems were obtained from existing, high-yield, advanced hydroponic modules based on 28 m^2 temperature-controlled steel shipping containers containing vertical aluminium towers (Freight Farms, 2021). Foreground activity data were combined with background process data from Ecoinvent v.3.6 database, with allocation at point of substitution (Moreno-Ruiz et al., 2018) in OpenLCA v.1.10.3 (GreenDelta, 2006). The six hydroponic system scenarios (Table 1) were adapted by applying different electricity generation and battery storage burdens to the same hydroponic system infrastructure and operational inputs (Table 2). The internal climate is regulated by a HVAC system which maintains steady temperature, humidity and air quality, in combination with LED lighting. Lettuce plug inputs require seeds, plastic trays and crop growth media (peat and coco-fibre). A liquid fertiliser mix, *Fertmax*, and pH buffers are added to the water solution pumped through the system. The solution is constantly measured for electrical conductivity, temperature, pH and nutrient concentration. A pump is required to allow the collected water solution to drip through the roots of the system. Electricity is required to maintain the internally regulated system, the HVAC system and LEDs being the largest consumers of electricity. It is assumed that 6 g of LDPE plastic is required as packaging per kg of lettuce produced (Table 2). CEA can be placed anywhere, so it is assumed that transport to RDCs is not necessary. Full life cycle renewable energy inputs are modelled using Ecoinvent process data for global (market) average supply of electricity from 3 kWp solar photovoltaic (PV) modules (H-RE$_{Solar}$) and from wind energy with onshore <1 MW wind turbine (H-RE$_{Wind}$). These aforementioned two scenarios also include off-grid battery storage, represented by the manufacturing burdens of producing an 85 kWh battery array of 7616 cell, annualised over a 10 year lifetime. Wind energy input was also modelled without battery storage, assuming a buffering grid connection (H-RE$_{WindG}$). A Norwegian grid input (H–NO) represents a primarily hydropower energy source. GB and South African grid electricity inputs represent a mixed grid of natural gas, renewable and nuclear energy sources (H-GB) and coal-dominated generation (H-ZA), respectively.

2.4. Conventional system cultivation inventories

Activity data for field cultivation of lettuce in GB and Spain were predominately extracted from Milà i Canals et al. (2008), whilst cultivation data for the USA were primarily drawn from reports on Californian lettuce production (Turini et al., 2011; Tourte et al., 2017). Data were adapted to generate individual inventories representing the four field cultivation supply chains summarised in Table 1, and based on iceberg lettuce to the extent that variety-specific data were available.

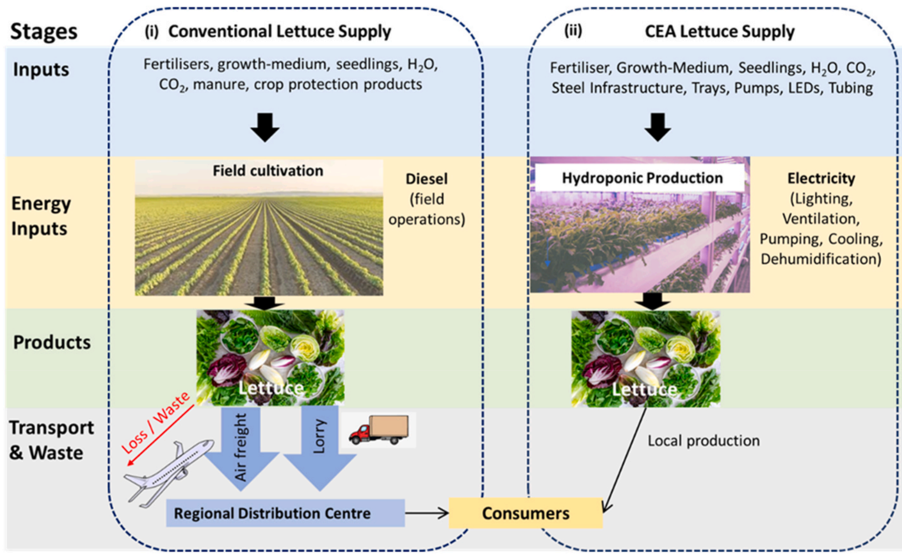

Fig. 1. Main stages and processes within LCA system boundaries to compare environmental footprints of lettuce supply from conventional open field systems vs controlled environment agriculture.

Table 2
Full inventories of inputs, processes and emissions for production and distribution to regional distribution centres in GB of 1 kg of fresh matter lettuce, produced in hydroponic controlled environment agriculture (Hydro-CEA) or from field systems (F-) in comparator countries.

Stage		Process/input	Unit	Hydro-CEA	Field cultivation				Refs
					F-ES	F-US$_{coast}$	F-US$_{desert}$	F-GB	
Construction	Infrastructure*	Steel structure	kg	0.029	NA	NA	NA	NA	Romeo et al. (2018)
		Aluminium towers	kg	0.035	NA	NA	NA	NA	Freight Farms (2021)
		Pump(s)	no.	3.7E-06	NA	NA	NA	NA	Romeo et al. (2018)
		LED lights	no.	0.081	NA	NA	NA	NA	Martin and Molin, 2018
Cultivation	Growing media	Peat	kg	0.008	NA	NA	NA	NA	Martin and Molin, 2018
		Coco fibre	kg	0.008	NA	NA	NA	NA	
	Fertilisers	Nitrogen	kg	0.002	0.013	0.003	0.005	0.003	
		Phosphorus	kg	0.001	0.010	0.000	0.004	0.001	Romeo et al. (2018); Freight Farms (2021); Turini et al. (2011)
		Potassium	kg	0.002	0.000	0.001	0.003	0.002	Freight Farms (2021)
		Calcium	kg	0.002	0.000	0.000	0.000	0.000	
		Magnesium	kg	0.0004	0.000	0.000	0.000	0.000	
		Sulphur	kg	0.0005	0.000	0.000	0.000	0.000	
		Iron	kg	0.0001	0.000	0.000	0.000	0.000	
		Lime	kg	0.000	0.000	0.023	0.065	0.012	Styles et al. (2015); García-Lorenzo et al., 2015; Miller et al. (2005)
	Other inputs	Electricity	kWh	15.0	0.059	0.030	0.033	0.031	Tourte et al. (2017)
		Diesel	kg	0.000	0.006	0.015	0.020	0.017	USDA (2021)
		Pesticide	kg	0.0000	0.0003	0.0002	0.0002	0.0002	Freight Farms (2021)
		CO_2	kg	0.081	0.000	0.000	0.000	0.000	Freight Farms (2021); Milà i Canals et al. (2008); Turini et al. (2011)
		Water	L	1.6	58.2	13.0	92.6	37.0	Styles et al. (2015)
		N_2O to air	kg	0.000	0.0001	0.0001	0.0001	0.0001	Styles et al. (2015)
		NH_3 to air	kg	0.000	0.0020	0.0005	0.0009	0.0016	
	Field Emissions	CO_2 to air	kg	0.000	0.008	0.015	0.036	0.018	
		P to water	kg	0.000	0.0001	0.0000	0.0000	0.0000	
		N to water	kg	0.000	0.0010	0.0001	0.0001	0.0011	Freight Farms (2021)
	Pack-aging	Cardboard	kg	0.000	0.026	0.026	0.026	0.026	Freight Farms (2021); Simko et al. 2015
Distribution		Plastic	kg	0.006	0.006	0.006	0.006	0.006	Tourte et al. (2017)
	Trans-port	Refrigerated lorry	t.km	0.000	2.6	0.3	0.4	0.2	Tourte et al. (2017)
		Air freight	t.km	0.000	0.0	8.6	8.8	0.0	Milà i Canals et al. (2008)

