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Sustainability of lettuce production: A comparison of local and centralized food production

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ABSTRACT

Communities are considering local food production in response to the pressing need to reduce food system greenhouse gas (GHG) emissions. However, local food systems can vary considerably in design and operation, including controlled environment agriculture (CEA), which refers to agricultural production that takes place within an enclosed space where environmental conditions, such as temperature, humidity, and light, are precisely controlled. Such systems require a considerable amount of energy and thus emissions; therefore, this study seeks to quantify these environmental impacts to determine how local CEA systems compare to alternative systems. For this study's methods, we apply life cycle assessment methodology to quantify the cradle-to-store-shelf GHG emissions and water consumption of four lettuce production systems: local indoor plant factory, local greenhouse, local seasonal soil, and conventional centralized production in California with transportation. Using geographically specific inputs, the study estimates the environmental impact of the different production systems including geospatially resolved growth modeling, emissions intensity, and transportation distances. The results include the major finding that baseline CEA systems always have higher GHG emissions (2.6–7.7 kg CO_2e kg^{-1}) than centralized production (0.3–1.0 kg CO_2e kg^{-1}), though water consumption is significantly less owing to hydroponic efficiency. In contrast, local seasonal soil production generally has a lower GHG impact than centralized production, though water consumption varies by crop yield and local precipitation during growing seasons. Scenario analyses indicate CEA facilities would need to electrify all systems and utilize low-carbon electricity sources to have equivalent or lower GHG impacts than California centralized production plus transportation. We conclude that these results can inform consumers and policy makers that local seasonal production and conventional supply chains are more sustainable than local CEA production in near-term food-energy-water sustainability nexus decision making.

1. Introduction

Globally, agriculture, forestry, and other land use accounts for 21% of global net anthropogenic greenhouse gas (GHG) emissions (Nabuurs et al., 2022), and food systems including supply chains account for 26% of global emissions (Poore and Nemecek, 2018; Ritchie et al., 2022). These impacts are large enough that achieving the 1.5 °C and 2 °C Paris Agreement targets may not be possible without decarbonizing the agricultural sector (Clark et al., 2020). The sustainability challenges will continue to grow as increasing population and affluence grows the demand for more GHG intensive foods (Clark et al., 2020). Under these pressures, the global food system will need to adapt technologies, practices, and policies.

One frequently explored option to improve food sustainability is the adoption of local production systems. The Milan Urban Food Policy Pact, for example, identifies urban and peri-urban production as a recommended action for its 211 signatory cities to consider (2015). Such urban production, however, encapsulates diverse techniques and technologies, from community gardens to year-round Controlled Environment Agriculture (CEA) facilities (Gómez et al., 2019). CEA systems have come under increased scrutiny; while their hydroponic systems can reduce land and water demands, these facilities can have far greater energy demands than conventional systems (Barbosa et al., 2015). Such energy intensity, and the associated emissions, could outweigh the supposed environmental benefits of local production such as reduced "food-miles" (Goldstein et al., 2016). Without systemic considerations, an assumption

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of local sustainability could have detrimental climate impacts.

Life cycle assessments (LCA) consider the resource inputs and environmental releases throughout a product's life cycle; thus, LCA can serve as a tool to holistically compare different food systems. Previous literature has used LCA to estimate the emissions from urban agriculture. Some studies focus on understanding and improving the environmental performance of CEA facilities (Martin and Molin, 2019) while others compare systems with different supply chains. Goldstein et al. (2016), for example, compared multiple CEA and soil facilities in the northeastern United States to conventional production and shipping, finding that high-yield, high-energy-input facilities had a greater environmental impact than conventional production. Similarly, Casey et al. (2022) compared agricultural production in shipping container modules to soil cultivation supply chains connecting London consumers to British, Spanish, and Californian producers. They found that local CEA production on the existing British grid mix only reduced GHG emissions compared to air-freighted Californian produce. Though previous work sheds light on the sustainability of urban agriculture and how particular systems perform, it often focuses on particular locations with a limited geographic resolution. As such, the literature does not yet provide a tool to facilitate more general CEA sustainability discussions.

This study addresses a gap in the literature by developing location-flexible models for multiple production systems and incorporating geographic resolution in climate, growing conditions, transportation distances, and electricity generation. A primary objective of this paper is to estimate and compare the carbon and water footprints of local and centralized crop production systems in the continental United States. The output will provide communities and local policymakers with clear environmental sustainability comparisons between local and centralized food production. Lettuce is chosen as the model crop as its production is highly centralized in the U.S. and leafy greens are a common crop grown in hydroponic indoor systems; therefore, lettuce enables a full-spectrum view of the complex localized-centralized production comparison. Four systems are examined: plant factories and greenhouses, because these local systems provide year-round produce at a high energy cost; conventional California production, because California currently supplies a majority of U.S. lettuce (USDA NASS, 2022) and provides the crop year-round (Smith et al., 2011); and local seasonal soil cultivation, because this system represents a common local food alternative. The LCA results of these four systems reflect the food-energy-water sustainability nexus of local food production compared to conventional food production across the contiguous U.S.

2. Materials and methods

2.1. Goal and scope

To compare the four production alternatives, this study's life cycle assessments were performed following ISO Standard 14040 (ISO, 2006) consisting of four phases: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation. The goal of the project was to provide policymakers and consumers with insights on the sustainability of local and centralized food options while providing insights to producers on potential sustainability improvement opportunities. Thus, the study's scope focused on a product of 1 kg of fresh lettuce. To provide a consistent comparison between local and centralized production systems, the system boundary included production, post-harvest processing, and transportation to the store, as illustrated in Fig. 1. Beyond this "cradle-to-store-gate" point, the storage and usage phases of lettuce were assumed to be identical between the four supply chains; thus, these stages were excluded from this comparative analysis. To provide expanded geographical insight, the geographic scope included 924 sites across the contiguous United States.

