Rationale for Vertical Farms

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The advent of agriculture has ushered in an unprecedented increase in the human population and their domesticated animals. Farming catalyzed our transformation from primitive hunter-gatherers to sophisticated urban dwellers in just 10,000 years. Today, over 800 million hectares is committed to soil-based agriculture, or about 38% of the total landmass of the earth. It has re-arranged the landscape in favor of cultivated fields at the expense of natural ecosystems, reducing most natural areas to fragmented, semi-functional units, while completely eliminating many others. A reliable food supply was the result. This singular invention has facilitated our growth as a species to the point now of world domination over the natural world from which we evolved. Despite the obvious advantage of not having to hunt or scavenge for our next meal, farming has led to new health hazards by creating ecotones between the natural world and our cultivated fields. As the result, transmission rates of numerous infectious disease agents have dramatically increased- influenza, rabies, yellow fever, dengue fever, malaria, trypanosomiasis, hookworm, schistosomiasis – and today these agents emerge and re-emerge with devastating regularity at the tropical and sub-tropical agricultural interface. Modern agriculture employs a multitude of chemical products, and exposure to toxic levels of some classes of agrochemicals (pesticides, fungicides) have created other significant health risks that are only now being sorted out by epidemiologists and toxicologists. As if that were no enough to be concerned about, it is predicted that over the next 50 years, the human population is expected to rise to at least 8.6 billion, requiring an additional 10^9 hectares to feed them using current technologies, or roughly the size of Brazil. That quantity of additional arable land is simply not available. Without an alternative strategy for dealing with just this one problem, social chaos will surely replace orderly behavior in most over-crowded countries. Novel ways for obtaining an abundant and varied food supply without encroachment into the few remaining functional ecosystems must be seriously entertained. One solution involves the construction of urban food production centers – vertical farms – in which our food would be continuously grown inside of tall buildings within the built environment. If we could engineer this approach to food production, then no crops would ever fail due to severe weather events (floods, droughts, hurricanes, etc.). Produce would be available to city dwellers without the need to transport it thousands of miles from rural farms to city markets. Spoilage would be greatly reduced, since crops would be sold and consumed within moments after harvesting. If vertical farming in urban centers becomes the norm, then one anticipated long-term benefit would be the gradual repair of many of the world's damaged ecosystems through the systematic abandonment of farmland. In temperate and tropical zones, the re-growth of hardwood forests could play a significant role in carbon sequestration and may help reverse current trends in global climate change. Other benefits of vertical farming include the creation of a sustainable urban environment that encourages good health for all who choose to live there; new employment opportunities, fewer abandoned lots and buildings, cleaner air, safe use of municipal liquid waste, and an abundant supply of safe drinking water.

Introduction

As of 2004, approximately 800 million hectares of land were in use for food production – approximating an area equivalent to Brazil (1), and allowing for the harvesting of an ample food supply for the majority of a human population approaching 6.3 billion. These land-use estimates include grazing lands (formerly grasslands) for cattle, and represents nearly 85% of all land that can support at least a minimum level of agricultural activity. In addition, farming produces a wide variety of feed grains for many millions of head of cattle and other species of domesticated farm animal (2). In 2003, nearly 33 million head of cattle were produced in the United States, alone (3) In order to support this large a scale of agricultural activity, millions of hectares of hardwood forest (temperate and tropical), grasslands, wetlands, estuaries, and to a lesser extent coral reefs have been either eliminated or severely damaged with significant loss of biodiversity and wide-spread disruption of ecosystem functions.