*Excluding onsite renewable electricity and battery storage infrastructure for relevant Hydro-CEA systems (accounted for within electricity inputs).

Iceberg is a crisphead lettuce with a relatively long shelf life, well suited for the long transport distances considered in some scenarios (Geisseler and Horwath, 2016). Planting via transplantation of young plants as plugs is widespread in both GB and Spanish lettuce production. Nursery production of plug plants takes place under cover (greenhouse production). We use inputs for salad plugs production from Ilari and Duca (2017) to estimate the burdens for lettuce plugs. Irrigation pumping energy within a greenhouse system was estimated using values for greenhouse lettuce production of 1.656 kWh m^{-3} from Milà i Canals et al. (2008). Lettuce plug fresh weight is estimated as 18 g plug^{-1}

(based on measurements from Cumming (2018) adjusted for a peat organic matter content of 80% and gravimetric moisture content of 1 g g $^{-1}$), and plugs are transported 40 km from the nursery to the farm (Bartzas et al., 2015).

Calculated field emissions included direct emission of nitrous oxide (N_2O) from crop residues and synthetic nitrogen fertiliser (SNF) application, based on the IPCC equation 11.2 (IPCC, 2019a); ammonia (NH_3) emissions based on SNF formulation volatilisation factors (IPCC, 2019a); indirect emission of N_2O due to volatilised SNF – calculated based on IPCC, equation 11.9 (IPCC, 2019a) – and nitrate (NO_3^-) losses to water calculated according to Styles et al. (2015); CO_2 emissions due to lime and urea application, according to IPCC (2006)CC (2006) and phosphorus (P) losses to water due to phosphate fertiliser application – calculated based on cropping system loss coefficients of 1% (Styles et al. 2015). Crop residue N inputs were calculated using measurements from Taft et al. (2018) for the proportion of aboveground lettuce remaining in the field after harvest (52% of total crop fresh matter; FM). We used measured values of 3% for lettuce moisture content and 39.9% for the carbon content of lettuce dry matter from Cumming (2018), along with a C:N ratio of 7.5:1 for lettuce residue from Baggs et al. (2000) to estimate aboveground residue N input. Belowground residue N input was estimated using the ratio of lettuce biomass belowground to aboveground (0.35:1), and the ratio of N content between roots and leaves (0.52:1) measured by Trinchera and Baratella (2018). Belowground and aboveground residue N inputs were summed to estimate total residue N inputs and the same method was applied for all scenarios.

GB field data were the average from three large farms in England (Milà i Canals et al. (2008)), each producing two lettuce crops annually. Production is highly mechanised with only crop harvest being performed manually. Lime use was estimated at 2.5 Mg every five years (Styles et al., 2015). We used irrigation water volumes from Milà i Canals et al. (2008) and assumed linear move spray irrigation, with energy consumption of 0.18 kWh m^{-3} (Plappally and Lienhard, 2012). Spanish data represent two large farms in the Murcia region of southeast Spain (Milà i Canals et al., 2008), also producing two crops of field lettuce annually. The ammonium and urea formulation split of SNF was estimated using Spanish fertiliser production data from FAOStat during the period 2002–2011. No lime application was assumed due to the basic soils in the region of Murcia (García-Lorenzo et al., 2015). Diesel inputs for Spanish production were dominated by fuel for worker transport as opposed to farm operations in the GB systems (Milà i Canals et al., 2008). Irrigation water in Spain is largely obtained from deep groundwater sources and requires pumping to the surface, consuming 0.4 kWh m^{-3} per (Plappally and Lienhard, 2012). We treated 20% of the total irrigation volume as spray irrigation to aid crop establishment and 80% as drip irrigation during the growing period. We used a value of 0.37 kWh m^{-3} for sprinkler irrigation energy use and 0.167 kWh m^{-3} for drip irrigation (Plappally and Lienhard, 2012). Transport distances from Murcia to London were calculated at 2600 via road, assuming a short ferry crossing or rail link via Eurotunnel to cross the English Channel.

