

Trading Soils for Ceilings: Comparing Resource Intensity of Vertical and Conventional Farming

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Abstract

Vertical farming concepts have gained interest from the investment community since Dickson Despommier's 2009 article in *Scientific American*, receiving \$652 million in capital funding in 2017.¹ Many existing vertical farming ventures tout resource conservation as a key value proposition over conventional farming techniques. Vertical farming has been identified as a potential component for future urban resilience and is represented in resilience-based initiatives like the Rockefeller Foundation's 100 Resilient Cities initiative and the Ellen MacArthur Foundation's Circular Economy 100. If the technique continues to gain adherents, it is necessary to understand the resource trade-offs compared to conventional methods that could better inform urban policy and planning.

This study develops a model to estimate and compare the resources required to grow an equivalent quantity of leafy greens between the two methods of vertical and conventional. This model assumes a hypothetical scenario, "If an entire neighborhood's production of lettuces and leafy greens could be replaced by locally-grown, vertically-farmed lettuces, what would the impact be on land use, water, and energy?" This first requires a method to estimate the current annual lettuce production for a single neighborhood using demographic data. The neighborhood used in this study is the South Bronx in New York City, which contains the largest produce distribution center in the United States and is a major destination for conventionally-grown produce.

The results of the model show a stark trade-off between land use and energy consumption; vertical farming requires just 2.8% of the land area, but twenty times the energy to yield the same quantity of produce. A carbon footprint analysis further examines the impact of the two farming techniques on overall greenhouse gas emissions. In this analysis, vertical farming techniques release nine times more carbon dioxide per pound produced, which runs counter to the resilience claims of vertical farmers. Since much of the energy used in vertical farming is electricity, the greenhouse gas emissions for each facility is dependent on the fuel mix of the electricity provider (assuming each facility is connected to the local utility grid). This has two implications; the greenhouse gas emissions of each vertical farming facility is highly dependent on location, and that these facilities have an opportunity to decouple from the grid and minimize its carbon footprint by including more renewable resources. As vertical farming techniques might become deployed more frequently, these strengths, weaknesses, and opportunities must be understood and applied in a more sustainable way. Otherwise, maintaining the status quo could lead to a farming system that is actually more detrimental to climate change.

Introduction & Key Concepts

Farming is one of the world's oldest professions and food production remains a source of income for 1 in 3 workers on the planet.² In the United States, however, agriculture is shrinking as a source of employment, and occupies barely 1.5% of the total workforce.³ Much of this disparity is due to a greater portion of the population moving to urban centers and increasing concentration on existing farmland. These "factory farms" continue to receive investments in GPS-guided equipment, advanced irrigation projects, and genetic engineering to improve yields.⁴ Greater fertilizer and pesticide usage has been studied as powerful ecological disruptors through eutrophication of waterways and bee colony collapse.⁵⁶ Despite technological advancements, social justice issues pervade the farming and food processing industry; large numbers of farms are staffed with a vulnerable class of migrant labor, and rural areas have stagnated economically.⁷⁸

These and other factors have begun altering consumer appetites--the number farmer's markets has more than doubled nationwide in the past ten years.⁹ As the "local" food movement has become mainstream through national grocers like Whole Foods, it is logical for agricultural producers to strive to be as local as possible. Urban agriculture has gained significant momentum as a method for offsetting the issues of wholesale factory farming while providing local benefits to urban consumers. To date, at least ten American cities have developed plans, strategies, or regulations for managing and promoting the growth of urban agriculture.¹⁰

Entrepreneurship in urban agriculture takes on a fascinating range of projects and scales and appearances; it is difficult to point to a unitary prototype. For this study, the focus will remain on large-scale vertical farming, which attempts to emulate the yield potential of conventional farming. Vertical farming is characterized by growing multiple beds of produce within the same physical footprint.[†] This theoretically decreases the amount of area needed to grow the same amount of produce, but each additional bed requires capital and operational expenditures for these yields to be possible. Citing benefits such as reduction in water consumption and land-use, local urban job-creation, and participation in the local food economy practitioners of vertical farming tout the eventuality of its establishment within the greater food system.¹¹

Vertical farming methods attempt to control for abiotic factors such as climate, sunlight, and irrigation. When placed indoors, maintaining stasis between these factors requires an intricate balance between the building systems, many of which require significant energy input. Additionally, vertical farming resembles manufacturing more than it does conventional farming and creates unique engineering challenges. Vertical farming operations located in urban settings also provide more opportunities for employment to local communities. There have been studies that have focused on developing a lifecycle analysis for comparing hydroponic growing methods to conventional farming, with the unsurprising result that "alternative" methods of agriculture require far greater energy input.¹²

* Vertical farming can also be defined as growing produce or raising livestock within a multi-story building. However that definition does not apply to this study.