The advantages of farming are obvious enough from a human perspective, but even our earliest efforts caused irreversible damage to the land. For example, some 8,000 to 10,000 years ago, the fertile, silt-laden soils of the floodplains of the Tigris and Euphrates River valleys were rapidly degraded below minimum food production limits due to erosion caused by intensive farming and mis-managed irrigation projects that were often interrupted by wars and out-of-season flooding events (4). Today, primitive farming practices continue to produce massive loss of topsoil (5, 6), while excluding the possibility for long-term carbon sequestration in the form of trees and other permanent woods plants (7). Agrochemicals, particularly fertilizers, are used in almost every major farming system regardless of location (8), largely due to the demand, year in and year out, for cash crops that extract more nutrients from the substrate that it can provide. Mono-crops are extraordinarily vulnerable to a wide range of insect pests and microbial disease agents due to the very nature of farming (i.e., growing large numbers of a given plant species in a confined area). To mount a counter-offensive, we have invented pesticides and herbicides. Their use has become routine in many situations, particularly in factory farms. Agricultural runoff, which typically contains all of the above-mentioned classes of chemicals, and is also often laden with unhealthy levels of heavy metals, as well, is generally acknowledged as the most pervasive and destructive form of water pollution, degrading virtually every freshwater aquatic environment that borders on human habitation (9, 10).

Many of the earth's most impacted regions (i.e., those with the highest population densities) are generally conceded to be unhealthy places to live (western Europe and North America excepted), with infant morbidity/mortality rates many times greater than those found in Europe and North America (11). These are the same places from which new kinds of emerging and known varieties of re-emerging infections are found (12). Many of them are zoonotic and their life cycles would not normally include humans were it not for encroachment, an activity driven by the need to expand farming into the natural landscape (13). Nonetheless, there is at present a wide variety of produce available, and in quantity (table 3), for those that can afford it. Ironically, many millions of people living predominantly throughout the tropics and sub-tropics are severely malnourished, while living within countries many of which export large amounts of agricultural products destined for the markets of the developed world.

Farming is an occupation fraught with a wide variety of health risks (14, 15, 16, 17, 18, 19, 20). Numerous infectious disease agents (e.g., schistosomes, malaria, geohelminths) take advantage of a wide variety of traditional agricultural practices (irrigation, plowing, sowing, harvesting), facilitating their transmission (Table 1) (21, 22, 23, 24, 25). These diseases take a huge toll on human health, disabling large populations, thus removing them from the flow of commerce, even in the poorest of countries. Other health risks to farmers include acute exposure to toxic agrochemicals (e.g., pesticides and fungicides) (26), bites from noxious wildlife (27), and trauma injuries (28, 29). The latter two risk categories are particularly common among "slash and burn" subsistence farmers. It is reasonable to expect that as the human population continues to grow, so do these problems.

Consensus among demographers regarding estimates of the rate at which the global human population will increase is difficult to achieve, but most agree that over the next 50 years, the number will increase to at least 9.2 billion (30). It is also conceded by some of the worlds' leading agronomists that they will require an additional 10^9 hectares of land (roughly the size of Brazil) if they are to produce enough food by conventional methods to meet their needs (31). Since there is essentially no high quality land remaining for this purpose, it seems obvious that a major crisis of global proportion may well be looming on the very near horizon. Limited resources (food, water, and shelter) are some of the major causes for civil unrest and war throughout the world.

Vertical farming practiced on a large scale in urban centers has great potential to: 1. supply enough food in a sustainable fashion to comfortably feed all of humankind for the foreseeable future; 2. allow large tracts of land to revert to the natural landscape restoring ecosystem functions and services; 3. safely and efficiently use the organic portion of human and agricultural waste to produce energy through methane generation, and at the same time significantly reduce populations of vermin (e.g., rats, cockroaches); 4. remediate black water creating a much needed new strategy for the conservation of drinking water; 5. take advantage of abandoned and unused urban spaces; 6. break the transmission cycle of agents of disease associated with a fecally-contaminated environment; 7. allow year-round food production without loss of yields due to climate change or weather-related events; 8. eliminate the need for large-scale use of pesticides and herbicides; 9. provide a major new role for agrochemical industries (i.e., designing and producing safe, chemically-defined diets for a wide variety of commercially viable plant species; 10. create an environment that encourages sustainable urban life, promoting a state of good health for all those who choose to live in cities. All of this may sound too good to be true, but careful analysis will show that these are all realistic and achievable goals, given the full development of a few new technologies.

