# Growing Up: An Exploration of the Past, Present, and Future of Hydroponics and Controlled Environment Agriculture

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**Dedication**

This paper is dedicated to my father, whose interest in engineering and agriculture inspires this research and so much more.

**Epigraph**

*"Water will be more important than oil this century"*

—Boutros Ghali*, 2003*

*“Cultivators of the earth are the most valuable citizens. They are the most vigorous, the most independent, the most virtuous, & they are tied to their country & wedded to its liberty & interests by the most lasting bonds. As long, therefore, as they can find employment in this line, I would not convert them into mariners, artisans or anything else.”*

—Thomas Jefferson, Letter to John Jay, August 23, 1785

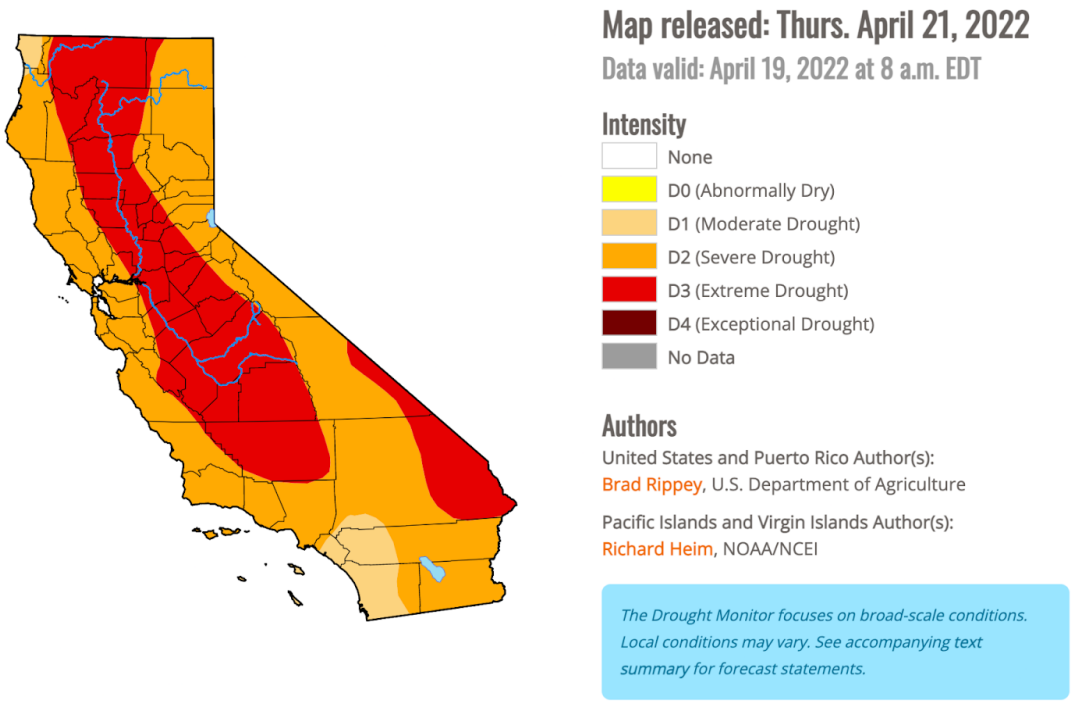
*“The most important thing about a technology is how it changes people.”*

—Jaron Lanier, You Are Not a Gadget: A Manifesto, 2010

**Drought And War**

In the midst of a year poised to find its place in the top ten hottest years on record, farmers and officials in California's agricultural belt are preparing for a grim year ahead. The US federal government announced in February of 2022 that the region, which produces roughly 25% of America's food, will not receive relief water from the Central Valley Project.

Over 95% of California is currently suffering from either severe or extreme drought, conditions under which "water levels are inadequate for agriculture, wildlife, and urban needs; reservoirs are extremely low; and risk of water theft is high.[1]




*The U.S. Drought Monitor's categorization of California, as of April 21, 2022*[1]

Ernest Conant, regional director for the US Bureau of Reclamation, admitted that this year's drought may turn out to be worse than in 2021, when conditions got so bad that farmers

[1] National Drought Mitigation Center University of Nebraska-Lincoln. (n.d.). *U.S. Drought Monitor*. | U.S. Drought Monitor. Retrieved April 24, 2022, from https://droughtmonitor.unl.edu/CurrentMap/StateDroughtMonitor.aspx?CA

were forced to abandon cultivation on hundreds of thousands of acres of plowed and harrowed cropland. “It’s devastating to the agricultural economy and to those people that rely on it,” said Conant, “but unfortunately we can’t make it rain.”[2]

While an increasing global population translates to higher demand for fresh water, a warming climate means supply is dwindling. The effects of this scarcity are being felt well beyond California: 40% of the world population lives in water-stressed regions.[3] Global metropolises including Rome, Cape Town, Chennai, and Lima have made headlines in recent years as they have been increasingly forced to ration water. The Middle East and North Africa have 6.3% of the world’s population, yet only 1.4% of the world’s renewable fresh water.[4] Water scarcity plays an increasingly large role in geopolitical tensions, with countries nervous of trends that point towards devastation, famine, and even war.

Unfortunately, water scarcity and related geopolitical tensions are set to get worse before they get better. The Grand Ethiopian Renaissance Dam, a hydroelectric dam being built near the source of the Nile River, has escalated tensions between Ethiopia, Egypt, and Sudan over how much the dam will impact water availability in downstream countries.[5] More than 10 dams built along the Mekong river in China have downstream countries including Myanmar, Laos, Thailand, Cambodia, and Vietnam worried about their larger neighbors' ability to control their water access.

