# Produce Sustainability

Meia Alsup

6.s898 Climate Change Seminar Final Project

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# Introduction

## Problem

This report examines the different ways that agriculture contributes to global greenhouse gas emissions, and investigates if indoor agriculture can serve as a viable climate-friendly alternative to conventional agriculture, given a clean electric grid.

Agriculture accounts for about ~20-25% of global GHG emissions[1]. Although the majority of this comes from animal agriculture practices, produce agriculture is still a significant contributor. The total environmental impact of a given produce item consists of its impact during the growing process, packaging process, and shipping process. Refrigerated trucks, ships, and airplanes move produce from their origins of production to their terminal markets. Of the impact of agriculture on emissions, 29% of emissions are directly related to crop production and land use for human food, with the majority of the rest related to animal agriculture.[2] See Figure, *Global greenhouse gas emissions from food production,* published by Oxford University's "Our World in Data", for a breakdown of the contribution of agriculture towards global emissions.

The spread of variable renewable energy resources such as wind and solar - whose capacity to provide energy is dependent on external factors, has helped make the electric grid more green, but in some cases has actually flooded the electric grid

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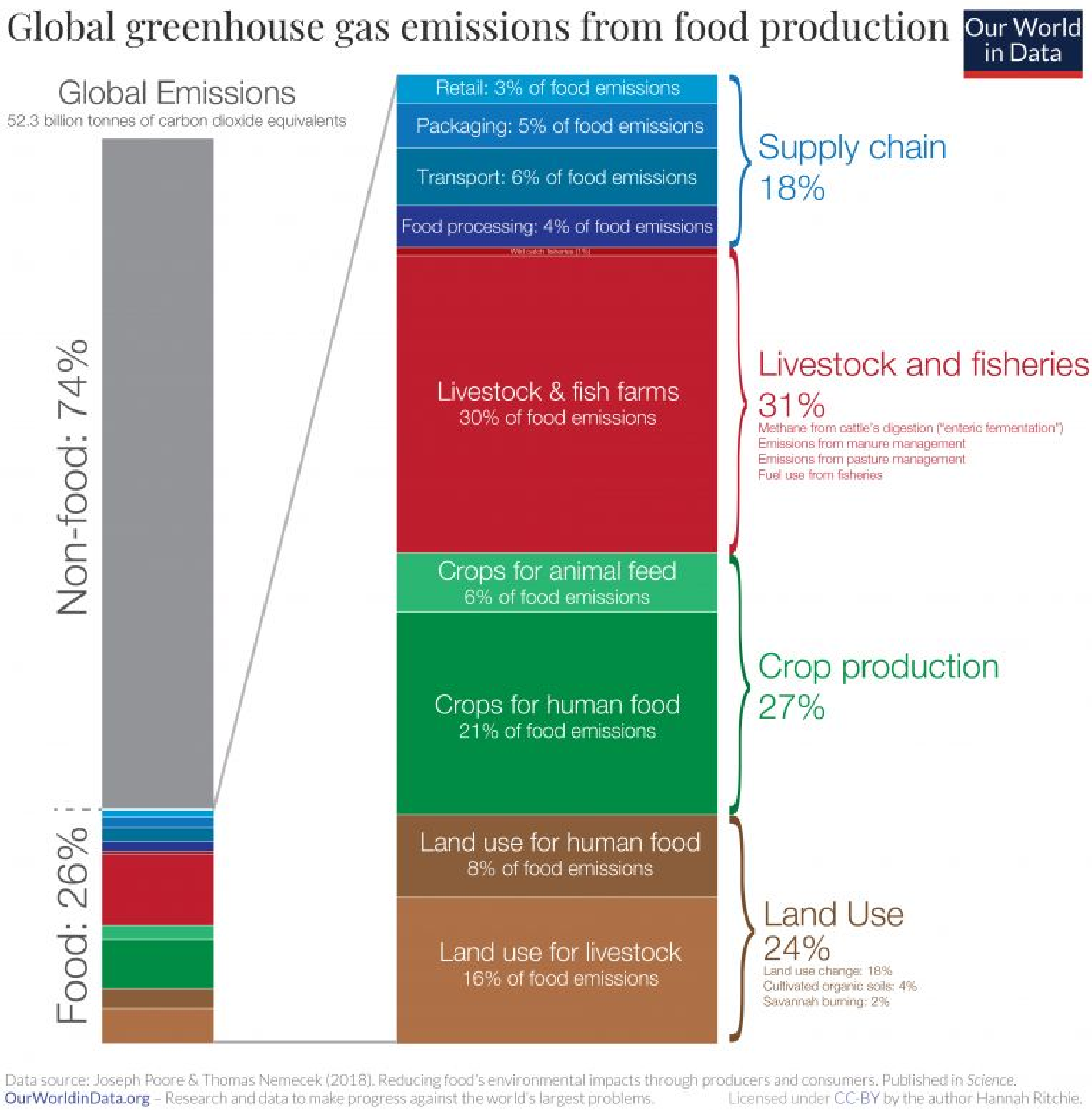
[1] https://web.archive.org/web/20141230092745/http://report.mitigation2014.org/report/ipcc_wg3_ar5_chapter5.pdf