High-rise food-producing building will succeed only if they function by mimicking ecological process, namely by safely and efficiently re-cycling everything organic, and re-cycling water from human waste disposal plants, 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 develop the concept. Ideally, vertical farms must be: a. cheap to build; b. durable and safe to operate; and c. 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 on-going, 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 (32). This migration is largely caused by the plight of the farmer. " People move to the city for various reasons, but the most significant reason is economic—when a city's economy is prospering it attracts people. The promise of jobs and comfort, glamour and glitter, "pulls" people to cities. There are also "push" factors: droughts or exploitation of farmers can cause extreme rural poverty and that "pushes" people out of the country-side" (33, 34).

What is meant by vertical farming?

Farming indoors is not a new concept, per se, as greenhouse-based agriculture has been in existence for some time. Numerous commercially viable crops (e.g., strawberries, tomatoes, peppers, cucumbers, herbs, and spices) have seen their way to the world's supermarkets in ever increasing amounts over the last 15 years. Most of these operations are small when compared to factory farms, but unlike their outdoor counterparts, these facilities can produce crops year-round. Japan, Scandinavia, New Zealand, the United States, and Canada have thriving greenhouse industries. As far as is known, none have been constructed as multi-story buildings. Other food items that have been commercialized by indoor farming include freshwater fishes (e.g., tilapia, trout, stripped bass), and a wide variety of crustaceans and mollusks (e.g., shrimp, crayfish, mussels).

What is proposed here that differs radically from what now exists is to scale up the concept of indoor farming, 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 city limits. Cattle, horses, sheep, goats, and other large farm animals seem to fall well outside the paradigm of urban farming. However, raising a wide variety of fowl and pigs are well within the capabilities of indoor farming. It has been estimated that it will require approximately 300 square feet of intensively farmed indoor space to produce enough food to support a single individual living in an extraterrestrial environment (e.g., on a space station or a colony on the moon or Mars)(35). Working within the framework of these calculations, one vertical farm with an architectural footprint of one square city block and rising up to 30 stories (approximately 3 million square feet) could provide enough nutrition (2,000 calories/day/person) to comfortably accommodate the needs of 10,000 people 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, engineering, industrial microbiology, plant and animal genetics, architecture and design, public health, waste management, physics, and urban planning, to name but a few. The vertical farm is a theoretical construct whose time has arrived, for to fail to produce them in quantity for the world at-large in the near future will surely exacerbate the race for the limited amount of remaining natural resources of an already stressed out planet, creating an intolerable social climate.

Expected benefits of vertical farming

Year-round crop production in a protected, managed environment:

The main advantages of vertical farming are summarized in Table 2. Currently, maximizing crop production takes place over an annual growth cycle that is wholly dependent upon what happens outside – climate and local weather conditions. Despite recent advances in predicting the occurrence of these natural processes by an extensive network of ground-based weather stations and remote sensing satellites (36), 2-dimensional farming remains a precarious way to make a living. Significant deviation (e.g., drought or flood) for more than several weeks 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 (37, 38). Climate change regimens (39) will surely complicate an already complex picture with respect to predicting crop yields (40, 41).

In addition, other elements conspire to take away from the harvest for which we worked so hard to produce. Despite the best application of modern agricultural practices, an unavoidable portion of what is grown rots in the fields prior to harvest time, or in the world's storage bins afterwards. Every year, depending upon geographic location and intensity of El Niño events, 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. In sub-Saharan Africa, locusts remain an ever-present threat (42), and can devastate vast areas of farmland in a matter of days. Even after a bumper crop is realized, problems associated with processing and storage lessen the actual tonnage that is available to the consumer. A large portion of the harvest, regardless of the kind of plant or grain, is despoiled or a portion consumed by a variety of opportunistic life forms (i.e., fungi, bacteria, insects, rodents) after being stored. While it is conceded that at present the abundance of cash crops is more than sufficient to meet the nutritional needs of the world's human population, delivering them to world markets is driven largely by economics, not biological need. Thus, the poorest people – some 1.1 billion – are forced to live in a constant state of starvation (43), with many thousands of deaths per year attributable to this wholly preventable predicament (44). Locating vertical farms near these human "hot spots" would greatly alleviate this problem.