Methodology: Crop Selection

Food products that have wide appeal have become highly concentrated in specific regions of the country. Therefore, it is a necessity for these products to be transported to distant regions of the country or other parts of the world, almost always through the burning of fossil fuels. One such product is lettuce, whose production is concentrated to parts of California and Arizona and usually reaches the market via refrigerated truck.¹³ Monterey County, California alone supplies a majority of the lettuce grown in the United States. Lettuce is also a product that lends itself well to vertical farming due to its short growth time compared to fruiting and cereal crops like tomatoes and corn. Lettuce plants also can weigh less than other crops, which reduces material costs of vertical farming systems.

Methodology: Site Selection

Instead of comparing conventional and vertical farming methods directly, this study examines the impacts of both farming methods on a single urban neighborhood. This approach has practical implications for the study. Practically, this provides definite endpoint for the lifecycle analysis, especially since this study aims to compare the embodied energy of transport included in the conventionally-grown lettuce.

A single neighborhood is also more relatable than arbitrary production values. This study chose the neighborhood of the South Bronx in New York City (as defined by the United Hospital Fund) as the area of interest.¹⁴

			<i>Ethnic Composition</i>				<i>Income Level (200% of Poverty Line)</i>	
	Area (acres)	Total Pop.	Hispanic	Black	White	Other	Low Income	High Income
TOTALS	6,666	573,563	381,443	168,232	9,148	14,740	363,488	210,075
Zip Codes:								
10451	649.5	48,289	60.00%	34.60%	2.00%	3.40%	60.18%	39.82%
10452	630.2	75,288	68.10%	27.80%	1.60%	2.50%	63.16%	36.84%
10453	586.2	80,516	68.80%	28.00%	0.90%	2.30%	62.33%	37.67%
10454	667.1	38,938	71.60%	24.90%	1.90%	1.60%	69.98%	30.02%
10455	455.8	42,779	72.40%	24.10%	0.90%	2.60%	66.28%	33.72%
10456	651.8	92,712	59.00%	36.30%	1.50%	3.20%	63.90%	36.10%
10457	679.2	74,010	64.50%	30.90%	1.90%	2.70%	62.56%	37.44%
10459	522.9	47,972	69.20%	27.40%	1.30%	2.10%	62.17%	37.83%
10460	841.9	60,266	70.40%	24.40%	2.60%	2.60%	61.71%	38.29%
10474	981.2	12,793	69.50%	28.70%	1.10%	0.70%	66.67%	33.33%

Figure 1: Basic area and demographic statistics of the South Bronx used in the model.

Hunts Point, located in the South Bronx is one of the largest food distribution centers in the world covering 329 acres (5% total land in the South Bronx). Despite the proximity to this vital link in the local food system, residents of the South Bronx live in a recognized food desert—an area with difficult access to healthy foods such as fresh produce.¹⁵ While diagnosing or alleviating the food access issues for South Bronx residents is beyond the scope of this study, it provides a poignant setting for comparing the impacts of different agricultural methods. When

looking into the future of urban agriculture, the South Bronx may become the site of vertical farming developments due to its proximity to that central food hub.

Conventional farming case For conventional farming, this study assumes that the lettuces produced comes from a single place, Monterey County, specifically the Salinas Valley. Known as the “America’s Salad Bowl”, Monterey County’s annual lettuce crop is valued at \$1.2 Billion. At 57% of the total national yield¹⁶, Monterey County dwarfs any other lettuce-producing area and is an important cog within the food system much like Hunts Point. After the devastating drought in California that threatened the Central Valley (one of the most productive agricultural area in the nation), water prices have increased significantly to the point of raising food prices.¹⁷

Vertical farming case The Bronx, a borough of NYC, already has at least two vertical farms in the Bronx, mostly growing lettuces. Many of these vertical farms operate using proprietary equipment and processes, therefore obtaining production data remains difficult or impossible. The direct operating data of one anonymous vertical farm is used in this study; estimates for other farms are obtained from additional publications and are found in the bibliography. The data are combined and anonymized to protect the proprietary nature of these businesses.