[2] https://ourworldindata.org/food-ghg-emissions




with more energy than it needs. California's electric grid experienced negatively priced electricity for 110 hours in 2017 [3]. In Texas, prices fell below US −$30/MWh (megawatt-hour) on 63% of days during the first half of 2008, compared to 10% for the same period in 2007 and 5% in 2006 due to excess wind power.

[3] http://www.caiso.com/Documents/2017AnnualReportonMarketIssuesandPerformance.pdf

## Report Context

*Some meta thoughts on assumptions, complexity, challenges, and a pivot in focus.*

I started this project with the intention to test my hypothesis that the combination of excess grid renewables and indoor agriculture could make a significant impact on emissions and be a financially viable business. In my project proposal, I outlined a few pros and cons of indoor agriculture. A major assumption was that transportation was a large component of emissions, and if this could be offset with a localized greenhouse, then emissions would be significantly less for our food. In the ensuing research, I found that the equation for emissions related to our produce is much more complex, and that transportation is only a small component (around 6% of total agriculture related emissions[4]). Another key assumption was that energy was a primary cost driver of expensive indoor agriculture. This assumption was based on a quote from Freight Farms, an indoor controlled environment operation, that energy is 70% of their operating cost. However, I found that across the indoor agriculture industry, that energy accounts for an average of about 11-12% of opex cost, significantly lower.[5]

With a few key assumptions proved wrong, I pivot in focus. In the remainder of my research, and in this report, I try to discern if indoor agriculture is in fact more sustainable and has a role in combating climate change. I disregard economics and

[4] https://ourworldindata.org/food-ghg-emissions
[5] https://artemisag.com/wp-content/uploads/2019/06/stateofindoorfarming-report-2017.pdf

cost, though I am still curious about this and leave it as an open question and area for future analysis.

## Types of Indoor Agriculture

The following figure gives an overview of different indoor agriculture methods. The most common growth method for indoor agriculture is hydroponics, which is essentially a soil-free system where crops are grown in a nutrient filled water bath. According to the Agrilyst State of Indoor Farming 2017 report, 49% of all indoor agriculture systems feature hydroponic systems. 47% of systems are glass or poly

greenhouses, and 30% of the systems are indoor vertical farms.[6] This report focuses on hydroponic greenhouse and hydroponic vertical systems, the two most common.

## Methodology and Data

The research examines leafy greens and tomatoes in greater depth. Since they are among the two crops most commonly grown indoors, more data exists around their operation than other crops of interest, enabling greater analysis.

For indoor agriculture electricity usage, a clean grid is assumed. Given the excess renewables on the grid in certain areas, this corresponds to smart greenhouse placement taking advantage of wind and solar.