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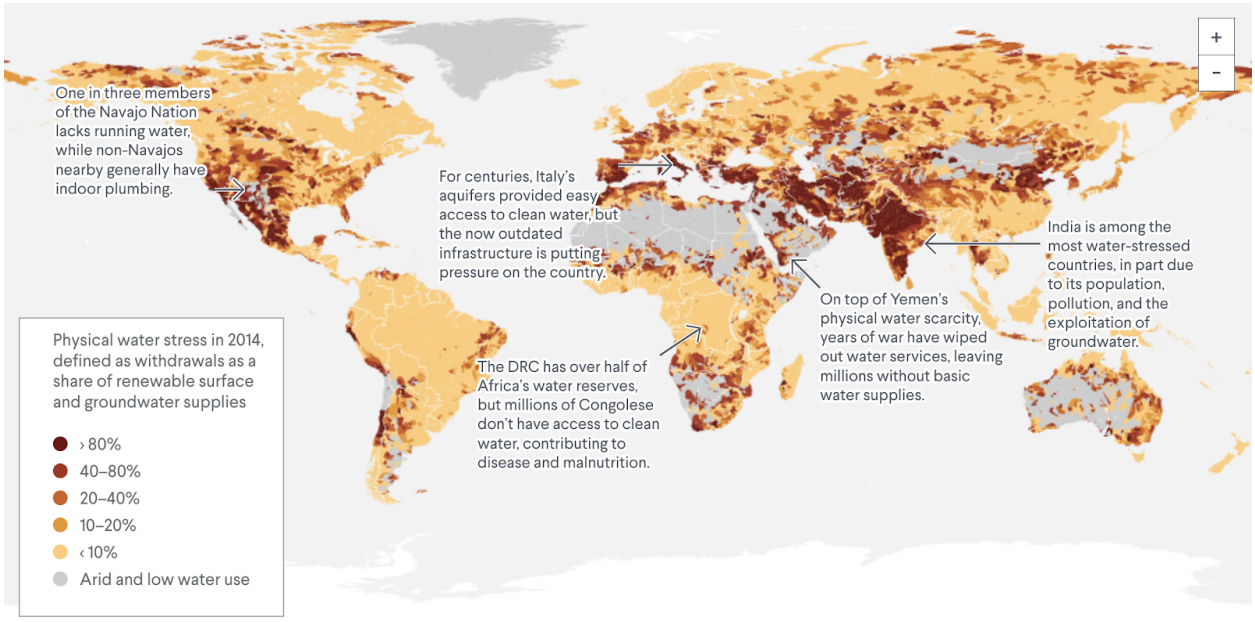
[2] Guardian News and Media. (2022, February 24). *'we can't make it rain': California farmers left out to dry as US government allots no water*. The Guardian. Retrieved April 24, 2022, from https://www.theguardian.com/us-news/2022/feb/23/rain-california-farmers-us-government-drought-water

[3] BBC. (n.d.). *How water shortages are brewing wars*. BBC Future. Retrieved April 24, 2022, from https://www.bbc.com/future/article/20210816-how-water-shortages-are-brewing-wars

[4] *Finding the balance: Population and water scarcity in the Middle East and North Africa*. PRB. (n.d.). Retrieved April 24, 2022, from https://www.prb.org/resources/finding-the-balance-population-and-water-scarcity-in-the-middle-east-and-north-africa/

[5] Mbaku, J. M. (2022, March 9). *The controversy over the Grand Ethiopian Renaissance Dam*. Brookings. Retrieved April 24, 2022, from https://www.brookings.edu/blog/africa-in-focus/2020/08/05/the-controversy-over-the-grand-ethiopian-renaissance-dam/

These worries heightened when, in 2018, water levels in the Mekong River fell to their lowest point in over 100 years.[6]




*Darker shaded areas have more physical water stress; but a myriad of factors, including infrastructure, governance, and population, all contribute to water availability.*[7]

The World Economic Forum has ranked water crises in the top five global risks for nearly every year since 2012, including a severe 2017 drought across Africa and the Middle East that displaced over 20 million people due to food shortages and conflict.[3]

**Agricultural and Supply Chain Pressures**

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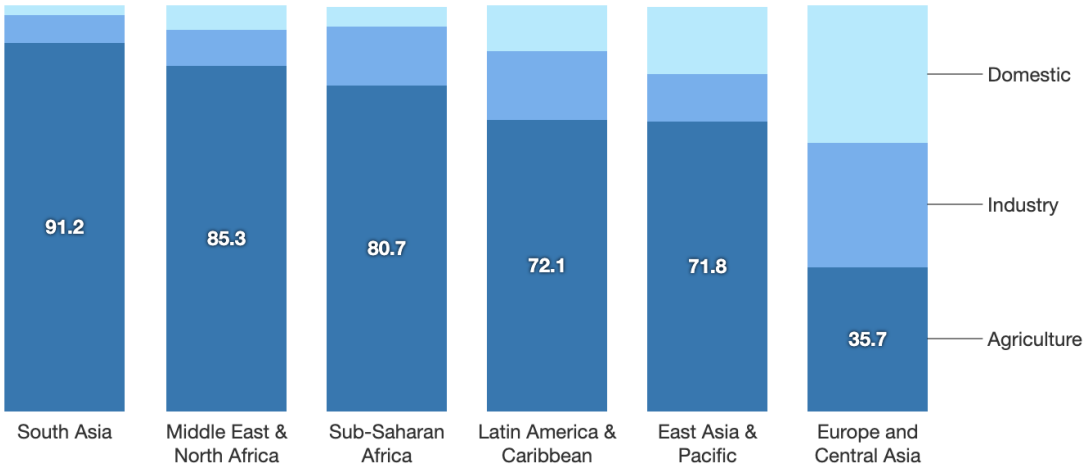
[6] Eyler, B. (2020, April 22). *Science shows Chinese dams are devastating the Mekong*. Foreign Policy. Retrieved April 24, 2022, from https://foreignpolicy.com/2020/04/22/science-shows-chinese-dams-devastating-mekong-river/

[7] Felter, C., & Robinson, K. (n.d.). *Water stress: A global problem that's getting worse*. Council on Foreign Relations. Retrieved April 24, 2022, from https://www.cfr.org/backgrounder/water-stress-global-problem-thats-getting-worse

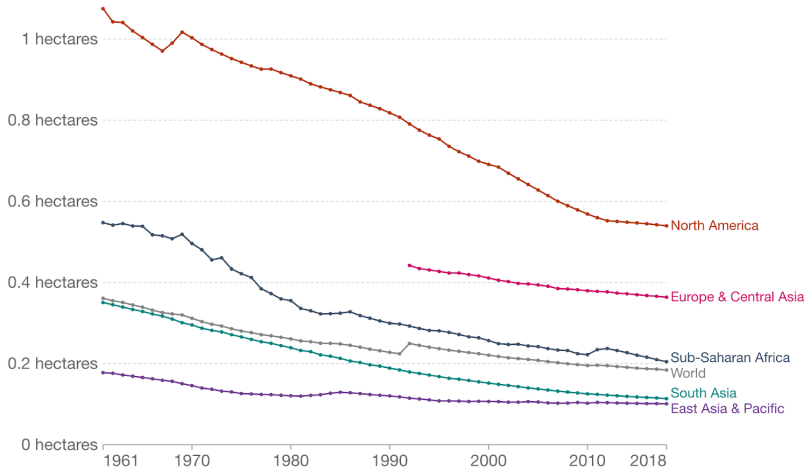
At a time when water shortages are leading to war, 70% of global freshwater usage goes to agriculture.[8] Routine irrigation can result in an increased yield per hectare, meaning farmers have leaned on water usage to address the constraint of arable land.[9] The more arid a region is, the more benefit they will get from irrigation. This means that the world's driest regions, including the Mediterranean and Middle East, have the highest proportions of agricultural fresh water use in the world.