2.2. Life cycle inventory analysis

The life cycle inventory analysis (LCI) phase was performed for all four systems to determine flow values like yields from production stages, energy consumption at all stages, and material inputs. For the plant factory and greenhouse models, the production stage was simulated using the United States Department of Energy's EnergyPlus software (2021) to calculate the electricity and heat inputs necessary to grow hydroponic lettuce indoors. Existing published CEA experimental data were used to estimate material inputs of water (Zhang and Kacira, 2020), fertilizer (Rufí-Salís, et al., 2020), and supplemental carbon dioxide (Kozai, 2013; Stranghellini et al., 2019, p. 234). For the California centralized model, the production stage utilized United States Department of Agriculture Statistical Data (USDA NASS, 2017), agricultural

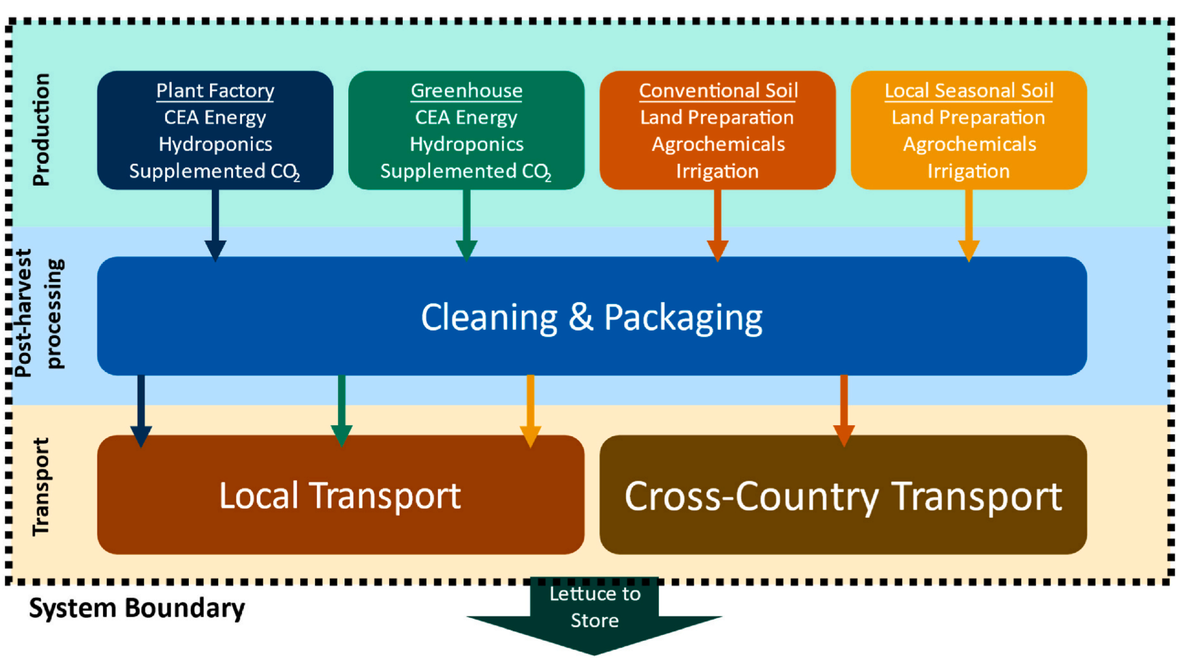

Fig. 1. A visual summary of the unit processes modeled in this work for four systems: local plant factory, local greenhouse, conventional production and shipping from California, and local seasonal soil production.

Extension office guidance documents (Smith et al., 2011), and existing literature data (Plawecki et al., 2014; Venkat, 2012) to determine model inputs. For local seasonal soil production, the UN Food and Agriculture Organization's AquaCrop model (Vanuytrecht et al., 2014) was used to estimate per hectare yield and irrigation demand in different climates. These intermediate outputs were then combined with data from the California conventional model to estimate farm machinery usage, irrigation system usage, and fertilizer usage. Post-harvest processing and packaging, including washing, initial cooling, and plastic packaging, was then modeled identically for each of the four production systems based on existing literature (Stoessel, et al., 2012; Plawecki et al., 2014) and California Extension guidance (Smith et al., 2011; Tourte et al., 2019). Finally, transportation by refrigerated truck was modeled for each of the production systems. Local systems used a 10 km estimate (Goldstein et al., 2016), while the California conventional model utilized Morgan et al.'s Google Maps API Python tool (2022) to estimate transport distances. Further details on these models, including summary input data tables, are included in Supplementary Information Section 1 and validation of model design assumptions are included in Supplementary Information Section 2. Sample model files are also included as Supplementary Material.

2.3. Life cycle impact assessment

In the life cycle impact assessment (LCIA) phase, data from the LCI models were translated to environmental impacts. The impact categories selected were global warming potential on a 100-year timeframe (GWP-100), owing to agriculture's significant contribution to global GHG emissions, and water consumption, examining the food-water nexus which can factor into agricultural decision making. The water intensity of the system included all blue water and excluded green and gray water impacts (Hoekstra et al., 2011). To determine characterization factors for most flows, OpenLCA (Rodríguez et al., 2017) was utilized to access the ecoinvent 3.7.1 database (Wernet et al., 2016), with processes summarized in Supplementary Section 3. The IPCC AR6 method (Barreiros et al., 2022) was utilized for GWP-100, while the ReCIPE 2016 midpoint (H) (Huijbregts et al., 2017) was used for water consumption. Two additional resources were utilized for geographically resolved electricity flow characterization factors: the U.S. EPA eGRID GHG emissions factors at the subregion level (2022) were utilized for electricity in plant factory and greenhouse systems, while electricity water footprints were calculated using North American Electric Reliability Corporation (NERC) region consumption factors (Lee et al., 2018). Through applying these characterization factors in a spreadsheet model, category indicator results were characterized for each of the four supply chain models.

