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Farming up the city: the rise of urban vertical farms

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The invention of agriculture dates back some 10 000 years and arose spontaneously at multiple sites throughout the world (Mexico, China, The Middle East, and Borneo). It rapidly spread to almost every culture, offering a better life to those who embraced it. The human population was estimated then to be around 1 million. Farming in all its forms increased over the next millennia by leaps and bounds, eventually changing forever the face of the Earth. Yet, for thousands of years, right up to modern times, agriculture was essentially practiced in the same way as the original farmers derived it: dig a hole, plant a seed, fertilize it, irrigate it, pick out the weeds, harvest the crop, ship/store/sell it. Granted, the advent of advanced irrigation systems, modern fertilizers, pesticides, herbicides, and a plethora of domesticated edible plants has significantly advanced this ancient practice in terms of annual yields of most crops, and removed food as a limiting factor for the growth of the human population. As a direct result of this single activity, we now number some 7 billion individuals; most of whom reside in densely settled regions (i.e., cities and their suburbs). In an effort to provide enough food for everyone, the global agricultural community currently farms a landmass larger in square kilometers than the continent of South America [1]. This estimate does not include land used for grazing domestic animals.

In the 1930s, Dr. William Gericke and colleagues, working at University of California, Davis, perfected hydroponics [2]; an alternative strategy to farming, in which plants are grown in the absence of soil. Instead, the plant roots are exposed to an aqueous solution that contains all of the essential nutrients. That work is credited with catalyzing the current boom in hydroponic [3] and aeroponic growing systems [4] that are currently in use by countless high-tech greenhouse operations throughout the world. Indoor farming in all its forms is now simply referred to as controlled environment agriculture (CEA). In the past 5 years, with the advent of spectrum-specific, higher efficiency light-emitting diode (LED) grow lights, together with computer-assisted control systems for monitoring and delivering precise amounts of nutrients, adjusting the pH, temperature, and oxygen content of the nutrient solution, and for assessing the growth and overall health of each crop, CEA has rapidly evolved into a commercially viable approach for the large-scale production of a wide variety of crops in close proximity to, or even within, urban centers (Table 1).

Indoor farming offers many advantages over traditional soil-based agriculture [5]; the most important one being total control of conditions necessary to achieve optimal survival, growth, and maturation of any given crop, thereby ensuring maximum yield per square foot of growing space. A wide variety of vegetables and fruits, as well as some species of fish, domestic fowl, and crustaceans, thrive under near ideal conditions employing CEA technologies [2–4]. In some extreme cases, such as hydroponically grown leafy greens (lettuce, spinach, kale, and basil), as many as eight crops per year are typically harvested, compared with just three from most outdoor farms [6]. For strawberries, the yield can be as great as 30 times more per acre compared to outdoor farms (personal communication).

From an environmental perspective, growing food indoors creates an opportunity for returning farmland to its original ecological function. In many instances, abandoned agricultural land results in the regrowth of hardwood forest [7]. Hence, in my opinion, the widespread application of CEA within urban centers could eventually have a significant positive effect on lowering the rate of climate change [8]. In addition, CEA has many other advantages over traditional farming: it produces no agricultural runoff; it allows year round crop production; it uses far less water (70–80%); CEA is not affected by most commonly occurring severe weather events (e.g., floods and droughts; tornadoes and massively powerful hurricanes excepted); and most importantly, it can be established anywhere in the world, because it does not rely on soil for producing food crops [2].

Outdoor farming is subjected to various levels of attack from a wide variety of microbes (viruses and bacteria) and plant pests (e.g., locusts), often resulting in significant loss of many types of annual harvest [9]. Well-engineered indoor growing facilities can minimize or even eliminate the possibility of such losses, and without the use of toxic pesticides. This can be accomplished by using proper barrier designs, in much the same way as hospitals use positive pressure systems to isolate and protect vulnerable patient populations. Should a breakdown in security occur, for whatever reason, the indoor farmer can sanitize the facility and replant within days to weeks after the incident, whereas the outdoor framer must usually wait until the following year before starting a new crop.

Another obvious advantage of CEA relates to the common use of human feces as a fertilizer in many parts of the world that cannot afford commercial products. As a result, in those places, the spread of numerous viral, bacterial, and eukaryotic infectious agents are commonplace, severely compromising the health of nearly 2 billion people [10]. Hydroponics and aeroponics use nutrient solutions that do not contain any metabolic byproducts from human metabolism, thereby avoiding altogether the problem of fecal contamination of food sources by design. If easy-to-implement indoor farming systems can eventually be made available to those most in need (i.e., all less developed countries),

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Table 1. Existing vertical farms