*Share of freshwater withdrawals by sector (%), as of 2014*[8]

In addition to the global water crisis, the last 50 years have seen the global population more than double. With a finite supply of arable land, farms are forced to produce more yield on the same amount of land, and consumers are being corralled towards foods which offer a lower land footprint.

[8] World Bank. (n.d.). *Chart: Globally, 70% of freshwater is used for Agriculture*. World Bank Blogs. Retrieved April 24, 2022, from https://blogs.worldbank.org/opendata/chart-globally-70-freshwater-used-agriculture
[9] Ritchie, H., & Roser, M. (2017, November 20). *Water use and stress*. Our World in Data. Retrieved April 24, 2022, from https://ourworldindata.org/water-use-stress




*Arable land use per person over time, by continental region*[10]

In addition to land and water constraints on agriculture, numerous recent global catastrophes have exposed the fragility of our compex intercontinental supply chains. Nearly $60 billion USD of trade was brought to a halt when the Ever Given, one of the largest container ships ever built, got stuck in the Suez Canal for nearly a week.[11] The COVID-19 pandemic caused movement restrictions for workers, volatility in consumer demand, closures of shipping and food production facilities, restrictions in trade policy, and financial pressures on the food supply chain.[12]

The recent Russian invasion of Ukraine has disrupted the global trade of fertilizer, animal feed, and sunflower oil. It's estimated that nearly 12% of the total calories traded in the world are

[10] Ritchie, H., & Roser, M. (2013, November 13). *Land use*. Our World in Data. Retrieved April 24, 2022, from https://ourworldindata.org/land-use
[11] Yee, V., & Glanz, J. (2021, July 17). *How one of the world's biggest ships jammed the Suez Canal*. The New York Times. Retrieved April 24, 2022, from https://www.nytimes.com/2021/07/17/world/middleeast/suez-canal-stuck-ship-ever-given.html
[12] Serpil Aday, Mehmet Seckin Aday, Impact of COVID-19 on the food supply chain, Food Quality and Safety, Volume 4, Issue 4, December 2020, Pages 167–180, https://doi.org/10.1093/fqsafe/fyaa024

sourced from Russia and Ukraine,[13] and with Russia under sanctions and Ukraine in the midst of an invasion, the supply of these crops and fertilizers have stalled.[14]

Global supply chain issues create not only short term shortages and waste but long term distrust towards an unstable international trade system. As water shortages, finite arable land, and supply chain jolts cause problems for agriculture and food production across the globe, one agricultural method has cropped up as a potential alleviator: controlled environment hydroponic agriculture (CEA). Before exploring the current landscape of CEA, I'll overview the origins of hydroponics and its journey towards relevance in modern agriculture.

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**An Introduction to Hydroponics**

At its most fundamental level, hydroponics is the practice of growing plants in water rather than soil. Its origins as a practice date back thousands of years with illustrious examples of ancient civilizations employing hydroponic methods at the Hanging Gardens of Babylon, floating gardens in China, ancient Egyptian hydroponic farms along the Nile River, and the Aztec chinampas in the valley of Mexico.[15]

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[13] Glauber, J., & Laborde, D. (n.d.). *How will Russia's invasion of Ukraine affect global food security?* Ifpri.org. Retrieved April 24, 2022, from https://www.ifpri.org/blog/how-will-russias-invasion-ukraine-affect-global-food-security

[14] Barbaro, M. (n.d.). *How the war in Ukraine is creating a global food crisis*. The New York Times. Retrieved April 24, 2022, from https://www.nytimes.com/2022/04/05/podcasts/the-daily/ukraine-russia-food-supply.html

[15] Folds, E. (2018, March 23). *The history of hydroponics*. Medium. Retrieved April 24, 2022, from https://evanfolds.medium.com/the-history-of-hydroponics-99eb6628d205

*The Aztecs cultivated crops such as vegetables, flowers, and maize on chinampas, rafts of rushes and reeds*[13]

Modern US interest in hydroponics emerged in the 1930s, when Dr. William Frederick Gericke from UC Berkeley began experimenting with a theory that the healthy and sustained cultivation of many crops did not require *soil itself* but, rather, the *nutrients* within the soil. By emulating the nutrient make-up of soil, he and his team cultivated over 1000 lbs of tomatoes including vines of over 25 feet using a shallow basin with nutrients and water.[16] The nutrient solution went on to inspire a modern take on what hydroponics could be: a cultivation system divorced from soil and scientifically contrived to match the requirements of whatever best suits the crop.

[16] *Hydroponics History*. Hydroponics PSU. (n.d.). Retrieved April 24, 2022, from https://sites.psu.edu/hydroponicspsu/what-are-hydroponics/hydroponics-history/

Indoor hydroponic cultivation took off with cannabis in the 1980s, when innovations in indoor grow lighting emerged at a time when outdoor growers faced concerns of herbicides and an aggressive government crackdown on cultivation of the plant.[17] Isolation from the natural environment meant liberation from both human and wild pests, evasions of toxins in the soil that could poison the crop, and year-round growth.[18]

The indoor cultivation of cannabis continued to gain popularity in the following decades, propelling the industry forward as farmers sought out cheaper and more efficient grow lights, pumps, and grow mediums. Today, over 80% of cannabis grown in the US is grown indoors.[19]

Without the same legal pressures, it took mainstream farmers a few decades to come around to the potential benefits of moving the farm indoors. As technology improved, farmers began to experiment with which crops would benefit most from an isolation from issues such as variable climate, pests, weeds, and a reliance on fertilizing soil year after year. Most crops being lower in value than cannabis, the high costs of energy and lighting staved off many agricultural players for decades for one simple reason: indoor agriculture was too costly.

