J. Verbr. Lebensm. (2011) 6:233–236
DOI 10.1007/s00003-010-0654-3

Journal für Verbraucherschutz und Lebensmittelsicherheit
Journal of Consumer Protection and Food Safety

LEITTHEMA: FOOD SECURITY

The vertical farm: controlled environment agriculture carried out in tall buildings would create greater food safety and security for large urban populations

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Received: 10 September 2010 / Accepted: 26 October 2010 / Published online: 3 December 2010

Abstract Over the next 50 years, rapid climate change issues will play a major role in agriculture. It is estimated for every 1° of increase in atmospheric temperature, 10 % of the land where we now grow food crops will be lost. The ability of governments to provide essential services for its citizens, and in particular to maintain systems that provide a reliable and safe food and water supply becomes more and more problematic. In less developed countries, other problems also exist that will become magnified because of global warming. For example, diseases transmitted by fecal contamination, such as cholera, typhoid fever and a plethora of parasitic infections, are commonplace where human excrement is used as fertilizer (an estimated 50 % of all farming on the planet). These infections are in large part responsible for widespread poverty and illiteracy. Geo-helminths, alone, cripple enormous numbers of children and adults alike. Heavy infections with ascaris, hookworm and whipworm can permanently reduce a child's capacity for learning, and the diarrheal diseases they cause routinely keep them out of school. Illiteracy, malnutrition, and poverty are the result. Today, even in more developed countries where many of these kinds of infectious diseases have been either eradicated or are under control, food safety and security issues dominate the headlines. Over the last 5 years, in the United States alone, food recalls due to bacterial infectious diseases have resulted in billions of dollars of lost income. In traditional farming, a plethora of plant pathogens (e.g., rice blast, wheat rust) and insect pests (e.g., locusts) account for staggering losses of crops worldwide, further pushing the yields of most grain and vegetable crops towards lower and lower limits. Soil erosion due to floods and droughts completes the picture of climate change issues that have already significantly reduced where we can grow our food. The majority of environmental experts agree that farming as we know it will become marginalized over the next 50 years, as climate changes accelerate even more due to deforestation. This is because forests are being sacrificed for farmland. The consequence of this activity is that the carbon cycle is out of balance and will only get worse if nothing is done on a global scale. Controlled environment agriculture is one answer to reversing this situation. Greenhouse technologies are well-established and guarantee a safer, more reliable food supply that can be produced year round, and they can be located close to urban centers. By "stacking" these buildings on top of each other in an integrated well-engineered fashion, we can greatly reduce our agricultural footprint, and the vertical farm concept can then be applied to every urban center, regardless of location.

Keywords Vertical farming · Food safety · Food security

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1 Rationale for creating vertical farms in urban centers

Farming inside tall buildings within the cityscape has many advantages over conventional agriculture: year

round produce, no crops lost to weather events, no use of fossil fuels to harvest, transport and refrigerate, no use of pesticides or herbicides, multiple job opportunities for urbanites, uses far less water (70 %) than outdoor farming (Molden 2007), safer crops without risk from human fecal contamination (Knudsen et al. 2008). Food grown locally would require much less transportation, thus avoiding spoilage due to excessive handling. There are many other reasons why this concept of vertical farming could solve several global problems if applied on a large scale.

2 Environmental and economic reasons for switching from traditional farming in favor of controlled environment agriculture

Over the last several years much has been written both in the scientific and popular press regarding the need for a safer and more reliable food and water supply. Climate change issues, mostly related to the increase of adverse weather events (floods, droughts, hurricanes), threaten to greatly reduce the availability of these two essentials. The alarming rate at which climate change has accelerated in over just the last 25 years has forced us to re-examine some of our most cherished ideas about how we carry out our daily lives. Farming is one of those human activities that has remained largely immune from criticism due to its central role in supporting some 6.8 billion of us. In fact, farming is considered so necessary that it uses most of the available freshwater, despite the fact that in many agrarian societies, drinking water is already is short supply. In industrialized countries such as the United States, up to 20 % of the fossil fuels used annually is for farming (FAO, UN's Food and Agricultural Organization). Ecologically, farming has other negative consequences, such as the despoliation of the world's estuaries (http://water.epa.gov/polwaste/nps/outreach/point6.cfm) and the systematic elimination of most of the world's hardwood forests (http://www.umich.edu/~gs265/society/deforestation.htm).

