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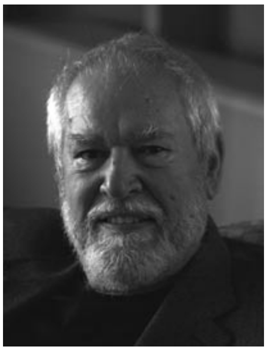

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Abstract
The human population has reached some 6.4 billion individuals. Over 800 million hectares (i.e., nearly 38% of the total landmass of the earth) is committed to producing crops to support this still growing population. Farming has dramatically transformed the landscape, replacing and redefining functional ecosystems. Undeniably, a reliable food supply has allowed for the evolution of culturally robust societies. Ironically, farming has created a set of new hazards unique to activities involved with the production of food, and has exacerbated many older ones. Exposure to toxic levels of agrochemicals (pesticides, fungicides) and a wide spectrum of geohelminths are transmitted with regularity at the tropical and sub-tropical agricultural interface. Emerging infections, many of which are viral zoonoses (e.g., Ebola, Lassa fever) have adapted to the human host following our encroachment into their environments. In 50 years, the human population is expected to increase to some 8.3 billion individuals. Feeding these new arrivals will require an additional 109 hectares of farmland; land that does not exist. Vertical, urban farming in tall buildings involves fully sustainable energy use and creation in a new and literal organic relationship between engineering, architecture, technology, and global agricultural imperatives in local based community solutions.

Keywords: urban farming, tall buildings, sustainable energy use and creation

Introduction

Figure 1: hypothetical vertical farm : Images courtesy Gordon Graff

As of January 2006, approximately 800 million hectares of arable land were in use, allowing for the harvesting of an ample food supply for the majority of a human population now in excess of 6.4 billion. These estimates include grazing lands (formerly grasslands) for cattle, representing nearly 85% of all land that could support a minimum level of agriculture. Farming also produces a wide variety of grains that feed millions of head of cattle and other domesticated farm animals. According the US Department of Agriculture, in 2003 nearly 33 million head of cattle were produced in the United States. In order to support this large a scale of agricultural activity, millions of hectares of hardwood and coniferous forest (temperate and tropical), grasslands, and wetlands were sacrificed, or at the very least severely reduced to fragmented remnants of their former ranges. In either case, significant loss of biodiversity and disruption of ecosystem functions on a global scale has been the result (Wilson, 1992).

While no one questions the value of farming in getting us to this point in our evolutionary history, even our earliest efforts caused irreversible damage to the natural landscape, and are so wide-spread now that it threatens to alter the rest of the course of our life on this planet. The silt-laden soils of the floodplains of the Tigris and Euphrates River valleys serve as a good example in this regard. This region was the cradle of western civilization attributable solely to the early invention of food growing technologies (mostly wheat cultivation). The land was soon degraded below a minimum level of food production due to erosion caused by intensive, primitive farming practices that rapidly depleted the earth of its scant supply of nutrients, while mis-managed irrigation projects were often interrupted by wars and out-of-season flooding events. Traditional farming practices (i.e., non-high tech) continue to this day to produce massive loss of topsoil, while excluding the possibility for long-term carbon sequestration in the form of trees and other permanent woody plants (Williams, 2003).

According to the IFA (International Fertilizer Industry Association), Agrochemicals, especially fertilizers, are used in almost every commercial farming scheme due to the demand for cash crops that require more nutrients from the substrate that it can provide. Fertilizer use is expensive and encourages the growth of weeds, making herbicide use almost a requirement. In commercial ventures, farming involves the production of single crop species, most of which are vulnerable to attack from a wide variety of microbes and arthropods (Carson, 1962; Zupan, 2003)). The agrochemical industries have, over just a short period of time (50+yrs), responded to these biological pressures, producing an astounding array of chemical deterrents that have, up to very recently, been able to control these unwanted guests attempting to sit at our table. The regular application of pesticides and herbicides has facilitated an ever-increasing agricultural bounty, but many arthropod and plant species have developed at least some level of resistance to both classes of compounds. As the result, higher and higher doses of these products are needed to do the same job as the year before, thus making agricultural runoff the single most damaging source of pollution. In the majority of intensive farming settings following even mild rain events, a toxic mix of agrochemicals leaves the fields and contaminates surrounding ecotones with predictable regularity. The ecological consequences of runoff have been nothing short of devastating. Furthermore, human health risks are also associated with high exposures to some agrochemicals (Molyneux, 2003). However, many chemicals manifest their toxic effects in the human body in ways far more subtle than, say for instance DDT and the thinning of birds of prey egg-shells, making them difficult to implicate in the disease process (Stromquist, Burmeister, 2003).