Vertical farming (i.e., faming in three dimensions) promises to eliminate external natural processes as confounding elements in the production of food, since crops will be grown indoors under carefully selected and well-monitored conditions, insuring an optimal growth rate for each species of plant and animal year round. It is estimated that one acre of vertical farm could be equivalent to as many as ten to twenty traditional soil-based acres, depending upon which crop species is considered. Growing food close to home will lower significantly the amount of fossil fuels needed to deliver them to the consumer, and will eliminate forever the need for fossil fuels during the act of farming (i.e., plowing, applying fertilizer, seeding, weeding, harvesting).

Advantages of Vertical Farming

- Year-round crop production
- Eliminates agricultural runoff
- Significantly reduces use of fossil fuels (farm machines and transport of crops)
- Makes use of abandoned or unused properties
- No weather related crop failures
- Offers the possibility of sustainability for urban centers
- Converts black and gray water to drinking water
- Adds energy back to the grid via methane generation
- Creates new urban employment opportunities
- Reduces the risk of infection from agents transmitted at the agricultural interface
- Returns farmland to nature, helping to restore ecosystem functions and services
- Controls vermin by using restaurant waste for methane generation

No-cost restoration of ecosystems: the principle of "benign neglect"

Proof of concept:

The best reason to consider converting most food production to vertical farming is the promise of restoring ecosystem services and functions (45). 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 a given area of encroachment and allowing the land to "cure" itself (46). This belief stems, in part, from numerous anecdotal observations as to the current biological state of some territories that were once severely damaged either by now-extinct civilizations or over-farming, and, in part, from data derived from National Science Foundation-sponsored long-term ecological research program (LTER), begun in 1980, on a wide variety of fragmented ecosystems purposely set aside subsequent to an extended period of encroachment (47). The following case studies will serve to illustrate these points.

Deforestation of vast tracts of tropical rainforest throughout Mesoamerica took place over several thousand years (48). It is estimated that there were as many as 50 million people living in this region, with some 17 million in Mexico, alone, when the conquistadores arrived in the 1500s. Re-forestation of deserted regions previously inhabited by pre-Colombian civilizations (e.g., Mayans) began during the Spanish imperial venture and continued on after it failed. Regions that remained populated continued to suffer the ecological consequences of deforestation (ibid), but in the abandoned areas the re-growth of the rainforests in some parts of Central America was so complete that by 1950 nearly all of the major ancient cities and monuments lying between Panama and southern Mexico had been canopied under them. Today, archaeological expeditions routinely discover previously unknown settlements and the life and times of the peoples that lived there, but they are hard-won victories, accompanied by much difficulty in navigating the dense growth that protect these treasures of the past from open view. New finds are now often aided by sophisticated remote sensing technologies (49).

Along the northern border of the Brazilian jungle live the Yanomami. These people have never been conquered by European colonialists. Left to evolve on their own without interference from the outside, they have formed a series of loosely knit tribes that have developed shifting agricultural methods to live off the land, mostly by hunting bush meat and subsistence farming, without causing permanent damage to the environment in which they must live (50). Their farming methods do not include fire as a forest clearing mechanism. Instead, they cut down the trees, creating large open circles. Then they burn the trees to get enough minerals to fertilize the cleared zone. They farm the nutrient-poor soils for several years, raising sweet potatoes, plantains, sugar cane, and tobacco, and then they move on. By the time the Yanomami return to the same farming locale, some years later, the area has re-grown to its former state. Without fire as a confounding factor, the Yanomami have achieved a rare a balance with the land in which crops are produced and forestland is repaired by a natural cycle that favors the survival of both sets of life forms. Many other cultures living close to the land were not as fortunate as the Yanomami to have conceived and implemented sustainable relationships with their surroundings and have paid the ultimate price, that of extinction (51).