It wasn't until the mid 2010s when leaps in LED innovation made farmers revisit indoor hydroponics as a potential alternative for cultivation. LED lighting had become economically viable and presented the opportunity to cut energy consumption by 85%, increase the lifespan of bulbs to 25 years, and emit much less heat than fluorescent or incandescent lights.[20]

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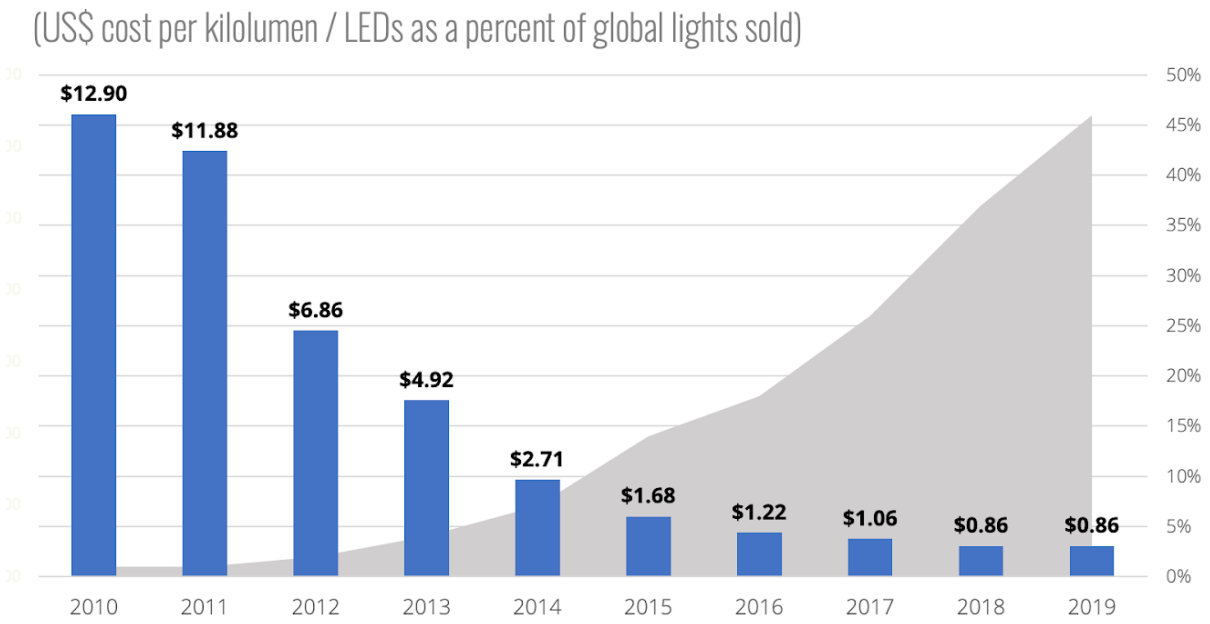
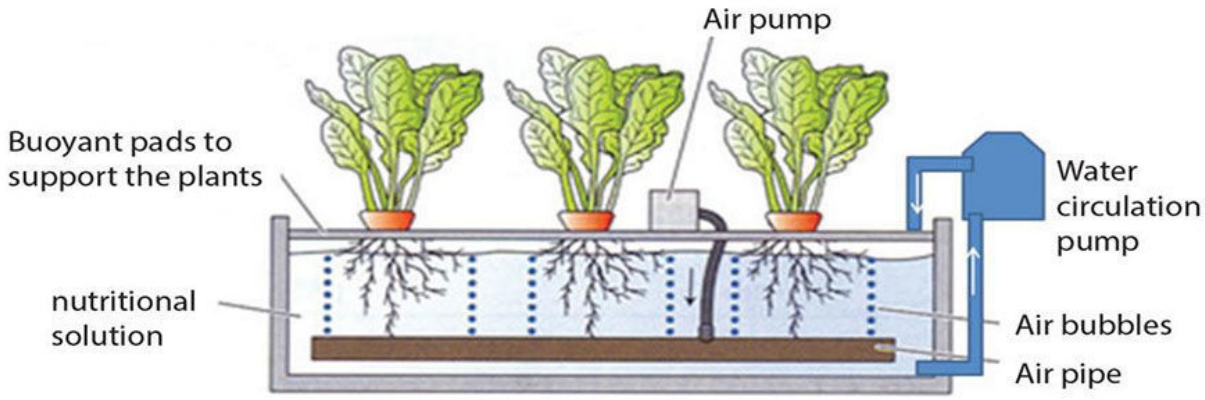
[17] St. Pierre, A. (2019, September 25). *A timeline of Cultivation Technology*. Cannabis & Tech Today. Retrieved April 24, 2022, from https://cannatechtoday.com/cultivation-tech/
[18] Lajeunusse, S. (2021, December 29). *Cannabis may contain heavy metals from the soil*. Futurity. Retrieved April 24, 2022, from https://www.futurity.org/cannabis-heavy-metals-2674872-2/
[19] Fertig, N., & Bade, G. (n.d.). *An inconvenient truth (about weed)*. POLITICO. Retrieved April 24, 2022, from https://www.politico.com/news/2021/08/10/weed-cannabis-legalization-energy-503004
[20] Popovich, N. (n.d.). *America's light bulb revolution*. Retrieved April 24, 2022, from https://www.nytimes.com/interactive/2019/03/08/climate/light-bulb-efficiency.html




*LED sales volume increasing over time as cost fall*[21]

Thus, the range of crops that could be financially viable to grow hydroponically indoors expanded to modern day staples such as leafy greens, herbs, and tomatoes. After several decades of optimizing methods, the drop in lighting costs tipped the scales for hydroponic use cases from marijuana and small-scale passion projects to commercially scalable business models, leading to thousands of hydroponics farms sprouting up across the globe.




[21] US Department of Energy. (2021, September 28). *Cost of LED lighting dropped 15-times as volumes increase*. Freeing Energy. Retrieved April 24, 2022, from https://www.freeingenergy.com/facts/led-bulb-light-cost-price-historical-decline-g213/

*Diagram of a basic hydroponics system*[22]

While the foundations behind hydroponics remain, the large-scale hydroponics we see today is unrecognizable to the Aztec chinampas in the valley of Mexico. Complete isolation from the outdoors and integrations of sensors, pumps, and indoor lighting have culminated in a new term to describe this style of farming: Controlled Environment Agriculture (CEA). CEA is a method of hydroponic cultivation in which plants are grown indoors with controllable variables such as temperature, humidity, light wavelengths (to simulate sunlight at various seasons of the year), pH, and nutrients. In a controlled environment, farmers can optimize conditions for any given crop's preferred nutrient levels, lighting, humidity level, and so on.