Methodology: Model Development

In order to compare the two different farming methods for a lifecycle analysis, we use the mass of production as the equivalent metric between the two farming methods to allow comparison of other inputs and outputs. The main factors chosen for comparison in this study are: (1) overall land use, (2) water consumption, (3) energy consumption through production, (4) energy consumption through transport, (5) fertilizer consumption and (6) overall greenhouse gas emissions. The timeline for comparison is over a single year, as most of the relevant data is reported on an annual basis. Overall, this methodology provides a basis for comparison of these two farming methods based on these factors. This methodology is not limited to a single location, and therefore could be used to compare the overall global impacts of lettuce farming in different regions of the country.

Before any comparison can be made, we must set one constant between the two methods, annual consumption of lettuce in the South Bronx. This value provides the production quantity that the two methods use for comparison. The total consumption of lettuce within the South Bronx is not a directly measurable value and therefore must be estimated from different sources. The United States Department of Agriculture’s (USDA) 2016 study on “U.S. Food Commodity Consumption Broken Down by Demographics” provides valuable per-capita consumption values. This along with recent population data from the United States Census Bureau provides valuable information to establish a base consumption value.

This study utilizes available demographic data (education, ethnicity, and income) to establish the Estimated Annual Consumption (EAC) of lettuce in the South Bronx. Such a methodology allows further contextualization of the study and can be applied to different neighborhoods. It is entirely feasible that an equally-populated area has an entirely different produce consumption patterns based on a mix of educational, ethnic, and income factors.

Once the EAC was determined, we selected land use, water consumption and energy as relevant factors to the overall output. (1) Overall land-use is determined by comparing the annual yield per area of the two methods. For conventional farms, a composite yield is developed from USDA's reported data on yield per acre on California-grown lettuces and leafy greens. For vertical farms, the yield per area is aggregated from several sources as many vertical farming businesses do not publish direct yield data and the USDA does not currently report their production.

For (2) water consumption and (5) fertilizer consumption, the data for conventional farming is obtained from the University of California Davis's cost studies on lettuce operations in Salinas Valley. These cost studies provide typical consumption patterns of these critical inputs and estimate their total usage per area. As mentioned previously for vertical farms, the accuracy of the water and fertilizer consumption data is dependent on the information obtained from its practitioners. Water shall be measured in volume, fertilizers measured in mass.

For (3) energy consumption through production, the value for conventional farming is determined (Barbosa et al.) which compares the energy requirements of lettuce in conventional and hydroponic settings. This factor includes the energy needed for operating equipment like tractors and pumps. The caveat here is that the energy requirements are calculated from a conventional farm in Arizona, as such study does not currently exist for Monterey County. The assumption is that the energy needed to produce lettuce is comparable on a per-acre basis despite its location. For the vertical farms, the energy utilized is an aggregate of electricity and fossil fuels needed (if any) to produce the lettuce. The energy compared shall be in kilo-joules per mass produced and is not dependent on area.

For (4) energy consumption through transport, the location of South Bronx provides practical information for this comparison. This study utilized the method outlined by Blanke and Burdick¹⁸ to determine the embodied energy of food transport. Conventionally-grown lettuces are assumed to be transported via refrigerated truck to its destination non-stop. Vertically-grown lettuces do have a non-zero embodied energy of food transport, therefore it is assumed that the lettuce is travelling from Highbridge, the neighborhood furthest from the Hunts Point Produce Market (a reasonable destination) within the South Bronx neighborhood designation.

For (6) overall greenhouse gas emissions, this output is a combination of elements from factors (2), (3), (4), and (5). For the vertical farm, it is assumed that the energy consumed via electricity assumes the greenhouse-gas portfolio of the electricity provider's fuel mix (in the case of the South Bronx, Con Edison is the provider). At the conventional farm, energy for equipment is provided via diesel fuel and the greenhouse gas emissions are calculated based off that fuel. For transport and refrigeration, the energy consumed is also primarily from diesel fuel. Greenhouse gas emissions from fertilizers are primarily calculated for the production of such fertilizers; this study focuses on the most common, nitrogen, phosphorus, and potassium (N,P,K). Because the production of such fertilizers can occur in many different regions around the globe, the transport energy of fertilizers is excluded.