2.4. Interpretation

In the interpretation phase of the LCA, the impact results were analyzed to provide comparative insights on the four supply chains for consumers, policymakers, and producers. To provide a geographically diverse overview to consumers and policymakers of sustainability trends, GHG and water impact results were compared for the four largest cities in the United States: New York City, NY; Los Angeles, CA; Chicago, Il; and Houston, TX. Further, for each of these cities, a one-at-a-time GWP sensitivity analysis was performed, adjusting inventory inputs by $\pm$ 20% to observe the effect on impact results. Beyond these four cities, an additional 920 simulated sites were considered with results interpolated on maps to show regional trends. To illustrate such patterns, impact results were mapped and interpolated in ArcGIS Pro (ESRI, 2023). Between stations, ordinary kriging was applied with a spherical semi-variogram model and default inputs. For extents and masking, the United States Census Bureau States Boundary File (2021), sans Alaska, Hawaii, and Puerto Rico, was used. Percent clip stretch symbology was then applied with default inputs, and colors and labels were manually adjusted to provide a clear display and discussion of results. Additionally, to provide insights to policymakers and producers on future industry trends, a series of scenario analyses were performed to examine CEA GHG intensity with new technology implementations. These analyses included electrifying dehumidification in greenhouses, using a geothermal heat pump with a consistent COP of 3.1 (EnergyStar, 2012) in greenhouses and plant factories, and sourcing 100% of electricity from wind or nuclear generation at a GWP of 13 kg CO_2e MWh^{-1} (NREL, 2021).

3. Results and discussion

3.1. Life cycle comparison overview

The results show energy-intensive local CEA systems have the highest global warming impact of the four agricultural systems evaluated in this paper; soil-based systems have the lowest impact, even when including conventional system transportation footprints. Fig. 2 provides an overview with results for the four largest U.S. cities; **2A** shows how CEA impacts range between 3 and 6 kg CO_2e kg^{-1} compared to the California and local soil systems which are detailed and magnified in **2B,** ranging between 0.3 and 1 kg CO_2e kg^{-1}. The impacts on water use, however, are generally reversed, as shown in Fig. 3. Across locations, the hydroponic CEA systems require less water per kilogram of lettuce produced than the conventional system. This analysis incorporates all of the water requirements including the indirect water footprints such as those associated with energy production. Local soil water footprints vary, but generally fall below conventional footprints depending on local seasonal precipitation.

These overview results largely align with the range of results observed in the existing literature, as observed in Supplementary Fig. 1 and Supplementary Fig. 2. Plant factory GWP values fall within the observed literature range (0.89–8.9 kg CO_2e kg^{-1}) (Casey et al., 2022) as do greenhouse GWP values when compared to heated greenhouses in the literature (0.5–26.51 kg CO_2e kg^{-1}) (Körner et al., 2021; Goldstein et al., 2016). This study's conventional model GWP values largely fall within literature values for centralized production with transportation (0.68–0.92 kg CO_2e kg^{-1}) (Casey et al., 2022; Goldstein et al., 2016), though the influence of transportation emissions means that locations very close or very far from California start to fall outside the range. This study's local soil lettuce GWP values are somewhat higher than the literature range (0.15–0.25 kg CO_2e kg^{-1}) (Goldstein et al., 2016; Venkat, 2012), but further inspection indicates this discrepancy is due to differences in system boundaries (e.g., previous work has excluded post-harvest inputs). For water consumption, similar considerations apply. This study's plant factory and greenhouse water results compare well to literature values (0.002–0.22 m^3 kg^{-1}) (Casey et al., 2022; Goldstein et al., 2016) for hydroponic systems; the available literature varies in its inclusion of indirect water consumption from flows like electricity. For California conventional production, this study compared very well to two studies of lettuce water usage in the region (0.21–0.25 m^3 kg^{-1}) (Venkat, 2012; Barbosa et al., 2015), though a more recent literature value appears to be an outlier (0.09 m^3 kg^{-1}) (Casey et al., 2022). Finally, for local soil cultivation water footprints, some of this study's locations estimate higher values than others found in the literature (0.01–0.06 m^3 kg^{-1}) (Casey et al., 2022); however, this discrepancy reflects the difficulty in comparing crop blue water footprints across multiple locations, as irrigation varies significantly with climate patterns. Thus, additional validation of the AquaCrop water consumption outputs was performed in Supplementary Section 2.3.2 with a focus on the American Southwest. These comparisons for GWP and water are discussed in greater detail in Supplementary Information Section 2.4.

Sensitivity analyses figures are included in Supplementary Section 4. For CEA systems, the most sensitive inputs differ depending on the system. In plant factories, yield per head has the highest impact, reflecting the high number of plants in the multi-level vertical farm