*A photo from Sky Greens, a modern CEA vertical hydroponics farm in Singapore*[23]

Being isolated from the outside world, the ability to reduce waste is high in CEA systems. Water, for example, can be targeted directly to the roots and can recirculate through a system

[22] *Hydro-, aqua-, and Aeroponics*. Terrascope 2024. (n.d.). Retrieved April 24, 2022, from https://terrascope2024.mit.edu/?page_id=313
[23] Sky Greens. (2017, May 15). Retrieved April 24, 2022, from https://www.skygreens.com/

with low evaporative loss. Growing from water chambers lends itself to vertical stacking, multiplying the yield per acre by as many levels as the vertical farmer chooses to build. Compared to traditional agriculture, CEA requires up to 95% less water and can produce 25 times as much per acre.[24] In a world fraught with water and land shortages, this level of improved production could be life-saving.

**Modern Commercial Hydroponics**

The US hydroponics market has nearly tripled over the past 5 years, and industry analysts predict the industry will eclipse $1 billion in revenue by 2028, driven largely by an increase in the market share of tomatoes.[25] Additionally, investment in CEA startups has dramatically increased year over year.[26]

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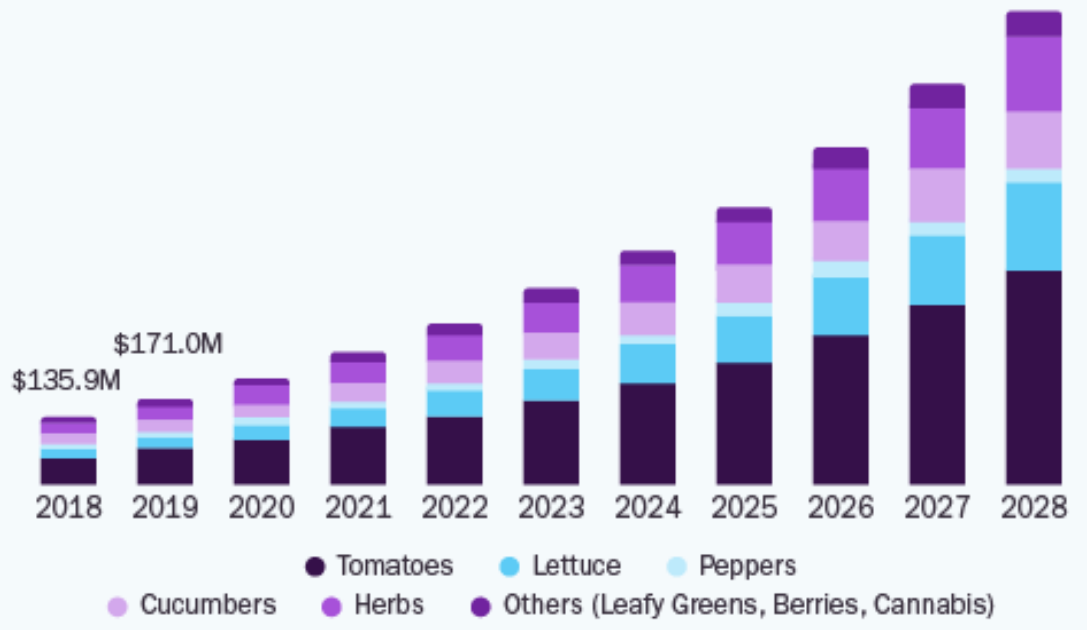
[24] Bailey, M. (n.d.). *Why controlled environment agriculture (CEA) is the future of farming*. Dantherm Group. Retrieved April 24, 2022, from https://www.danthermgroup.com/en-gb/calorex/why-controlled-environment-agriculture-cea-is-the-future-of-farming

[25] *Hydroponics market share, research 2025: Industry growth report*. Hydroponics Market Share, Research 2025 | Industry Growth Report. (n.d.). Retrieved April 24, 2022, from https://www.millioninsights.com/industry-reports/hydroponics-market

[26] Hullett, J., & Sparks, B. D. (2021, July 22). *Why investors are putting their money toward controlled environment growing*. Greenhouse Grower. Retrieved April 24, 2022, from https://www.greenhousegrower.com/crops/why-investors-are-putting-their-money-towards-controlled-environment-growing/




*U.S. Hydroponics Market Size from 2018-2028, by crop*[27]

Investors in CEA are betting on overcoming current technology and cost hurdles that stand in the way of achieving completely controlled and automated agriculture. Today, hydroponics companies struggle with high costs of startup, labor, and energy. Nearly 50% of indoor farms fail to make a profit and farms are under constant pressure to drop the cost of production to a level where their prices can compete with traditional farms that use lower cost inputs like the sun for light, earth for soil, and rains for water.[28]

Labor stands out to many CEA companies as the cost variable to focus on, as it accounts for nearly 50% of operating costs.[29] Innovations in automation and robotics offer a promising outlook on the potential to replace maintenance and harvesting labor at scale, and the result is

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[27] *Hydroponics market size & share report, 2021-2028*. Hydroponics Market Size & Share Report, 2021-2028. (n.d.). Retrieved April 24, 2022, from https://www.grandviewresearch.com/industry-analysis/hydroponics-market

[28] Agrilyst. (2018, October 1). *Agrilyst releases Third State of Indoor Farming Survey*. Produce Grower. Retrieved April 24, 2022, from https://www.producegrower.com/article/agrilyst-state-of-indoor-farming-survey/

[29] *Economic feasibility*. Terrascope 2024. (n.d.). Retrieved April 24, 2022, from https://terrascope2024.mit.edu/?page_id=314

an industry race towards incorporating technology to optimize and automate as much of the cultivation process as possible.

In the face of investor scrutiny over losses, CEA giant AppHarvest recently divided operations into three internal branches, one of which (TechCo) will develop the company's key technologies, including "proprietary FarmOps, robotic harvesting capability, and AI/machine learning for growing—as well as the potential to develop a new revenue stream through licensing of CEA technology to global operators."[30] That's to say, one of the three main pillars of AppHarvest is entirely dedicated to using data and machines to cut costs and improving crop yields.