Methodology: Assumptions[‡]

The model has assumptions that constrain the scope and allow a more direct comparison of the two methods of lettuce farming. One key assumption is that the vertical farms located within the South Bronx only distribute its products to South Bronx residents. This may be infeasible considering it is prudent for businesses like vertical farms to diversify their customers to reduce structural risk. Additionally, this study does not assume that all the lettuce purchased in the South Bronx is consumed in the South Bronx (and vice versa), especially since neighboring districts are also considered to be food deserts.

Typically, products of urban agriculture are priced higher than conventionally-grown produce, which means that the price increase for this lettuce may lower consumption. Conversely, consumer sentiment for participating in the local food movement could attract a greater number of consumers to 'buy local', thus potentially increasing the total quantity of lettuce consumed in the neighborhood relative to conventional methods. An economic study regarding the price elasticity of the two goods could strengthen the findings of this study.

One component of agriculture that is prevalent in both vertical and conventional farming is fertilizers. Due to the proprietary nature and regional needs of fertilizer applications, a comparison of fertilizer consumption is omitted from this study but could be included in further research to enhance the overall comparison of resource intensity.

Results & Discussion

Estimated Annual Consumption (EAC):

Using the methodology outlined previously, the EAC for the South Bronx is 7,704,596 pounds of lettuces and leafy greens consumed annually (3,852 tons). This quantity will inform the additional parameters for vertical and conventional farming.

Comparison of Land Use:

Based on the results of the model, to grow 3,852 tons of lettuce, conventional farming would require 242 acres of land to produce that, which is 3.6% of the South Bronx's total land area.

Vertical farming techniques would only require 6.2 acres of land to produce the same quantity of lettuce; less than one thousandths of a percent of South Bronx's total land area. Comparatively, vertical farming is 37 times more efficient when considering land use alone. This finding supports the claims of vertical farming practitioners and proponents and makes this method viable in dense areas such as cities.

Comparison of Water Use:

For the same quantity of lettuce, conventional farming requires 268 acre-feet of water per year, or roughly 87.4 million gallons. Vertical farming methods require just 58 acre-feet of water per

[‡] Other assumptions include utilization of per-capita consumption of lettuce to estimate the total consumption; the utility and marketability of products from both methods are the same for consumers and grocers; utilizing a constant carbon emissions rate for different types of fuels.

year, or roughly 18.7 million gallons and 78.5% less than conventional farming. This finding supports the claims of vertical farming proponents that this method uses less water.

Comparison of Energy Use of Production:

Conventional farming required 10,675 megawatt-hours (MWh) to produce 3,852 tons of lettuce. This equates to 1.38 kilowatt-hours per pound of lettuce produced. Most of the energy used to produce the lettuce conventionally comes in the form of operating equipment like tractors and water pumps. Conversely, vertical farming within controlled environments must consume energy to create the light that substitutes sunlight, pump water, condition the air, and transport product within the facility. The result is that vertical farming utilizes twenty times more energy than conventional farming to produce the same quantity of produce; it requires 28.2 kilowatt-hours per pound of lettuce produced. Most of the 217,298 MWh of energy comes in the form of electricity, which requires permanent capital infrastructure unlike the mobile operating equipment of conventional farms.

Comparison of Energy Use of Transport:

To transport all 3,852 tons of lettuce from Monterey County, California to the South Bronx, 246 truckloads are needed, assuming they are fully loaded with lettuce. For each of the 2,998 mile trips, 447.5 gallons of fuel is needed, totaling 110,076 gallons required to transport all the lettuce to the South Bronx. This diesel fuel means 4,177 MWh of additional energy is needed to bring the lettuce to market from its specialized region, representing a 39% increase. The total energy consumption including transport for conventional lettuce is now 1.92 kilowatt-hours per pound of lettuce produced.

This study assumes that vertical farms are located within the entirety of the South Bronx, meaning that transport energy is minimized to bring the produce to market. Accounting for a smaller truck capacity to complete the 7 mile trip to market, 533 truckloads would be needed for a total of 557 gallons needed to deliver the produce. This creates an additional energy load of 21.1 MWh, or 0.51% of the energy required compared to conventional farming. When accounting for transport energy, vertical farming now utilizes only 14 times more energy than conventional farming.

