Skyfarming

by
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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

ABSTRACT

Food production is unquestionably the most important industry to the well-being of humanity. Unfortunately, it is also the industry that best exemplifies our species' destructive impact on the rest of Earth's ecology. This thesis presents the argument that the concept of vertical farming could transform food production to resolve this long standing paradox. The document is comprised of two parts. The first establishes the intellectual framework necessary to assess agriculture's effect on human and ecological systems, and explores the philosophies central to rationalizing high-density indoor agriculture with the objectives of human sustainability. The second part focuses exclusively on exploring the technologies and design strategies of the vertical farming concept. This aim is facilitated through the illustration of three design projects, each of which represents a distinct variant of the vertical farming concept. In order to ground this conceptual work within a real-world context the thesis includes a thorough cost-analysis of a simple, hypothetical vertical farm. The thesis concludes by addressing the vertical farm's potential to transform urban resource metabolism from its existing linear dependence on the external environment to a more self-contained, cyclical resource flow reminiscent of that exhibited by natural ecosystems.

ACKNOWLEDGEMENTS

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This thesis is also indebted to the help of many individuals outside of the University of Waterloo. While a fully inclusive list would be far too long for this format, those that must be mentioned include Ted Marchildon of Omega Garden, David Konwinski of Onsite Power Systems, Craig Applegath of DIALOG, Mathew Knegt of CTV, Dr. Louis Albright of Cornell University, Harry Shaw of Canadian Commercial Geothermal, and Illan Kramer of the University of Toronto. In addition, I must thank Dr. Dickson Despommier, Norm Kelly, Suzanne Elston, and the many others that have promoted my work with vertical farming and over the past 5 years.

This thesis is dedicated to my family - Jim & Gail Graff, Leigh & Mike Lauwaert, the Brownridge*s* and the Pyear*s*. Thank you for the unwavering love and support you constantly provide, and enabling me with every opportunity I could hope for. And to Tatha; thank you for the love, patience, and keen analytical mind you offered along the course of this journey, I am forever grateful.

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INTRODUCTION

It is becoming increasingly understood that both our forms of settlement and methods of sustenance are functionally incompatible with a planet of limited natural resources. Modern cities exhibit decisively *linear* resource metabolisms where food, fresh water, energy, and other resource demands are imported from great distances, consumed, and then swiftly dispensed as sewage or rubbish that the natural world cannot easily process. Likewise, the high-yield farming methods that support our immense population are characterized by their insatiable consumption of the limited reserves of freshwater, fossil-fuel energy, and soil.

A glimpse of humanity's predictable future indicates that the way cities and agriculture consume the Earth's precious natural capital will only worsen with the passage of time. The projected addition of 2.25 billion people to the global population by 2050 and another 2 billion by the end of the century forces us to consider what our world will be like with nearly twice as many consumers.[1] [2] Considering humanity's current population is already effectively degrading the ecological conditions we require to thrive, it appears the only way to avoid both a global ecological tragedy and widespread famine in the next century is to significantly transform the way cities and agriculture utilize natural resources.

This thesis presents an argument for the implementation of an emerging building typology, the vertical farm, as potential solution to the conflict between ecological stability and humanity's persistent demographic and economic growth.

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[1] United Nations Department of Economic and Social Affairs – Population division (2009) http://www.un.org/esa/population/unpop.htm

[2] U.S. Census Bureau (2009) http://www.census.gov/

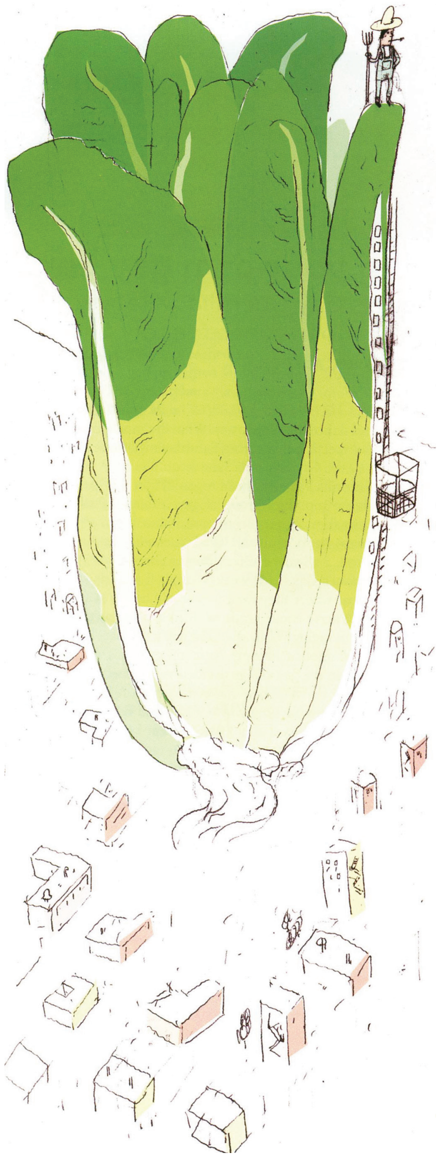

Fig 1.1
"Vertical Farm" illustration by Peter Mitchell, THIS Magazine 2009

Background

My interest in large-scale urban agriculture began in 2006 while researching the principal theories on human sustainability and sustainable urbanism. During this process I began to focus on two phenomena which are central to human civilization's relationship to the natural environment. The first was the catalytic role that agriculture has played in the formation of complex human society and, by association, how essential highly productive agriculture is to the functioning of modern civilization. The second was that agriculture is arguably the most ecologically destructive facet of human society, accounting for over 98% of human land use[3] , 72% of human water use [4], and 22% of human greenhouse gas emissions – the most of any industrial sector.[5]

This interest was amplified by what I perceived as widespread failure of sustainability theorists to appreciate agriculture's impact on human society and the Earth's ecology. This failure was expressed primarily through the advocacy of solutions that did not meaningfully improve agriculture's long-term environmental impact or by simply ignoring the issue altogether. An example of the latter is best exemplified in the many eco-city projects currently under development – each of which has received widespread praise as the vanguard of radically sustainable urban planning. Abu Dhabi's *Masdar City*, the much-lauded eco-city planned by Foster + Partners, claims to be "the world's first carbon-neutral city", yet the design brief makes no reference to accommodating the food requirements of its expected 50,000 citizens.[6] The same can be said

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[3] (1) Global agricultural land cover = 3,789,395,200 Ha (FAO Land Use and Human Settlement Tables) (2) Urban/Industrial land cover = 65,700,000 Ha (Schneider A, Friedl M and Potere D 2009 Monitoring urban areas globally using MODIS 500 m data: new methods based on urban ecoregions Remote Sens. Environ. in review)

[4] Rosegrant, Mark; Ximing Cai, and Sarah A. Cline (2002) World Water and Food to 2025: Dealing with Scarcity. Washington D.C.: International Food Policy Research Institute

[5] (1) Agricultural by-products - 12.5%, (2) Deforestation for agriculture - 8%, (3) Fertilizer production – 1.2% = 21.7% Sources: (ref. 1) Emission Database for Global Atmospheric Research version 3.2, fast track 2000 project, (ref. 2) UNFCCC (2007). Investment and financial flows to address climate change, (ref. 3) Wood, Sam & Annette Cowie. (2004) A Review of Greenhouse Gas Emission Factors for Fertilizer Production. IEA Bioenergy, June 2004. Note: does not include pesticide production, food transportation, or farm machinery contributions

[6] Masdar City Official Website. http://www.masdarcity.ae/en/index.aspx. Retrieved on July 10, 2010.

for Office of Metropolitan Architecture's eco-city *RAK Gateway*, designed to house 150,000 residents in the nearby emirate Ras Al Khaimah.[7] The eco-city planned for San Francisco's *Treasure Island* proudly boasts a 20-acre organic farm as a provision of sustainable living, however, such a small acreage could only supply approximately 0.1% of the food requirements of the development's planned 13,000 residents.[8]

An example of failure by way of advocating unsatisfactory solutions to agriculture's long-term impact can be found in the seemingly universal support for the conventional soil-based organic agriculture movement. Ironically, the argument against this farming strategy echoes a common line of reasoning used for its advocacy, which refers to the need to look beyond the immediate productivity statistics of industrial agriculture to consider its long-term adverse environmental externalities. Likewise, one must look beyond the local scale at which conventional organic agriculture tends to be discussed to consider the adverse impact it may have on the environment if implemented universally.

While conventional organic agriculture's reductions to both resource use and environmental pollution are clearly commendable, extensive studies of commercial scale applications have shown organic agriculture to be notably less productive than the industrial farming it is advocated to replace.[9] [10] In light of the rising concerns of feeding our rapidly expanding population, the promotion of a less productive form of agriculture would either exacerbate global malnutrition or, more likely, expedite the conversion of natural habitat into new farmland. This habitat destruction would then be amplified by the continual growth of the human population, which is projected to increase 33% in the next 40 years.[11] Unless conventional organic agriculture experiences a major increase in productivity it seems likely it will remain a niche farming method, and as such not a viable candidate to reduce agriculture's impact on the natural world.

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[7] OMA Official Website. http://www.oma.eu/ Retrieved on July 10, 2010.

[8] This calculation was obtained by using 1.2 acres as the minimum land requirements to produce the basic dietary needs of one person. Pimentel, David, Giampietro, Mario (1994) Food, Population, Land, and the U.S. Economy. *Carrying Capacity Network*

[9] Mäder P., Fließbach A., Dubois D., Gunst L., Fried P., Niggli U. (2002) Soil Fertility and Biodiversity in Organic Farming. *Science* 296, 1694-1697

[10] Posner, Joshua L., Jon O. Baldock & Janet L. Hedtcke (2008) Organic and Conventional Production Systems in the Wisconsin Integrated Cropping Systems Trials: I. Productivity 1990–2002, *Agronomy Journal,* 100 253-260Scarcity. Washington D.C.: International Food Policy Research Institute

[11] United Nations Department of Economic and Social Affairs – Population division (2009) http://www.un.org/esa/population/unpop.htm

At this time I also became aware of the wider ideological incongruity that exists between the eco-centric ideals leading the charge for human sustainability and the human-centric ideals that promote human health and well-being. On the one hand environmentalists wisely call for restrictions on humanity's economic and demographic growth to curb our destructive impact on the biosphere, yet in the process risk pushing general human welfare into decline. On the other hand economists wisely promote the need for increased productivity to curb levels of global malnutrition and improve general welfare, yet in the process risk further degrading the stability of the ecological systems we depend on. From each vantage point compromise appears to offer nothing but a slowing of economic or ecological decline, and encourages either zealous support of one ideology over the other or pessimism in the recognition of a no-win situation.

From this apparent ideological impasse I discovered two concepts that offered an optimistic solution to the above dilemma, which ultimately formed the basis of this thesis. The first concept came from a small group of authors professing the virtues of resource productivity as beneficial to the both ecological and economic interests of society. These authors include Ernst Ulrich von Weizsäcker, Amory and L. Hunter Lovins, and Paul Hawken, who in various pairings authored two seminal books, *Factor Four: Doubling Wealth, Halving Resource Use*[12] and *Natural Capitalism: Creating the Next Industrial Revolution*.[13] At the heart of each publication is the message that continued technological advancement can lead to radically increased resource productivity wherein significantly more human benefit could be derived from the natural resources we consume. Thus, a society that quadruples its resource productivity (i.e. "factor four") could double its material wealth while consuming just half of the natural resources of its present economy.

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[12] von Weizsacker, Ernest; Lovins, Amory B.; & Lovins, L. Hunter (1997). *Factor 4: Doubling Wealth - Halving Resource Use: The New Report to the Club of Rome*. Allen and Unwin, 322pp. ISBN 1 86448 438 1.

[13] Hawken, P., Lovins, A., and Lovins, H.L, (1999). *Natural Capitalism: Creating the Next Industrial Revolution*, New York: Little, Brown, and Company.

The second concept was that which could realize the general strategy for productivity improvement within agriculture – vertical farming. Vertical farming is a form of high-density indoor agriculture that is professed to achieve the theoretical maximum efficiencies of resource use and space efficiency in crop production. While the notion of such agricultural systems have existed for over a century in science fiction, a recent convergence of economic trends and technological innovations have lifted the concept from fantasy to plausibility almost overnight. As a result of this fast rise, however, the concept's bibliography is rather limited. The vast majority of published material on vertical farming consists of small journalistic articles intended as introductory explanations for the general reader. Until recently few peer-reviewed essays[14] and no books had been dedicated exclusively to the concept, the latter being corrected by the release of Dickson Despommier's *The Vertical Farm: Feeding the World in the 21st Century* in October of 2010.

With respect to this lack of established academic discourse on the concept, the primary goal of this thesis is to contribute to the study of the efficacy of vertical farming.

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[14] Graff, Gordon. (2009). A Greener Revolution: An Argument for Vertical Farming. *Plan Canada*, 2009 Summer, v.49, n.2, p.49-51

Structure

This thesis is comprised of two parts. Part I, titled *The Exponents of Agriculture*, is an essay that presents the sociological arguments for the emergence of vertical farming. The essay seeks to reconcile the seemingly radical notion of high-density indoor farming with the blueprint of human civilization as it has evolved since the Neolithic Revolution.

Separated into four chapters, the first chapter establishes the intellectual framework necessary to assess agriculture's effect on human and ecological systems. Using the language of systems theory the chapter examines the correlative relationship between population dynamics, the consumption of resources, and homeostasis in natural ecosystems. Pre-agrarian hunter-gatherer societies are one of the subjects of this examination, used to establish a default ecological signature for human society that will form a point of reference for later chapters.

The second chapter examines how the rise of agriculture rapidly transformed human society from primitive stability to the volatility of growth and progression in the modern world. These arguments are inspired primarily by A. Duncan Brown's Feed or Feedback (2003) and Jared Diamond's Guns, Germs, and Steel (1999), which analyse agriculture's emergence from biological and anthropological lenses, respectively. The concept of 'memes', first introduced in Richard Dawkins' The Selfish Gene (1976), is employed as a methodology to trace agriculture's systemic impact on human society; therein connecting modern cultural phenomena such as cities and market economies to the origins of agriculture.

The theme of exponential progression continues in the third chapter, which is devoted to the ecological consequences of humanity's conversion to agrarian living. Primarily the chapter explains agriculture's catalytic relationship to environmental phenomena that traditionally defines discourse on ecological sustainability, such as population growth, deforestation, loss of biodiversity, soil degradation, and environmental pollution.

Following a brief overview of the existing strategies for agricultural reform, the essay concludes with a thorough examination of the philosophies central to rationalizing high-density indoor agriculture with the objectives of human sustainability. These philosophies include the environmentalist strategies of Malthusianism and cornucopianism, the economic phenomena of Kuznets' Curves and Kondratiev Waves, and the concept of environmental decoupling.

With the philosophical context having been established, Part II focuses on explaining the intricacies of the vertical farming concept. The initial chapters include a summary of the precedents pivotal to the emergence of the vertical farming concept, a description of its associated technology, and an explanation of vertical farming's advantages over contemporary farming systems.