US scenarios represent large scale intensive production in the Central Coast (F-US$_{coast}$) and Southern Desert (F-US$_{desert}$) regions of California, important regions for lettuce production (Geisseler and Horwath, 2016). On the Central Coast, climate conditions allow two lettuce crops to be produced annually. However the shorter growing season in the Southern Desert allows production of only a single lettuce crop per year. Lettuce yields for F-US$_{coast}$ and F-US$_{desert}$ were calculated using the iceberg regression equations for Monterey County and Imperial County (Simko et al., 2015), respectively (111.7 & 40.0 t FM ha^{-1} a^{-1}). Inputs of N, phosphorous (P) and potassium (K) were derived from Turini et al. (2011). On the Central Coast, N applications range from 168 to 202 kg ha^{-1} for the first crop and 112–168 kg ha^{-1} for the second crop. Combing the averages gives an annual N input of 325 kg ha^{-1} for F-US$_{coast}$. In the Southern Desert, early season crops require ~168 kg ha^{-1} whilst late season crops can require 224–280 kg ha^{-1}, so we took an average input of 210 kg ha^{-1} a^{-1}. Proportions of SNF applied as ammonium and urea formulations were taken from FAOStat for US agricultural use data for the period 2008–2016. P inputs of 22 and 151 kg ha^{-1} prior to each planting were modelled for F-US$_{coast}$ and F-US$_{desert}$, respectively. Potassium applications of 134 kg ha^{-1} a^{-1} were deemed adequate to maintain soil fertility, with no differences between regions or the number of crops produced. Lime application was based on the recommendations and median soil properties observed for Californian soils in Miller et al. (2005). Diesel use for a single lettuce crop was obtained from Tourte et al. (2017) and doubled for F-US$_{coast}$. Average seeding rate for a single lettuce crop was taken from Tourte et al. (2017), using an average seed weight of 0.6175 g per 1000 seeds from de Souza et al. (2019). Average annual pesticide application rates in kg active ingredient ha^{-1} were calculated using USDA NASS data for Californian lettuce crop production for the period 1992–2016 (USDA, 2021), doubled for F-US$_{coast}$ to account for the second crop. Crop water requirements vary considerably between the two US regions due to climatic differences. An average lettuce crop in the Southern Desert requires 3700 m^3 ha^{-1} (Turini et al., 2011). Surface-drip irrigation covers at least 60% of the vegetable production area on the Central Coast and covers (Johnson, 2013). We assume the remaining 40% is sprinkler irrigated and that these proportions apply to lettuce. Using values of 500–700 m^3 ha^{-1} for a drip irrigated lettuce crop and 750–1000 m^3 ha^{-1} for sprinkler irrigated lettuce, and assuming two crops per year on the Central Coast, gives an average irrigation water requirement of 1450 m^3 ha^{-1} a^{-1} for F-US$_{coast}$ (Turini et al., 2011). Irrigation energy use for the F-US$_{coast}$ was calculated using aforementioned values for drip irrigation and sprinkler irrigation, and 0.24 kWh m^{-3} for groundwater pumping from a depth of 60 m. Irrigation in the Imperial Valley (F-US$_{desert}$) is predominately furrow irrigation from canals (84%) with sprinkler irrigation making up the remainder (Scott et al., 2014). We used the value for sprinkler irrigation above and the value of 0.045 kWh m^{-3} for furrow irrigation, with no groundwater pumping (Plappally and Lienhard, 2012).

2.5. *Packaging & transport*

Initial vacuum cooling of lettuce was estimated to use 0.086 MJ kg^{-1} FM (Plawecki et al., 2014). For packaging we assume the use of LDPE at the rate of 3 g per lettuce, with an average lettuce head weight of 0.5 kg, giving a packaging weight of 0.006 kg kg^{-1} FM. Using the value of 42 lbs for packed carton weight (Tourte et al., 2017) and assuming a 0.5 kg weight for the box itself gives cardboard packaging of 0.026 kg kg^{-1} FM. Refrigerated transport is necessary to preserve lettuce and ensure acceptable shelf-life. We modelled refrigerated trucks for overland transport and refrigerated planes for air transport. We followed the approach of Milà i Canals et al. (2008), in assuming a 200 km distance from GB farms (or point of entry to the GB for US production) onward to a regional distribution centre. We used the distance of 2600 km overland transport from farms in Spain to the GB RDC from Milà i Canals et al. (2008). Vehicle freight within the US was estimated as 128 km for F-US$_{coast}$ (Salinas Valley, CA to San Jose International Airport, CA) and 200 km for F-US$_{desert}$ (Imperial Valley, CA to San Diego International Airport, CA) using Google Maps. Air freight distances were estimated as 8626 km (San Jose to London) and 8817 km (San Diego to London), respectively, using Google Maps.

2.6. *Life cycle impact assessment and uncertainty*

Life Cycle Impact Assessment (LCIA) was performed using Environmental Footprint (EF) v2.0 impact assessment suite in OpenLCA v.1.10.3. Results for all 16 impact categories determined in this method are presented at high level. Impact categories explored in more detail include: global warming, acidification, freshwater eutrophication, marine eutrophication, resource depletion – energy carriers and terrestrial eutrophication. In addition, land occupation and water use for cultivation were also considered, based on inventory data. Various approaches have been suggested for dealing with uncertainty in LCA, with a core principle of focussing uncertainty analyses on uncertain variables that significantly influence burden results (Huijbregts et al., 2001). Here, field and hydroponic-CEA scenarios (Table 1) were designed to span the range of energy and global warming impacts for both types of system, thus addressing important uncertainty across appropriate comparator systems via sensitivity analyses. A simple post-hoc error propagation approach was taken to indicate uncertainty associated with inventory inputs, where aggregate uncertainty was expressed as the square root of the sum of the squares of estimated uncertainty ranges for major contributing categories – ranging from e.g. 10% for plug production to 50% for infrastructure, field irrigation and field emissions (see S1).

3. Results

Environmental footprints differ by orders of magnitude across the different systems (Table 3 and Fig. 2). For example, global warming burdens (carbon footprints) vary from 0.15 (field-grown in Great Britain) to 18 (CEA in South Africa) kg CO_2 eq. per kg lettuce, and terrestrial eutrophication burdens vary from 0.0037 (CEA with wind electricity and grid connection) to 8.4 (CEA in South Africa) mol N eq. per kg lettuce. Normalised scores varied from 4.3 E−06 to 8.8E-03 per capita equivalent for main results in Fig. 2, and up to 1.4 per capita equivalent for all results (see S2). It is clear that the energy source can have a greater impact than the type of system (CEA vs field) in determining environmental footprints, and CEA-grown lettuce has both the smallest and largest footprint across three impact categories (acidification, land use and terrestrial eutrophication) (Table 3 and Fig. 2).