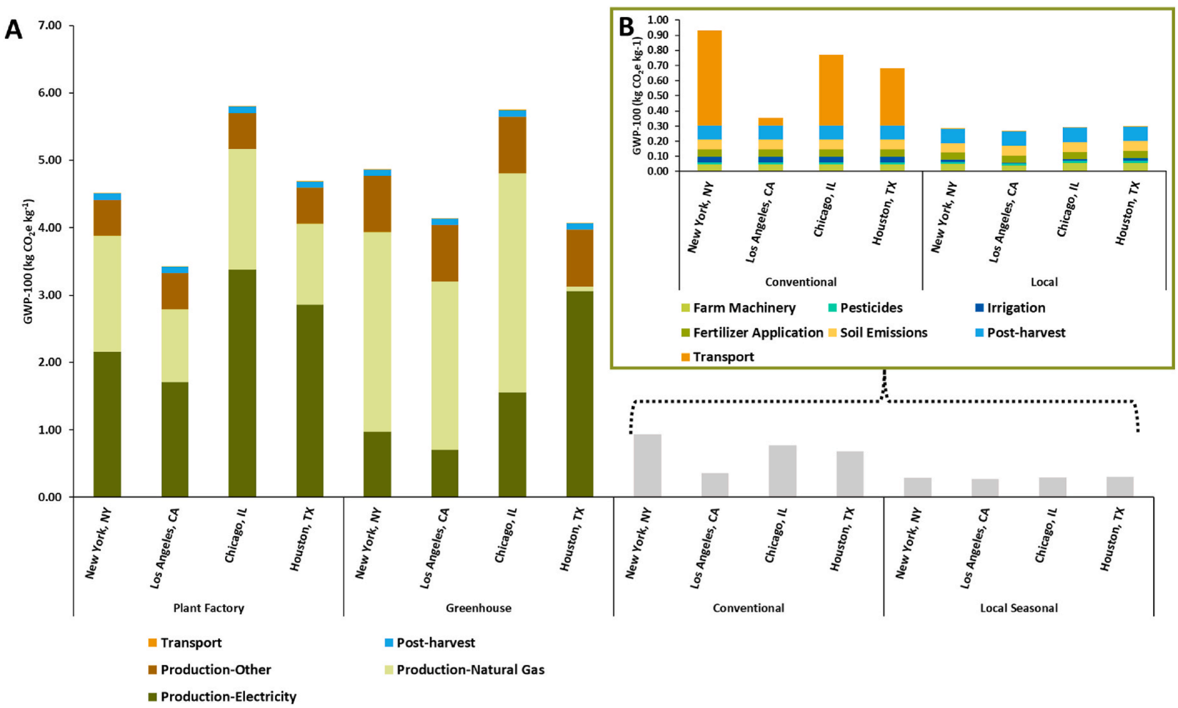

Fig. 2. Cradle-to-shelf GHG emissions of leaf lettuce production for four system types in the four largest United States cities. **a.** Emissions of local CEA systems, with total emissions of soil-based systems for comparison. **b.** Magnified and detailed emissions of soil-based systems.

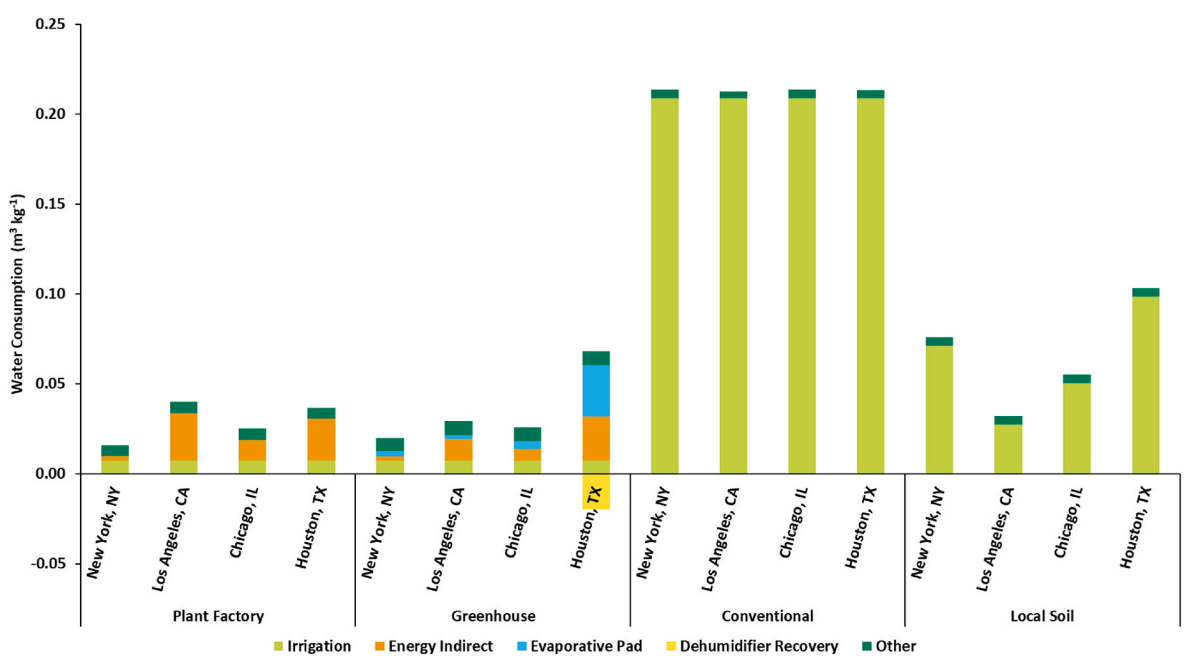

Fig. 3. Cradle-to-shelf water consumption of leaf lettuce production for four system types in the four largest United States cities. Where electric dehumidifiers are the primary dehumidification technology, recovered condensed water has been included.

setup. A significant amount of energy-intensive activity (lights, dehumidification load, etc.) is based on that high number of crops; thus, an increase or decrease in the final produced mass across the facility can cause a significant swing in the impact intensity. Further, the energy-intensity of these facilities is reflected in the sensitivity attributable to electricity and natural gas inputs. While some sensitivity is associated with material flows like fertilizer and supplementary carbon dioxide, energy sensitivity predominates.

The sensitivity analysis of greenhouse facilities differs from plant factories in two significant ways. First, yield per head is not the most significant input for greenhouses. This difference likely corresponds to the lower density of heads in the modeled single-layer greenhouse and that energy inputs were not as directly related to the number of heads present; for example, since greenhouses utilize sunlight in addition to supplementary lamps, not as much lighting demand and radiated heat is associated with a plant as in the artificially lit plant factory. The second difference between greenhouses and plant factories is the variation of energy inputs between some sites. In sites using vent-reheat dehumidification, natural gas dominates the sensitivity of the system; meanwhile, in the electric dehumidification sites along the Gulf Coast, natural gas input has little impact on the model output, with electricity input increasing its relative impact.