The data on indoor agriculture comes from a few sources. Many summary statistics are compiled from the Agrilyst 2017 State of Indoor Farming report, which summarizes data from ~150 indoor agriculture operations (81% US based). Food waste (shrink)[7], transportation[8], and yield data comes from various USDA reports. Greenhouse gas equivalencies (conversions to make units comparable) are from an EPA report.[9]

In addition to published reports, I interviewed several farmers and employees in the agriculture space. This comprised ~30 cold calls / emails, and leveraging connections in the space for more introductions. A few key interviews were with Jim Wilson of Wilson Farms in Lexington, Massachusetts, Darlene Steward of NREL, John de la Parra, a Harvard postdoc focused on indoor agriculture research, and Federico of

[6] https://artemisag.com/state-of-indoor-farming/
[7] https://www.ers.usda.gov/webdocs/publications/44100/eib-155.pdf?v=0
[8] https://www.marketnews.usda.gov/mnp/
[9] https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references

Evergreens Farm, an indoor controlled environment operation near Boston. The Evergreens Farm team as well as Jim Wilson both shared information about Backyard Farms, a greenhouse based tomato operation in Maine, that is used in this analysis.

For the sustainability comparison, the focus is on the two most common indoor agriculture systems (polycarbonate / glass greenhouse hydroponic and vertical controlled environment hydroponic). Further, seven key emissions contributors of conventional and indoor agriculture are chosen to be investigated in further depth. These are food waste, facility life cycle emissions, energy usage, transportation, pesticide use, land use, and water use.

# Sustainability Analysis

## Food Waste

Approximately 40% of food produced in the US is never consumed at an average level.[10] This food loss is driven by overplanting, low market prices and demand, labor shortages, product quality, shelf life and spoilage. Unfortunately at the farm level this is not well quantified on a crop by crop basis - most information is based on self-reported estimates by farmers. Loss at the retail level is much better understood.

A study by the NRDC (with an admittedly small data set comprising only California farms - but the best available), suggests that about 10% of head lettuce is lost from field to retail due to a walk-by (where an entire field is left unharvested), crops left

[10] https://www.nrdc.org/resources/left-out-investigation-fruit-and-vegetable-losses-farm

in the field due to cosmetic, size, or quality considerations, and packing culls (crops harvested that never end up at retail - lost in shipment)[11]. No reliable data was found for tomatoes or other greens in the farm to retail stage. A USDA study[12] found that at the supermarket, romaine and leaf lettuce experience a shrink (product loss due to a variety of factors including spoilage, oversupply, bruising, etc) of 21%, collard greens a shrink of 44.2%, head lettuce of 6.4%, spinach of 20.2%, and tomatoes a shrink of 14.7%.

Tomatoes and lettuce grown via indoor methods still likely experience at least as much shrink as is lost by conventional produce at the retail stage (potentially less due to longer shelf lives from shorter transit time). But a larger benefit, while impossible to quantify given the data available, is minimized walk-bys (crops left in the field), no packing culls, and harvest schedules better matched with demand fluctuations.

## Facility Life Cycle

### Polycarbonate Greenhouse

The greenhouse manufacturers contacted either did not respond, or responded, but did not know their environmental impact. Two manufacturers shared via phone conversations - dimension, sizing, and material information, but no carbon impact.

This following estimate is admittedly rough, but provides a useful lower bound on facility emissions. Greenhouses primary input is polycarbonate sheets. Other inputs include lighting, HVAC, irrigation, growth mediums, etc, but their life cycle emissions are

[11] https://www.nrdc.org/sites/default/files/hea_12121201a.pdf
[12] https://www.ers.usda.gov/webdocs/publications/44100/eib-155.pdf?v=0

not included in this estimate. Life cycle emissions is approximated as the life cycle emissions of polycarbonate walls in the facility.

Each square foot is associated with ~0.8 g CO2 per year for a 10,000 sq ft greenhouse. This calculation is based on the following assumptions and statistics.