Farming itself is an activity fraught with health risks. The mechanisms of transmission for numerous agents of disease (e.g., the schistosomes, malaria, some forms of leishmaniasis, geohelminths) are linked to a wide variety of traditional agricultural practices (e.g., using human feces as fertilizer, irrigation, plowing, sowing, harvesting). These illnesses take a huge toll on human health, disabling large populations, thus removing them from the flow of commerce, and this is especially the case in the poorest countries. In fact, they are often the root cause of their impoverished situation. Trauma injuries are considered a normal consequence of farming by most who engage in this activity and are particularly common among "slash and burn" subsistence farmers. It is reasonable to expect that as the human population continues to grow, these problems will worsen at ever increasing rates.

To address these problems and those perceived to soon emerge onto the horizon, an alternate way of food production was proposed; namely growing large amounts of produce within the confines of high-rise buildings. This idea appeared to offer a practical, new approach to preventing further encroachment into the already highly altered natural landscape. The Vertical Farm Project was established in 2001, and is an on-going activity at the Mailman School of Public Health at Columbia University in New York City [figure 1-5]. It is in its virtual stages of development, having survived 4 years of critical thinking in the classroom and worldwide exposure on the internet to become an accepted notion worthy of consideration at some practical level. We have identified an extensive list of reasons why vertical farming may represent a viable solution to global processes as diverse as hunger, population growth, and restoration of ecological functions and services (e.g., returning land to natural process, carbon sequestration, etc.). If vertical farming (VF) were to become widely adopted, then the following advantages would most likely be realized:

1. Year-round crop production; 1 indoor acre is equivalent to 4-6 outdoor acres or more, depending upon the crop (e.g., strawberries: 1 indoor acre = 30 outdoor acres).
2. VF holds the promise of no crop failures due to droughts, floods, pests, etc..
3. All VF food will be grown organically employing chemically defined diets specific to each plant and animal species: no herbicides, pesticides, or fertilizers.
4. VF eliminates agricultural runoff.
5. VF would allow farmland to be returned to the natural landscape, thus restoring ecosystem functions (e.g., increases biodiversity) and services (e.g., air purification).
6. VF would greatly reduce the incidence of many infectious diseases that are acquired at the agricultural interface by avoiding use of human feces as fertilizer for edible crops.
7. VF converts black and gray water into potable water by engineering the collection of the water realized through evapotranspiration.
8. VF adds energy back to the grid via methane generation from composting non-edible parts of plants and animals.
9. VF dramatically reduces fossil fuel use (no tractors, plows, shipping.).
10. VF eliminates much of the need for storage and

preservation, thus reducing dramatically the population of vermin (rats, mice, etc.) that feed on reserves of food.

11. VF converts abandoned urban properties into food production centers.

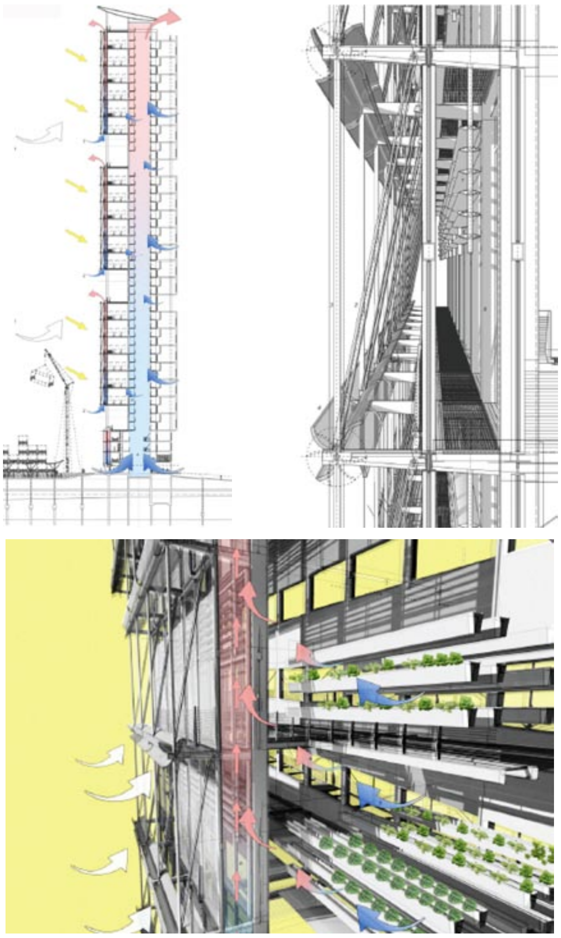
12. VF creates sustainable environments for urban centers.