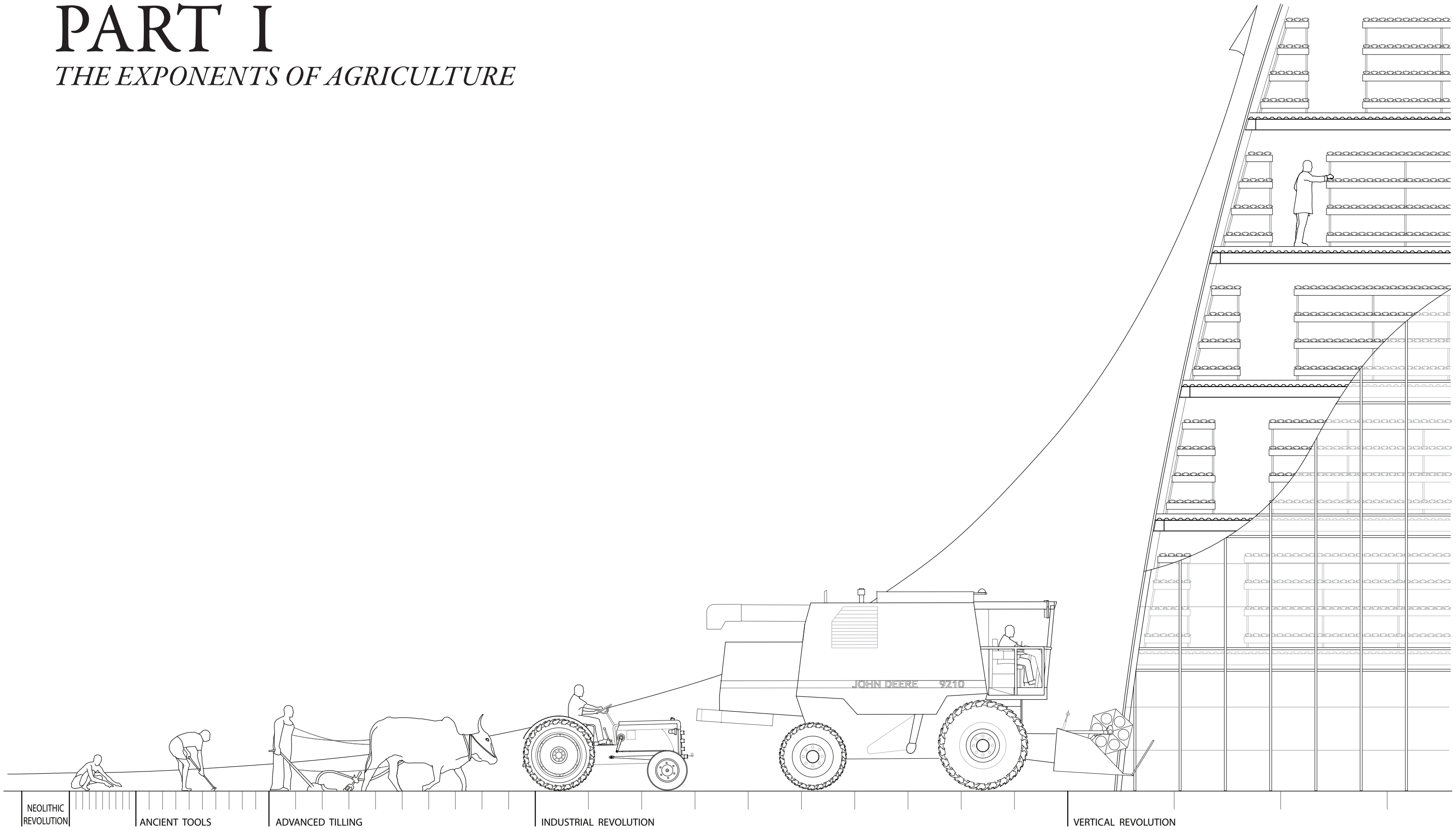
In order to ground the concept within a real-world context the next chapter examines the economic rationale of vertical farming. This includes a brief discussion of the principle macroeconomic variables dictating the financial viability of vertical farming, as well as a thorough cost-analysis of a simple vertical farm. As the cost analysis includes illustrations and itemized descriptions of each of the farm's components it also serves as a system diagram for a working vertical farm, one of the first such studies for the concept.

The final chapter is devoted to illustrating the thesis' three design projects. SkyFarm, a 68 storey skyscraper farm, explores vertical farming at its highest conceivable density. The second, Agro-arcology, demonstrates the symbiotic resource relationships that can be established when uniting vertical farming with multi-unit residential buildings. Lastly, the Ontario Vertical Food Terminal demonstrates how vertical farms could operate as peri-urban centres for regional food distribution. As each project works at a different level of the food distribution chain and a different sector of urban fabric they serve as a summary of the basic vertical farm typologies.

The thesis concludes with an analysis of vertical farming's potential impact on the form and function of urban areas. After using systems theory to explain the similarities and distinctions of ecosystems and cities, the vertical farm is identified as an emergent meme capable of significantly altering the city's relationship to its external environment. By establishing a new 'producer' trophic level within the homogenously consumptive metabolic structure of urban areas, vertical farms can encourage cities to mimic, and thereby become more commensurate with, the Earth's ecology.

PART I

THE EXPONENTS OF AGRICULTURE



Today it is difficult to picture humanity realizing a sustainable mode of existence. With the relentless growth of our population and resource consumption, human life appears disconcertingly similar to that of an invasive species ravaging an ill-prepared ecosystem. Prior to the advent of agriculture, however, humanity's effect on the Earth's ecology was not much different from that of any other animal species. Living as nomadic hunter-gatherers, our ancestors achieved the low impact, low density lifestyle typical of organisms that compose stable ecosystems. Their means of subsistence came from whatever their environment provided – be it fish, animal meat, or edible vegetation. Though hunter-gatherers had the technological capacity to alter their environment with fire and wield tools that offered a competitive advantage over other species, their scale and behaviour remained consistent with the limits of their environment.

In sharp contrast to the behaviour of modern human societies, the resource metabolism of hunter-gatherer tribes was defined by a cyclical, symbiotic exchange of materials with their neighbouring organisms. The nutrient elements they consumed swiftly flowed back into their environment's stores through their excreta, food trimmings, and the bodies of their dead, ready for consumption by another trophic level of the food chain. While some hunter-gathers did achieve a degree of sedentarianism their typical nomadic behaviour ensured a more or less scattered distribution of these wastes, avoiding the concentrations necessary to be considered a pollutant. This lifestyle enabled hunter-gathers to persist for hundreds of millennia, many times that of recorded human history, while leaving only the faintest physical traces of their existence.

Fig 1.3
Cave painting from the Upper Paleolithic era. 14,000 BC. Lascaux, France.

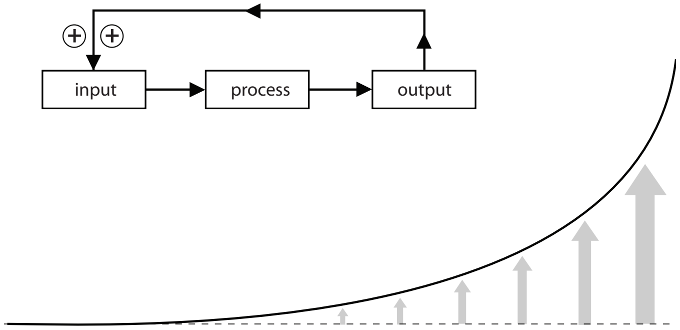


Fig 1.4
Schematic diagram of positive feedback loop

Yet, perhaps the most effective indicator of our hunter-gatherer ancestors' ecologically benign lifestyle is the long-term stability of their population. Over the million year period ending 10,000 BC, humanity's[1] population growth rate is estimated to have been no more than 0.0015% per annum, resulting in a doubling time of over 46,000 years.[2] As a comparison the average growth rate for the following twelve thousand years of agrarian living has been 3.74%[3] per annum, with a doubling time of approximately 19 years. Calculating the effect of these figures over time reveals that agrarian populations could rise from 100 to 5000 people in just 105 years, whereas Palaeolithic hunter-gatherers would require over 260,000 years to achieve the same growth.[4]

To understand how hunter-gatherers realized this stable lifestyle we must examine two natural laws of ecosystem population dynamics. The first of these is essential to the proliferation of life – the relentless drive to reproduce. Humans, like all organisms in the biosphere, are instinctually compelled to exploit resource opportunities in their environment and pass on their genes through procreation. Both are central principles of biological evolution, as the ability for one group with a particular genetic mutation to out-compete another for resources, and hence reproduce more effectively, enables the resource-advantaged genes to be passed on more readily.

When unencumbered the reproductive expansion of organisms exhibits the mathematical phenomenon of exponential (a.k.a. geometric) growth, as opposed to the intuitive nature of arithmetic linear growth. In exponential growth the amount added to a total grows proportionally with the increase of that total, forming what is termed a *positive feedback cycle* - a state that encourages a system to intensify as it progresses. Beginning with the number one, thirty

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[1] Here "humanity" refers to anatomically modern humans up to ~200.000 BC, as well as our evolutionary precursor hominids to 1,000,000 BC.

[2] Caldwell, John C. & Caldwell, Bruce K. (2003) Was there a Neolithic Mortality Crisis? *Journal of Population Research*, vol. 20, no. 2, 153-168

[3] (((6750 million - 15 million) / 12008 years) / 15 million) * 100 = 3.74%

[4] $\mathrm{Ln}\ (N_2) = \mathrm{Ln}\ (N_1) - rt$, where r=growth rate and t=years. $\mathrm{Ln}\ (5000) = \mathrm{Ln}\ (100) – 0.000015t$ t=260,802 years

steps of linear growth would simply result in a value of thirty, while thirty steps of exponential growth – as exemplified in the infamous Rice on a Chessboard story[5] – would yield a value of over one billion.[6]

This inclination for organisms to expand their numbers at an intrinsic exponential rate is one of the most powerful forces in nature. For instance, consider the reproductive capability of a typical bacterial cell. It is common for many species of bacteria to grow with a mean generation time (doubling time) of 30 minutes in ideal conditions. At this rate of growth it would take a single bacterium, weighing an infinitesimal 10^{-13} grams, just over 4 days (64 hours) of replication to create a bacterial community with a mass equal to that of the Earth (6×10^{21} metric tons). If left to replicate just half an hour longer this bacterial community would grow to twice the mass of Earth.[7]

Obviously, within the limited confines of the physical world, the perpetually increasing resource demands of exponentially growing populations cannot be sustained indefinitely. This brings us to another natural law of ecosystem population dynamics - environmental resistance. Environmental resistance is the collective term for the many *limiting factors* that restrict an organism's access to resources or otherwise promote opportunities for their death. An organism's access to food is limited by a range of factors, such as competition, the physical limitations of the food source, and unfavourable changes to the food source's habitat. Opportunities for untimely death are generally the result of exploitation by an organism higher on the food chain through predation (or hunting) or one lower on the food chain through disease.

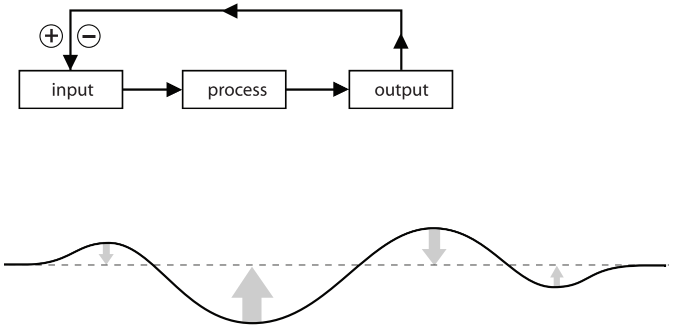
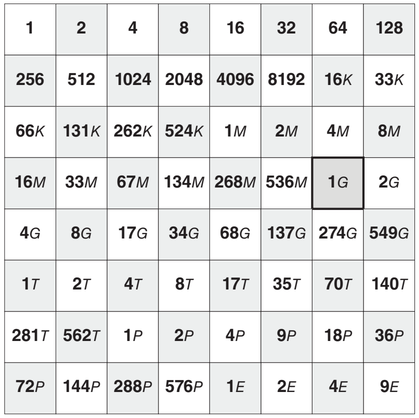


Fig 1.5
Schematic diagram of negative feedback loop



1	**2**	**4**	**8**	**16**	**32**	**64**	**128**
256	**512**	**1024**	**2048**	**4096**	**8192**	**16***K*	**33***K*
66*K*	**131***K*	**262***K*	**524***K*	**1***M*	**2***M*	**4***M*	**8***M*
16*M*	**33***M*	**67***M*	**134***M*	**268***M*	**536***M*	**1***G*	**2***G*
4*G*	**8***G*	**17***G*	**34***G*	**68***G*	**137***G*	**274***G*	**549***G*
1*T*	**2***T*	**4***T*	**8***T*	**17***T*	**35***T*	**70***T*	**140***T*
281*T*	**562***T*	**1***P*	**2***P*	**4***P*	**9***P*	**18***P*	**36***P*
72*P*	**144***P*	**288***P*	**576***P*	**1***E*	**2***E*	**4***E*	**9***E*

Fig 1.6
Graphic depiction of the Rice on a Chessboard story. Note the highlighted 30th step with an approximate value of 1 billion. Metric symbol definitions: K = thousand, M = million, G = billion, T = trillion, P = quadrillion, E = quintillion

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[5] "A courtier presented the Persian king with a beautiful, hand-made chessboard. The king asked what he would like in return for his gift and the courtier surprised the king by asking for one grain of rice on the first square, two grains on the second, four grains on the third etc. The king readily agreed and asked for the rice to be brought. All went well at first, but the requirement for 2^{n-1} grains on the *nth* square demanded over a million grains on the 21st square, more than a million million (aka trillion) on the 41st and there simply was not enough rice in the whole world for the final squares." (From Meadows et al. 1972, p. 29 via Porritt 2005)

[6] Beginning with the number 1, thirty doubling periods (steps) results in a value of 1,073,741,824 (2^{30})

[7] Brown, A. Duncan. (2003). *Feed or Feedback: Agriculture Population Dynamics and the State of the Planet.* Tuross Head, NSW: International Books

In their attenuation of the tendency for exponential population growth, limiting factors exemplify instances of *negative feedback*, which encourage systems to remain within a constant set of conditions. This constancy in biological systems is referred to as homeostasis, and achieved when the 'positive' population pressure (or biotic potential) of an organism is effectively regulated by the 'negative' limiting factors of its environment. The resultant force of an organism to sustain itself in its environment ultimately establishes a threshold that defines the maximum number of individuals its environment can support – its carrying capacity.

Since humans reside atop our respective food chain and have few natural predators, the natural environment's carrying capacity for us is determined primarily by our efficiency of procuring food energy from the environment. The maximum allowable population of hunting and gathering societies was dictated by the natural availability of edible organisms in their environment, over which they had no control. With each upward movement of the number of individuals, food supply per capita would decrease. As a typical cycle goes, the increased food consumption of their expanding population would eventually compromise the food source's next generation, as there would be fewer specimens of the food-supplying organism left to reproduce. This would result in a diminished food supply the following year that would lead to malnutrition, loss of female fertility, starvation, and subsequently population decline until their numbers receded to a level their environment could support. In practice this well defined negative feedback cycle established a carrying capacity for hunter-gatherers at a miniscule 15 million people.