*Bowery, another CEA giant, demonstrates their plans for full production integration by comparing their food production process to the production and supply chain status quo*[31]

[30] *AppHarvest Q2 2021 results*. AppHarvest. (n.d.). Retrieved April 24, 2022, from https://investors.appharvest.com/news-releases/news-release-details/appharvest-announces-q2-2021-results-plans-new-holding-company

[31] *How To Invest In Controlled Environment Agriculture With Confidence*. Bowery Farms. (n.d.). Retrieved April 24, 2022, from https://www.youtube.com/watch?v=acovNsx8tYw

The goal is a facility where robots manage the process from start to finish: the planting, farming, harvesting, transport, storage, and packaging. Even the delivery to retail, at some point, will likely be a task for a machine.

**Growing Forward**

CEA is taking hold in a handful of agriculture niches, but it's nowhere close to replacing traditional agriculture. The commercial indoor hydroponics industry finds itself constrained by three main bottlenecks:

1. Labor and energy costs
2. Machinery and AI capabilities
3. Cost-effective crops to produce

These constraints limit the purview of CEA today, but they all share a promising commonality: the rate of change on these constraints has them moving in the direction CEA needs.

Lighting continues to get cheaper, more efficient, and more tailored for indoor growing. This translates to lower overhead costs in purchasing lights, lower operational costs in increased efficiency, and higher output per dollar spent on lighting in specialized lighting. Additionally, the US energy grid is shifting its weight towards renewables, and those renewables are becoming cheaper and more efficient.[32]

[32] Marcacci, S. (2022, April 14). *Renewable energy prices hit record lows: How can utilities benefit from unstoppable solar and wind?* Forbes - Energy Innovation: Policy and Technology. Retrieved April 24, 2022, from https://www.forbes.com/sites/energyinnovation/2020/01/21/renewable-energy-prices-hit-record-lows-how-can-utilities-benefit-from-unstoppable-solar-and-wind/

The potential for innovation in sensors and machinery benefits from translatable discoveries made by a variety of industries, from self-driving cars to insurance and hospital systems. A growing indoor agriculture sector means that development of these machines will be increasingly tailored towards the needs of CEA. Machine learning and artificial intelligence are similarly cross-functional, meaning that discoveries shared in open-source libraries like TensorFlow could very quickly benefit the production at CEA companies like AppHarvest. These systems will become more effective and efficient over time, and stand to replace a substantial portion of operating costs in labor.

CEA is just getting started with respect to the growing environment iteration process: identifying the optimal parameters, quantities, and methods will be key to optimizing yield. Additionally, further research on the soil microbiome and plant hardiness will continue to inform environment optimization for taste and productivity. Crops like corn and wheat do not currently make sense for CEA, and many argue never will. Nearly every plant *can* grow hydroponically, but various aspects of the cultivation process, such as pollination and plant architecture, make some crops less suitable. Although this as the limiter of hydroponics, I believe that if CEA becomes the major method of producing leafy greens, tomatoes, herbs, and strawberries, gene-editing research will see a lucrative draw to tailor the development of plant architecture towards hydroponic conditions.


*Potential for growth based on the rate of change of key factors, Agritecture*[29]

While outdoor agriculture faces environmentally prohibitive issues such as volatility of climate and soil, indoor agriculture faces issues of technology and efficiency. Although indoor agriculture struggles to compete with traditional agriculture's free sunlight and rain water, in the long-term outdoor agriculture cannot compete with CEA's ability to grow locally year-round, produce quick yields, optimize efficiency of space, conserve water usage, and establish consistency in production.

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**A Post-growth Society**

Given the rates of innovation of CEA's key constraints, I find it reasonable to imagine a future where CEA is tasked with a large share of our agriculture. As such, I will use the second half of this paper to discuss potential long-term societal changes that may occur from these constraints being taken to the extremes.

These extremes are aggressive assumptions. Forecasting the development of technology is tough enough on its own, let alone gene-editing on plants for purposes barely explored before. Predicting things like how the influx of capital to this space will accelerate innovation in this

innovation is difficult, but trends outlined above lead me to believe these assumptions are possible.

While the specifics of timelines, crop breakdowns, and market share are beyond my knowledge, I have a handful of eventualities that I foresee coming to fruition. In the event that they do, I'm curious about where that would put us as a society. Those eventualities are the following:

1. Costs of lighting and energy fall out of the picture. Hydroponics farms source energy from clean energy sources and lighting to grow in hyper-efficient conditions. As these costs fall, CEA operations expand their breadth into more crops.
2. Operational cost of labor falls to near-zero. Development in software and hardware eliminates human involvement in the cultivation process: everything from planting the seeds to harvesting the ripe produce is done by machines.
3. Research and development has broadened the range of crops suitable for indoor growth. Research in soil has allowed hydroponically grown food to emulate soil cultivation in any part of the world.

In a world where these assumptions come to fruition, humans would be able to grow nearly any kind of plant in nearly any part of the world at very low cost and very high quality, at any time of the year. Low costs and industry knowledge would make CEA the industry standard for growing cannabis, herbs, vegetables, tomatoes, mushrooms, and much more. With cheap, reliable, local produce, transportation time and costs disappear. Hundreds of millions of hectares are liberated from the reigns of agriculture. Efficiency in water use frees up freshwater for other uses. Runoff and environmental damage from non-organic compounds such as pesticides, herbicides, and fertilizers falls drastically.

The largest question becomes just how much of agriculture CEA can overtake. With costs diminished and efficiency optimized, the only prohibitor becomes what is physically and methodologically possible. In order to expand as an industry, CEA is thus faced with two options: either develop methods to grow more important crops, such as corn, soy, and wheat, or explore plant derivatives that can drive up demand for hydroponically efficient crops, such as lettuce or tomatoes.

With respect to the first option, although most large-scale hydroponics currently focus on leafy greens, herbs, cannabis, and tomatoes, researchers are exploring hydroponic production of vegetables such as beans, peas, onions, cucumbers, peppers, radishes, and carrots. Fruits, including strawberries, watermelon, berries, and grapes are similarly garnering more attention from experimental growers. Even trees such as mini cherry trees, banana trees, nut trees, and dwarf apple trees can be grown hydroponically, albeit expensively.

If efficiency and scale of hydroponics ramps up, the method could compete with outdoor agriculture on staple crops. Leaps forward in sugar, corn, cacao, coffee, soybeans, or rice would likely lead to massive investment in CEA. Particularly with players such as NASA investing in hydroponics soybean production, I foresee potential CEA breakthroughs on a crop that currently seems nonsensical to grow indoors. Crop by crop, research and development teams will discover feasible methods and variations for CEA.