The soil systems, both centralized and local, demonstrate less sensitivity to energy inputs than to material inputs. For the conventional system, sensitivity varies by distance from California. For Los Angeles, CA, yield dominates the sensitivity analysis, followed by material inputs like cardboard packaging and fertilizer. Energy-related inputs like transportation, farm machinery, and irrigation then follow, reflecting the low energy intensity of outdoor cultivation. However, in distant locations like New York City, NY, refrigerated shipping predominates the sensitivity analysis. This change reflects the energy-related impact of "food-miles" and how transportation can become a significant factor in soil systems at a great enough distance. By contrast, in the local soil system, the removal of this significant transportation footprint results in farm-level inputs such as fertilizer usage dominating the sensitivity analysis.

Overall, this sample of locations highlights that CEA systems have higher GWP impacts driven by energy inputs but lower water impacts than California centralized production and local seasonal production. Further exploring regional trends beyond these case studies can illustrate the factors driving these impacts.

3.2. Mapped results comparison to conventional

This section discusses the mapped comparisons of different system impacts, particularly the results of EnergyPlus outputs for the plant factory and greenhouse models, highlighting their high energy intensities and low water footprints, and the implications of these factors on the GWP impacts of CEA compared to conventional agriculture. When this energy intensity is translated to climate impact, the CEA GWP impacts are always higher than conventional impacts, as illustrated in Fig. 4. The plant factory energy footprint stems largely from lighting and from dehumidification via the overcool-reheat process; thus, impacts largely reflect the GHG intensity of eGRID subregions. Greenhouses, meanwhile, are dominated by their heating duties, followed by lighting, and so impacts reflect differences in local climate: the colder the location, the greater the natural gas usage in winter. Breakdowns of building average energy demand by category are included in Supplementary Figs. 7 and 8, and impact maps for each production system type are included in Supplementary Figs. 9, 10, 11, and 12.

Considering water consumption, CEA impacts are universally lower than conventional usage, as seen in Fig. 5. Even when considering evaporative cooling water usage and indirect water impacts, the simulated facilities used at most half the amount of life cycle water as conventional irrigation methods. Similar to the GWP results, the water impacts of CEA also exhibit regional variations. In the case of the plant factory, the water footprint is mainly influenced by energy consumption, and hence the map for plant factory water impacts reflects the water footprints of electricity generation in different NERC regions. The water usage in greenhouses is affected by both energy consumption and evaporative cooling. As a result, while some patterns in NERC region water footprints can be observed, the water consumption in greenhouses is higher in warmer and drier climates, where the demand for cooling and evaporative pad water usage is high.

The baseline CEA results show a significantly higher GWP impact than the conventional system, as the emissions resulting from CEA energy inputs far outweigh the food mile impacts of centralized production. These impacts can vary by distance, local grid mix, climate, and system type, but no CEA system GWP simulated in this study outperforms growing lettuce in California and transporting it by refrigerated truck. In contrast, simulated CEA blue water consumption is universally lower than conventional consumption owing to the efficiency of hydroponic systems; even when considering evaporative cooling consumption and upstream water associated with energy production, CEA systems are more water efficient. Consumers and other local stakeholders would need to weigh these trade-offs when considering the value of year-round local food production in their community.

As a comparison to the year-round CEA systems, a mixture of local seasonal soil consumption and conventional soil impacts was created to reflect a consumer pattern of buying local when in-season, mapped in Supplementary Figs. 13 and 14. Generally, local soil production represents the most sustainable system when in-season, though some locations whose dry seasons coincide with lettuce growing seasons demand more water than the conventional system. However, even if local produce is more sustainable from a GHG and water perspective, it is not available year-round. Consuming a mix of conventional and local food more accurately represents annual consumption and illustrates the same conclusion: from a climate change perspective, eating locally in-season is generally more sustainable, followed by centralized conventional production. Thus, in most locations, consumers and policymakers can view local outdoor produce as a more environmentally sustainable addition to local markets than CEA systems.

3.3. Controlled environment agriculture scenario analyses

This section evaluates the GHG impacts of different CEA facility designs with three scenarios evaluated. First, the vent-reheat greenhouse dehumidification model is associated with high heating loads. The

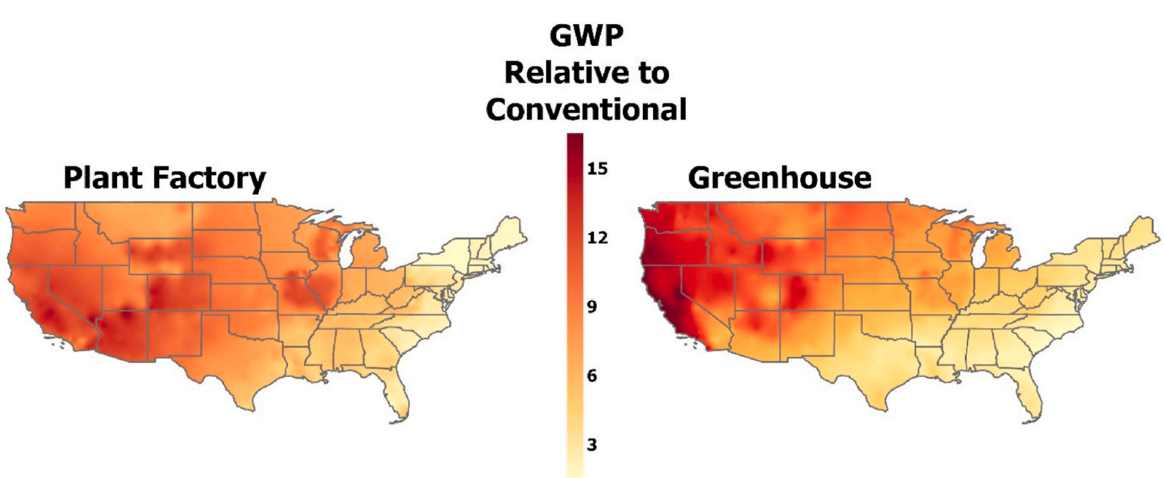

Fig. 4. GHG impacts per kg of lettuce from local CEA systems relative to conventional production and transport: $\frac{GWP_{CEA}}{GWP_{Conventional}}$. A value less than one indicates the evaluated technology performs better than the conventional system. Note that no CEA system simulated here results in a ratio less than one.