One publication dealing with the economic impact of climate change that was both stunningly on point with respect to in its fact gathering, and down right ominous in its prognostications was the *Stern* Review on the Economics of Climate Change (Stern Review on the Economics of Climate Change (PDF online at World Bank website), published in 2006. It was sponsored by the British government and was the product of several years of intensive research and review by Nicolas Stern and colleagues. Their conclusions were: (a) The benefits of strong, early action on climate change outweigh the costs. (b) The scientific evidence points to increasing risks of serious, irreversible impacts from climate change associated with business-as-usual (BAU) paths for emissions. (c) Climate change threatens the basic elements of life for people around the world—access to water, food production, health, and use of land and the environment. (d) The impacts of climate change are not evenly distributed—the poorest countries and people will suffer earliest and most. And if and when the damages appear it will be too late to reverse the process. Thus we are forced to look a long way ahead. (e) Climate change may initially have small positive effects for a few developed countries, but it is likely to be very damaging for the much higher temperature increases expected by mid-to-late century under BAU scenarios. (f) Integrated assessment modelling provides a tool for estimating the total impact on the economy; our estimates suggest that this is likely to be higher than previously suggested. (g) Emissions have been, and continue to be, driven by economic growth; yet stabilisation of greenhouse gas concentration in the atmosphere is feasible and consistent with continued growth. (h) Central estimates of the annual costs of achieving stabilisation between 500 and 550 ppm CO_2e are around 1 % of global GDP, if we start to take strong action now. […] It would already be very difficult and costly to aim to stabilise at 450 ppm CO_2e. If we delay, the opportunity to stabilise at 500–550 ppm CO_2e may slip away (http://www.saynotogmos.org). (i) The transition to a low-carbon economy will bring challenges for competitiveness but also opportunities for growth. Policies to support the development of a range of low-carbon and high-efficiency technologies are required urgently. (j) Establishing a carbon price, through tax, trading or regulation, is an essential foundation for climate change policy. Creating a broadly similar carbon price signal around the world, and using carbon finance to accelerate action in developing countries, are urgent priorities for international cooperation. (k) Adaptation policy is crucial for dealing with the unavoidable impacts of climate change, but it has been under-emphasised in many countries. (l) An effective response to climate change will depend on creating the conditions for international collective action. (m) There is still time to avoid the worst impacts of climate change if strong collective action starts now.

Their last statement is remarkable in its simplicity and directness. Strong collective action is needed if

we are to avert ecological disaster. Reducing our carbon footprint is the bottom line with respect to our impact on global systems. Yet, despite this conservatively constructed document, its message has yet to be fully heard, let alone heeded. Many world leaders and industrialists are still quibbling over the meaning of climate change and who is to blame for the accelerated rate at which it is proceeding. This back and forth bantering is now referred to as the *Red Queen Effect*, named after a story segment in Lewis Carroll's "Alice Through The Looking Glass". The faster she runs, the more she remains in the same place.

Farming requires water and applied nutrients in the form of artificial fertilizers. Most countries can find the water, but less developed ones have a difficult time when it comes to purchasing fertilizers. Most of these are located in the tropics. They rely instead on a product we all produce each and every day as the result of our metabolism; feces. It is a wonderful source of nutrients for the plants and is readily available. There is a heavy price to pay for its use, however. The transmission of many forms of parasites depends upon our carelessness with our own feces. Lack of sanitation is the bane of most less well-developed countries. Geo-helminths (hookworm, *Ascaris*, and whipworm), the latter two whose eggs can survive for years in soil under the right conditions, cause diarrheal diseases, induce permanent learning deficit in heavily infected children (Hotez and Pecoul 2010), and keep them out of school. The result in endemic areas is an illiterate, poverty-stricken population unable to work at maximum efficiency. Farming indoors creates the opportunity of returning land back to nature, allowing it to resume its multiple ecological functions, many of which are directly beneficial for us.

As if the current fix we find ourselves in is not enough, demographers the world over conservatively predict that with just another 40 years, there will be another 2.6–3 billion people to feed (Demeny and McNicoll 2006; WHO (2004) World Population to 2300). How this will be accomplished is more than problematic, since we now use some 80 % of the land that can be farmed for food production (Monfreda et al. 2008). A new batch of farmland the area of the size of Brazil would be adequate for the purpose, but is obviously not available. The constant pressure to put more and more land into farming, mostly through the cutting down of hardwood forest, as farmland now in use continues to fail (droughts, floods, etc.) has a predictable negative endpoint (http://www.fao.org/newsroom/en/news/2006/1000385/index.html). Several alternative strategies have been suggested to address this impending crisis.