CHAPTER 2 - AGRARIAN LIFE

At the end of the Stone Age, and coincidental to a significant warming period of the Earth's climate, human societies around the Earth spontaneously began to shift from hunting and gathering to the domestication of edible plants and animals – an event known as the Neolithic Revolution. According to the current state of anthropological research The Fertile Crescent (present day Iraq, Syria et al), China, Mesoamerica, and New Guinea emerged as the primary centres of agriculture development between 10,000-8,000 BC, followed by South America and North America in the succeeding millennia. Together these 6 regions proceeded to domesticate the majority of agricultural products used throughout the world today. Wheat, barley, and lentils were developed from wild plants in the Fertile Crescent; rice, soybeans, and cabbage in China; squash, corn, and beans in Mesoamerica; and potatoes, peppers, and pineapples in South America, to name just a few. Those areas where agriculture took longer to appear, such as Australia, Southern Africa, and southern South America never saw local species evolve into agricultural varieties.[1]

Fig 1.7
Egyptian wall painting depicting early agricultural life

It is virtually impossible to overstate the significance of agriculture's emergence, both in terms of its effect on the human species and on the biosphere as a whole. The cultural, intellectual, and behavioural disposition of every human on Earth is a direct product of the agrarian lifestyle. So too is humanity's new found capacity to unfavourably alter the ecological world on a grand scale. In his book *Feed or Feedback* microbiologist A. Duncan Brown went so far as to state that the emergence of agriculture was second only to the accumulation of elementary oxygen in the atmosphere in terms of its effect on the development of the Earth's environment and ecology.[2]

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[1] Diamond, Jared. (1997). Guns, Germs, and Steel: The Fates of Human Societies. New York, W.W. Norton & Company.

[2] Brown, A. *Feed or Feedback*

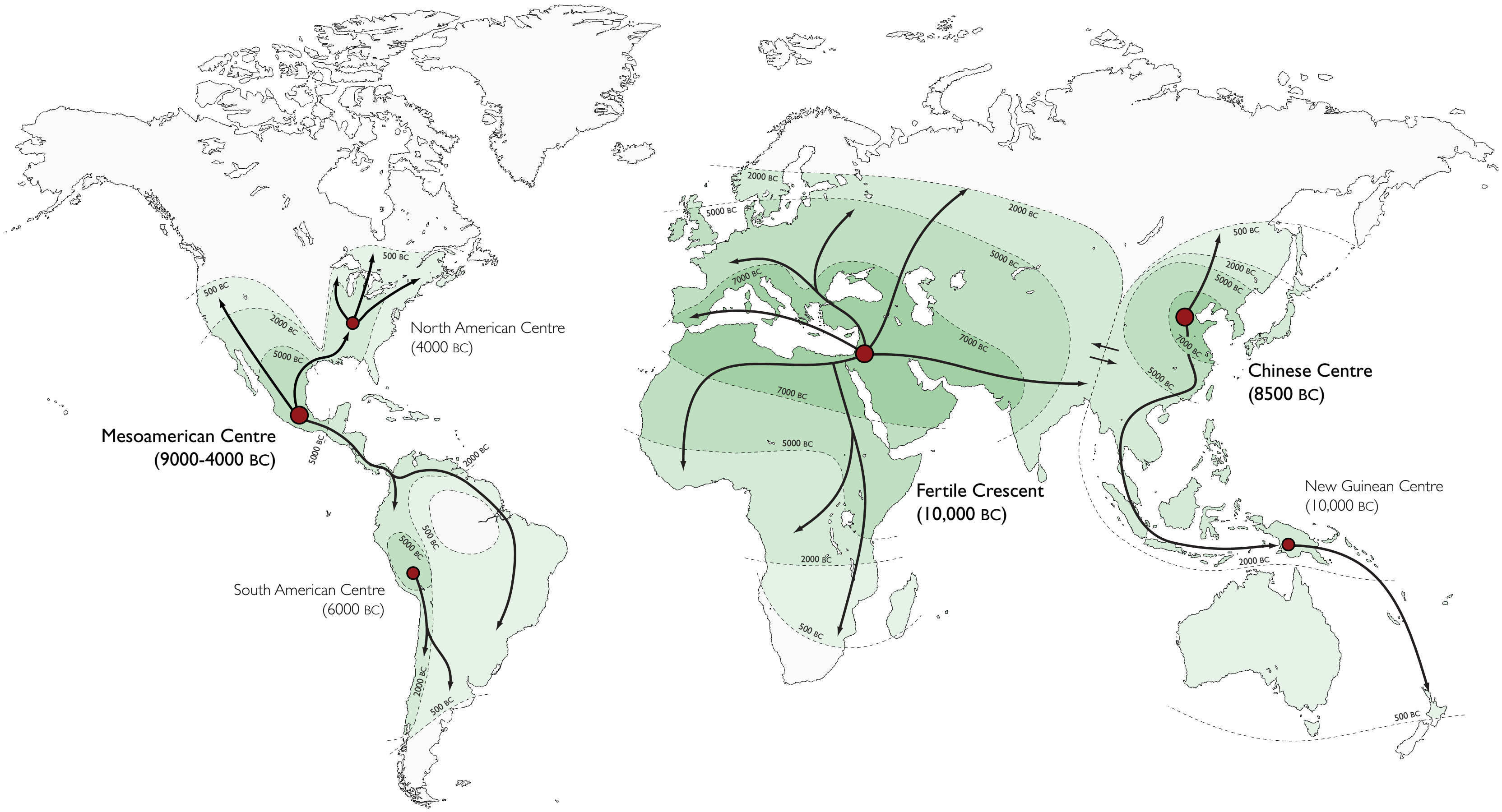

Fig 1.8
Centres of origin and areas of extension of the neolothic agricultural revolution

To fully understand the extent to which agriculture impacted human society one must address the fundamentally different signature of resource metabolism it offered. Since hunter-gatherer diets were a product of the natural availability of food in their environment, their survival was directly tied to the biodiversity of this environment. If a particular band of hunter-gatherers were to stalk the edible animals or pick the edible plants of their region into scarcity they would be forced to relocate to a more favourable environment, giving the over-consumed ecosystem time to re-establish itself. With the arrival of agriculture humans discovered more food could be obtained by converting natural ecosystems into farms than by relocating to another region. This eroded the systemic deterrent to destroy natural ecosystems and unleashed humanity's tendency for unbridled consumption of the Earth's material resources.

By clearing ecosystems that catered to a wide diversity of species and re-populating them with plants and animals geared solely for human consumption, we greatly increased our share of food energy available from the environment. In this humanity circumvented the most important limiting factor controlling our species – the availability of food – creating an imbalance between our instinctual drive to reproduce and our ecosystem's ability to control us. As a result the negative feedback relationship that had previously existed between humanity's food supply and its population growth shifted into a positive feedback cycle. That is to say, while hunter-gatherer populations were confined by the limitations of the natural availability of food, the expandable food yields of agriculture obliged agrarian populations to increase at their intrinsic exponential rate. As Jared Diamond explains,

> *"[The] gradual rise in population densities impelled people to obtain more food by rewarding those who unconsciously took steps toward producing it. Once people began to produce food and become sedentary, they could shorten the birth spacing and produce still more people, requiring still more food."*[3]

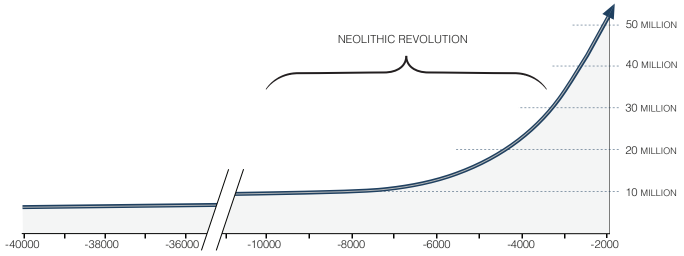

Fig 1.9
Exponential population explosion during the Neolothic Revolution

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[3] Diamond, *Guns, Germs, and Steel*

It is also important to note that the emergence of agriculture converted our means of sustenance from one restricted by the natural limits of our environment to one limited only by our own ingenuity. As a result the success of any particular society became less a product of its biological fitness and more a product of its 'memetic fitness'. Coined by Richard Dawkins in *The Selfish Gene*, a "meme" is the cultural analogue to a biological gene that "conveys the idea of a unit of cultural transmission, or a unit of imitation", such as communicable knowledge or technologies.[4] Memetic fitness, in turn, is analogous to the concept of genetic fitness that quantifies the capability to successfully reproduce.

Societies that displayed the most advantageous memes, such as the most efficient resource-collecting technique, were the most able to reproduce successfully. In agriculture human societies discovered a memetic package that not only offered a competitive advantage over other forms of resource collection, as a technology it could be improved upon to offer still greater advantages. This consecrated the drive for cultural progress as the primary determinant of human action, which persisted throughout the millennia to greatly define the complex societies of today.

Although one could write extensively on the complex co-evolution of agriculture and human society, I have limited the analysis to the five memes most important to understand agriculture's underlying imprint on contemporary human society. These are: the practice of ***plant and animal domestication***, the ***rise of sedentarianism***, the ability to ***stockpile resource surpluses***, the ***division of labour***, and the ***formation of centralized government***.

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[4] Dawkins, Richard (1989), 11. Memes:the new replicators, *The Selfish Gene* (2nd ed., new ed ed.), Oxford: Oxford University Press, p.368

The Practice of Plant and Animal Domestication

Consider the distinction between gathering vegetable products from the wild and sowing agricultural crops. A band of 50 hunter-gatherers in the most favourable conditions would need to forage over a radius of more than 6 km (on average) in order to support itself perpetually - equating to roughly 2.5 km^2 per person.[5] This is because only a small minority of wild plant species are edible to humans, or yield enough calories to warrant collecting. As a comparison the most basic contemporary farming systems require just 0.03 km^2 of land per person – an 84-fold increase in caloric production per area of land.[6]

Animal husbandry rewarded farmers with equally significant caloric yields over hunting. The eggs supplied from domesticated chickens, and milk products from domesticated cattle, sheep, goats, and other large mammals offered many times more calories over the lifespan of the animal than if it were simply hunted and consumed in the wild.[7] In addition, the ability to control animal breeding habits ensured farming people could maintain a stable source of protein that required little energy or personal risk to slaughter.

When the processes of animal husbandry and domestic plant cultivation became interconnected with the intensification of agrarian living, still further increases in caloric yields were realized. The use of animal manure as fertilizer significantly increased crop production by returning vital nutrients to the soil. Today animal manure is still the most widely used form of crop fertilizer in the world.[8] Large domesticated mammals also increased crop yields by pulling ploughs, which enabled more land to be tilled than was economically possible without animal power. Reciprocally, animal cultivation benefitted from crop production through the provision of a reliable feed source for the animals.

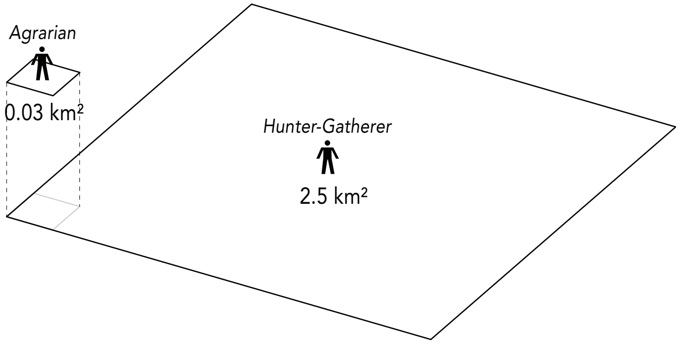

Fig 1.10
Comparison between the average land area required to sustain one person of agrarian societies and hunter-gatherer societies

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[5] Brown, A, *Feed or Feedback*

[6] Ibid

[7] Diamond, *Guns, Germs, and Steel*

[8] Ibid

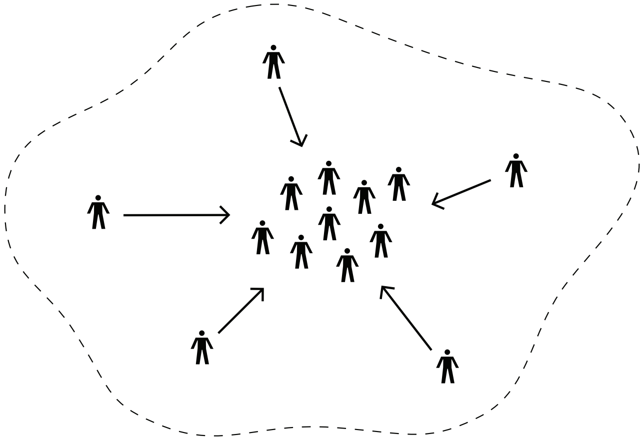

Fig 1.11
Localized food production led to formation of permanent settlements and concentrated human influence on the environment

The Rise of Sedentarianism

It is often overlooked from our contemporary urban-based vantage points that humans were nomadic beings for nearly 95% of our anatomically modern existence. In addition to redefining the degree of material wealth possible, permanent settlements facilitated and intensified information sharing. This created the conditions necessary for human culture, knowledge and technology to evolve and progress at an exponentially faster rate than was possible in pre-agrarian times. In the words of Steven Johnson,

> *"Cities bring minds together and put them into coherent slots. Cobblers gather near other cobblers, and button makers near other button makers. Ideas and goods flow readily within these clusters, leading to productive cross-pollination, ensuring that good ideas don't die out in rural isolation."*[9]

Additionally, sedentary living impacted human reproduction in a number of ways. For one, the higher concentrations of humans allowed greater opportunity for genetic diversity in mating than could occur within small, isolated tribes of hunter-gatherer communities. When mating did occur, sedentarianism drastically reduced the impediments to child rearing and increased the fertility of women. As Diamond explains,

> *"A hunter-gatherer mother who is shifting camp can carry only one child, along with her few possessions. She cannot afford to bear her next child until the previous toddler can walk fast enough to keep up with the tribe and not hold it back. In practice, nomadic hunter-gatherers space their children about four years apart by means of lactational amenorrhea, sexual abstinence, infanticide, and abortion. By contrast, sedentary people unconstrained by problems of carrying young children on long treks can bear as many children as they can feed. The birth interval for many farm peoples is around two years, half that of hunter-gatherers"*[10]

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[9] Johnson, Steven (2001) *Emergence: The Connected Lives of Ants, Brains, Cities, and Software*. New York: Scribner

[10] Diamond, *Guns, Germs, and Steel*

Sedentarianism also restructured the way human populations exchanged resources with the environment. The concentration of populations led to the concentration of the wastes associated with human life, namely excrement and, for later societies, processed refuse. Simultaneously sedentarianism increased the separation between food production and consumption, which converted the flow of nutrients from locally cyclical for hunter-gatherers to regionally linear for agrarian societies. These two phenomena of urban living contributed to the disadvantageous ecological signature of human societies and the prevalence of disease in human populations.

Emergence of Complex Society

The sedentary lifestyle of agrarian communities, mixed with the higher food-producing capacity of agriculture, led to a vital development in the efficiency of resource utilization – the ability to **stockpile resource surpluses**. The nomadic nature of most hunting and gathering societies does not accommodate the accumulation of surplus goods, as transporting the surpluses would create an added burden to their journeys. Additionally, storing large volumes of food is of little use since their tendency to migrate would not permit the protection of the stockpile.[11] Since farmers are permanently fixed to a particular area, the protection of large stockpiles of surplus food is easily accommodated.

Food surpluses provided a readily available source of capital that encouraged trade and generated the incentive for technological growth. Farmers who grew more food than they required became free to trade this surplus to others for desirable skills or services. Those worthy of trade, now unrestrained from the need to grow food for themselves, were free to hone those skills or crafts most useful as trade. This newfound demand for tradable services encouraged **the division of labour**, where non-food producing 'specialists' could be sustained within a community. Pioneer industries like tool makers, clothes weavers, and potters emerged to satisfy the diversifying needs of the agrarian community, marking the beginning of complex market economies. New devices became available that increased agricultural yields, which in turn created greater surpluses for trade.