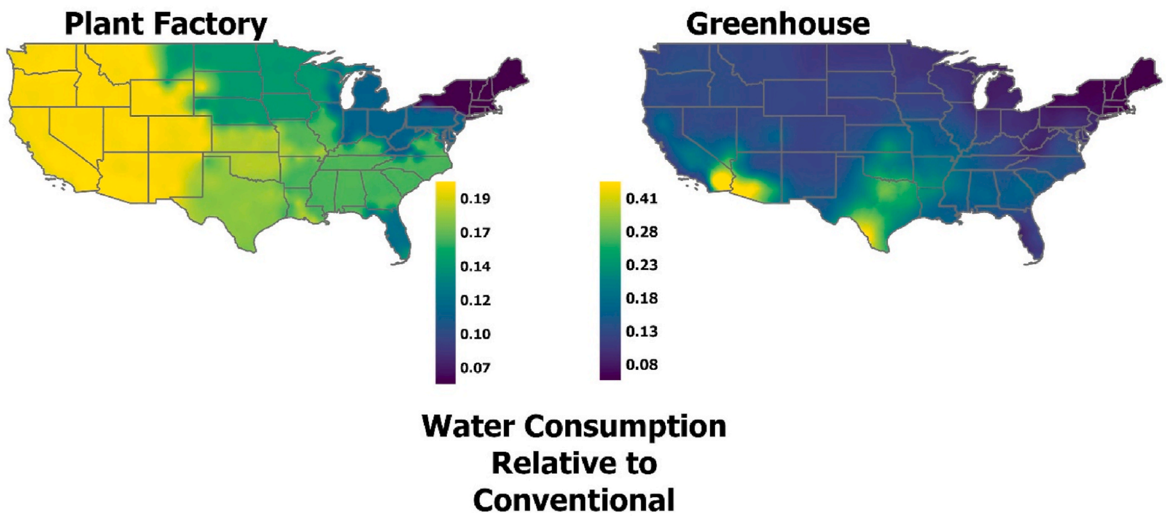

Fig. 5. Water consumption per kg of lettuce from local CEA systems relative to conventional production and transport: $\frac{Water_{CEA}}{Water_{Conventional}}$. A value less than one indicates the evaluated technology performs better than the conventional system. Note that all CEA systems here result in ratios less than one.

widespread application of electric dehumidification could lower energy consumption and GHG emission profiles. Second, as both CEA models evaluated in this paper utilize natural gas for heating demand, the electrification of heating could reduce emissions depending on heat pump performance and local grid cleanliness. In the third scenario, these dehumidification and electrified heating technologies are combined with low carbon electricity. Each scenario is considered across this study's simulation sites.

3.3.1. Greenhouse dehumidification technologies

The baseline simulation models a traditional ventilation with reheat dehumidification system for most sites; the exceptions are humid areas where this system fails to maintain humidity control targets, so electric dehumidification is employed. One scenario to consider is the wider replacement of the older ventilation method with electric dehumidification. These simulations result in lower energy footprints and thus lower climate impact, as shown compared to the conventional system in Fig. 6. Notably, the regional patterns more closely resemble the grid-dependency of the plant factory simulation due to the reduction in natural gas usage for reheat and the concurrent increase in dehumidification electricity. For example, in Madison, Wisconsin, the technology change reduces energy intensity by 54%, and at a similar latitude and climate in Rochester, New York, electric dehumidification reduces energy intensity by 58%. However, in Madison the GWP reduces by only 27% while in Rochester it reduces by 59%. The difference stems from the MRO East grid subregion in Wisconsin having one of the highest carbon intensities in the country while the Upstate New York subregion has one of the lowest.

3.3.2. Electrification of CEA heat sources

Utilization of natural gas for heating and reheating purposes is another traditional technology in the CEA baseline simulations. Replacing this incumbent technology with a geothermal heat pump would result in environmental improvements, especially if paired with low-emission electricity generation. The resulting GWP impacts of electrified CEA heat are shown in Fig. 7. Across regions, the patterns reflect grid cleanliness, and greenhouses broadly perform better than plant factories. Additionally, the electrified systems generally perform better than natural gas systems, even in areas with greater grid carbon intensity (compare to Fig. 4), reflecting the energy efficiency gains of a reliably efficient heat pump. As in the electric dehumidification scenario, Madison, Wisconsin and Rochester, New York provide a clear

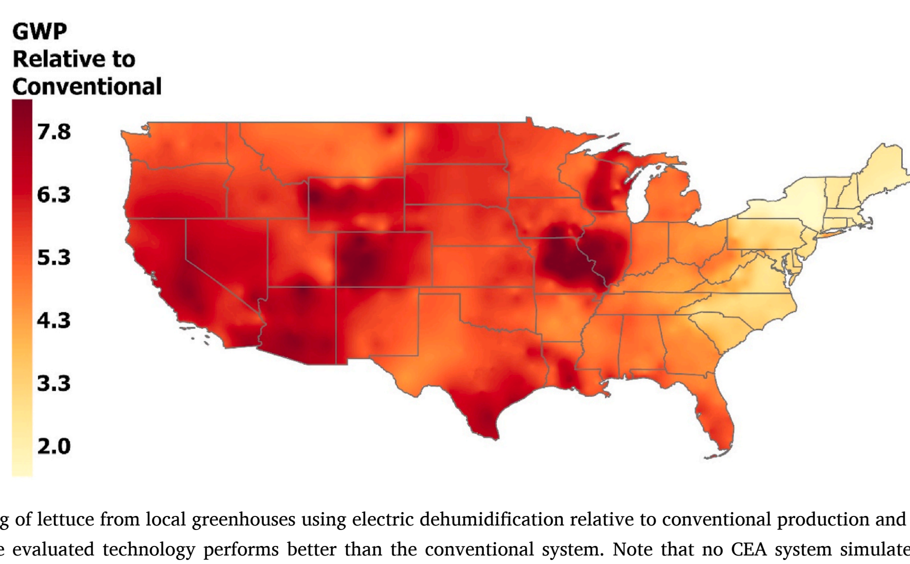

Fig. 6. GHG impacts per kg of lettuce from local greenhouses using electric dehumidification relative to conventional production and transport: $\frac{GWP_{Greenhouse}}{GWP_{Conventional}}$. A value less than one indicates the evaluated technology performs better than the conventional system. Note that no CEA system simulated here results in a ratio less than one.