The second possibility entails creating value from easily growable produce. Corn, the most abundant crop in North America, is a great example of this. Nearly 45% of corn becomes animal feed, 44% becomes ethanol, and only 10% becomes human food. Within the share of corn used for human food, roughly a third is converted into high-fructose corn syrup.[33]

[33] *Corn*. Engage the Chain. (2019, August 27). Retrieved April 24, 2022, from https://engagethechain.org/corn

If hyperproductive CEA farms can grow lettuce at a nearly costless rate, the opportunity arises for humans to discover a use for it. Lettuce is just one example, but it shows promise in derivative oils addressing sleep disorders and as feed for animals.[34]

**Concerns Growing into the Future**

Unlike other well known advances in agriculture such as fertilizers or GMOs, hydroponics has perplexed critics as it not only increases crop yields and lowers costs, but does so in a way that stands to benefit the environment in several major ways. That said, the industry has found pushback from those who cite issues with financial feasibility and scalability beyond lettuce, herbs, and tomatoes.

In the past, consumers have called out a lack of taste from hydroponically grown produce and voiced concerns about a future where such a standardized grow process leads to mono-tasting crops. In the past few decades, numerous experiments have shed quite a bit of light on the factors that create taste, and learnings are applied at most large-scale CEA farms. This research has shown that a number of Inputs, including light exposure, temperature, and nutrients consumed in the growing process all influence flavor. Given that these are controllable variables in CEA, the process now has the potential to provide tastier crops on a more consistent basis than traditional farming.[35] Beyond the mechanics of cultivation, the revamped supply chain of CEA means a potential for less than 48 hours between hydroponic cultivation and consumer purchase, ensuring peak freshness of the produce.

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[34] Yakoot, M., Helmy, S., & Fawal, K. (2011). *Pilot study of the efficacy and safety of lettuce seed oil in patients with sleep disorders*. International journal of general medicine. Retrieved April 24, 2022, from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3119588/

[35] Dupuis, A. (2021, August 24). *Hydroponic produce: What the foodies are saying*. Eden Green Technology. Retrieved April 24, 2022, from https://www.edengreen.com/blog-collection/hydroponic-produce-what-the-foodies-are-saying

With the assumptions that automation and renewable energy sources reduce variable labor costs to near zero, and that gene-editing and optimization for hydroponics allows any plant to be grown in a controlled environment, the interesting examination then becomes how the development of CEA will alter the relationship between humans and cultivation going forward. If produce can be grown anywhere, what happens to products who currently derive much of their value from the location they're grown?

Consider grapes, a crop that I could imagine transitioning towards CEA over the next 30 years. As research develops on what attributes of soil and environment contribute to the hints of blackberry and plum in an Argentine Malbec or notes of pear and guava from a French Chardonnay, those conditions could become emulatable by CEA farms anywhere in the world. In fact, many elements of terroir, including soil, climate, and altitude will become controllable parameters for a CEA farm.[36] The indoor farm could even use targeted lights to replicate the direction a vineyard faces. With a controlled system that can replicate the environment of agriculture, the remaining terroir would come solely from the actions of a winemaker. What happens when the connection between food and place is dissolved? What happens to the culture, traditions, and stories wrapped up in local food, as we understand it today?

On a related note, CEA companies often boast the fact that their produce is local, and given the proximity of agriculture to consumption is indeed close, it is locally grown. How will this alter our perception of *local food,* a concept that inherently belongs to a particular area or community? Similarly, many CEA operations meet organic certification requirements, but a process so divorced from the natural world is not what comes to mind for many when they think of 'organic.' Further, high startup costs, complexity, and economies of scale lends CEA to

[36] McIntyre, D. (2021, May 27). *How vineyard soils affect the taste of your wine*. The Washington Post. Retrieved April 24, 2022, from https://www.washingtonpost.com/food/2021/05/28/soil-effects-on-wine-taste/

developing into a very centralized space. Supporting ‘local’ and buying ‘organic’ might begin to confuse consumers who want to support the small-plot romantic *cultivation* of agriculture. Should local CEA be allowed to sell in farmers markets? What happens if the taste of hydroponics becomes *too* good? Sounds like a sweet problem to have, but it would worry me to grow too accustomed to something that relies so much on technology.

If quality produce is cheap and plentiful, will we lose respect for it? Although the abundance of goods should not affect the level of value we prescribe them, humans show time and time again that it does. This could be a contributing factor to the correlation between consumer food waste and per-capita GDP.[37,38] For thousands of years, food has carried with it an air of spirituality, one which abundance may erode.

I worry that low costs for fresh, quality produce could contribute to a disregard for waste and a further removal between humans, cultivation, and nature. With increasingly technological human involvement in the cultivation process, I fear that respect derived from a more traditional process will be lost. Perhaps there could be compelling stories told from machines, or from those farm workers who work with machines, but my lack of familiarity with such stories makes me think otherwise.

That said, I’m not sure how far we have to fall in this respect. I imagine a relatively small portion of America is exposed to the firsthand stories of industrial farmers, and I don’t foresee CEA replacing subsistence or small-plot boutique farming.

Will the mechanization of cultivation further remove humans from nature? Although most consumers are entirely removed from the agriculture behind the food they consume, there’s

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[37] Barrera, E. L., & Hertel, T. (2020, March 13). *Global food waste across the income spectrum: Implications for food prices, production and resource use*. Food Policy. Retrieved April 24, 2022, from https://www.sciencedirect.com/science/article/pii/S0306919220300762

[38] Xue, L. (n.d.). *Correlation between per-capita GDP and per-capita consumer food waste*. Retrieved April 24, 2022, from https://researchgate.net/figure/Correlation-between-per-capita-GDP-and-per-capita-consumer-food-waste-a-households-R_fig6_316864687

something unsettling about the idea of robot-filled towers churning out produce. Unsettling as it may be, AI already plays a massive role in agriculture and I doubt that the end consumer, already entirely removed from the process, would notice the final severing of human interaction with the produce—rather that their produce has gotten a bit cheaper and fresher.

For the farmers of our society, however, I worry about the transition from traditional outdoor agriculture, however removed it may already be from society and from yeoman ideals, to an industry dominated by tech. Darin Kelly, a farmer from Indiana transitioned some of his operations to hydroponic agriculture with the goals of growing year-round, remarked about the growing method: “hydroponics is technical, and not simple. You’ve got to worry about plumbing, slope, pressure, and measuring nutrients. You become a plumber, you become an electrician.”[39]

As farms become increasingly technical, farming teams will increasingly be made up of data scientists, software engineers, and designers. This ‘white colorization’ of farming will likely bring about a variety of subtle shifts, many of which lend themselves to human alienation from the natural world.