3 Potential solutions to the food crisis (safety and security)

One approach relies heavily on science and technology: produce food crops better adapted to a changing environment. Genetically modified plants, so-called GMOs, manipulated in the laboratory have been developed to resist longer droughts, and higher levels of herbicides (the weeds are winning that war). The protein from *Bacillus thuringiensis* that is toxic for insects has been engineered into tomatoes. Rice and wheat plants have been selected for resistance to fungal and viral diseases, and much more of this kind of research is in the pipeline. Not all of these ingenious efforts have been successful, however. But even if the plant scientists were to triumph in producing better strains of crop plants for all the right reasons (i.e., not for pure profit), consumer opposition to GMOs might negate what otherwise would have been a temporary victory (http://www.saynotogmos.org/). Eventually, evolution wins and the pests and plant pathogens re-gain the upper hand within several years.

Another approach suggests that urban environments should be the new agricultural setting. Converting roof tops into gardens, planting and harvesting crops in empty lots, and other suitable abandoned city spaces has become the norm for many western hemisphere cities. However, raising crops in abandoned city lots has some serious problems associated with contaminated soils and heavy metals. The idea of urban farming has gained so much traction within the last 5 years that city farm produce is competing at the green markets each summer next to more distantly grown vegetables, herbs and fruits (http://www.cnn.com/2009/LIVING/06/29/bia.urban.farming/index.html). The movement towards urban farming has raised awareness among city dwellers that their food needn't come from so far away as the highly irrigated valleys of California or the fruited plains of distant countries like Chile, Argentina, Thailand or New Zealand (http://attra.ncat.org/attra-pub/farm_energy/food_miles.html). Of course, meat production presents another level of problem not solvable with urban farms. The main drawback to any open air farming operation, whether it is located within the city or in the countryside, is the seasons. One crop per year is all too common in most parts of the subtropical and temperate zones.

Throw in insect pests and plant diseases and one gets the impression that no progress at all has been made, except maybe for moving the food production closer to where most people now choose to live. In fact, within the next 20 years, as many as 80 % of us will live in or very near a city (http://www.unfpa.org/pds/urbanization.htm), making urban agriculture even more relevant a practice.

Move urban farming indoors and problems of pest control and plant disease outbreaks are greatly reduced. This is especially true if the greenhouse is positively pressured and secure entry ways are built into the structure. Secure greenhouses on rooftops situated on apartment complexes, schools, shopping Malls, and other buildings could supply significant amounts of vegetables, herbs, and some fruits, such as strawberries and blueberries. Hydroponic (http://www.hydroponics.com) and aeroponic (http://www.aeroponics.com) technologies, well-established methods for growing a wide variety of crops, would serve as the main methods of indoor agriculture, saving huge amounts of water when compared to outdoor farming. The re-use of gray water could serve as the source for such operations. However, to maximize production and minimize the agricultural footprint, another advance in greenhouse construction must occur; namely the vertical farm (http://www.verticalfarm.org).

4 The vertical farm concept

The idea for the vertical farm arose in response to the inadequate model of a rooftop garden. The amount of space provided by the roof is dwarfed when one takes into account the floor space of the entire building, even one just 2–6 stories tall. Retro-fitting existing buildings with hydroponic and aeroponic growing systems seems like a logical next step towards constructing a free-standing vertical farm with all its "bells and whistles". The main consideration in using already built structures is providing enough lighting for the plants. There are some commercially available hydroponic grow systems that could accommodate a commercial grower, provided that the price of the crop was high enough to compete with soil-grown produce (http://www.omegagarden.com). Nonetheless, buildings designed for people are usually not adequate for maximum yield indoor farming. LED lighting can solve some of these issues (http://www.ledgrowlights.com/university%20of%20minn%20study.PDF), but ideally, a new, totally transparent building designed with plants in mind from the start would overcome many of these objections. Capture of passive energy (wind, solar, geothermal, tidal) and recovery of energy from the inedible portions of the crops could result in a net zero energy building that at the same time sequesters huge amounts of carbon and releases oxygen into the atmosphere. Making the vertical farm out of self-cleaning, transparent material for the skin of the building, such as ETFE (ethylene tetrafluoroethylene), and the emergence of the high-tech vertical farm becomes a thing of functional beauty. ETFE is already a standard building material and covers the massive, ethereal domes of the Eden Project in the south of England (http://www.edenproject.com).

In summary, creating an urban environment in which human populations produce most of their food and re-cycle all freshwater poses no technological difficulties, given the available technologies at our disposal. With the right kind of economic incentives and enough social pressure, the eco-city of the future could be realized sooner rather than later.

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