1. A ton of polycarbonate is associated with 4 million grams of greenhouse gas emissions according to a life cycle report out of the University of Michigan[13].
2. A 10,000 sq ft greenhouse with dimensions 100 ft by 100 ft requires three 10.8 meter panels on each side.
3. Each 10.8meter panel weighs 1.5kg[14], so 12 total panels weighs a total of 18kg.
4. Greenhouse polycarbonate panels have an average lifetime of 10 years.

The lifetime emission of the greenhouse is ~80,000 g CO2, or 8g CO2 / sq ft. This translates to ~0.8 g CO2 per sq ft per year quoted above.

### Vertical Controlled Environment

The vertical controlled environments were highly variable, and no simple averaging system exists for this analysis. Growing Underground, a London based indoor agriculture startup growing leafy greens, uses the city's underground tunnels (an artifact of the world wars) as their growing facility. Freight Farms in Boston, repurposes old shipping containers into urban farms. Evergreens Farm, near Boston, builds their own vertical farm; but specific details are protected IP so the materials and

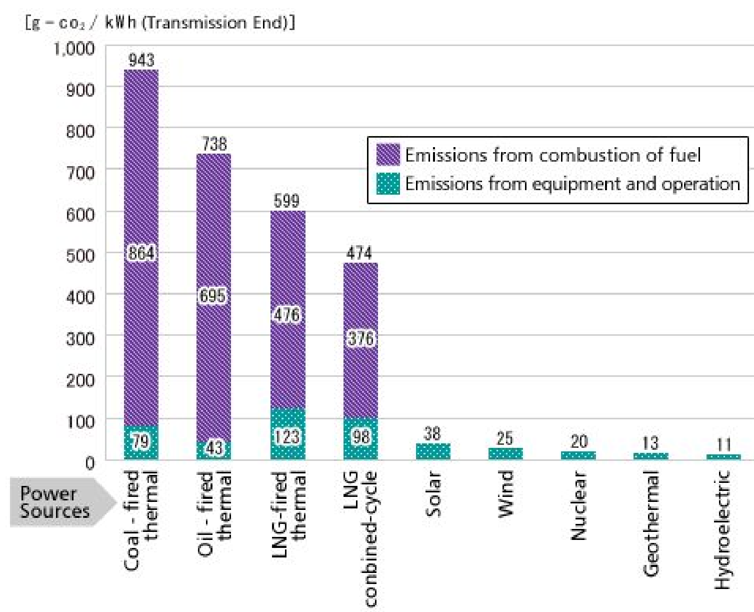
[13] 2012 Report: Life Cycle Material Data Update for GREET Model, University of Michigan

[14] https://www.gwx-polycarbonatesheet.com/why-is-the-greenhouse-of-coping-polycarbonate-hollow-sheet-commonly-used-in-northern-area/

environmental impact is unclear. Aerofarms, a vertical farm in NYC, builds their own large facilities from the ground up, but did not share any environmental impact metrics.

# Energy

Indoor controlled environments rely on energy as an input for light, temperature and humidity control, and any other more "advanced" or niche controls. Outdoor conventional growing does not share the same operating energy input. An average sense of this energy inputs environmental impact can be calculated from average energy expenditure, average electricity price, and carbon intensity per kWh of electricity source. In the following calculations, I assume an electricity mix that is 50% solar and 50% wind with emissions as shown in the chart,[15] and use the US average electricity rate of 13.19 cents per kWh (updated August 2019)[16]. Indoor vertical farms spend an average of $5.23 / sq ft per year, while greenhouse facilities spend an average of $1.69 per sq ft per year. Thus a vertical farm is using approximately 40kWh / sqft a year while a polycarbonate greenhouse is using approximately 13 kWh / sqft a




15 http://www.chuden.co.jp/english/initiatives/eini_environment/eenv_measures/emea_co2emissions/index.html

16 https://www.electricchoice.com/electricity-prices-by-state/

year. In summary, each sq ft in a vertical farm emits 1260 g-CO2 annually and each sq ft in a greenhouse emits 409 g-CO2 annually.