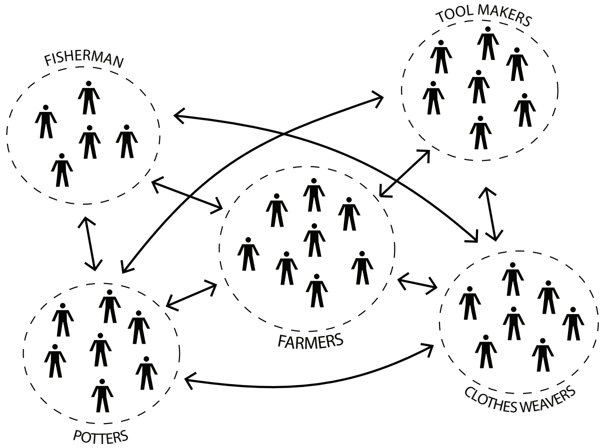

Fig 1.12
Hypothetical depiction of the formation of distinct, interrelated industries in a society as a result of the diversification of labour

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[11] Diamond, *Guns, Germs, and Steel*

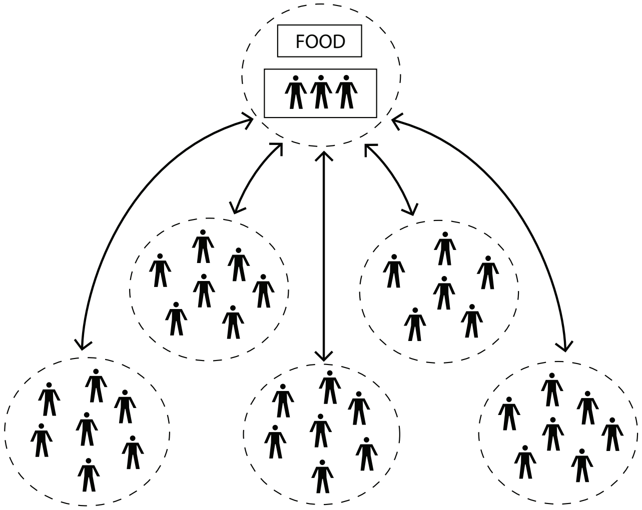

Fig 1.13
Centralization of power in human societies as a result of food stockpile control

The availability of surplus food also acted as the catalyst to allow **centralized government** to flourish. As Jared Diamond explains of early agrarian communities,

> *"Once food can be stockpiled a political elite can gain control of food produced by others, assert the right of taxation, escape the need to feed itself, and engage full-time in political activities."*[12]

Vocations of benefit to the collective soon emerged as a result of the centralized control over food production. Professional soldiers were sustained to protect the community and wage wars of conquest, something rarely seen in hunter-gatherer societies.[13] Bureaucrats, engineers, educators, artists, entertainers, and countless other vocations became possible thanks to subsidies from the distributed agricultural trade.

With more minds freed from the toil of manual labour and placed in the "coherent slots" necessary for intensified dialectic exchanges to occur, human culture, knowledge, and technology progressed in their own positive-feedback cycles. New memetic units like cartography (6th millennium BC) and the wheel (5th millennium BC) soon emerged to improve our ability to define and navigate the world around us, while writing (4th millennium BC) enabled heightened information storage and retrieval. Eventually this rate of progression would prime our intellectual palate for comprehension of the abstract – philosophy, mathematics, physics – that is essential to modern civilization. In this process of internalizing the human intellect, however, we promptly lost the intuitive understanding of the external 'natural' world that is indispensible to the hunter-gatherer.

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[12] Diamond, *Guns, Germs, and Steel*

[13] Diamond, *Guns, Germs, and Steel*

Economic historian Sydney Pollard traced the inception of a conscious motivation for progress in human society to just 350 years ago; around the emergence of the scientific method during the Enlightenment.[14] It appears that for much of our history the incremental steps of technological innovation had occurred too slowly for an appreciation of the cause and effect of progress. Observing the cumulative effect of these steps over millennia, however, suggests the notion of progress is an unconscious motivation of our collective intelligence, hardwired into the very nature of agrarian human society.

For instance, consider our evolving ability to carry resources and traverse our environment. For the hundreds of thousands of years prior to the advent of agriculture it was difficult for our ancestors to transport more than a few kilograms of goods and travel more than a few kilometres per day due to the limitations of our physiology. After the domestication of animals our capacity to transport was amplified to hundreds of kilograms with animal-drawn carts and over a hundred kilometres per day with horses – an event that greatly impacted our economic and cultural development. Ten thousand years of subsequent memetic syntheses has granted us the ability to travel thousands of kilometres per day with ease and build maritime vessels capable of transporting loads in excess of five hundred thousand tonnes per journey.

Our modes of cultural expression exhibit a similar geometric progression. One can trace backward over fifty thousand years from the advent of agriculture and see little change in the cave paintings and musical instruments that defined human artistic expression, yet trace forward little over ten thousand years and find the work of Michelangelo and Mozart. The impermanent, rudimentary shelters that defined human construction for millions of years gave way to monumental structures like the Great Ziggurat of Ur and the Giza Necropolis shortly after the Neolithic Revolution, to say nothing of the more elaborate constructions that followed.

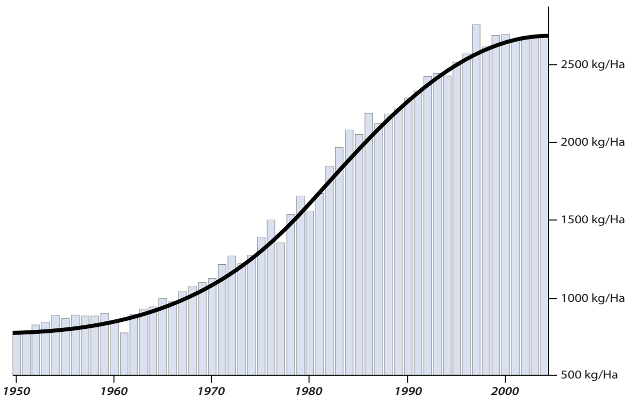

Fig 1.14
Agricultural yields of developing countries, 1950-2005

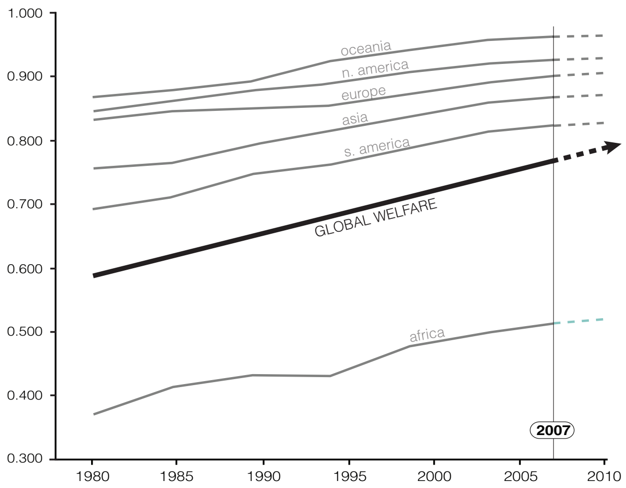

Fig 1.15
Human Development Index (HDI) 1980-2010

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[14] Victor, Peter A. (2008) Managing Without Growth: Slower by Design, Not Disaster *Advances in Ecological Economics*, Northampton, Mass: Edward Elgar Publishing Limited

The numerous qualitative improvements to general human welfare are perhaps the most significant measures of progress since the Neolithic Revolution. It is quite remarkable to consider our species' average lifespan has more than doubled – and in some regions nearly tripled – since our conversion from hunting and gathering.[15] More broadly, most initiatives to quantify the qualitative aspects of human life – such as the U.N.'s Human Development Index (HDI) – have shown a clear improvement with the passage of time. Taking into consideration factors such as health care and nutrition (life expectancy), education, and standard of living, the HDI trend has shown a marked improvement in every major geo-political region.

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[15] Galor, Oded & Moav, Omer (2007). *The Neolithic Revolution and Contemporary Variations in Life Expectancy.* Brown University Working Paper. Retrieved 12 September 2010

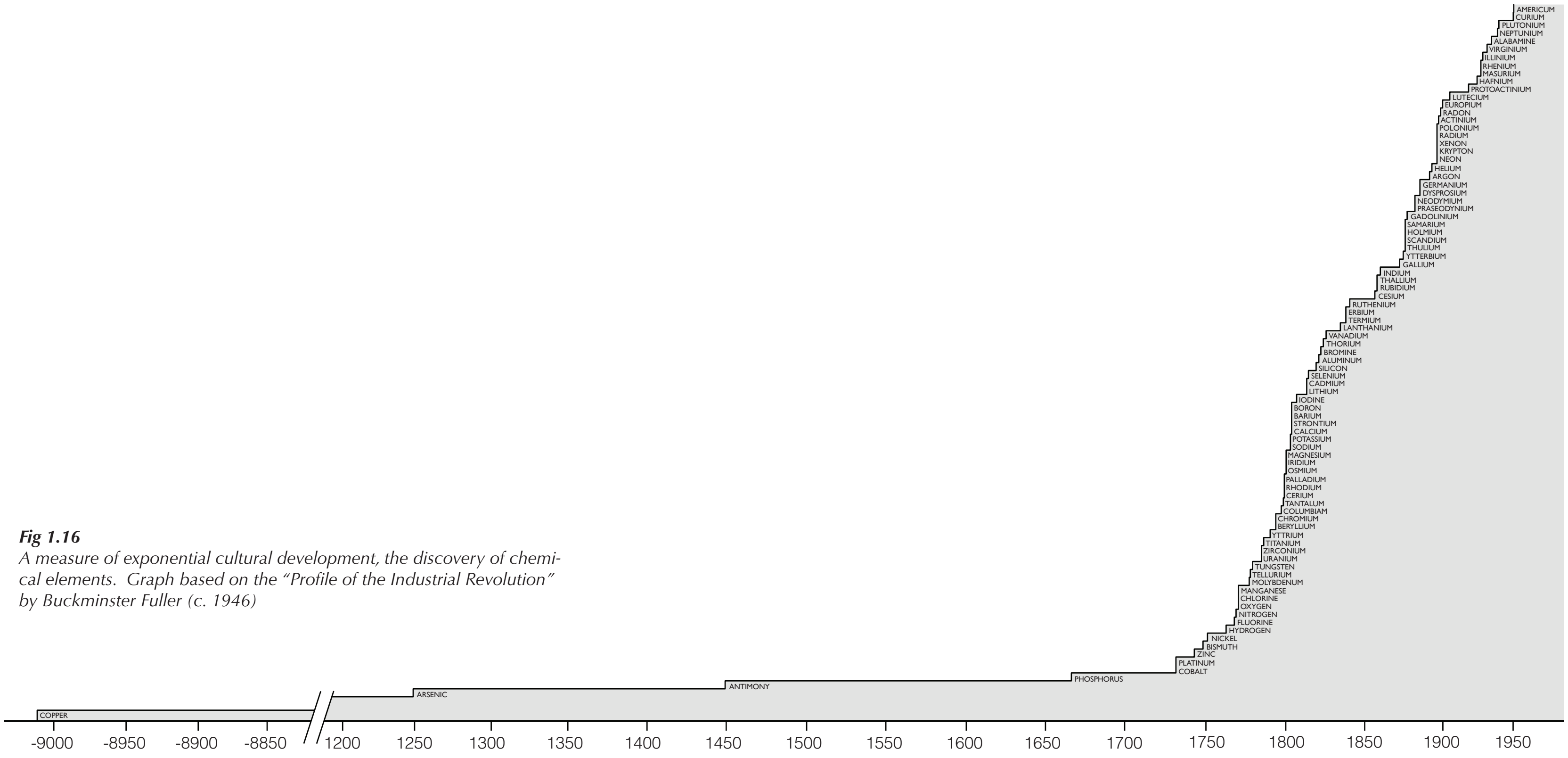

Fig 1.16
A measure of exponential cultural development, the discovery of chemical elements. Graph based on the "Profile of the Industrial Revolution" by Buckminster Fuller (c. 1946)

CHAPTER 3 - VICIOUS CIRCLE

> *"Systems in a state of positive feedback are commonly known as vicious circles. They contain more than just the seeds of their own destruction; unless a limit is placed on the flux of energy through it, a system in a state of positive feedback will destroy itself"*
>
> A. Duncan Brown, *Feed or Feedback*

In addition to the addressed qualitative changes to human society, the agrarian evolution had a similarly remarkable quantitative dimension. The continual expansion of agricultural activity increased the number of humans the environment could support, causing our populations to explode in number and increase in influence. In the first twelve thousand years of agrarian living – a mere moment in the time scale of our species' existence – our growth rate skyrocketed to an average of 3.74% per year; nearly 2500 times higher than the rate during the hunter-gatherer era.[1]

The primary driver of this population explosion was the constant evolution of agricultural technology. For instance, the population boom of the 4th century BC corresponds to the development of hydraulic systems of aquatic rice growing in China, India, and Southeast Asia.[2] The growth beginning around the 9th century AD was a result of the implementation of horse-drawn ploughing in European agriculture, further improvement to rice growing systems in Asia, and the advent of crop-rotation during the Muslim Agricultural Revolution.[3] The notable increases of the 15th-18th centuries came by way of an even more