3.1. Closed systems require large energy inputs

Resource depletion across energy carriers ranged from 1.4 (field grown, GB) to 239 (CEA in South Africa) MJ per kg lettuce (Table 3). Energy (electricity) generation and manufacture of infrastructure dominates resource depletion for the CEA systems, whilst packaging and transport (especially air-freight) processes are the main contributors to energy carrier resource depletion for lettuce produced in field systems, with significant contributions from fertiliser and crop protection agents and irrigation (Fig. 3). The hydroponic CEA systems require 15 kWh of electricity to produce 1 kg of lettuce, though different energy sources translate into resource depletion burdens of between 4.1 and 239 MJ per kg lettuce. The resource depletion footprint of lettuce produced in a H-

Table 3
Heat map of environmental burdens per kg lettuce across the ten studied horticultural systems. Impacts are measured across each respective impact category. Blue indicates the system with the lowest impact, red indicates the system with the highest impact.

Impact category	Unit	H-RE$_{Solar}$	H-RE$_{Wind}$	H-RE$_{WINDG}$	H-NO	H-GB	H-ZA	F-ES	F-US$_{coast}$	F-US$_{desert}$	F-GB
Global warming	kg CO_2e	1.33	0.56	0.48	0.89	8.9	17.8	0.68	9.95	10.0	0.15
Acidification	mol H+ eq ($x10^{-2}$)	1.6	1.2	1.0	1.3	6.2	25	1.8	5.2	5.3	5.5
Freshwater eutrophication	g P eq (X10)	13.5	5.1	3.1	6.2	38	130	1.1	2.5	2.9	0.26
Marine eutrophication	g N eq ($X10^{-4}$)	17	6.5	5.1	8.3	85	330	16	170	170	3.3
Land use	Pt	2.4	3.3	3.1	1.6	9	36	6.0	4.3	4.7	0.67
Resource depletion energy	MJ	17	5.2	4.1	12	183	239	8.7	139	143	1.4
Human health (cancer)	CTUh ($x10^{-8}$)	4.4	4.1	3.8	28.8	11.6	28	0.77	251	291	0.12
Freshwater ecotoxicity	CTUe	1.67	0.77	0.58	8.4	3.2	8.4	1.3	1.6	1.6	0.15
Ionising radiation	kBq U-235 eq	0.14	0.041	0.031	0.78	4.3	0.78	0.061	0.67	0.68	0.015
Human health (non-cancer)	CTUh ($x10^{-8}$)	47	16	10	351	134	351	11	20	22	2.5
Ozone Depletion	kg CFC-11 eq ($x10^{-8}$)	14	3.2	2.1	30	55	30	13	229	229	1.6
Photochemical ozone	g NMVOC eq	5.25	1.6	1.2	0.0003	23	0.0003	4.0	49	49	0.47
Resource depletion minerals	g Sb eq	0.053	0.011	0.0035	0.014	0.012	0.014	0.0025	0.0025	0.0029	0.0004
Respiratory inorganics	disease inc. ($x10^{-8}$)	8.37	3.1	2.5	32	13.6	32	10.0	18.5	19.7	4.0
Terrestrial eutrophication	mol N eq	0.015	0.0049	0.0037	0.034	0.087	8.4	0.042	0.19	0.19	0.024
Water scarcity	m^3 deprived	111	18	17	37	23	24	13	10	12	2.2

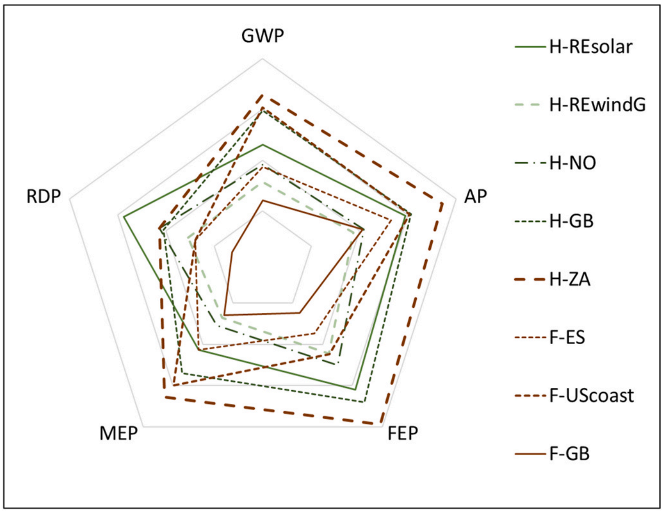

Fig. 2. Radar plot of normalised scores for lettuce supplied from hydroponic CEA systems (H-) and field cultivation (F-), across Global Warming Potential (GWP), Acidification Potential (AP), Freshwater Eutrophication Potential (FEP), Marine Eutrophication Potential (MEP) and Resource Depletion Potential energy carriers (RDP). Maximum y-axis value 0.01 per capita equivalents. H-RE_{wind} and F-US_{desert} similar to H-RE_{windG} and F-US_{coast}, and omitted for clarity.

RE_{WindG} system is almost 60 times less than that of lettuce grown in a H-ZA system, and less than that of imported lettuce (F-ES and F-US) but still over twice that of regional field-grown lettuce (F-GB). Use of grid electricity for CEA in GB (or ZA) results in considerably larger resource depletion footprints than for lettuce air-freighted from the US to GB.

3.2. Carbon footprints

Global warming burdens (carbon footprints) vary 51-fold from 0.48 to 17.8 kg CO_2 eq. per kg lettuce grown in hydroponic CEA systems, and from 0.15 to 10 kg CO_2 eq. per kg lettuce supplied from field cultivation (Table 3). Lettuce imported to Britain from Spain (F-ES) has a larger carbon footprint (0.68 kg CO_2 eq. kg^{-1}) than lettuce produced in hydroponic CEA systems powered by wind (H-RE_{windG} and H-RE_{wind}), but a smaller footprint than lettuce produced in hydroponic CEA systems powered by solar PV or grid electricity from Norway (H–NO), Britain (H-GB) or South Africa (H-ZA) (Table 3). However, all hydroponic CEA grown lettuce, with the exception of that using the South African grid, has a smaller carbon footprint than lettuce air-freighted from the US to GB. The same processes contributing to resource depletion energy carriers contribute to carbon footprints, in particular for the hydroponic CEA systems, with the major difference being the significant contribution of field (soil) emissions for field-grown lettuce – most visible for the F-GB system owing to low energy generation and transport burdens (Fig. 3).