## Transportation

Found in the USDA produce shipment data, Boston leafy greens came from California, Arizona, New Jersey, Georgia, Texas, Florida, South Carolina, and Massachusetts in the past year. In the same time period, the tomatoes in Boston originated from California, Mexico, Canada, Florida, Georgia, Tennessee, Virginia, North and South Carolina, Maryland, Ohio, Maine, Rhode Island, Utah, New York, and Massachusetts.[17] Product origin varies largely with season, but California was a relatively consistent supplier for both produce types, and is the primary origin considered in the following calculations.

For tomatoes traveling in a refrigerated truck from California to Boston, ~100g of CO2 are emitted per pound. This is calculated based on an average trip length of 3,000 miles, a full truckload of 50,000 lbs of tomatoes, and a fuel economy of 6-7mpg. A gallon of diesel emits .010180 metrics tons of CO2[18]. Trucks often make the return trip empty; about 20% of all truck miles driven are empty miles[19]. Further, not all trucks always drive at full capacity. The emissions estimate of 100g of CO2 per pound assumes only the one way trip and a truck at full capacity, and thus is an underestimate of total emissions.

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[17] https://www.marketnews.usda.gov/

[18] https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references

[19] https://convoy.com/blog/empty-miles-in-trucking/

Using the same methodology and assumptions, tomatoes from Maine which travel ~200 miles are associated with 7 kg of CO2 emissions per lb.

Unfortunately data on transportation and packing volume of greens and lettuce is opaque. My contact at the Boston office of the USDA also did not have any information he was willing to share to help here, and this area requires further research.

## Pesticides and Fertilizers

According to a 2010 USDA study of over 3,000 farms, conventional tomatoes are treated with fertilizers, insecticides and fungicides at very high rates. For farms treated with fertilizers, on average, tomatoes receive each year on a per acre basis with 142 lbs of nitrogen, 111 lbs of phosphate, 182 lbs of potash, and 47 lbs of sulfur[20]. For insecticides, 37% of farms treated their tomatoes with zeta-cypermethrin, at an average rate of .101 lbs / acre. Another 33% treated their tomatoes with imidacloprid at an average rate of .376 lbs / acre. While the exact climate impact of fertilizers and pesticides varies, some of the biggest issues lie in excess application, runoff into streams and ground water sources, and release of nitrous oxide from nitrogen fertilizer, an extremely potent greenhouse gas[21]. Both zeta-cypermethrin and imidacloprid are highly toxic to various animals and fish, in addition to being dangerous for human consumption[22]. While I did not find any good sources on aggregate pesticide

[20] https://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Chemical_Use/VegetableChemicalUseFactSheet.pdf

[21] https://www.ceaconsulting.com/wp-content/uploads/greenhouse-gas-emissions-and-nitrogen-pollution-in-us-agriculture.pdf

[22] http://npic.orst.edu/factsheets/cypermethrin.pdf

environmental impact on GHGs emissions basis, they are responsible for a variety of other environmental concerns hard to quantify.

Many articles and sources state that indoor agriculture requires less pesticides and fertilizers, but none I found quite quantify this relationship at an aggregate and average level. Backyard Farms, a hydroponic tomato greenhouse farm in Maine mentions that they use pesticides "sometimes", but much less than conventional[23]. Evergreens Farm, a vertical controlled environment farm in Massachusetts growing leafy greens, uses no pesticides and 97.2% less fertilizer than conventional according to a conversation with their CEO. I use this estimate in the summary analysis.

## Land Use

According to the 2016 USDA vegetable summary tables, conventional outdoor tomatoes have a yield of 1.85 lbs / sq ft and leafy greens have a yield of .69 lbs / sq ft annually[24].

Greenhouse hydroponic tomatoes have a yield of 10.59 lbs / sq ft and greenhouse hydroponic greens have a yield of 8.71 lbs / sq ft annually[25].