13. VF creates new employment opportunities.

14. VF could provide year round production of medically valuable plants (e.g., the anti-malarial plant-derived artemesinin).

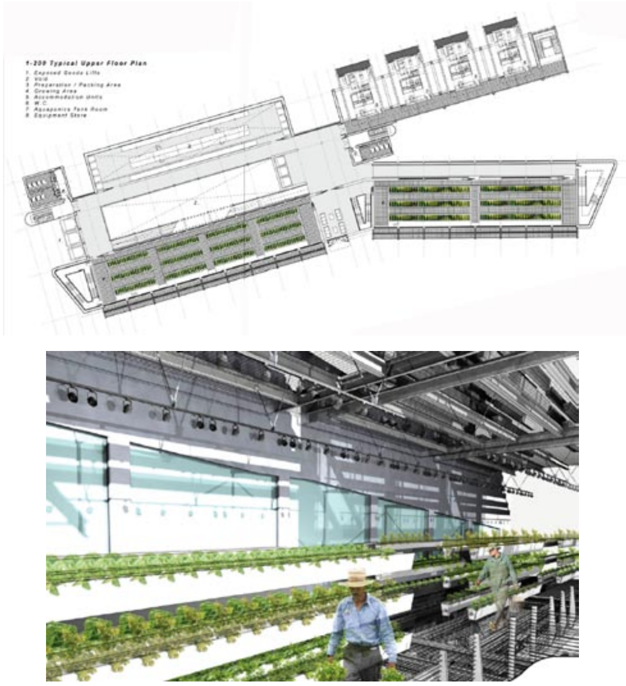
15. VF could be used for the large-scale production of sugar (sucrose) to be used in the revolutionary new method for the production of non-polluting gasoline.

Defining the vertical farm



Figures 2-4: hypothetical vertical farm : images courtesy Waimond Ip

Indoor farming (e.g., hydroponics and aeroponics) has existed for some time. Strawberries, tomatoes, peppers, cucumbers, herbs, and spices grown in this fashion have made their way to the world's markets in quantity over the last 5-10 years. Most of these operations are small when compared to factory farms, but unlike their outdoor counterparts, they produce crops year-round. Japan, Scandinavia, New Zealand, the United States, and Canada have thriving greenhouse industries. Freshwater fishes (e.g., tilapia, trout, stripped bass, carp), and a wide variety of crustaceans and mollusks (e.g., shrimp, crayfish, mussels) have also been commercialized in this way. Fowl and pigs are well within the capabilities of indoor farming, and if we were to proceed to do so, offers some interesting advantages in addition to providing the world with a convenient food supply. For example, if chickens and ducks were to be raised entirely indoors, then the current epidemic of avian influenza might well have been aborted, or at the very least, significantly reduced in scope. None have been configured as multi-story entities. In contrast, cattle, horses, sheep, goats, and other large farm animals seem to fall well outside the paradigm of urban agriculture.



Figures 5-6: hypothetical vertical farm : images courtesy Waimond Ip

What is proposed here differs radically from what currently exists; namely to scale up the scope of operations, in which a wide variety of produce is harvested in quantity enough to sustain even the largest of cities without significantly relying on resources beyond the urban footprint. Our group has determined that a single vertical farm with an architectural footprint of one square New York City block and rising just 30 stories (approximately 3 million square feet) could provide enough calories (2,000 cal/day/person) to comfortably accommodate the needs of 50,000 people, and mainly by employing technologies currently available. Constructing the ideal vertical farm with a far greater yield per square foot will require additional research in many areas – hydrobiology, material sciences, structural and mechanical engineering, industrial microbiology, plant and animal genetics, architecture and design, public health, waste management, physics, and urban planning, to name but a few.