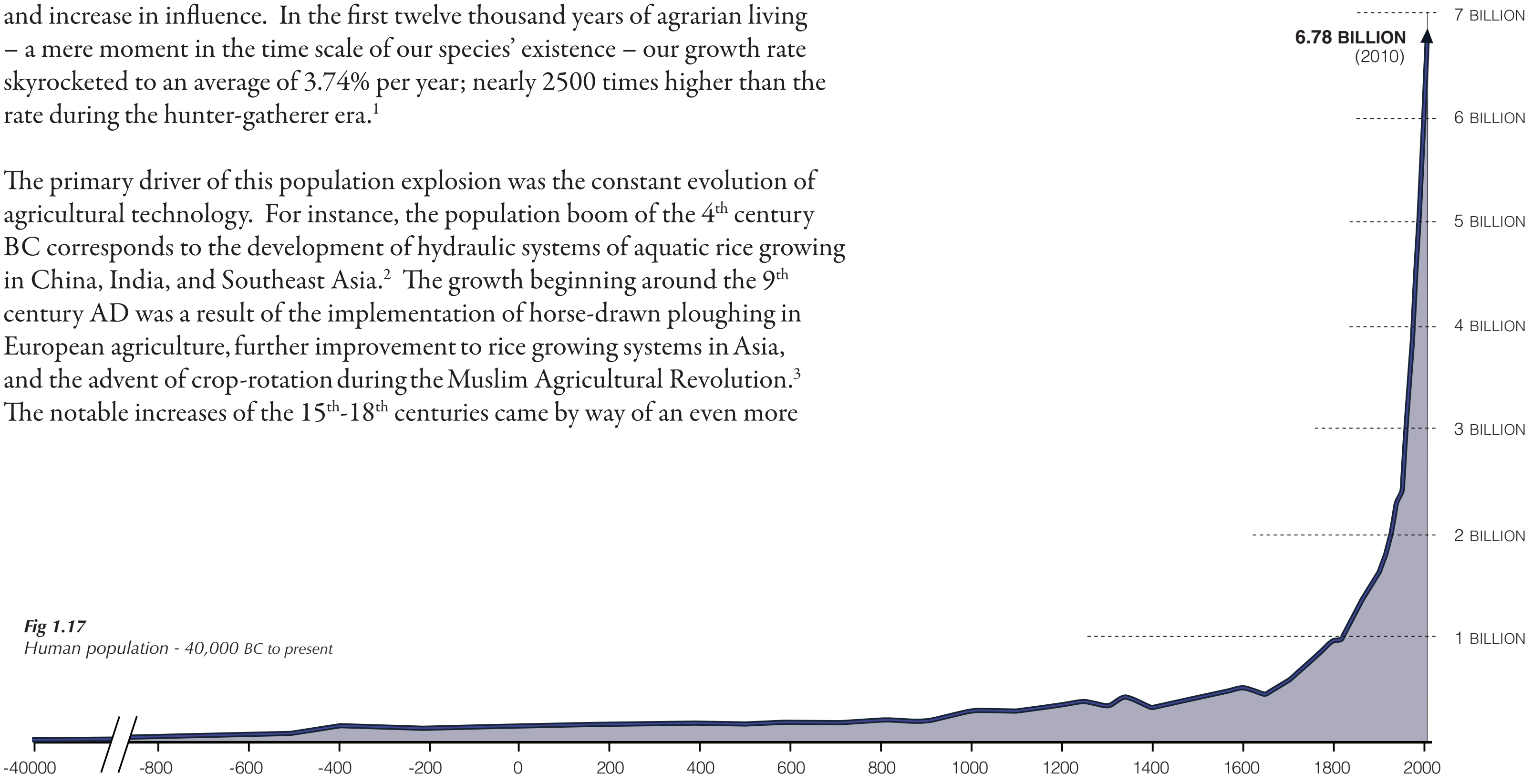

Fig 1.17
Human population - 40,000 BC to present

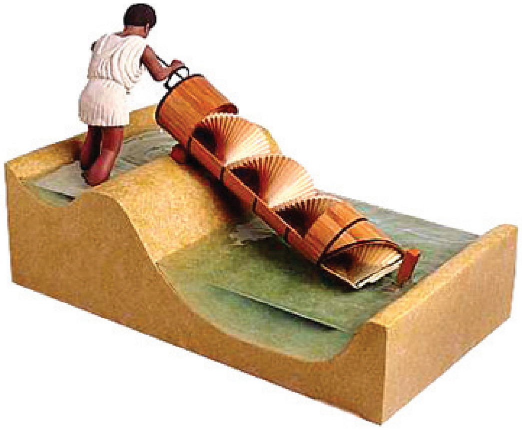

Fig 1.18
During the 3rd century BC Archimedes developed a screw pump for transferring water from low-lying rivers to elevated irrigation ditches. The Archimedes screw helped revolutionize irrigated cultivation, and ushered in a new age of agricultural productivity

productive four-field crop rotation system in Europe, as well as the massive territorial expansion of European agriculture through the colonization of the Americas and Oceania. Finally, the shocking spike in our numbers from the 19th-21st centuries was made possible by the huge increases in food production brought by the innovations of "motorized, mechanized, and chemicalized agriculture" of the Green Revolution.[4]

At the dawn of the 19th century our population first exceeded 1 billion. Though it took the entirety of human existence to reach this mark, we would require just 123 years to expand by another billion, reaching 2 billion in 1927. As the phenomenon of exponential growth goes, the years required to expand by the same interval shrank. Only 33 years were needed to reach 3 billion (1960) and 14 years to reach 4 billion (1974). Fourteen years were again required to jump to 5 billion (1987), then 12 years later the 6th billionth human arrived (1999). Today we are more than 6.75 billion, and still expanding rapidly. In 2009 there were approximately 135.5 million births and 55.7 million deaths, leading to a natural increase of around 79.8 million humans for this past calendar year.[5] This equates to 6.65 million added every month, 218,000 per day, 9,111 per hour, and 152 per minute.

As mentioned in the last section, agriculture alleviated the limited availability of food that had previously been suppressing the growth of humanity; however, in the physical world environmental resistance is always at play. The omnipresent limiting factors exist at the global scale, such as the Earth's limited supply of material resources necessary for our sustenance, as well as a limited capacity for its biosphere to accommodate the interventions and wastes of our societies. Though fears of reaching this limit have existed for centuries, there is a growing body of data suggesting industrialized society will soon be met with unfamiliar hardships, both from the demographic and ecological pathways for resistance.

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[1] (((6750 million - 15 million) / 12008 years) / 15 million) * 100 = 3.74%

[2] Mazoyer, Marcel & Roudart, Laurence. (2006). *A History of World Agriculture: from the neolithic age to the current crisis.* James H. Membrez (trans.) New York: Monthly Review Press

[3] Ibid

[4] Ibid

[5] United Nations POPClock. Retrieved September 25, 2009

Demographic Resistance

According to population projections from both the United Nations and the U.S. Census Bureau, by 2050 our planet will have some 9 billion human inhabitants.[6] [7] This equates to an expansion of the human presence on Earth by nearly half (48%) over the first 50 years of the 21st century. Renowned agronomists Marcel Mazoyer and Laurence Roudart have stated that in order to feed the incoming billions...

> *"...without undernourishment or shortages, the quantity of vegetable products designated as food for humans and domestic animals will have to more than double for the whole world. It will almost have to triple in the developing countries, more than quintuple in Africa, and increase more than ten times in several African countries."*[8]

In respect to this population increase, the United Nation's Food and Agriculture Organization (FAO) has warned that if more land is not utilized for food production, 370 million people could face famine by 2050.[9] The FAO specifically calls for the creation of 120 million hectares of additional farmland in the developing world, particularly sub-Saharan Africa – three times the area of arable land currently in use in Canada.[10] [11]

Unfortunately, studies on human land use suggest the prospects of expanding agricultural lands to account for the incoming population will be severely limited. As of 2005 39% of the Earth's land surface is dedicated to agriculture (12% cropland, 27% pasture), while just 29% remains as forest or grassland habitat.[12]

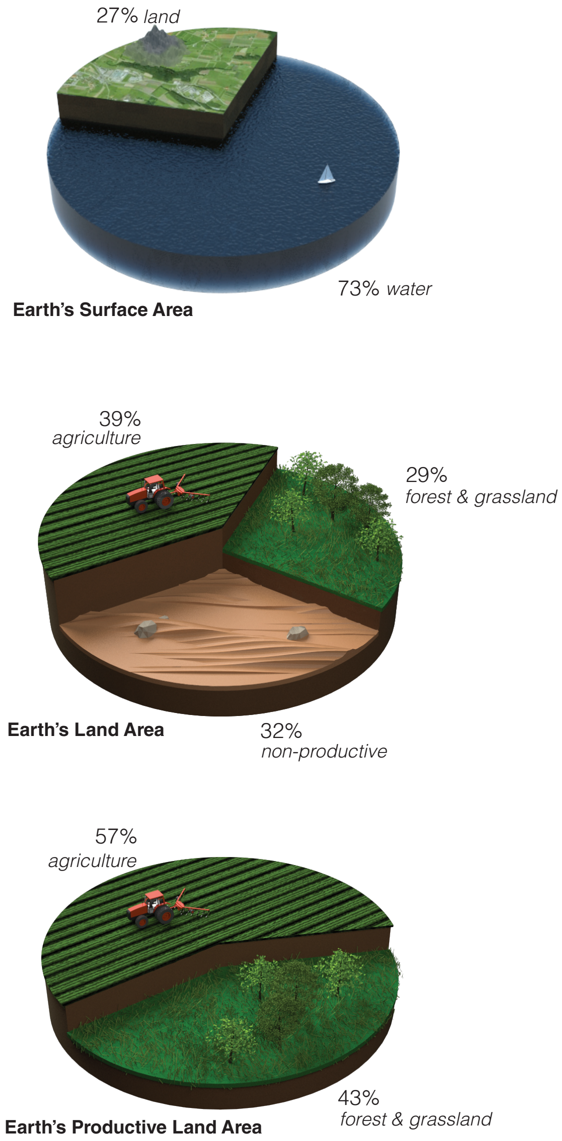

Fig 1.19
Breakdown of global land cover

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[6] United Nations Population Division. 1999. *The World at Six Billion.* http://www.un.org/esa/population/publications/sixbillion/sixbilpart1.pdf. Retrieved on August 27, 2008.

[7] U.S. Census Bureau (2009) International Database (IDB)

[8] Mazoyer & Roudart, *History of World Agriculture*

[9] Food Production Must Rise 70%. *BBC News.* (2007, October 12) http://news.bbc.co.uk/2/hi/europe/8303434.stm

[10] Food and Agricultural Organization. (2009). *2050: A Third More Mouths to Feed: Food Production Will Have to Increase By 70 Percent – FAO Convenes High-Level Expert Forum.* http://www.fao.org/news/story/0/item/35571/icode/en/. Retrieved March 11, 2009

[11] CIA World Factbook, Canada. Retrieved June 12, 2009.

[12] Land Use and Human Settlements. (2005). World Resources Institute. http://multimedia.wri.org/wr2005/072.htm. Retrieved April 18, 2009

Fig 1.20
Results of a fertilizer demonstration by the Tennessee Valley Authority in 1948

Discounting the remaining 32% of land that consists of mountains, deserts, ice, and other land that cannot support vegetation, humans have already consumed approximately 3/5ths of the landmass that could possibly sustain soil-based agriculture. Of the biologically productive land that remains, much of it is too steep, wet, dry or lacking in essential soil nutrients for high-yield agriculture to flourish.[13]

The largest unexploited sources of biologically productive land exist within the tropical rain forest, a biome that is largely unsuited for conventional agriculture. The high precipitation rates of tropical ecosystems tend to leach the topsoil of nutrients vital to conventional agricultural crops, while around a third of all tropical soils are simply too acidic for conventional crops to take hold.[14] [15] As such, agricultural expansion into tropical rainforests tends to be of the slash and burn variety, which involves using the ash remains of a clear-cut mature forest patch as a nutrient source for domestic crops. Since the fertility of the ash-infused soil lasts for only a season or two, slash and burn farmers continuously consume forested area to maintain a stable supply of food. Not only does this prove disastrous to global biodiversity, it also results in an agricultural method that is far more land-intensive, and in that far less efficient, than existing forms of agriculture.

Consequently, the hope of expanding food production lies predominantly within the initiative to increase the productivity of farmland already in use. This is achieved primarily through the advancement of agricultural technology, as has been demonstrated through the ongoing evolution of industrial farming methods over the past half century. Collectively known as the Green Revolution, these technologies include the use of artificial irrigation, chemical fertilizers and pesticides, and high-yield disease resistant crop varieties – such as Norman Borlaug's "dwarf" wheat and rice hybrids.
From 1961 to 1983 the wheat, corn, rice, and soybean yields per hectare increased at an average rate of 2.81% per year; at least matching and generally

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[13] Buringh, P. (1989). Availability of agricultural land for crops and livestock production. D. Pimental and C.W. Hall (eds.) *Food and Natural Resources*. San Diego: Academic Press, p.69-83

[14] Mazoyer & Roudart, *History of World Agriculture*

[15] Ibid

exceeding the population growth rate of that period.[16] The effects of the Green Revolution were most strongly felt in developing nations like Mexico, India, and Pakistan who evolved from severe (or projected) malnourishment in the 1950s to achieve food security by the 1960s and food surpluses geared for export by the 1970s.

For the past 26 years, however, this trend of increasing land productivity has slowed considerably; suggesting high-yield agricultural technologies may be approaching their saturation point for improving global food yields. From 1983 to 2005 the growth rate of the staple crops above dropped to just 1.57% per year, below the population growth rate of the same period (1.68%).[17] [18] Per capita production of the "big three" grains - wheat, rice, and corn - peaked in 1984 at 342 kilograms per person; over the succeeding 22 years it dropped to 302 kilograms per person – a 12% decrease in per capita production.[19]

As a result, seven of the first eight years of the 21st century saw world grain production fall short of consumption, dropping world carryover stocks of grain to their lowest levels in decades.[20] Subsequently, the incidence of chronic malnutrition has begun to increase once again after decades of decline, rising 4% from 1996 to 2003.[21] As of October 2009 1.02 billion people suffer from undernourishment throughout the world, the most ever experienced by the human race.

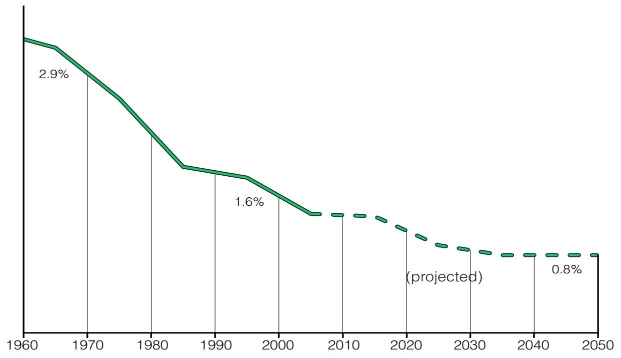

Fig 1.21
Average annual rate of growth in world grain yeilds per decade

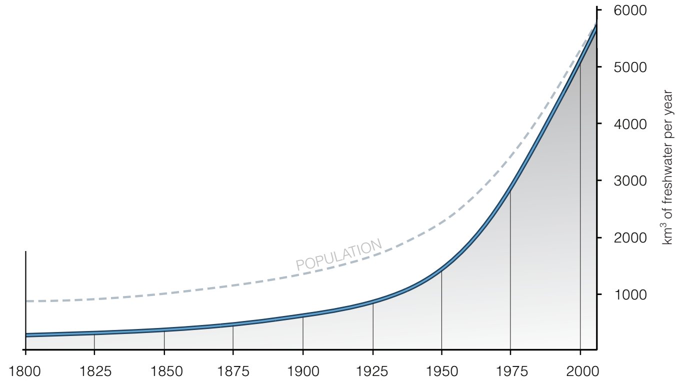

Fig 1.22
Human water usage as compared to population growth

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[16] Cline, William R. (2007) Global Warming and Agriculture: Impact Estimates by Country. Washington: Center for Global Development and Peterson Institute for International Economics.

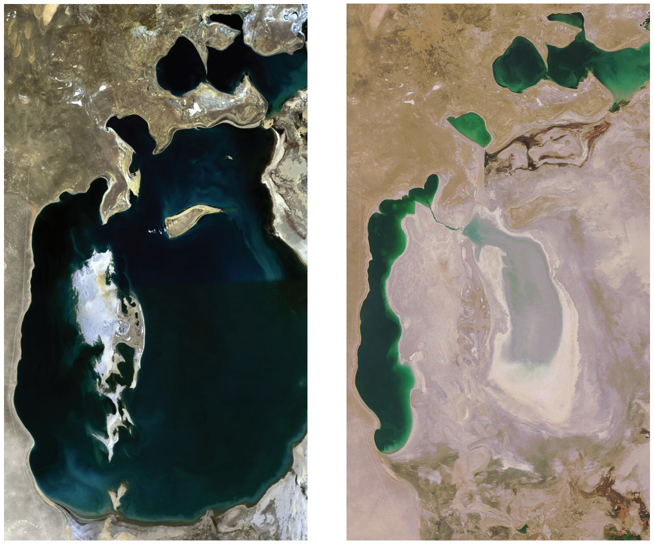
[17] Ibid

[18] U.S. Census Bureau POPClock Projections, Retrieved April 20, 2009

[19] Earth Policy Institute using 1960-2007 grain data from U.S. Department of Agriculture (USDA), Production, Supply & Distribution, electronic database, www.fas.usda.gov, updated 11 January 2008; 1950-1959 grain data from USDA, cited in Worldwatch Institute, Signposts 2001, CD-Rom. Washington, DC: 2001; population from United Nations, World Population Prospects: The 2006 Revision. New York: 2006.