Location	Owner	Details	Location type	URL
South Korea	Rural Development Authority	Three stories tall Experimental Uses grow lights	Rural	NA
Japan	Plant factories (numerous – 50+) Nuvege	Half use sunlight and the others use grow lights (Nuvege). Many are commercially successful.	Peri-domestic	www.nuvege.com
Singapore	Sky Greens	Commercial Four stories tall Uses sunlight	Inside the city limits	www.skygreens.com
Chicago	The Plant	Three stories NGO Uses grow lights	Inside the city limits	www.theplant
Chicago	Farmed Here	Commercial Uses grow lights	Inside the city limits	www.farmedhere.com
Vancouver	Alterrus	Uses sunlight Four stories tall	Inside the city limits	www.alterrus.com

NGO, non-governmental organization.

then we would be closer to raising the health status of literally billions of people to that of those living more privileged lives in the developed world by permanently interrupting the transmission cycles of many important human pathogens.

There is one major downside to the high-tech greenhouse industry, because most large greenhouse operations are typically located hundreds to thousands of miles away from most urban centers (www.eurofreshfarms.com). That is because land is invariably cheaper the further away from the city one goes. This forces most commercial growers to harvest before their crops are fully ripened, particularly regarding delicate to handle crops such as tomatoes and strawberries. This is seen by the industry as an absolute necessity, however, allowing them to ship their produce over long distances with minimal damage from handling and packaging. Moving the greenhouse closer to where most people live (i.e., cities), would of course reduce or even eliminate this drawback, and would establish the option for buying on-demand, ultra-fresh (i.e., hours old), locally grown, pathogen-free food. Thus, the final step in the evolution of urban agriculture is to stack high-tech greenhouses on top of one another, creating vertical farms, thereby reducing greatly the architectural footprint of CEA, allowing them to locate within the city proper.

Job creation is an anticipated advantage of establishing vertical farms within cities. A wide spectrum of job descriptions describe the work force in a typical large indoor growing facility: management of the nursery (seed germination); transplanting seedlings into the vertical farm; resource procurement and management (i.e., water, nutrients, growing systems, lighting systems, and automation); monitoring plant growth and development; pollination strategies; harvesting; distribution of harvest to local greengrocers; waste-to-energy management; quality control (DNA-based laboratory surveillance for plant pathogens and arthropod pest control); IT personnel; human resource management; and business office personnel. These are some but not all of the more important tasks awaiting a new work force in the emerging vertical farm industry. Community outreach, education, and a business center could also be considered after the basic operations of the vertical farm complex become established.

Although vertical farming has been advocated for some time (beginning in 1999) by a few spokespersons, up until 3 years ago, there were no examples to be found anywhere in the world. During the interim, however, a handful of vertical farms, many of them commercially viable, have been established (Table 1). Nonetheless, the concept of farming within the city inside high-tech vertical greenhouses is still too new to conclude that these technology-driven agricultural initiatives will be successful on a worldwide scale, either from an economic and/or social perspective. Furthermore, even if they should become commonplace as part of the normal built environment, their impact on ecological processes will take many years to manifest itself in terms of global climate change.

In conclusion, the number of technological options available for reducing our agricultural impact on the land and the oceans, while at the same time sustaining a growing human population is very limited. In my view, vertical farming represents one of the few new opportunities that we should fully explore over the next 10–20 years, especially if we are serious about living our lives in balance with the rest of the life forms on Earth without further endangering both theirs, and ultimately ours.

References

1 Ramankutty, N. *et al.* (2008) Farming the planet: geographic distribution of global agricultural lands in the year 2000. *Global Biogeochem. Cycles* http://dx.doi.org/10.1029/2007GB002952 GB1003

2 Gericke, W. (2010) *The Complete Guide To Soilless Gardening*. Kessinger Legacy Reprints (Originally printed in 1940)

3 Resh, H.M. (2012) *Hydroponic Food Production*. CRC Press p. 513

4 Peterson, C. (2012) *Advanced Aeroponics*. Kindle Edition

5 Despommier, D. (2010) *The Vertical Farm*. Martin's Press

6 Wheeler, R.M. *et al.* (1996) Proximate composition of CELSS crops grown in NASA's biomass production chamber. *Adv. Space Res.* 18, 43–47

7 Tak, K. *et al.* (2007) The South Korean forest dilemma. *Int. Forest. Rev.* 9, 548–557

8 Bonan, G. (2008) Forests and climate change: forcing, feedbacks, and the climate benefits of forests. *Science* 320, 1444–1449

9 Showler, A.T. (1995) Locust (Orthoptera: Acrididae) outbreak in Africa and Asia, 1992-1994: an overview. *Am. Entomol.* 41, 179–185

10 Cuest, J. (2013) A world free of poverty... but hunger and malnutrition? *Eur. J. Dev. Res.* 25, 1–4

http://dx.doi.org/10.1016/j.tibtech.2013.03.008 Trends in Biotechnology xx (2013) 1–2