Yet, despite the obvious enthusiasm for the idea, there are cautions to consider. High-rise food-producing buildings will only succeed if they function by mimicking ecological process; namely by safely and efficiently re-cycling everything organic, and re-cycling "used" water (e.g., human and animal waste), turning it back into drinking water. Most important, there must be strong, government-supported economic incentives to the private sector, as well as to universities and local government to fully develop the concept. Ideally, vertical farms must be cheap to construct, durable and safe to operate, and independent of economic subsides and outside support (i.e., show a profit at the end of the day). If these conditions can be realized through an ongoing, comprehensive research program, urban agriculture could provide an abundant and varied food supply for the 60% of the people that will be living within cities by the year 2030.

Waste management and urban sustainability

Today, we face the challenge of trying to understand enough about the process of ecological balance to incorporate it into our daily lives (i.e., do no harm). Our willingness to try to solve problems that we ourselves have created is a measure of our selflessness and altruistic behavior as a species. Thus, the second most important reason to consider converting to vertical farming relates to how we handle waste (Malkow, 2004; Eckenfelder, 1999). Waste management throughout the world, regardless of location, is in most cases unacceptable, both from a public health and social perspective, and exposure to untreated effluent often carries with it serious health risks. However, even in the best of situations, most solid waste collections are simply compacted and relegated to landfills, or in a few instances, incinerated to generate energy. Liquid wastes are processed (digested, then de-sludged), then treated with a bactericidal agent (e.g., chlorine) and released into the nearest convenient body of water. More often in less developed countries, it is discarded without treatment, greatly increasing the health risks associated with infectious disease transmission due to fecal contamination.

All solid waste can be re-cycled (returnable cans, bottles, cardboard packages, etc.) and/or used in energy generating schemes with technologies that are currently in use. A major source of organic waste comes from the restaurant industry (Wie, 2003). Methane generation from this single resource could contribute significantly to energy generation, and may be able to supply enough to run vertical farms without the use of electricity from the grid. For example, in New York City there are more than 21,000 food service establishments, all of which produce significant quantities of organic waste, and they have to pay to have the city cart it off. Often the garbage sits out on the curb, sometimes for hours to days, prior to collection. This allows time for vermin (e.g., cockroaches, rats, mice) the privilege of dining out at some of the finest restaurants in the western hemisphere, albeit second-hand. Vertical farming may well result in a situation in which restaurants would be paid (according to the caloric content?) for this valuable commodity, allowing for a greater measure of income for an industry with a notoriously small (2-5%) profit margin (Mann, 1999). In New York City, on average 80-90 restaurants close down each year, the vast majority of which are precipitated by inspections conducted by the New York City Department of Health. A common finding by inspectors in these situations is vermin (mouse and rat droppings, cockroaches) and unsanitary conditions that encourage their life styles.

Agricultural runoff despoils vast amounts of surface and groundwater (Foster, 2003; Holt, 2000). Vertical farming offers the possibility of greatly reducing the quantity of this non-point source of water pollution. In addition, it will generate methane from municipal waste currently being funneled into water pollution control facilities. The concept of sustainability will be realized through the valuing of waste as a commodity so indispensable to the operation of the farm that to discard something –any thing - would be analogous to siphoning off a gallons' worth of gasoline from the family car and setting it on fire. Natural systems function in a sustainable fashion by recycling all essential elements needed to produce the next generation of life. This way of doing business is being incorporated by NASA engineers into all future programs that focus on colonizing outer space. If we are to live in closed systems off the surface of the earth then the concept of waste becomes an outdated paradigm. Unfortunately, this goal has yet to be fully realized by NASA or by the ill-fated Biosphere 2 Project (Allen, 1997). If we are to live in a balanced extraterrestrial environment, we must somehow learn how to do it here first.