Depending on accounting method, deforestation is considered one of the three largest contributors to greenhouse gas emissions[26]. The issue is that not only does removal of rainforest for agricultural purposes remove vital carbon sinks, but that trees are most efficient at carbon removal once they are on the older side[27]. Thus,

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[23] https://www.backyardfarms.com/site/page-bwf/frequently-asked-questions
[24] https://usda.library.cornell.edu/
[25] https://artemisag.com/wp-content/uploads/2019/06/stateofindoorfarming-report-2017.pdf
[26] https://psmag.com/environment/tropical-deforestation-leads-to-more-carbon-emissions
[27] https://blog.ucsusa.org/elliott-negin/would-reforestation-help-counter-deforestation

reforestation is not the most effective short term option, but more important in the long run. The immediate impact of saved square footage from indoor agriculture is stronger from an avoided deforestation perspective than from enabling reforestation efforts.

## Water Use

Conventional lettuce growth requires 15-30 gallons / lb of lettuce depending on the data source while tomatoes require ~26 gallons / lb produced[28].

Hydroponically grown lettuce requires 4 gallons / lb of lettuce on average based on the 150 farms in the Agrilyst report.

Hydroponic tomatoes require 25 gallons / sq ft per year according to a Purdue class on hydroponic tomato growth[29]. Given a yield of 10.59 lbs / sq ft per year as determined in the Agrilyst report, this comes to 2.36 gal gallons / lb of tomatoes produced hydroponically.

# Analysis

Tomatoes and leafy greens were examined for their environmental impact. The following three tables summarize findings (as available). Some areas are left as unquantified when data was unavailable or inconclusive. These require further research and remain open questions.

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[28] Mekonnen, M.M. and Hoekstra, A.Y. (2011) The green, blue and grey water footprint of crops and derived crop products, Hydrology and Earth System Sciences, 15(5): 1577-1600.

[29] https://ag.purdue.edu/hla/fruitveg/Presentations/Hydroponic%20Tomato%20Production%20in%20Soilless%20Culture_February%2013,%202018_Petrus%20Langenhoven.pdf

## Environmental Impact Comparison (Shared Metrics)

| | Conventional Outdoor | Hydroponic Greenhouse | Hydroponic Vertical Farm |
|---|---|---|---|
| Facility Life Cycle | 0 | .8 g $CO_2$ / sq ft each year | 0 if brownfield, higher if greenfield |
| Energy | 0 | 409 g $CO_2$ / sq ft each year | 1260 g $CO_2$ / sq ft each year |
| Pesticides | high | unquantified, but less | Evergreens Farm - 97.2% less |

## Tomato Environmental Impact Comparison

| | Conventional Outdoor | Hydroponic Greenhouse | Hydroponic Vertical Farm |
|---|---|---|---|
| Food Waste | ~40% | greater than 14% | greater than 14% |
| Transportation | 100 g $CO_2$ / lb (CA - Boston) | 7 g $CO_2$ / lb (Maine - Boston) | 0 (urban setting) |
| Land | 1.85 lbs / sq ft | 10.59 lbs / sq ft | unquantified |
| Water | 26 gallons / lb | 2.36 gallons / lb | 2.36 gallons / lb |

## Leafy Greens Environmental Impact Comparison

| | Conventional Outdoor | Hydroponic Greenhouse | Hydroponic Vertical Farm |
|---|---|---|---|
| Food Waste | ~ 40% | greater than 20% | greater than 20% |
| Transportation | unquantified | unquantified | 0 |
| Land | .69 lbs / sq ft | 8.71 lbs / sq ft | 5.45 lbs / sq ft |
| Water | 15-30 gallons / lb | 4 gallons / lb | 4 gallons / lb |

Some limitations of the research include that many of the metrics are summary statistics derived from various resources and not always true for a particular real farm. In particular, hydroponic vertical farms vary greatly across different technologies and implementations, and are thus hard to characterize end to end. Further, a few areas are not considered in this analysis, including negative soil effects of deforestation and chemicals used in agriculture as well as packaging and materials required for produce transportation. These are two other areas that local indoor agriculture could have a positive impact on.