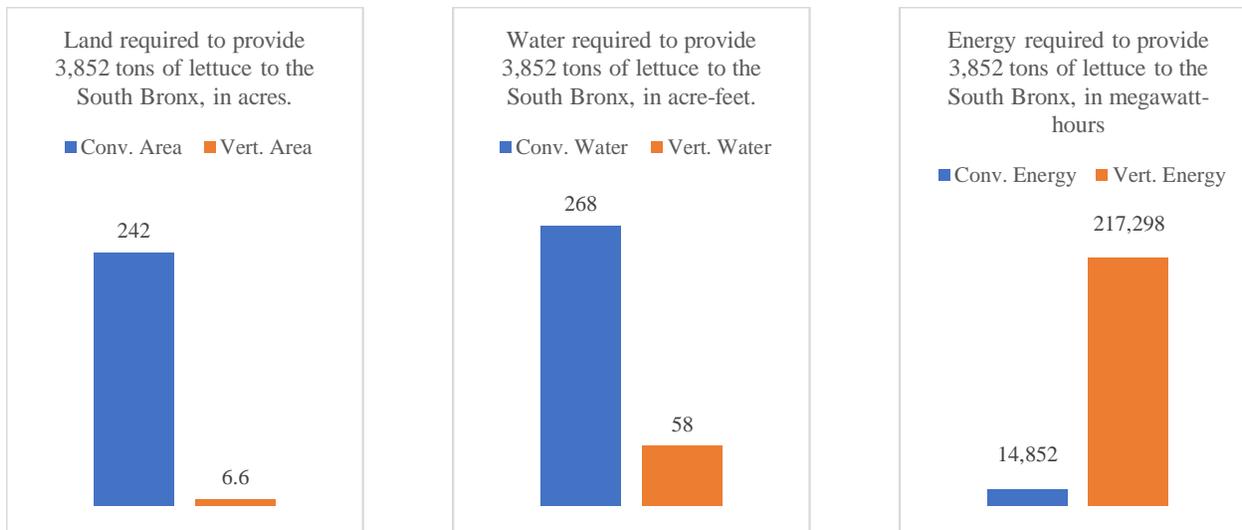


Figure 3: Direct comparison of the resource utilization to produce the equivalent quantity of produce.

Comparison of Carbon Footprint:

When including transport and production energy, the carbon footprint of both methods can be calculated to provide a comparison for each method's contribution to overall carbon dioxide emissions. For conventional farming, 4,697 tons of carbon dioxide are emitted to produce 3,852 tons of lettuce. Most of these emissions are due to diesel exhaust that emits 24 pounds of carbon dioxide per gallon when used.

Vertical farms must utilize electricity as the primary means of energy consumption, but that energy is not consumed on site but rather at the point of generation. Energy sources vary by location and type of generation; coal power plants for example release more carbon dioxide than natural gas plants while nuclear and renewable energy release no carbon dioxide when the energy is produced. This study assumes the energy diversity of New York City to calculate the carbon footprint of the vertical farms.¹⁹ In all, vertical farming releases 43,895 tons of carbon dioxide for the 3,852 tons of lettuce produced. This is nine times greater than carbon dioxide produced from conventional farming methods.

Since the source of energy is decoupled from the vertical farm itself, it is possible to power the vertical farm with enough nuclear or renewable energy to be less carbon intensive than conventional farming. However, the energy portfolio of each facility must be almost entirely renewable energy with at most 5% sourced from natural gas.

Conclusion

When comparing the main resources of agriculture—land, water, and energy—vertical farming provides two key benefits that could strengthen the resilience, flexibility, and diversity of future food systems. It uses considerably less land and less water than conventional farming but

requires much more energy to produce the same quantity of lettuce. That additional energy requirement creates greater carbon dioxide emissions, meaning that vertical farming is more harmful to the overall impacts of climate with current electrical distribution. However, the increased prevalence of renewable energy due to state and local policy goals means that the emissions of vertical farming could see a reduction in the future.

For urban policy makers and entrepreneurs interested in developing more vertical farms, this model serves as a benchmark for evaluating the overall environmental impact of such a farm. For agricultural policy makers, vertical farming allows some flexibility for facing the future challenges that climate change and population rise could place on the food system. This may not be possible for all crops, but vertical farming methods currently provide an (albeit infinitesimal) opportunity for spatial diversification for lettuces.

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