Sludge, derived from waste water treatment plants of many, but not all cities throughout the US, and treated with a patented process referred to as *advanced alkaline stabilization with subsequent accelerated drying*, is being turned into high grade topsoil and sold as such to the farming community at-large by N-Viro Corporation, Toledo, Ohio. The limiting factor in using municipal sludge for farming appears to be heavy metal contamination, mostly from copper, mercury, zinc, arsenic, and chromium (Scancar, 2000). Vertical farms will be engineered to take in black or gray water, depending upon availability, and restore it to near drinking water quality using bioremediation (Bonaventura, 1997) and other technologies yet to be perfected. Fast growing inedible plant species (e.g., cattail, duckweed, sawgrass, *Spartina spp.),* often referred to collectively as a *living machine* (Todd, 1994; Todd, Josephson, 1996) will be used to help remediate contaminated water. They will be periodically harvested for methane generation employing state-of-the-art composting methods yielding energy to help run the facility. By-products of burning methane – CO 2, heat, and water – can be added back into the atmosphere of the vertical farm to aid in fostering optimal plant growth. The resulting purified water will be used to grow edible plant species. Ultimately, any water source that emerges from the vertical farm should be drinkable, thus completely re-cycling it back into the community that brought it to the farm to begin with. Harvesting water generated from evapo-transpiration appears to have some virtue in this regard, since the entire farm will be enclosed. A cold brine pipe system could be engineered to aid in the condensation and harvesting of moisture released by plants. Nonetheless, several varieties of new technology will be needed before sewage can be handled in a routine, safe manner within the confines of the farm. Lessons learned from the nuclear power plant industry should be helpful in this regard.

Some "proofs of concept"

1. Year round crop production

Traditional farming takes place over an annual growth cycle that is wholly dependent upon what happens outside. Significant deviation (e.g., drought or flood) for more than several weeks away from conditions necessary for insuring a good yield has predictable, negative effects on the lives of millions of people dependent upon those items for their yearly food supply (Cairns, 2000). Every year, somewhere in the world, crops suffer from too little water and wither on the spot, or are lost to severe flooding, hailstorms, tornados, earthquakes, hurricanes, cyclones, fires, and other destructive events of nature. Many of these phenomena are at best difficult to predict, and at worst are impossible to react to in time to prevent the losses associated with them. Climate change regimens will surely complicate an already complex picture with respect to predicting crop yields (Tilman, 2001).

In addition to losses due to bad weather events, an unavoidable portion of what is grown spoils in the fields prior to harvest time. Another large portion of harvest, regardless of the kind of plant or grain, is laid waste by a variety of opportunistic life forms (i.e., fungi, bacteria, insects, rodents) after storage. In Africa, locusts remain an ever-present threat (Abate, 2000), devastating vast areas of farmland in just days. Finally, armed conflict halts all normal human activity in any given war zone. Faming usually suffers greatly during those stressful times, with crops being burned or otherwise made unavailable by those wishing to severely limit the opposition's access to a reliable food supply.

Vertical farming obviates all external natural processes as confounding elements in the production of food. Growing food within urban centers will lower or even eliminate the consumption of fossil fuels needed to deliver them to the consumer, and will eliminate forever the need for burning fossil fuels during the act of farming. So where does the energy come from that is needed to run the vertical farm? Ideally, they will take full advantage of technologies centered around methane digestion of the inedible portions of what is grown (i.e., biogas production). Solar, wind, and tidal power could also contribute to reducing their dependence on fossil fuels. Iceland and other geologically active regions (e.g., Italy, New Zealand) will have the distinct advantage of harnessing geothermal energy, which they have at their disposal in abundance.

2. No-cost restoration of ecosystems: the principle of benign neglect

Converting most food production to vertical farming holds the promise of restoring ecosystem services and functions. There is good reason to believe that an almost full recovery of many of the world's endangered terrestrial ecosystems will occur simply by abandoning farmland and allowing the countryside to "cure" itself (Gunderson, 2000). This belief stems, in part, from numerous anecdotal observations as to the current biological state of some regions that were once severely damaged either by now-extinct civilizations or by over-farming, and, in part, from data derived from the National Science Foundation-sponsored long-term ecological research program (LTER), begun in 1980, on a wide variety of fragmented ecosystems purposely set aside for study subsequent to an extended period of encroachment. One of the most intensively studied of these fragmented ecozones is Hubbard Brook in northern New Hampshire (Likens, 2001; Likens, 1970). The area is a mixed boreal forest watershed that has been extensively harvested at least three times in modern times (1700s-1967). The Hubbard Brook LTER lists its research objectives as: vegetation structure and production; dynamics of detritus in terrestrial and aquatic ecosystems; atmosphere-terrestrial-aquatic ecosystem linkages; heterotroph population dynamics; effects of human activities on ecosystems. A portion of the watershed was clear-cut and the trees left in place, in contrast to farming regimes in which trees are removed to make way for crop production. Re-growth of some plants (shade intolerants) occurred within 3 years. By 20 years, the trees (shade tolerant plants) grew back to the same density as before the experiment was begun. These data give credence to the hypothesis that if vertical farming could replace most horizontal farming, then ecosystem services that reinforce a healthy life style (e.g., clean water, clean air, carbon sequestration) would be restored.