The “dust bowl” was created by farming in what was formerly short and tall grasslands prairie in the central Great Plains of the United States (portions of Kansas, Colorado, Oklahoma, and Texas). This represents one of the best-documented examples of how misuse of land not at all suited for traditional farming, coupled with a 100-year drought that affected nearly 2/3rds of the country, resulted in the seemingly irreversible collapse of a diverse assemblage of plants and animals adapted to that semi arid environment. Between 1889-1895, a total of 6 land rushes were sponsored by the government, at the insistence of the “Boomers”, to jump start settlement of the Oklahoma territories. They attracted thousands of hopeful immigrants from the eastern United States and Europe to that area of the west. Over the next 20 years, rainfall was above average and farming flourished. However, the next 20-30 years saw some of the worst droughts in recorded history for that region. The result was a systematic erosion of millions of tons of topsoil (52). The situation intensified from 1932-1938 with increasingly devastating results (53). During that short time, all farming ceased and thousands of families abandoned the land and headed further west, mostly to California, in search of a better life (re-John Steinbeck’s Grapes of Wrath). The weather patterns had conspired to defeat these early settlers in their quest to re-shape the landscape into productive farmland. Lesions learned, no one returned to the dust bowl region for some 15 years. During the intervening period, nurturing precipitation regimens returned, and the assemblages of wildlife long absent re-populated the region. Tall and short grasses re-built the soil enough to attract back the kit fox, antelope, prairie dog, and a wide variety of endemic birds and other support plants, reclaiming their niches and restoring the region to a mixed grasslands prairie. Seeds of native plants that had lain dormant germinated and thrived when competition with cash crop species for limited resources ceased. Following WWII, the area once again suffered ecological loss from the impacts of farming. This time that activity was supported by groundwater pumped from the Ogallala aquifer for irrigation of wheat, which requires additional water to achieve maximum yield (54). However, this initiative, too, will apparently fail soon for the same reason that the first wave of farming on the Great Plains did, namely the lack of a reliable source of freshwater. In this case, too much groundwater has already been drawn off (55, 56), lowering the water table and resulting in an economic conundrum, where the price of oil, a necessary ingredient to fuel the heavy-duty pumps needed to raise water from a greater depth than at present (currently fueled by cheaper natural gas-driven pumps), will not prove to be cost-effective with respect to the price of wheat (57). It is anticipated that when this generation of farmers abandons the land, the prairie will once again dominate the landscape.

The de-militarized zone between North and South Korea represents a small strip of land some 1,528 km2 in area and off limits to people since the end of the Korean War in 1953 (58). Farming communities once abundant there no longer till the soil. The result of abandonment has been striking, and in favor of ecological recovery (59). During the intervening years, remnant populations of wildlife have re-bounded into robust populations within that narrow region, including the Asiatic black bear, musk deer, and the red-crowned crane. An unexpected (and unwanted) example of "proof of concept", vivax malaria has also retuned to the area next to the DMZ in South Korea, as the result of that country's inability to carry out effective mosquito-control programs that would ordinarily include portions of the DMZ (60).

The above observations give hope for an almost complete recovery of abandoned land. But it is long-term ecological research projects (61, 62) (see also: National Science Foundation-Long Term Ecological Research programs – http://www.lternet.edu; LTER) that have presented the scientific community with reliable data, allowing a far greater measure of insight into the process of recovery from encroachment. Twenty-seven countries are currently engaged in some form of long-term ecological research, while 19 LTER projects are conducted within the continental United States. One of the most intensively studied is Hubbard Brook in northern New Hampshire (63, 64, 65, 66). The area is a mixed boreal forest watershed that has been 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. Originally under the directorship of Gene Likens, a portion of watershed was cut and the wood left in place (66). Weirs were installed to collect and monitor the quality of the water draining into Hubbard Brook from the tributary in the altered portion. The study revealed a remarkable resiliency of that watershed. It took only three years for the water draining the damaged area to return to its original high quality (66). This came about largely because of the seeds of species of pioneer shade-intolerant plants that lay dormant until exposed to direct sunlight. Growth was rapid, and they served as a temporary soil conservation element in that environment until the trees (shade tolerant) once again grew to displace them. Ecologists from several collaborating institutions converge on the Hubbard Brook watershed each summer to monitor a wide variety of ecological processes (for a complete list see: http://www.hubbardbrook.org/research/pubs/hbbibentire.htm). Other LTER sites within the US study grasslands, estuaries, alpine forest, wetlands, semi-arid desert, lakes, rivers, and coastal savannas. All have a similar story to tell regarding the ability of the natural landscape to return to a functional state when allowed to re-establish ecological relationships fostering the uninterrupted flow of energy from one trophic level to the next. These data give credence to the hypothesis that if vertical farming could replace most of the world's traditional food production schemes, then ecosystem services that reinforce a healthy life style (e.g., clean water, clean air) would be restored.