3.3. Nutrient footprints

Leakage of reactive nitrogen and phosphorus drive acidification and freshwater, marine and terrestrial eutrophication burdens. Energy (electricity) generation dominates these footprints for the hydroponic CEA systems (Fig. 2), with coal electricity generation on the South African grid driving very high footprints for lettuce grown in the H-ZA system – up to 0.25 mol H+ eq., 13 g P eq., 33 g N eq. and 8.4 mol N eq. for acidification, freshwater, marine & terrestrial eutrophication, respectively (Table 3). These footprints are between 69 and 2270 times larger than the smallest footprints for F-GB and H-RE_{windG} lettuce. Ammonia emissions from fertiliser-N application in field systems with otherwise very low reactive nitrogen emissions from energy sources (notably F-GB) means that lettuce produced in hydroponic CEA systems powered by wind RE have the smallest acidification and terrestrial eutrophication footprints (Table 3). Air-freight results in intermediate acidification and eutrophication burdens for lettuce cultivated in the US (Table 3; Fig. 2).

3.4. Potential for land sparing

Finally, to identify the potential for hydroponic CEA systems to spare land, we calculated the simple land occupation of lettuce cultivation (Fig. 4). Hydroponic CEA systems produce 154 kg per m^2.yr, up to 38 times more than the field systems (F-US_{desert}). Consequently, land occupation ranges from 0.0065 m^2 yr per kg for CEA lettuce to 0.25 m^2 yr per kg for F-US_{desert} lettuce, with F-GB requiring 0.24 m^2 yr per kg lettuce produced (Fig. 4). Representing land occupation in terms of carbon opportunity costs (CoC) for field-grown lettuce in non-arid climates (Searchinger et al., 2018) increases the carbon footprint of F-ES, F-US_{coast} and F-GB lettuce to 0.80, 10 and 0.46 kg CO_2 eq., respectively (Fig. 4). Thus, accounting for CoC results in lettuce from H-RE_{wind} (on- or off-grid) having among the lowest carbon footprints (0.48 and 0.56 kg CO_2 eq. kg^{-1} lettuce, respectively).

3.5. Water stress

From a full life cycle perspective, water scarcity impacts are highest from the CEA systems owing to manufacture of infrastructure (steel, aluminium and LEDs) and energy generation (Table 3). In fact, solar-PV generation incurs a particularly high water scarcity burden according to the Ecoinvent process for electricity generation from multi-Si laminated solar PV panels. However, water scarcity footprints are highly sensitive to geographically differentiated scarcity coefficients (Boulay et al., 2018), and have only recently been integrated into impact assessment methods for the Ecoinvent database. A recent study found that underlying flows and regionalised characterisation factors are not yet fully reliable (Schestak et al., 2022), and the global average data used for this study will not represent important geographic specificities. Therefore, direct water usage for cultivation (Fig. 4) provide a more certain, albeit narrow, indication of potential water use efficiency across the systems. Water use requirements range from 1.6 to 93 L of water per kg of lettuce produced, with field cultivation requiring eight to 60 times more water hydroponic CEA systems. Whilst the F-US_{desert} supply chain may be comparatively efficient in terms of carbon footprint compared with hydroponic CEA supply chains, exclusive of air-freight (i.e. where lettuce is consumed regionally), the very high water use within the context of an arid climate represents a major environmental hotspot. Similarly, the 58 L of water required to produce 1 kg lettuce in the water stressed region of Murcia, Spain, represents a significant environmental hotspot.

4. Discussion

4.1. Energy and carbon footprints

Whilst hydroponic CEA systems can be highly efficient in terms of water and land use, this study confirms that electricity consumption for lighting, cooling, ventilation and pumping is very high (15 kWh per kg lettuce), in agreement with recent studies (Barbosa et al., 2015; Martin and Molin, 2018; Romeo et al., 2018). The environmental footprint of lettuce produced in CEA systems is therefore highly sensitive to the form of electricity generation. Use of coal-heavy (South Africa) and mixed (Britain) grid electricity results in large carbon footprints of 17.8 and 8.9 kg CO_2 eq. per kg lettuce, respectively. Local CEA cultivation and consumption can therefore require more primary energy and generate more GHG emissions than even long-distance air-freight lettuce supply chains. A relatively small footprint (0.68 kg CO_2 eq. kg^{-1}) for Spanish lettuce imported to GB via lorry and ship confirms that "food miles" are not always a good indicator of the environmental impact of food supply (Edwards-Jones et al., 2008). Grid electricity generation contributes to a