AI systems and machine learning models rely on ‘flattened’ data, created by converting what is observable by humans into numbers that machines can work with. A 2021 article titled *Managing the risks of artificial intelligence in agriculture* summarized my concerns with this eloquently: “The world is not data and plants and animals are not machines. Coming to treat the natural world as a data system to be analyzed and manipulated may be bad for us, intellectually and spiritually, and also bad for the world.”[40]

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[39] Hughes, A. J. (n.d.). *Experts: Hydroponic growing offers advantages, but won't replace soil*. Seedstock. Retrieved April 24, 2022, from http://seedstock.com/2016/03/15/experts-hydroponic-growing-offers-advantages-but-wont-replace-soil/
[40] Sparrow, R. (n.d.). *Managing the risks of Artificial Intelligence in agriculture*. Taylor & Francis. Retrieved April 24, 2022, from https://www.tandfonline.com/doi/full/10.1080/27685241.2021.2008777

**The Yeoman Strikes Back**

That isn't to say our relationship with nature is doomed; many large-scale hydroponics farms are putting roots down around urban centers, and those farms are working to become community hubs with tours and tastings of produce and by-products created entirely on site. Over the past several decades, urban hubs have developed in the absence of agriculture and I believe the reuniting of the two could provide cities a much needed reconnection with nature, however artificial.

Outside the industrial scale, hydroponics startups such as Click and Grow and Smallhold are bringing agriculture into restaurants, home kitchens, and grocery stores. Such spaces have developed into independent stops along food's journey from farm to table, and I believe people will embrace the reappearance of agriculture adjacent to the preparation and consumption of food. These types of small scale CEA and hydroponic towers have found patrons from organizations including the Chicago O'Hare International Airport and Wholefoods. Whether these small systems prove to become a new household staple or merely a fad will depend on their ability to introduce real value to the lives of their customers. It's unlikely that these smaller farms will be able to out-price larger, more technologically advanced farms but perhaps they will find success in reconnecting the coming generations with agriculture.

*Hydroponic towers in Chicago O'Hare International Airport*[41]


*Smallhold farm in Whole Foods supermarket in New Jersey*[42]

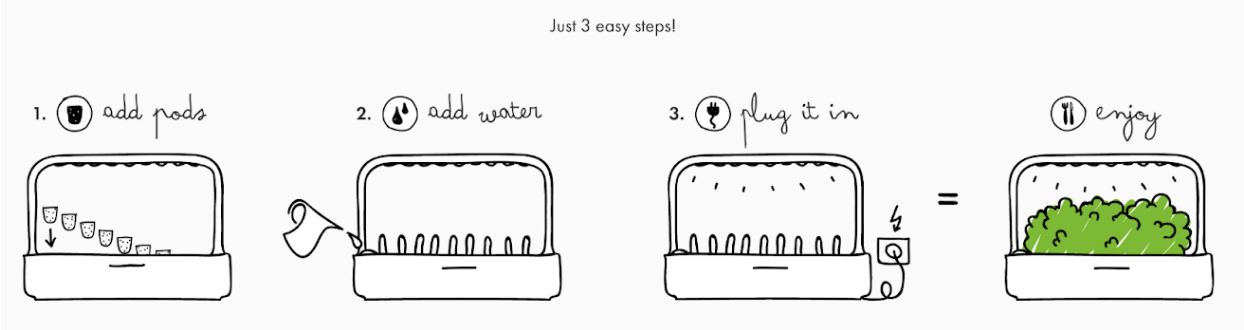
I see potential in a HelloFresh type subscription model, where consumers receive seeds every week or so to plant with a recipe for a meal three weeks down the line. The customer

[41] *O'hare Airport Urban Garden - indoor farming with Tower Farms*. Tower Farms. (n.d.). Retrieved April 24, 2022, from https://www.towerfarms.com/us/en/possibilities/indoor-farming/chicago-ohare-airport

[42] Dawson, G. (2018, March 26). *New Whole Foods cultivates mini mushroom farm in produce section*. Supermarket News. Retrieved April 24, 2022, from https://www.supermarketnews.com/produce-floral/new-whole-foods-cultivates-mini-mushroom-farm-produce-section

could either pick up the necessary ingredients or opt in for the company to ship them around harvest time. Either way, consumers are afforded the pleasure of planting their crops, watching them grow, and enjoying them in a fresh meal. Properly done, I can see a model like this capitalizing on the same pride felt after cooking a HelloFresh meal: the company provides almost everything and chooses produce that's easy enough to grow correctly but hard enough to give you the feeling that you played a part in the cultivation and success of the meal. Finding the level of involvement that makes people feel like self-sufficient farmers is imperative, and I believe that feeling like a farmer would translate into a society with more empathy and care for our environment.

Businesses endeavors like this could help make small CEA products a kitchen staple. Companies like Click and Grow present a potential paradigm shift of what makes up a kitchen, bringing fresh produce into every home.




*How the Click and Grow system works, as per their website*[43]

What would this mean for Thomas Jefferson's agrarian hopes? I imagine he envisioned a bit more toil in the process, but perhaps a system like this would be a step in the right direction. Do those philosophies rely on self-sustainability or rather the toil and labor? What aspect of cultivation creates the connection with nature? Is that the goal? I struggle to see a society in which we all return to the yeoman ways, but I can imagine a CEA farm in every kitchen.

[43] *Indoor Herb Gardens and indoor gardening kits*. Click & Grow. (n.d.). Retrieved April 24, 2022, from https://www.clickandgrow.com/

If organic small plot farming is the means by which to understand the yeomen philosophies of honesty, virtue, hard work, and independence through agriculture, perhaps CEA can serve as a metaphorical religion to fast-track those learnings to the general populace.

The winds of innovation are blowing in favor of controlled environment agriculture, and I am inclined to believe the innovation won't stop at lettuce and tomatoes. The current burden on outdoor agriculture is too water dependent, inefficient with land use, and destructive to our soil. Capitalism isn't known to pay much respect to negative externalities, but as research and innovation drives down the costs of CEA and access to arable land and water continues to slim, the financial benefits of producing with CEA will overtake more and more traditionally grown crops.

CEA exists independent of our environment, liberating the resources of croplands, water, and human time for whatever else we choose to do. I have concerns given humanity's track record of increasing waste with affluence, as well as our digitization of nature, but I'm excited at the opportunity for CEA and hydroponics to rekindle a relationship between our society and agriculture.