[20] Ibid

[21] Brown, Lester R. (2008). *Plan B 3.0: Mobilizing to Save Civilization.* New York: Earth Policy Institute, W.W. Norton & Company.



September 1989

October 2008

Fig 1.23
Once the fourth largest lake in the world (over three times the area of Lake Ontario), the Aral sea has been steadily shrinking since the 1960's after its replenishing rivers were diverted by the Soviet Union for irrigation.

In addition to this troubling trend of slowing yield increases, the future of conventional agriculture becomes even more uncertain when considering the projected availability of resources vital to its operation – particularly freshwater, fossil-fuel, and suitable soils. Though only 17% of the world's aggregate arable land is irrigated, it produces a disproportionate 40% of our total food production.[22] Prospects to increase food yields in the future rely heavily on expanding this percentage of irrigated arable land. However, the existing use of freshwater for irrigation already appears to be breaching the limit of sustainable water usage.

As of 2002, an astonishing 72% of all human water consumption was for the purposes of agriculture, the vast majority of which for irrigation.[23] Those countries with the highest percentages of irrigation are showing clear signs of water table depletion. In southern India groundwater levels declined 25 to 30 metres during the 1970s alone due to the intensification of irrigation for agriculture.[24] China has experienced similar freshwater depletions due to its well over half a million square kilometres of irrigated land, more than twice that of the USA.[25] The Ogallala aquifer, one of the world's largest spanning some 450,000 km^2 below central USA, is being consumed 3x faster than its replenishment rate, while in Arizona some aquifers are being consumed 10x faster than their replenish rates.[26] [27] On average, the United States as a whole consumes 25% more freshwater than its water cycle can replenish.[28] Many developing countries earmarked for a future conversion to high-yield agriculture, such as those in Northern and Southern Africa, the Middle East, and Central

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[22] Pfeiffer, Dale Allen. (2006). *Eating Fossil Fuels: Oil, Food and the Coming Crisis in Agriculture.* Gabriola Island, B.C.: New Society Publishers.

[23] Rosegrant, et. al. *World Water and Food to 2025: Dealing with Scarcity.*

[24] Postel, S.Â 1989.Â Water for Agriculture: Facing the Limits.Â Worldwatch Paper 93. Washington, DC: Worldwatch Institute

[25] World Factbook – Irrigated Land. https://www.cia.gov/library/publications/the-world-factbook/fields/2146.html, retrieved December 2010.

[26] Pimentel, David & Pimentel, Marcia (2004). The Future: World Population and Food Security. *Sustaining Life on Earth: Environmental and Human Health Through Global Governance.* ed. Soskoline, Colin et. al. (2007). Landham, MD: Lexington Books.

[27] Ibid

[28] Ibid

Asia, face existing water scarcity issues that all but eliminate them as potential sites to increase worldwide land productivity.[29]

The limited availability of cheap fossil-fuel sources has been the most well documented problem for the future of agriculture because it poses the most serious consequences. Fossil fuel is undeniably the lifeblood of conventional 'intensive' agriculture. A 1994 study by David Pimentel and Mario Giampietro revealed the ratio of energy expended in the production of food – exosomatic energy – as compared to the caloric energy obtained from the consumption of food – endosomatic energy – is around 10:1 for the high-yield agricultural systems of the developed world.[30]

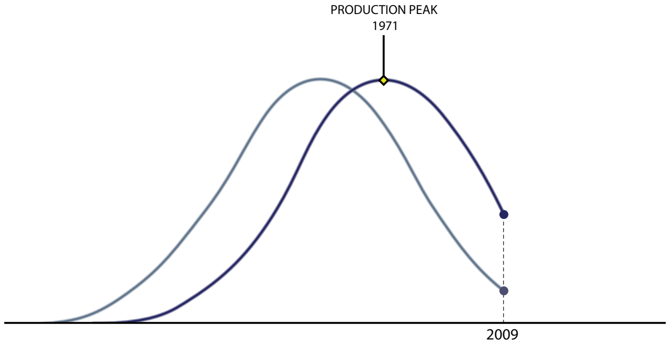

Fig 1.24
Peak oil, United States of America

This massive energy imbalance has been able to persist due to its subsidisation by our consumption of Earth's fossil fuel stockpiles. Conventional agriculture utilizes fossil fuel energy at virtually every stage of production. Natural gas is the primary feedstock for the production of ammonia, via the Haber Bosch process, for use in inorganic fertilizer production. It is often cited that the worldwide use of fertilizer is currently responsible for sustaining roughly one-third of the current human population.[31] Gasoline, diesel, and kerosene fuels the farm machinery required to produce the food, as well as the airplanes, trucks, and trains that transport it to the consumer. Electrical energy (most of which is supplied by coal, natural gas, and other petroleum products) power irrigation systems, crop dryers, and other miscellaneous activities.

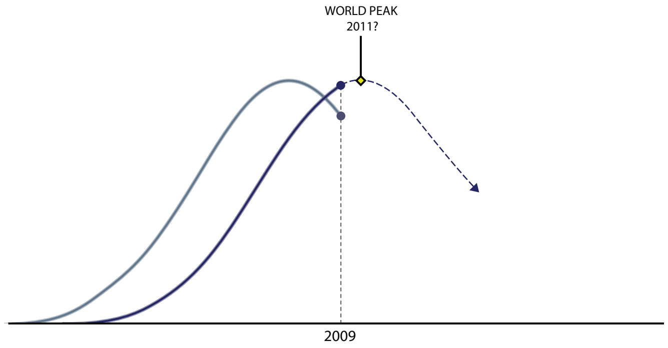

Fig 1.25
Global peak oil projected trends

Unfortunately, the age of cheap fossil-fuels will be ending in the first half of this century, with peak-oil projected to arrive in the next decade and peak-natural gas two decades later.[32] The massive energy deficit that is expected to arise will not only restrict the possibility of expanding the energy-intensive forms of

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[29] Consultancy Group on International Agricultural Research (CGIAR) http://www.cgiar.org/enews/june2007/images_06_07/story12c.gif. Retrieved March 6, 2009

[30] Giampietro, Mario & Pimentel, David. (1993). *The Tightening Conflict: Population, Energy Use, and the Ecology of Agriculture.* Ed. Grant; L. Negative Population Forum. Teaneck, NJ: Negative Population Growth, Inc.

[31] Wolfe, David W. (2001). *Tales From the Underground: A Natural History of Subterranean Life.* Cambridge, Mass: Perseus Pub

[32] Pfeiffer. *Eating Fossil Fuels*

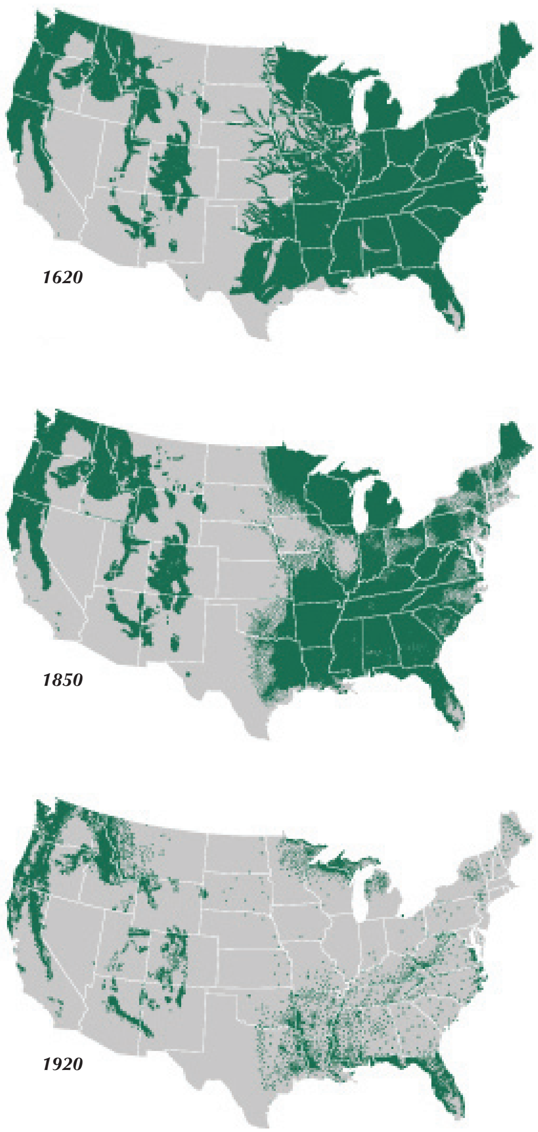

Fig 1.26
Deforestation of the continental USA

agriculture to account for population growth, but also destabilize that on which our existing population relies.

The last point to consider is the emerging 'wild card' in the future efficacy of conventional agriculture, biofuel production. Plant products have begun to fill the additional role as a source of energy due to the dwindling availability of fossil-fuel, intensifying the need for yield improvements to keep up with demand. In a report published by the FOA in 2009, it was estimated that by 2020 the industrial world could consume as much grain per capita in their vehicles as the developing world consumes per capita for food energy.[33]

Ecological Resistance

The massive expansion of agriculture to account for our growing numbers has been coupled with an equally massive alteration in the ecology of the Earth. Consider our impact on forest ecosystems. As mentioned above agriculture now accounts for nearly 3/5th of all vegetative land on Earth, meaning we have appropriated well over half of the ecologically productive habitat that once existed. Though developed nations in North America and Europe tend to have stable or increasing forest covers today, they are small fractions of the forested habitat that existed before their principle period of development. Mature old-growth forests once covered half the United States' land area and nearly all of Europe; today just 10% and 3% remain, respectively.[34] [35] While most of this conversion occurred before an understanding of ecology and the importance of natural ecosystems, its detrimental effect on the climatic regulatory mechanisms of the biosphere is just as severe.

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33 Fischer, R.A. Derek Byerlee & G.O. Edmeades (2009), *Can Technology Deliver on the Yield Challenge to 2050?* Food and Agriculture Organization of the United Nations, Economic and Social Development Department

34 University of Michigan, Global Change Program, *Global Deforestation*. http://www.globalchange.umich.edu/globalchange2/current/lectures/deforest/deforest.html. Retrieved on March 24, 2009.

35 Greenpeace International, Intact Forest Landscapes. (2006, March 21) http://www.greenpeace.org/international/en/campaigns/forests/our-disappearing-forests/intact-forest-landscapes/ Retrieved March 29, 2009

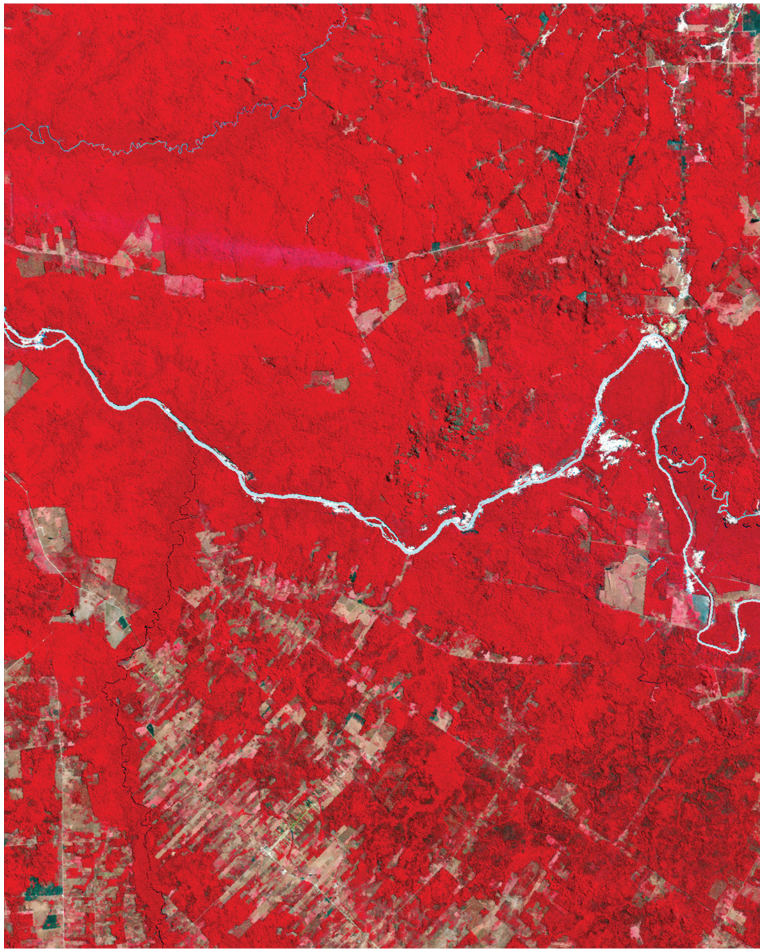


Fig 1.27
Landsat 5 image from 1992 of a section of the Amazon Rainorest in the state of Mato Grosso, Brazil. The land area visible in this image is approximately 1,600 square kilometres.

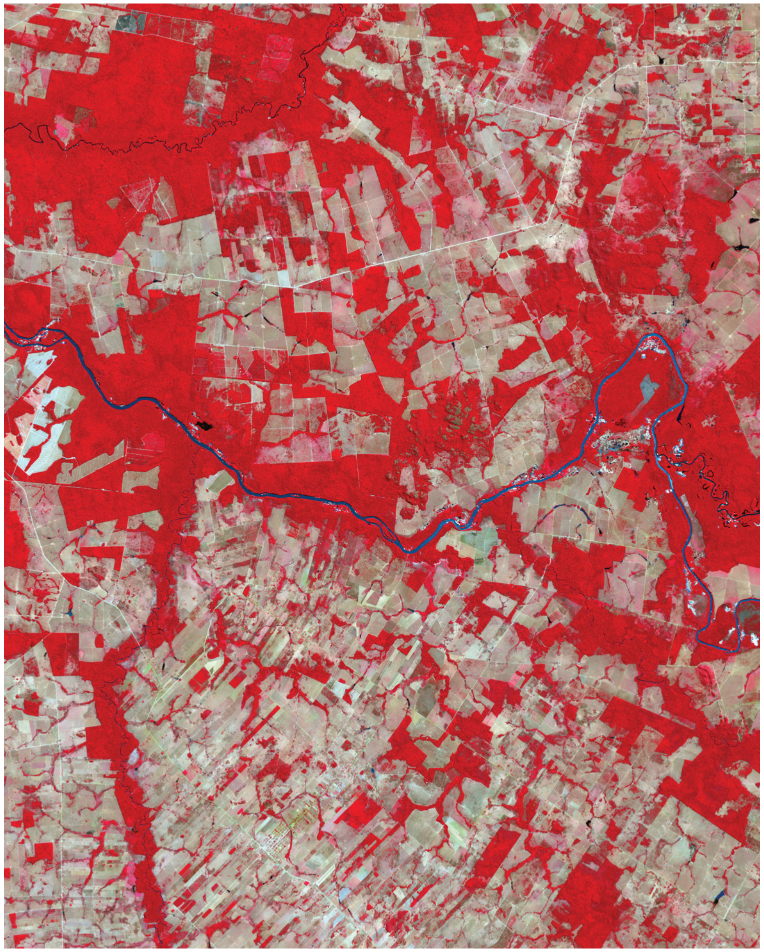
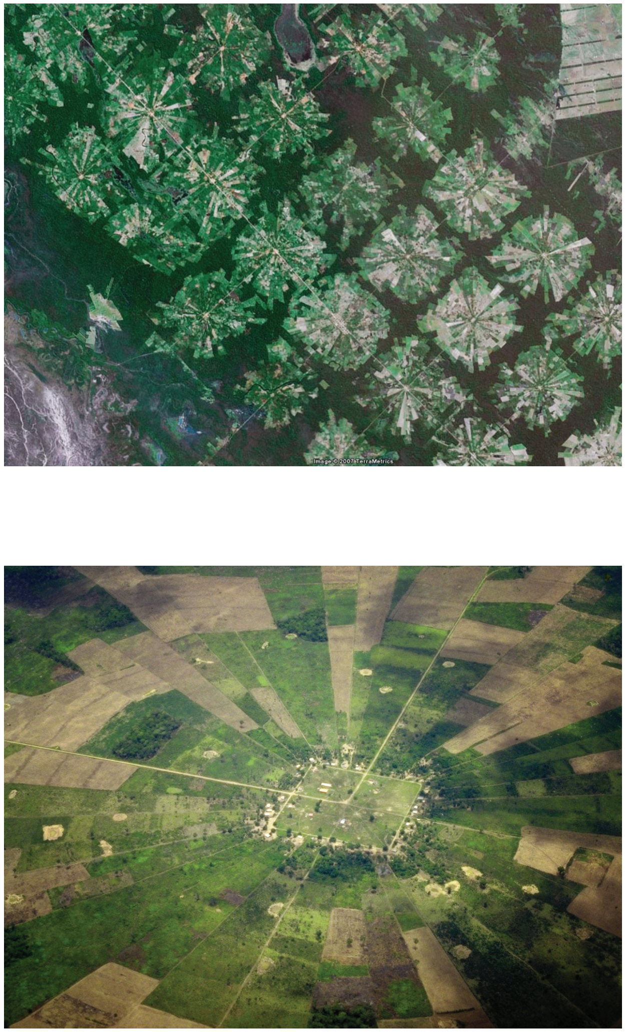


Fig 1.28
Landsat 5 image from 2006 of the same section of Mato Grosso's rainorest.