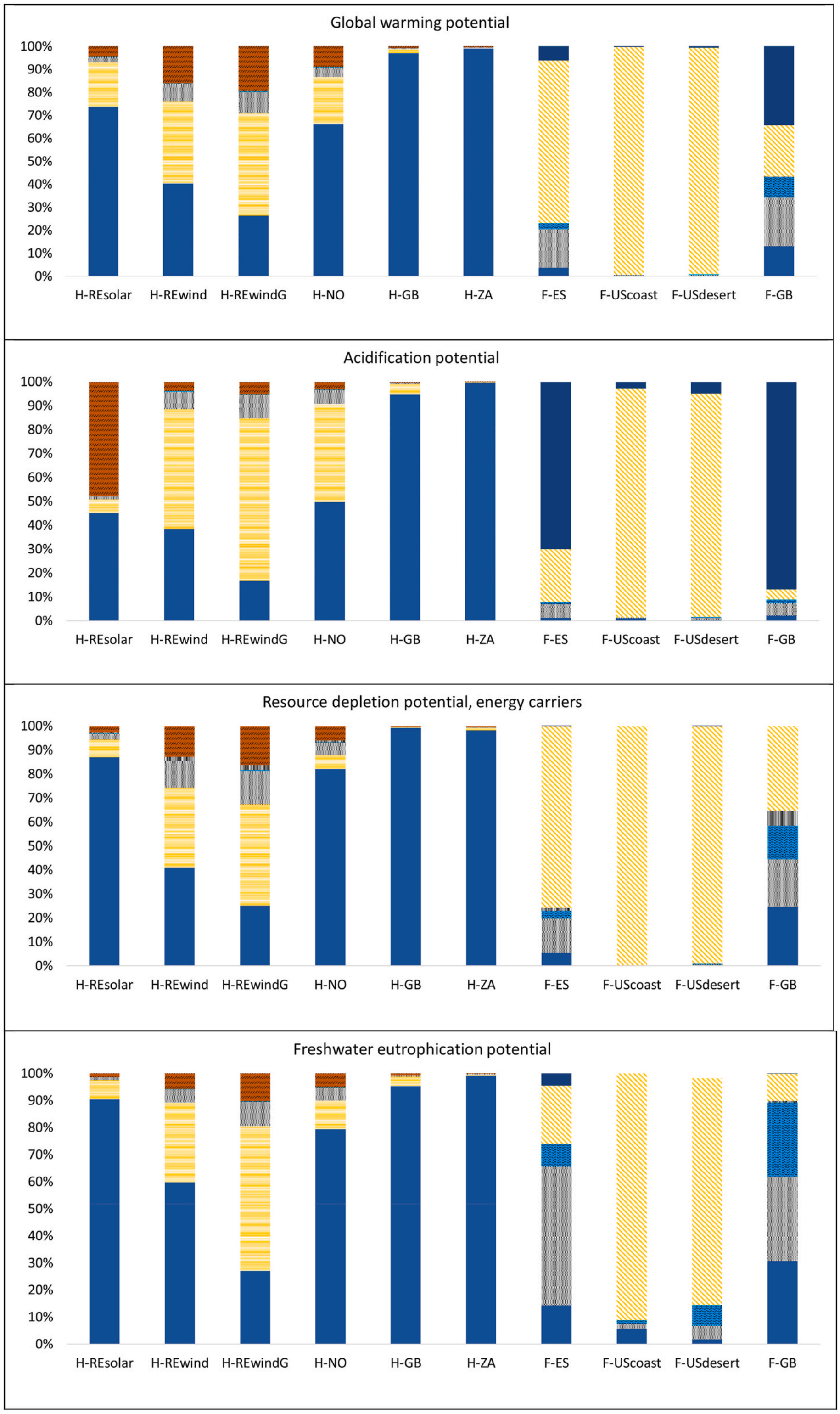

Fig. 3. Contribution analysis across global warming potential, acidification potential, resource depletion potential (energy carriers) and freshwater eutrophication potential burdens for lettuce supplied from different systems.

wide spectrum of environmental impacts in addition to climate change, including acidification, eutrophication, photochemical smog, etc. Thus, CEA cultivation fed by national electricity grids risks being considerably less environmentally sustainable than conventional lettuce supply chains.

Nonetheless, where electricity can be sourced from a "clean" grid (e.g. Norwegian grid considered here), or dedicated renewable generation, in particular medium-scale wind generation, CEA systems can produce lettuce with comparatively small environmental footprints, and can reduce emissions relative to continental (and certainly inter-continental) supply chains. Data from the Ecoinvent database indicate that global "market average" footprints for lettuce range from 0.24 to 3.63 kg CO_2 eq. kg^{-1}, increasing up to 6.1 kg CO_2 eq. kg^{-1} for lettuce grown in heated greenhouses. Hydroponic CEA systems powered by