3. Urban sustainability

Natural systems function in a sustainable fashion by recycling all essential elements for the next generation of life (Eugene, 2005). One of the toughest challenges facing urban planners is trying to incorporate the concept of sustainability into waste (both solid and liquid) management. Even in the best of situations, most solid waste collections are compacted and relegated to landfills. In a few rare instances they are incinerated to generate energy (Ragossnig, 2005). Liquid wastes are processed, then treated with a bactericidal agent (e.g., chlorine) and released into the nearest body of water. More often than not in less developed countries, it is discarded without treatment, greatly increasing the health risks associated with infectious disease transmission due to fecal contamination (Khosla, 2005). From a technological perspective, all solid waste can now be efficiently re-cycled (returnable cans, bottles, cardboard packages, etc.) and/or used in energy generating schemes with standard methods that are currently in use (Malkow, 2004). Incorporating modern waste management strategies into the vertical farm model should work the first time out without the need for new technologies to come to the rescue. It must be emphasized that urban sustainability will only be realized through the valuing of waste as a commodity, deemed so indispensable that to discard something –anything - would be analogous to siphoning off a gallons' worth of gasoline from the family car and setting it on fire.

Since agricultural runoff despoils vast amounts of surface and groundwater (Stalnacke, 2001; Fawell, 2003; Foster, 2003), any water that emerges from the vertical farm should be drinkable, re-cycling it back into the community that brought it to the farm to begin with. Harvesting water generated from evapo-transpiration appears to have some virtue in this regard, since the entire farm will be enclosed. A cold brine piping system could be engineered to aid in the condensation and harvesting of moisture released by plants. The only perceived missing link is the ability to easily handle untreated human and animal wastes in a safe and efficient fashion. Several varieties of new technology may be required. Perhaps lessons learned from the nuclear power industry in handling plutonium and enriched uranium may prove helpful in designing new machinery for this purpose.

4. Social benefits of vertical farming

The social benefits of urban agriculture offer a rewarding set of achievable goals. The first is the establishment of sustainability as an ethic for human behavior. This ecological concept is currently only a property of the natural world. Ecological observations and studies, beginning with those of J. Teal in Georgia (Teal, 1962) showed how life behaves with regards to the sharing of limited energy resources. Tight knit assemblages of plants and animals evolved into trophic relationships that allowed for the seamless flow of energy transfer from one level to the next, regardless of the type of ecosystem in question (Ricklefs, 2000). In fact, this is the defining characteristic of all ecosystems. In contrast, humans, although participants in all terrestrial ecosystems, have failed to incorporate this same behavior into their own lives. If vertical farming succeeds, it will establish the validity of sustainability, irrespective of location or life form. Vertical farms could become important learning centers for future generations of city-dwellers, demonstrating our intimate connectedness to the rest of the world by mimicking the nutrient cycles that once again can take place in the natural world that has re-emerged around them as the result of returning land back to the natural landscape.

Finally, hydroponic and aeroponic technology has increased yield potential by more than 23 times while decreasing water usage by well over 30 times; LED's (Light Emitting Diodes, the kinds used in many traffic lights) and sulfer-mircrowave lamps are being employed as alternative light sources in agricultural environments which grow and harvest within 'biomass production systems' and 'plant research units' by the Bioregenerative Life Support Project at Dynamac, Inc., at the Kennedy Space Center. These are constantly regulated, environmentally maintained, and hermetically controlled completely sustainable agricultural solutions which we have at our disposal today. Nourishing Vertical Farms right within the intolerably impoverished regions of the worlds largest urban settings, such as Ethiopia, India, Central African Republic, the Gaza Strip, etc. is not only realistic, it's practical. Taking these ideas from outer space and deploying these strategies in the space of our cities is not only rationally feasible it may be one of the best vehicles we have to take on agricultural challenge of the near and now future.

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