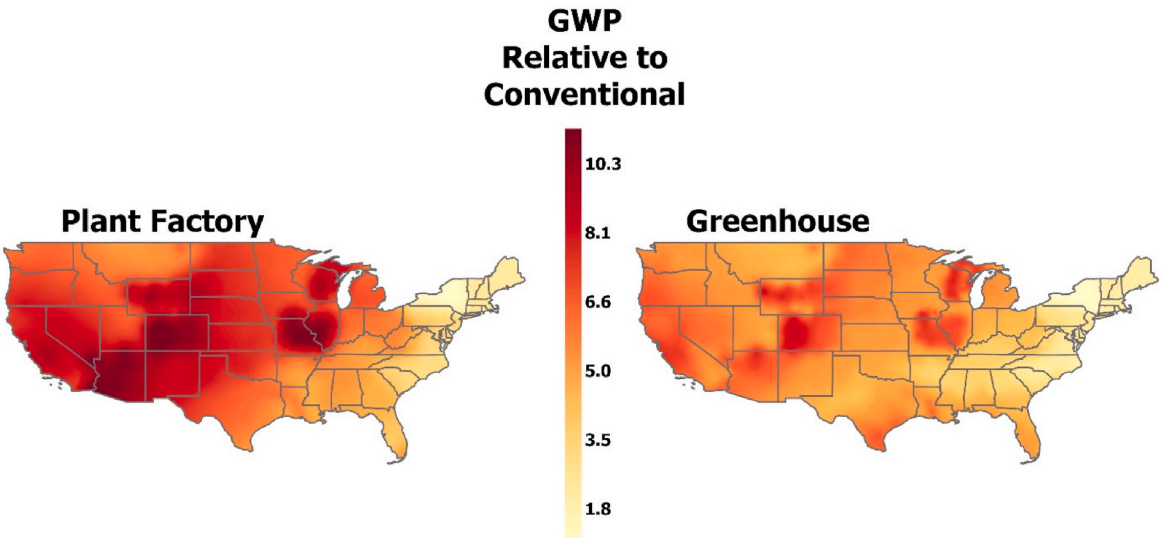

Fig. 7. GHG impacts per kg of lettuce from local CEA systems using electrified heating relative to conventional production and transport. A value less than one indicates the evaluated technology performs better than the conventional system. Note that no CEA system simulated here results in a ratio less than one.

example. Energy intensity reduces by about 58% in both cities, but Madison's GWP reduces by only 17% while Rochester's reduces by 66%. Thus, heat pump performance paired with clean electricity can have significant impacts on the sustainability improvements of electrified CEA systems.

3.3.3. Clean electrification scenario

In addition to energy efficiency and electrification efforts, CEA operators may consider utilizing low carbon energy through purchasing renewable energy credits or siting facilities next to low carbon generation resources. As a test case, this study considers the energy footprint of CEA facilities with electrified heating and dehumidification combined with low-emissions electricity, shown in Fig. 8.

Under such a scenario, distance from the conventional production location dominates. For example, the Madison, WI plant factory breaks even with Californian production and transportation, but further east Rochester is 15% less GHG-intensive than the conventional system. Notably, the break-even line for greenhouses is farther east than for plant factories due to higher supplemental CO_2 usage; the Madison greenhouse is 30% more GHG-intensive than the conventional California system, while the Rochester greenhouse is 10% more intensive. Thus, once energy emissions are addressed, other factors become significant in the comparative life cycles; previously negligible inputs like infrastructure could warrant further consideration if an operator successfully addressed their energy emissions. Through such a combination of energy efficiency and clean energy, CEA operations could begin to perform similarly to the conventional system on greenhouse gas emissions.