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 (67), and particularly that which comes from living in urban centers (68; see also: http://www.usmayors.org/uscm/mwma/). 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 (69, 70, 71). 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 (72). 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 (73). 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 (74).

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 (72). A major source of organic waste comes from the restaurant industry (75). 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 (cockroaches, rats, mice) the privilege of dining out at some of the finest restaurants in the western hemisphere; albeit second-hand (76). 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 (77). 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 (78, 79, 80, 81, 82). 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 (83). 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 (84), then the concept of waste becomes an outdated paradigm. Unfortunately, this goal has yet to be fully realized by NASA (84) or by the ill-fated Biosphere 2 Project (85, 86). 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 (87). 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 (88) 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 (89, 90) will be used to help remediate contaminated water. They will be periodically harvested for methane generation employing state-of-the-art composting methods (91), 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. Lesions learned from the nuclear power plant industry should be helpful in this regard.

Social benefits of vertical farming

Eliminating a significant percentage of land dedicated to traditional farming has obvious health advantages regarding the restoration of ecosystem services, and for the immediate improvement of biodiversity by simultaneously restoring ecosystem functions, as well. The social benefits of urban agriculture promise an equally rewarding set of achievable goals. However, since the vertical farm is still a theoretical construct, it is difficult to predict all of the potential benefits that may arise from producing food in this manner. The first is the establishment of sustainability as an ethic for human behavior (92). At present, there are no examples of a totally sustained urban community anywhere in the world. The development of this keystone ecological concept has remained identified solely with the natural world, and specifically with reference to the functioning of ecosystems. Ecological observations and studies, beginning with those of Teal (93), show how life behaves with regards to the sharing of limited energy resources (94). Tight knit assemblages of plants and animals evolve into trophic relationships that allow for the seamless flow of energy transfer from one level to the next, regardless of the type of ecosystem in question (95). 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 (urban vrs rural).

Vertical farms could become important learning centers for generations of city-dwellers, demonstrating our intimate connectedness to the rest of the world by mimicking the nutrient cycles that once again take place in the world that has re-emerged around them. Furthermore, the elimination of large, currently unmanageable amounts of waste will improve the attractiveness of the local environment and help to correct the imbalance in energy utilization by recycling organic waste through methane digestion systems. Rene Dubos wrote in So Human an Animal (96) that people tend to support the institutions that they grow up with, regardless of whether or not they foster a nurturing environment in which to live. Dubos advocated that all humans deserve to live in places that encourage healthy, useful lives, but that to do so will require massive reconstruction of the urban landscape. By transforming cities into entities that nurture the best aspects of the human experience is the goal of every city planner, and with vertical farming serving as a center-piece, this may eventually become a reality.

Providing all urban populations with a varied and plentiful harvest, tailored to the local cuisine eliminates food and water as resources that need to be won by conflict between competing populations. Starvation becomes a thing of the past, and the health of millions improves dramatically, largely due to proper nutrition and the lack of parasitic infections formerly acquired at the agricultural interface. Given the strength of resolve and insight at the political and social level, this concept has the potential to accomplish what has been viewed in the past as nearly impossible and highly impractical.

It is further anticipated that large-scale urban agriculture will be more labor-intensive than is currently practiced on the traditional farm scene, since the deployment of large farm machinery will not be an option. Hence, employment opportunities abound at many levels. Finally, the vertical farm should be a thing of architectural beauty as well as be highly functional, bringing a sense of pride to the neighborhoods in which they are built. In fact, the goal of vertical farm construction is to make them so desirable in all aspects that every neighborhood will want one for their very own.

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