Most of the mature forest ecosystems that remain are located within the tropics, which now serve as the front line for this agricultural encroachment. It has been estimated that half of the Earth's mature tropical forests, around 8 million square kilometres of the original 16 million square kilometres that covered the planet until 1947, have now been cleared.[36] Much of this has taken place in Brazil, which until 2005 had the highest rate of deforestation in the world (which now belongs to Nigeria), and still has the largest area of forest removed annually.[37] Agricultural uses account for 95 percent of deforestation in the Amazon, most prominently the creation of pasture for cattle and, recently, the arrival of mechanized crop cultivation.

Using NASA satellite data it was discovered that in 2003, Brazil's peak year of deforestation, more than 20 percent of the Mato Grosso state's forest area was converted into arable land for soybean production.[38] In all more than 5 million square kilometres (or 13 percent) of the Amazonian Rainforest has been converted to crops and pastures since 1972.[39] Unfortunately the pervasive pressure to expand agricultural land impacts the Earth's other tropical biomes much in the same way. Within the Southeast Asian "biodiversity hotspots" alone – the Philippines, Indonesia, and Indo-Burma – cropland grew by over 1 million square kilometres from 1984-1994, nearly all of which was cleared from mature forest.[40] Renowned ecologist E.O. Wilson noted in 2002 that if current rates of deforestation persist, by 2030 only ten percent of the world's mature tropical rainforests will remain intact, with another ten percent in a severely degraded condition.[41]



Figs 1.29 & 1.30
Tierra Bajas Project in Bolivia. Satiating the global demand for agricultural products, soybean cultivation has ravaged what was once one of the largest forest formations in Latin America.

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[36] Maycock, Paul F. *Deforestation*. WorldBookOnline. Retrieved February 27, 2007

[37] World deforestation rates and forest cover statistics, 2000-2005. November 16, 2005. Mongabay.com. Retrieved April 23, 2009

[38] NASA Earth Observatory. (2006, September 19). Growth in Amazon Cropland May Impact Climate and Deforestation Patterns. Retrieved April 24, 2009.

[39] Blackburn, Harvey W. & de Haan, Cornelius. (1999). Livestock and biodiversity. In Wanda W. Collins & Calvin O. Qualset, eds., Biodiversity in Agroecosystems. Washington, D.C.: CRC Press

[40] Oldfield, S., Lusty, C., & MacKinven, A. (1998). The World List of Threatened Trees. Cambridge: IUCN.

[41] Wilson, Edward O. (2002). *The Future of Life,* New York: Knopf.

The seriousness of this phenomenon cannot be overstated. Although tropical rainforests cover less than six percent of the Earth's surface, they are home to well over half of the Earth's known plant and animal species, many of which are endemic.[42] Beyond the intuitive loss felt with the eradication of another life form, a reduction in biodiversity can destabilize an ecosystem by interrupting processes vital to their health and stability, such as nutrient recycling, water purification, and pollination. Biodiversity is further reduced by the geological and climactic consequences of deforestation. The loss of the water-sequestering root network of forested lands causes major landscape transformations by way of soil erosion and flooding, while also altering certain climactic conditions vital to native species. As hydrogeologist Jim Anscombe notes:

> *"Driven by energy from the sun, the trees pump water from the water table, through the roots, trunk and leaves, up into the atmosphere through the process of transpiration. Collectively the forest pumps millions of litres of water daily to the atmosphere."*[43]

Every year 10 million hectares of topsoil are lost to erosion[44], while another 10 million hectares become unusable due to soil salinization[45], a combined area nearly equivalent to that of Great Britain. The primary cause of this land degradation is improper tilling of arable land and excessive irrigation of arable land, respectively.[46] Like oil, the long regeneration time for the natural world to produce new topsoil renders it a limited resource. It has been calculated that approximately 500 years are required for decaying plant matter and weathering rocks to form a layer of topsoil one inch thick.[47] For the natural world to produce the six inches of topsoil necessary

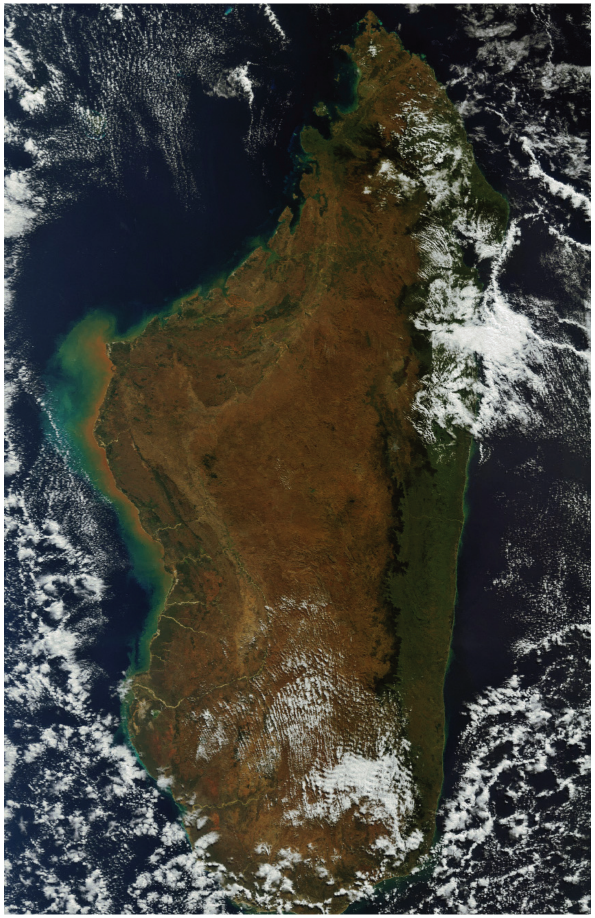

Fig 1.31
Stripped of vegetation and organic matter due to decades of slash and burn farming and over-grazing, the soils of Madagascar's high central plateau have begun eroding into the Indian Ocean (visible here on the island's western shore). In some areas as much as 250 metric tons of soil per hectare is lost every year. (Philemon Randrianarijaona, "The Erosion of Madagascar")

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[42] Baillie, Jonathan, Georgina Mace, Hillary Masundire, et al. (2005) Millennium Ecosystem Assessment, Volume 1 – State and Trends Assessment, Chapter 4 – Biodiversity. Washington, D.C.: Island Press

[43] Anscombe, Jim as quoted in Charles Mkoka's Unchecked Deforestation Endangers Malawi Ecosystems. *Environment News Service*. (2004, 16 November). Retrieved from Lester Brown's *Plan 3.0B*

[44] Pimentel, David; Harvey, C; Resosudarmo, P. et al, Environmental and Economic Costs of Soil Erosion and Conservation Benefits. *Science*. (1995, February 24), vol. 267, no.5201, p.1117-1123.

[45] Thomas, D.S.G. & Middleton, N.J. Salinization: new perspectives on a major desertification issue.*Journal of Arid Environments,* (1993, January). vol.24, issue 1, p.95-105

[46] Pimentel & Pimentel, *The Future: World Population and Food Security.*

[47] Troeh, Fredrick R., Hobbs, J Arthur & Donahue, Roy. (2004), *Soil and Water Conservation, 3rd edition*. Englewood Cliffs, NJ; Prentice Hall,

for conventional agriculture or a typical forest ecosystem to thrive, some 3,000 years must pass. As Richard Manning states from his essay *The Oil We Eat*,

> *"When we say the soil is rich, it is not a metaphor. It is as rich in energy as an oil well. A prairie converts that energy to flowers and roots and stems, which in turn pass back into the ground as dead organic matter. The layers of topsoil build up into a rich repository of energy, a bank. A farm field appropriates that energy, puts it into seeds we can eat."*[48]

Lastly, the conversion of mature forested lands into pasture or cropland drastically reduces the terrestrial environment's ability to regulate the greenhouse effect by the sequestration of carbon dioxide and production of oxygen. In James Lovelock's infamous book *Gaia: A New Look at Life on Earth* (1979) he explains how photosynthetic organisms like trees form a vital negative-feedback relationship with the composition of the atmosphere, regulating levels of oxygen and carbon dioxide. If carbon dioxide levels increase photosynthetic organisms that feed on carbon dioxide will grow more easily, consuming greater amounts of the gas while emitting more oxygen – therein resisting the atmospheric change.[49] The opposite would happen if carbon dioxide levels dropped; photosynthetic organisms would have more difficulty growing, extracting less carbon dioxide and emitting less of the overabundant oxygen. As Lovelock explains in his follow-up book *The Revenge of Gaia* (2006), the massive reduction in terrestrial forest ecosystems have made the biosphere more susceptible to potentially catastrophic climactic changes in the future.[50]

Climate change is actually expected to increase crop yields in some parts of the world, with longer growing seasons and increased precipitation in the future. However, most regions, including those that contain the nations most susceptible to food insecurity, are expected to see a marked decline in agricultural productivity. With what it considers "medium confidence", the IPCC's Fourth Assessment on Climate Change predicts by 2050 eastern and south-eastern

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[48] Manning, Richard, The Oil We Eat: Following the Food Chain Back to Iraq, *Harper's Magazine*, (2004, February)

[49] Lovelock, James. (1979). *Gaia: A New Look at Life on Earth.* Oxford: Oxford University Press.

[50] Lovelock, James. (2006). *Revenge of Gaia.* London: Allen Lane

Asia would see crop yields reduce by 20%, while central and south Asia would experience yield reductions of 30%.[51] Likewise, many African countries have projected rising temperatures would lead to a sharp reduction in the production of corn, as existing conditions have already reached the maximum temperature tolerance for certain staple crops.[52]

Figs 1.32
Eutrophication in the Gulf of Mexico. Note the turquoise algae blooms along the (from left to right) Mexico, Texas, and Louisianna coastline

Perhaps not coincidentally, the agricultural chemical most responsible for ecological degradation is the one most vital to sustain consistently high yields - fertilizer. In order to maintain the high productivity of conventional agriculture, the various nutrients and organic matter that are "exported" through crop harvest must be constantly replenished artificially. This is done through the application of nitrogen and phosphorous fertilizers, obtained from artificial "inorganic" sources (Haber-Bosch process) or natural "organic" sources (e.g. manure). Despite the nomenclature that would suggest otherwise, the use of either can lead to equally severe ecological consequences.

When farmers apply fertilizers to cropland, significant amounts may be washed away by heavy rains to inadvertently fertilize something else; an event known as eutrophication. Just as the intended application of fertilizers results in the increased growth of terrestrial vegetation, the unintended application of fertilizers in rivers, lakes, and costal ecosystems have led to localized explosions in the growth of algae and aquatic vegetation. Positive as this may sound, the artificially-increased photosynthetic life depletes oxygen levels in the water, causing what are colloquially referred to as "dead zones" that stifle native marine life.

The Mississippi River's heavily fertilized effluvium has produced a dead-zone in the Gulf of Mexico the size of New Jersey.[53] The UN Environment Programme reported 146 dead-zones globally in 2004, ranging from less than a square

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[51] IPCC; Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

[52] Vidal, John In the Land Here Life is on Hold. (2005, June 30). *The Guardian.* http://www.guardian.co.uk/climatechange/story/0,12374,1517935.html.

[53] McNeely, J. & Scherr, S. (2003) *Ecoagriculture: strategies to feed the world and save wild biodiversity.* London: Island Press. p.71

kilometre in size to over 70,000 square kilometres. As of 2008 the number of reported dead-zones had grown to 405, affecting a total of 245,000 square kilometres of ocean habitat.[54]

These trends indicating the decline of both aquatic and soil-based ecosystems provide strong evidence that humanity's agricultural production has degraded natural systems at a rate well beyond the pace of their regeneration. Likewise, the declining availability of the natural resources necessary for conventional agriculture, such as soil, water, and fossil-fuel, pose a significant limitation to the future efficacy of the conventional high-yield agriculture modern human society depends on.

Logically one can deduce two sobering points from this situation. Firstly, the continued expansion of conventional agriculture to satiate our growing population will at some point in the future alter the character of the Earth's ecosystems in a manner catastrophic to the continued progression of human society. On the other hand if we limit agricultural expansion to avoid the decline of natural systems we would be unable to feed our growing population, yet again leading toward a demographic catastrophe. This demographic-ecological paradox is perhaps the most poignant illustration of the incongruence of our geometrically progressing society and the limited environment within which we exist. If human society does not evolve in a manner that resolves this paradox, our future will undoubtedly be marked by the re-emergence of environmental resistance and the end of our age of universal progression.

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[54] Diaz, R.J., & Rosenberg, R. (2008). Spreading dead zones and consequences for marine ecosystems. *Science* vol.321, no.5891 p.926-929

CHAPTER 4 - CONVENTIONAL AGRICULTURAL REFORM

With respect to the evident incongruity between human society and the Earth's ecology described in the previous chapters, two vastly different strategies for agricultural reform have emerged. One of these methods – agroecology – is attracting significant interest from those disillusioned by the large-scale agricultural practices of the past half century. Though agroecology has more than one meaning, it is most often used as an umbrella term to denote more eco-centric forms of food production like permaculture, biodynamic agriculture and organic agriculture. These strategies contend food production should be sensitive to the local environment and social populace, rather than simply focus on maximizing food production at any cost. Foregoing intensive agriculture's package of fossil-fuel powered farm machinery, artificial fertilizers, and hybrid crop varieties, agroecology promotes initiatives like no-till farming, organic fertilizers, responsible irrigation, the use of native crop varieties, and the introduction of biodiversity into farming ecosystems.

Figs 1.33
Volunteers pick black beans at the Instituto de Permacultura e Ecovilas da Pampa (IPEP) in Bagé, Brazil.