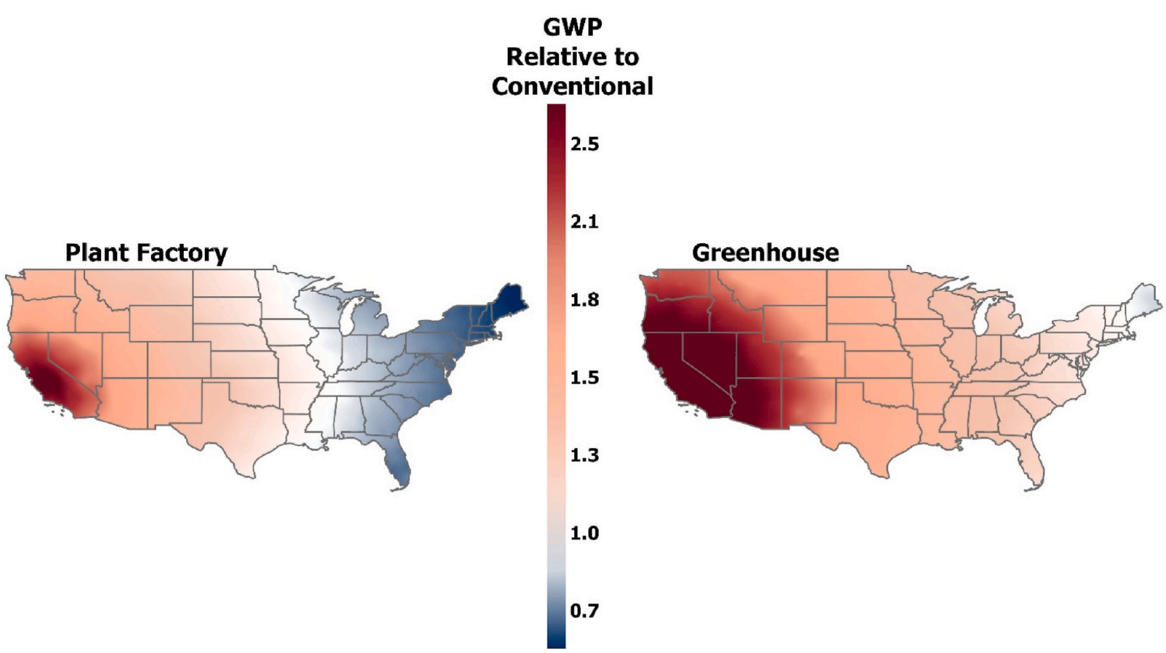

Fig. 8. GHG impacts per kg of lettuce from local CEA systems relative to conventional production and transport. A value less than one indicates the evaluated technology performs better than the conventional system. Note that in this figure, values around one are white and below one are blue. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3.3.4. Scenario analyses implications

This study's scenario analyses suggest that CEA operators have opportunities to improve environmental performance. One analysis indicates that replacing traditional CEA methods with new technologies could improve energy efficiency. For example, this study's greenhouse simulations found that electric dehumidification would halve the national average energy intensity compared to traditional ventilation and reheat dehumidification methods. Additionally, operators could replace incumbent combustion-based technologies like furnaces and unit heaters with heat pumps and see improvements with existing grid mixes, suggesting even greater potential with cleaner energy mixes. Indeed, once full electrification and clean generation are combined, some simulations achieve a lower GWP than the conventional system. Through such efforts, CEA operators could reduce operating costs and environmental impacts.

However, these CEA operational and design changes present tradeoffs. Dehumidifiers and heat pumps may reduce environmental impacts, but higher capital costs could present economic challenges for producers and consumers. Further, the crop's energy intensity would remain high, and large-scale production with such electrical demand could burden grid generation and transmission. Stakeholders would need to consider that generation and transmission capacity impacted by CEA may present an opportunity cost for other electrification targets, such as space heating or transportation. Relatedly, adoption of heat pumps could increase refrigerant leak emissions footprints. As electrification of HVAC increases and energy efficiency improves, increased refrigerant leakages could become a prevalent emissions category in CEA. Thus, CEA producers would benefit from considering refrigerant leakage impacts in their system maintenance and design, including leakage reduction efforts and using refrigerants with low GWP or no GWP. With such tradeoffs, the CEA industry and communities could consider the optimal path to sustainable food production within the local energy and environmental systems.

3.4. Limitations and future research

While this study provides insights on the sustainability of agricultural systems, local food production may continue to be an area of future sustainability considerations; therefore, future studies could build upon the energy and life cycle models presented here. This study focuses on the geography of the United States; however, with the necessary inputs, the models (included as Supplementary Material) could be applied to locations around the world. Such geographic variation would be useful to understand wider food production potential and circumstances. In some regions, an abundance of low-carbon energy could keep energy-related CEA impacts low. Further, in some regions a lack of arable land or nearby conventional sources could incentivize CEA; if the only fresh vegetable supply chains available utilize energy-intensive shipping methods like air freight, CEA may be the more sustainable option. Considering the energy models, future studies could incorporate more complex, advanced systems beyond the baseline models considered in this work. As the CEA field continues to expand and evolve, the adoption of better facility designs, technologies, and operational practices will likely improve sustainability outcomes; the building models created for this study could be adapted to evaluate the effects of such improvements. In addition to these energy considerations, the scope of water footprints could be expanded to consider green water footprints, such as precipitation on crop fields, and gray water footprints, such as the treatment of flushed hydroponic solution. Beyond the energy and water models, the life cycle boundaries of this study could be expanded. This study did not consider food waste, as all food grown was assumed to be delivered to the store. More advanced food spoilage models could refine the comparison of centralized and local systems, estimating the extent to which greater food mileage results in more waste. Further, this study did not consider land use change effects; CEA facilities were assumed to be built on already-developed land while local seasonal cultivation was assumed to occur on existing cropland. Future work could consider direct land use change effects in terms of biomass carbon and soil carbon stock changes. For example, forest land cleared for a farm or greenhouse would have additional associated emissions; conversely, soil cultivation on previously barren or paved urban land might create soil C stock where little previously existed. Beyond direct land use change, indirect land use change effects could be considered. For example, were local cultivation of vegetables to reach a large enough scale, changes in economic demands could cause changes in land utilization where vegetables are currently cultivated. Through such additions, life cycle practitioners could provide even more robust food-energy-water insights to stakeholders around the world.

4. Conclusions

This study's production and life cycle models demonstrate that the environmental considerations of food production systems are complex and local is not always more sustainable. Local lettuce CEA systems have a greater GHG impact than California conventional production and truck transport in all simulated United States locations. By comparison, local seasonal soil cultivation of lettuce is associated with the lowest GHG emissions for most simulation sites, and local climate variations can also result in lower water consumption; however, seasonality limits the capacity of such local operations to meet year-round demand. At present, consumers and policymakers can look to a mixture of local seasonal soil systems and conventional systems as the most sustainable option. Thus, this study illustrates the need for local stakeholders to consider all aspects of the food-energy-water sustainability nexus when deciding on sourcing from local compared to centralized food production.

CRediT authorship contribution statement

Reid Maynard: Investigation, Methodology, Formal analysis, Validation, Writing – original draft, Visualization. **Jesse Burkhardt:** Conceptualization, Supervision, Writing – original draft, Writing – review & editing. **Jason Quinn:** Conceptualization, Supervision, Project administration, Writing – original draft, Writing – review & editing, 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.

Data availability

data and models are supplied as supplementary files

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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.2023.139224.

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