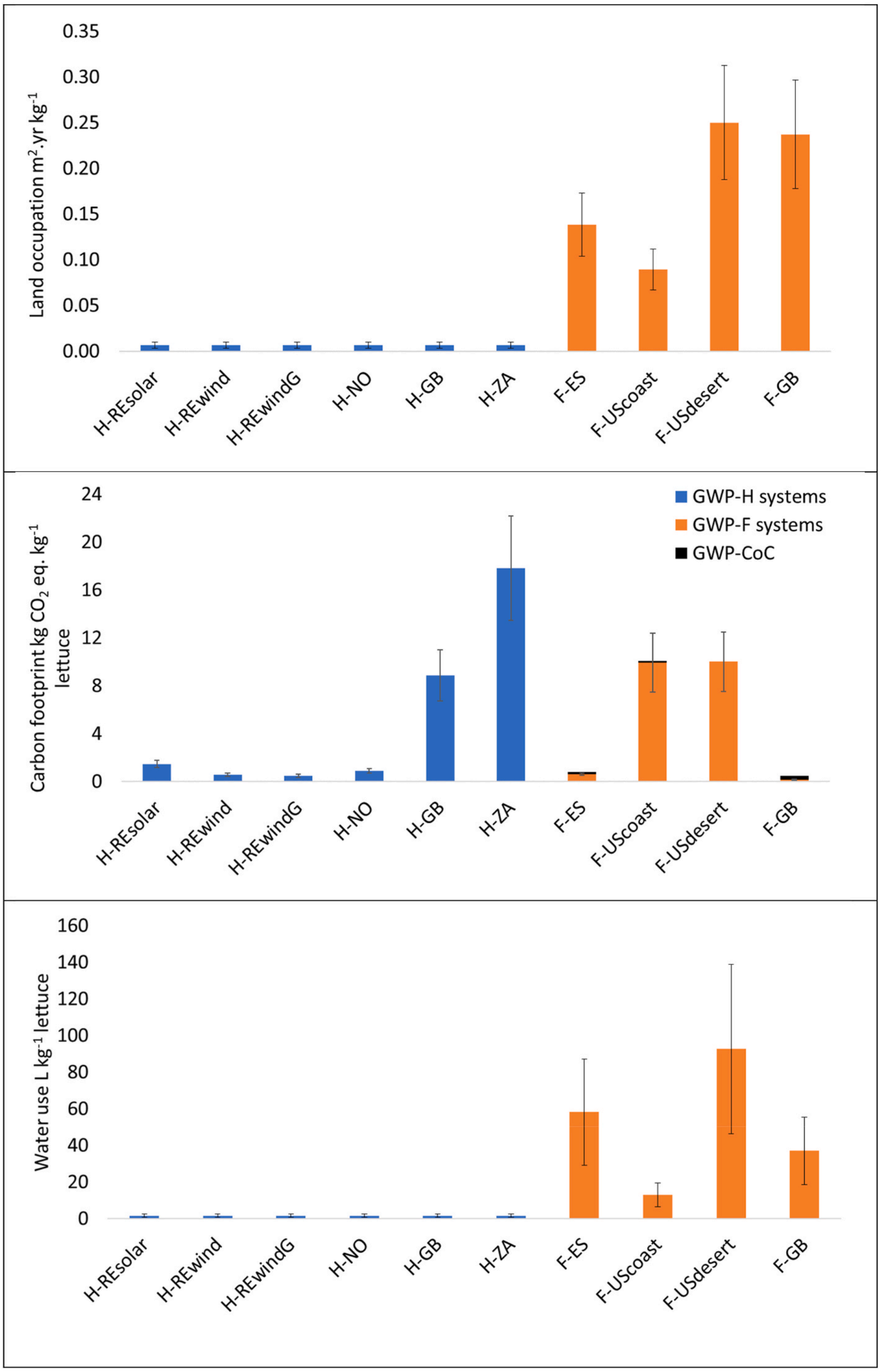

Fig. 4. Land occupation (top), carbon footprint (including carbon opportunity cost of land occupation, middle) and water use (bottom) across the hydroponic CEA (H-) and field (F-) lettuce supply chains. Error bars indicate aggregate uncertainty propagated as the square root of the sum of squares of estimated uncertainty ranges for major processes.

renewable energy or clean grids compare favourably with these values, indicating a potential contribution of carefully designed CEA systems in the right context (i.e. to provide local salads in regions where long-distance transport or heated greenhouse production is otherwise required). Solar PV electricity generation resulted in an intermediate footprint, owing to the relatively high emissions associated with small-scale system installation, including relatively large demand for material resources per kWh generated, in Ecoinvent. Rapid development of solar PV technologies, and circular use of resources at end-of-life (Gallagher et al., 2019) is likely to drive these emissions down considerably through time, towards those arising from wind-electricity driven systems. Indeed, sustainable supply and circular reuse and recycling of materials such as steel, aluminium, copper, nickel, lithium and cobalt required for the extensive infrastructure supporting CEA systems will be critical to enable sustainable out-scaling in a manner that avoids burden shifting and opportunity costs arising from more beneficial use of constrained resources to decarbonise economies (Bobba et al., 2020).

4.2. Land sparing opportunities

Land is under increasing pressure from demand for food production, bioenergy generation, urbanisation, biodiversity and carbon dioxide removal practices such as afforestation (IPCC, 2019b). In this context, the land sparing potential of stacked or extended vertical CEA systems could be significant. The particular (single story) configuration of CEA system looked at here could produce up to 38 times more lettuce per m^2. yr of land occupation. Land requirements for onsite solar PV and wind electricity generation could increase net land take for CEA systems, depending on configuration. However, based on land occupation values for solar PV and wind electricity generation in Ecoinvent, land requirements per kg lettuce would remain considerably smaller for CEA than for any field system even if neighbouring land was used for electricity generation. Furthermore, solar PV cells and wind turbines could be located on non-cultivable land and integrated into buildings or existing urban areas, thereby sparing agricultural land.

Modular CEA systems could also be stacked on top of one another, or designed in different (taller) vertical farming configurations, potentially leveraging more land sparing. Furthermore, such systems can be located on roof-tops, in basements, disused warehouses and other types of under-utilised urban space (Toboso-Chavero et al., 2019), or indeed on marginal agricultural land or in existing farm out-buildings. Therefore, developing such systems in small areas could leverage significant land sparing of over 100 times the net land take (e.g. if containers considered here are stacked three deep) – making land available for, *inter alia*, afforestation, other types of food production, bioenergy generation or land preservation to aid biodiversity (Searchinger et al., 2018; IPCC, 2019b). After accounting for the CoC of field systems, hydroponic CEA systems powered by wind electricity can supply lettuce with a lower environmental footprint than most field systems. Therefore, if CEA systems can be combined with a land use strategy to regenerate areas spared from intensive horticulture, they could make a contribution towards addressing the climate and biodiversity emergencies – albeit a modest contribution compared with large areas that could be spared from livestock production (Prudhomme et al., 2021).

4.3. Reconfiguring resilient food supply chains

The COVID-19 pandemic has revealed the fragility of globalised markets (Aday and Aday, 2020), underlined at the time of writing by the war in Ukraine. Combined with vulnerability to climate change impacts such as water scarcity (Gosling and Arnell, 2013), this invites scrutiny of long and resource- (fertiliser, water and land) intensive food supply chains where consumers have become disconnected from producers (Albrecht and Smithers, 2017). Hydroponic CEA systems in urban areas could act as a disruptive technology that facilitates a reconfiguration of shorter supply chains with less transport, potentially helping to reconnect producers and consumers with strengthened local markets and promoting greater self-sufficiency and resilience (EEA, 2014; Toboso-Chavero et al., 2019; Albrecht and Smithers, 2017; Nakandala and Lau, 2018). The concept of 'hyper-localism' is linked with a shift in consumer habits, driven by the reconnection of producers with consumers (Albrecht and Smithers, 2017). Reducing transport logistics could also reduce food loss and food waste. UNEP (2021) estimate that one third of food produced (circa 1.3 billion tonnes) is lost or wasted each year. Food loss and waste accounts for circa 4.4 Gt CO_2 eq., 8–10% of total annual GHG emissions (UNEP, 2021). Risk of food loss in post-harvest handling and storage is significantly reduced for CEA systems located in close proximity to consumers, and where growth rates and harvest timing can to some degree be synched with volatile demand for fresh produce (Plazzotta et al., 2020). However, in agro-climate regions favourable for horticultural production, low-input peri-urban systems could supply produce to local consumers with much lower environmental footprints than CEA systems, and may also drive more sustainable consumption patterns by reconnecting consumers with producers (Puigdueta et al., 2021). A recent study found that fresh vegetables could be produced with a cumulative energy demand of just 2.2–5.1 MJ kg^{-1} and a carbon footprint of 0.12–0.27 kg CO_2eq kg^{-1} (Pérez-Neira and Grollmus-Venegas, 2018) – considerably smaller than equivalent footprints in this study.