Taking a simplified lens and considering only energy and transportation, the analysis shows that even with renewable resources indoor agriculture doesn't necessarily make production that much more sustainable. Considering tomato production from 1 square foot of hydroponic greenhouse space (10.59 pounds), we see 409 g of $CO_2$ for the year due to energy and ~70 more g of $CO_2$ due to transportation (Maine to Boston) compared with ~1000 g of $CO_2$ due to transit from California. For the tomatoes produced in an urban environment, they are associated with an energy usage impact of 1260 g of $CO_2$, which is more than the emissions associated with the transit from California. Considering just these two factors, the tomatoes from Maine have half as many emissions as those from California, both of which have less than those produced locally in a vertical farm. While the Maine tomatoes are a large improvement, it is not quite as shocking or impactful as hoped for and urban vertical farming fails to live up to their hype. The caveat here is that the urban vertical farm performs better in every other category examined, but that these categories are not easily directly translated to emissions outputs.

# Conclusion

## Discussion

While this analysis provides preliminary evidence that indoor agriculture can offer a more sustainable alternative to conventional, this is largely case dependent. Energy inputs for the greenhouse must be clean and the transit of the conventional produce must be far. As alluded to by Mike Berners Lee in his book, *There Is No Planet B,* eating local does not matter for climate change as much as we think. Further analysis needs to explore how the collection of various sustainability factors including water usage, land usage, and local pollutant control contribute to the sustainability of indoor agriculture.

Still, not all hope is lost for indoor agriculture as a sustainable alternative given a simplified analysis. Displacing produce traveling by air poses a large opportunity for greater impact. Delicate produce including fresh berries, pineapples, and avocados are shipped via plane[30]. Not many indoor operations have profitably or successfully grown these - as such there is a lack of data surrounding indoor operations for these crops. A sustainability comparison for crops traveling by air is an interesting area to explore.

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30 https://www.independent.co.uk/environment/green-living/food-miles-the-true-cost-of-putting-imported-food-on-your-plate-5333264.html

## Personal Takeaways

This analysis was more challenging than I anticipated. There are many more variables to consider in a full end to end sustainability analysis, much less a cost based analysis as well. While there exist some good data sets, there is also a lot of information that goes untracked in the agriculture industry.

Further, it is often difficult to translate all environmental impacts into a single value that is easy to compare. Land use, water use, and local environmental pollutants due to pesticides and fertilizers are difficult to translate into a comparable "emissions" number the same way energy and transportation can be more readily translated.

I am simultaneously surprised by how so many individuals in different organizations were willing to chat with me when I offered nothing in return, but also disappointed by the often found lack of knowledge around sustainability metrics when asked. When I asked farmers about their greenhouse life cycle sustainability, they would always somehow spin the conversation toward costs. I found myself asking "please do a thought experiment and forget profitability for a moment". While many of the individuals were eager to share sustainability initiatives and upgrades they had (ie lights, insulation), none could quantify the impact of these changes or their systems overall in any meaningful way.

In general, sustainability is not as well studied as I had thought. I hypothesized a life cycle analysis on a greenhouse would be simple, and this turned out to be one of the most challenging pieces to fill in. Still, I am grateful to everyone who answered the phone when I cold-called, and shared what knowledge and resources they had to fill in the pieces as best they could.

## Acknowledgements

I would like to give a huge thank you to all the individuals who shared their time and resources to help me with this report. In particular, I would like to specifically highlight Federico Toro of Evergreens Farm, who provided invaluable help pointing me at several resources driving a bulk of this analysis. Jim Wilson of Wilson Farms provided a ton of useful information, and was endlessly kind and patient with answering my questions. I would also like to especially thank Professor Ronald Rivest for his immense help and support - suggesting several resources and individuals to talk to, and making introductions where possible. Professor Christoph Reinhart deserves a huge shout out not only for useful introductions to relevant individuals in the space, but also for the first conversation that originally sparked my interest in the space. John de la Parra provided invaluable introductions, pointers to several helpful resources, and infinite enthusiasm. I would also like to thank the entire 6.s898 course staff for making this rewarding class and final project possible!