Currently, 504 billion litres or 184 km^3 of water are extracted each year for human use (Flörke et al., 2018), 72% of which is for food production (UN, 2021) – although only a small share of this is for horticulture. Meanwhile, over 2 billion people in 43 countries are currently experiencing elevated water stress (UN, 2021). Many Asian, Central American, African and Mediterranean countries are approaching water scarcity or are water stressed (Fitton et al., 2019). Renewable water resources in the Mediterranean region are distributed irregularly. The Middle East, Spain and North Africa have particularly limited water resources (Scoullos et al., 2010). Circa 11% of current croplands are at risk of decline due to projected reduced water availability (Fitton *et* al., 2007). Our results demonstrate that hydroponic CEA systems have much lower direct water requirements than field systems. Murcia is a water stressed region in the south of Spain, where agricultural practices have overexploited groundwater resources (Fleskens et al., 2013). Water demands are estimated to reach 10–13.5 trillion m^3, or triple the current amount used by humans, in order to meet food demands by 2050, whilst climate change is likely to reduce availability in some regions (Fitton et al., 2019). CEA systems could play an important role in reducing the vulnerability of some food supply to future water stress, thus increasing resilience. However, although highly imprecise owing to lack of geographic specificity applied to renewable energy generating scenarios in this study, the high water scarcity footprints associated with CEA systems reflect a risk of shifting water stress "upstream" to regions producing components for renewable energy and battery systems, and/or generating grid electricity for use in CEA systems. Ultimately, the role of CEA systems in sustainable and resilient food supply chains is likely to be constrained to areas with high demand for horticultural products but low agro-climatic suitability for horticultural production. It is also important that scrutiny of the environmental footprint of fresh fruit and vegetables does not distract from the need for dietary shifts towards higher intake of such foods, and lower intake of animal products in industrialised countries, to deliver sustainable and healthy food systems (Springmann et al., 2018).

4.4. Limitations and further research

This study was based on relevant operational data available for lettuce cultivation in a commercial hydroponic CEA system and a range of field cultivation systems, combined with process data for cultivation inputs and distribution activities. We did not have equivalent data for commercial greenhouse systems using natural lighting, which could be significantly different. A detailed comparison with such systems would be useful, and the Ecoinvent data referred to above indicates that CEA systems could compare favourably. Similarly, it would be useful to obtain energy consumption data for CEA systems in different climates and configurations, where cooling energy demand (estimated at 40% of total electricity use in this study) could vary. We assumed all nutrient inputs were exported in lettuce produce. A detailed nutrient balance should be undertaken to identify whether any nutrients may be flushed out during periodic maintenance, which could lead to some field emissions (albeit much smaller the for field cultivation). Whilst good data were available for direct water use, water scarcity impacts depend on where that water is sourced throughout the value chain, including for the manufacture of renewable energy infrastructure, and it would be useful to update current water scarcity footprints with a more detailed, geographically explicit breakdown of supply chains and life cycle water use. Whilst we looked at the effect of using dedicated renewable energy generation combined with a large (85 kWh) battery, there is a need to establish whether and how off-grid systems could be configured to deliver reliable production. There may be planning and space issues that restrict the erection of wind turbines or solar panels in urban areas for CEA systems – given that there is likely to be high demand for such micro-generation in future to satisfy basic building energy requirements. However, there could be interesting opportunities to combine cooling, CO_2 enrichment and water demands of CEA systems with building air handling systems that often treat these outputs as "wastes". Such opportunities may represent the most sustainable "niche" for hydroponic CEA systems, alongside (peri-urban) agro-ecological cultivation methods and diversification to improve the sustainability of horticultural supply chains in regions with appropriate agro-climatic conditions (Vaarst et al., 2017). There remains an urgent need for foresight studies to evaluate the most suitable role for hydroponic-CEA systems alongside the plethora of agro-ecological techniques and systems that are also likely to be needed to drive a sustainable transformation of our food system (Aguilera et al., 2020).

5. Conclusions

Hydroponic closed-environment agriculture systems use a large amount of electricity for lighting, cooling, ventilation and pumping, equating to 15 kWh per kg of lettuce cultivated. Based on typical current national grid electricity generation mixes with significant fossil fuel dependence, this would result in very large environmental footprints, up to 17.8 kg CO_2 eq. per kg lettuce – even larger than the 10 kg CO_2 eq kg^{-1} emissions associated with supply of inter-continental air-freighted produce. Furthermore, such systems rely on elaborate infrastructure, and thus large inputs of material resources such as steel, aluminium and copper – which could put limits on sustainable scaling of closed-environment agriculture in the absence of successful circular reuse and recycling. However, hydroponic closed systems can produce orders of magnitude more produce per m^2.yr of net land occupation, and in fact may not require any net land occupation if they can be integrated into existing infrastructure and buildings (e.g. on roof tops, in basements and disused warehouses, etc). Factoring in the carbon opportunity costs of land use, and meeting electricity requirements exclusively through renewable generation, could result in closed hydroponic systems delivering produce with a smaller carbon footprint than most field-based supply chains, at 0.48 kg CO_2 eq. per kg lettuce. However, this would only be the case where renewable electricity originates from genuinely additional capacity, and where a land use policy or other mechanisms are in place to ensure that land spared from horticultural production is used for "nature based solutions" such as afforestation. Similarly, closed hydroponic systems use orders of magnitude less direct water than field-based systems, and could help to mitigate water stress and associated soil degradation in arid and semi-arid regions that many fruit and vegetable produce supply chains rely upon. Closed-environment agriculture could be one of the least sustainable forms of food production if poorly implemented, and has many environmental hotspots. But with careful design, scaling and business models, deployment of hydroponic closed-environment agriculture could play a role in positive food system transformation, reducing environmental footprints, sparing land to deliver other ecosystem services, and potentially helping to reconnect consumers with (urban) producers.

CRediT authorship contribution statement

Leanne Casey: Conceptualization, Methodology, Formal analysis, Writing – original draft. **Ben Freeman:** Conceptualization, Investigation, Formal analysis, Writing – review & editing. **Kurt Francis:** Conceptualization, Investigation, Writing – review & editing. **Galina Brychkova:** Investigation, Writing – review & editing, Project administration. **Peter McKeown:** Investigation, Writing – review & editing, Project administration. **Charles Spillane:** Conceptualization, Writing – review & editing, Funding acquisition. **Andrey Bezrukov:** Investigation, Writing – review & editing, Project administration. **Michael Zaworotko:** Conceptualization, Writing – review & editing, Funding acquisition. **David Styles:** Conceptualization, Methodology, Investigation, Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.133214.

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