In the most comprehensive comparison of agroecology to conventional agriculture to date researchers provide concrete evidence that organic/biodynamic farms are able to produce reliable yields while improving both the fertility of the soil and the biodiversity of the local ecosystem. Conducted by the Research Institute for Organic Agriculture in Frick, Switzerland over a 21 year period ending in 2002, the findings discovered a connection between energy efficiency in cultivation practices and production efficiency in the soil. Specifically the study revealed the lower the human-induced energy inputs per unit of yield are, the higher the microbial activity in the soil per unit of yield.[1] When subjected to intensive interventions like fertilizers and pesticides, soil-based microorganisms were found to become stressed and make heavier demands on resources for their own survival. As these microorganisms are fundamental to the health of soil-grown crops, influencing everything from nutrient content to flavour, agroecology also offers an improvement of the qualitative aspects of food production.[2]

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[1] Mäder et. al., *Soil Fertility and Biodiversity in Organic Farming*

[2] Pollan, Michael. (2006). *The Omnivore's Dilemma: A Natural History of Four Meals*. New York: Penguin

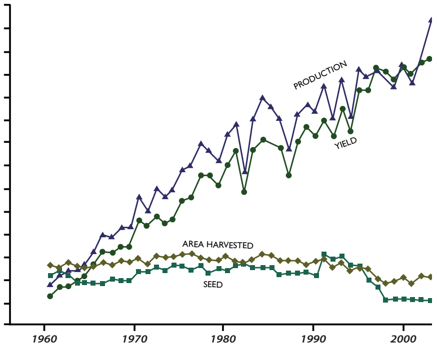

Fig 1.34
The Green Revolution Impact: comparison of total production, crop yields, area harvested, and seeds planted for the period 1961-2004. Source: FAO

At the other end of the spectrum another agricultural movement is gaining momentum; a second wave of the Green Revolution. As plant breeders now know the gene sequence of nearly all modern agricultural plants, they are using the knowledge to create more productive 'hybrid' crop varieties. Among the most important genetic-design initiatives include crops that are more drought resistant and require less fertilizer than those presently in use, a move that would not only boost yields but also reduce reliance on fossil-fuels. Though often overlooked, this strategy of increasing productivity to reduce the demand food production places on natural ecosystems can be astonishing. One study calculated that the yield increases resulting from crop productivity improvements since 1961 has forestalled the conversion of 3.55 billion hectares of natural habitat globally, including just under 1 billion for permanent crops.[3] As a comparison, the entire continent of North America contains just 2.45 billion hectares of land, and much less that would be applicable to agricultural uses.

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[3] Goklany, Indur M. (1998). Saving habitat and conserving biodiversity on a crowded planet. *BioScience*. vol. 48, no.11, p.941-953.

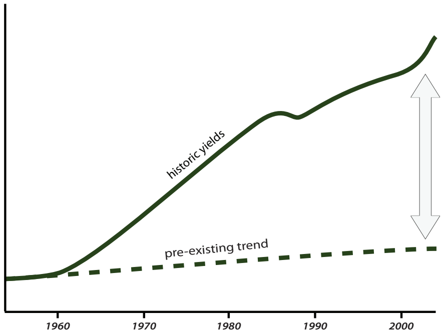

Fig 1.35
Comparison of the growth of agricultural yields due to the Green Revolution to the pre-existing yield growth trend. The land area necessary or this hypothetical "non-Green Revolution" scenario to achieve contemporary yields is 3.55 billion hectares, which is more than the land mass of Africa, the Arabian Peninsula, and Asia Minor combined

The focus of this second wave of the Green Revolution is directed squarely on the developing world. For reasons including political instability, corruption, and lack of necessary infrastructure, intensive farming failed to take-hold in certain parts of the world – most notably Africa. With a rapidly rising population and an absence of significant yield increases between 1970 and 2000, sub-Saharan Africa fell into an annual food deficit of over 9 million metric tons.[4]

Philanthropic and international financing organizations have championed the successful introduction of high-yield agriculture as a solution to sub-Saharan Africa's chronic malnourishment. Since 2006 the Rockefeller Foundation, which spearheaded the first Green Revolution, along with the Bill and Melinda Gates Foundation have donated close to half a billion dollars to fund The Alliance for a Green Revolution in Africa (AGRA).[5] Headed by former U.N. Secretary-General Kofi Annan, AGRA's initiative has already showed significant signs of success. Consider the case of Malawi; in 2005 Malawi's agricultural production was so inadequate that a third of its 13 million people required food aid to survive. Three years later, after the traditional helping of hybrid seed and fertilizer from advocates like AGRA, Malawi's farms produced an astonishing 53% surplus to their needs; allowing food to be exported to neighbour Zimbabwe for a much-needed economic stimulus.[6]

However, despite the undeniable merit of these two strategies for agriculture reform, glaring deficiencies preclude them from satisfactorily responding to the dilemmas of the coming century. Agroecology does offer a form of agriculture that elegantly reduces the negative impact food production inflicts on natural environments and local populaces; yet it does so in a way that would greatly intensify the demographic crisis of global malnutrition. In the same study by the Research Institute of Organic Agriculture noted above, the food yields

Figs 1.36
Man collecting fertilizer from government storage depot. The new-found food security of countries like Malawi is in large-part due to the subsidization of fertilizer from national governments and international organizations.

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[4] Bourne, Joel K jr. The End of Plenty, (2009, June). *National Geographic*. p.26-59

[5] Ibid

[6] Ibid

of organic/biodynamic farms were found to be an average of 20% lower per hectare than those of conventional intensive farming systems.[7] A similar study by researchers from the University of Wisconsin-Madison found crop yields of organic farms in Wisconsin to be 10% shy of those of conventional farms in similar conditions.[8]

Even if one assumed the lower figure to be more accurate, a 10% drop in global food yields would be catastrophic to the human population. If implemented today, a ten percent reduction in agricultural productivity would cause an additional 675 million mouths to go unfed, or force the conversion of 1.73 million square kilometres of natural habitat into farmland to make up the difference – just shy of the area of Mexico. In reality the numerous and distinct biomes that populate the biosphere are not equally applicable to the traditional package of crops that constitute the global diet. Therefore, the above assumption that worldwide crop production would react as favourably to organic agriculture in the state of Wisconsin is highly unlikely.

In order for the less productive agroecology methods to suffice as humanity's primary form of food production for the coming century one of two scenarios must come to fruition. In one, global food consumption must decrease considerably, which could only be achieved with a massive population decline. In the other, the land devoted to crop production must increase without converting more natural environment to farmland – an event only possible through a greater global commitment to vegetarianism. A clause for both these scenarios is the necessity of a stable population to ensure food production capacity is not exceeded in the future, which would again intensify demand for land conversion. As the arrival of any of these three events is highly improbable barring an unforeseen catastrophe, one must conclude that agroecology's future could only be as a supportive role to a more productive form of agriculture.

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[7] Mäder et. a., *Soil Fertility and Biodiversity in Organic Farming*

[8] Posner et. al., *Organic and Conventional Production Systems in the Wisconsin Integrated Cropping Systems*

The strategy to broaden the Green Revolution's implementation also suffers from serious inherent flaws. Since intensive farming methods require large inputs of limited resources, such as freshwater and fossil fuel, its success (or pervasiveness) becomes inversely proportional to its long-term efficacy. In other words, the more widespread intensive agriculture becomes, the faster the material resources it requires will be exhausted. To quote Michael Pollan,

> *"The only way you can have one farmer feed 140 Americans is with monocultures. And monocultures need lots of fossil-fuel-based fertilizers and lots of fossil-fuel-based pesticides. That only works in an era of cheap fossil fuels, and that era is coming to an end. Moving anyone to a dependence of fossil fuels seems the height of irresponsibility."*[9]

For a second wave of the Green Revolution to overcome the demographic and economic pressures of the next century it must realize a major efficiency improvement in the use of these limited resources. Hypothetically this could be achieved through the genetic engineering of crop varieties to fix their own nitrogen requirements and suffice on massively reduced water consumption; however, breakthroughs of this magnitude have proved elusive to scientists. Since the numerous agricultural innovations of the past many decades have shown little ability to free intensive agriculture from its dependence on limited resources, or even meaningfully reduce the consumption of these resources, the incongruity of intensive agriculture and our physically-limited world becomes apparent.

Of course, this is to say nothing of the serious ecological ramifications of advancing intensive agriculture. As addressed in the previous chapter, intensive farming's chemical buffer to the natural limits of food production has a long legacy of tainted soil, depleted aquifers, and degraded aquatic ecosystems throughout the world, while also being a major contributor to greenhouse gas emissions. Thus, any plan to further these methods could only exacerbate the troubling phenomenon of ecological destabilization.

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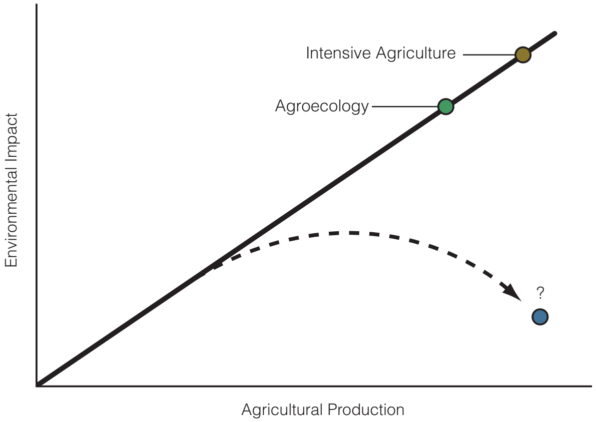
[9] Bourne, *The End of Plenty,*

CHAPTER 5 - DECOUPLING AGRICULTURE

The failures of agroecology and intensive agriculture noted in the previous chapter could be summarized by their inability to break from the long-standing correlative relationship that exists between food production and ecological impact. As exemplified, the larger food yields of intensive agriculture are achieved through practices that clearly escalate the destruction of the ecological world. Inversely, the more ecologically-benign farming methods employed by agroecology suffer from a notable reduction in the volume of food production. This echoes the more familiar correlations between human productivity and environmental pressure found elsewhere in our economies, such as a nation's per capita gross domestic product (GDP) and CO_2 emissions, or more generally its human development index (HDI) and ecological footprint.[1] [2] [3] [4]

This inconvenient paradox of modern industrial society exists because our relationship to the natural environment has not progressed in step with our extensive cultural development. Unlike all other Earthly organisms humans have developed the capacity to overcome our environmental limiting factors to increase our numbers and resource consumption at an exponential rate. Like all other organisms, however, humans still rely on the natural environment to derive the nutritional and material resources necessary for our society's existence and to process the wastes produced by our life functions (e.g. sewage, refuse, emissions, etc.).



Figs 1.37
Hypothetical depiction of the correlation between agricultural productivity and ecological degradation.

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[1] World GDP (PPP) & Country population, World Economic Outlook Database-October 2009, International Monetary Fund.

[2] US Department of Energy's Carbon Dioxide Information Analysis Center (CDIAC)

[3] Human Development Report (2006). United Nations: Development Programme. hdr.undp.org. Retrieved on June 22, 2009.

[4] Global Footprint Network. Ecological Footprint Atlas 2009. (2009, November 24).

Figs 1.38
Sir Thomas Malthus

Malthusianism versus Cornucopianism

At the heart of the two aforementioned strategies for agricultural reform lie two competing philosophies for resolving the conflicting goals of human progression and ecological stability. The view most in-line with agroecology contends that the introduction of new limiting factors to suppress human growth is the best path to achieve sustainability. Those adhering to this view, such as prominent environmentalists Paul Ehrlich, Edward O. Wilson, and Lester Brown, have suggested "top-down" government restrictions could create the desired limiting forces for human society in lieu of a superior environmental resistance.[5] [6] [7]

The intellectual touchstone of this viewpoint continues to be the work of 18th century demographer Thomas Malthus. In his infamous treatise *An Essay on the Principle of Population* of 1798, Malthus first presented the notion that humanity's tendency toward exponential population growth will ultimately exceed the Earth's capacity to accommodate agriculture. The result, which would involve a return to subsistence-level conditions characterized by widespread malnutrition, disease, and strife, has since become known as a Malthusian Catastrophe.

To support this logic "Malthusians"[8] often point to the decline of ancient civilizations like the Sumerians, Mayans, and Easter Islanders as evidence of the destructive capacity of unrestrained growth. In each case unbridled resource consumption exceeded their environment's capacity for sustenance, leading to a swift demise.[9] On the other hand, those historical instances where societies took steps to limit their growth to avoid ecological catastrophes have confirmed the validity of the top-down approach. As Lester Brown notes in his book *Plan 3.0B: Mobilizing to Save Civilization*,

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[5] Ehrlich, Paul R. (1968). *The Population Bomb.* New York: Ballantine Books.

[6] Wilson, Edward O. (1998) *Consilience: The Unity of Knowledge.* New York: Vintage

[7] Brown, L, *Plan B 3.0*

[8] Also referred to as Neo-Malthusians

[9] Brown, L, *Plan B 3.0*

> *"Six centuries ago...Icelanders realized that overgrazing on their grass-covered highlands was leading to extensive soil loss from the inherently thin soils of the region. Rather than lose the grasslands and face economic decline, farmers joined together to determine how many sheep the highlands could sustain and then allocated quotas among themselves, thus preserving their grasslands. The Icelanders understood the consequences of overgrazing and reduced their sheep numbers to a level that could be sustained."*[10]

Such views have led to the advocacy of zero growth economics and population control methods as essential initiatives for human society's long-term preservation. Zero growth or "steady state" economics identifies the persistent drive for economic growth as fundamentally incongruent with the limitations of planet Earth. Citing the tendency for wealth generation and its associated technological progression as the main drivers of increased material and energy consumption, zero growth economics seeks to establish a new economic paradigm that is harmonious with a limited, stable environment.

On the topic of population control this has involved advocating the subsidy of contraceptive devices and abortions in the developing world, as well as more controversial family planning initiatives, like China's one-child policy.[11] At the more extreme end, Paul Ehrlich and others have even endorsed the introduction of "compulsory birth regulation" where contraceptives would be added to the water and staple foods to make all people sterile. Afterward, doses of the antidote would be rationed at the discretion of a government body to produce the desired family size.[12] With such measures in place to achieve zero population growth, the human-ecological interface could then be transformed by functionally "integrating" human and ecological systems, as with agroecology.

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[10] Brown, L, *Plan B 3.0*

[11] Connolly, Matthew. (2008) *Fatal Misconception: The Struggle to Control World Population*. Cambridge, Mass: Belknap Press

[12] Knudsen, Lara. (2006). *Reproductive Rights in a Global Context: South Africa, Uganda, Peru, Denmark, United States, Vietnam, Jordan,* Nashville: Vanderbilt University Press,

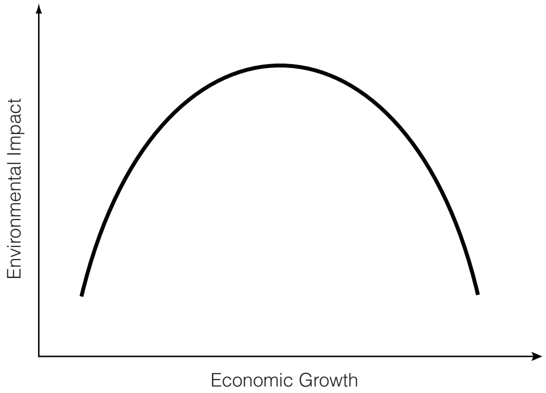

Fig 1.39
Hypotheical depiction of an Environmental Kuznets Curve.

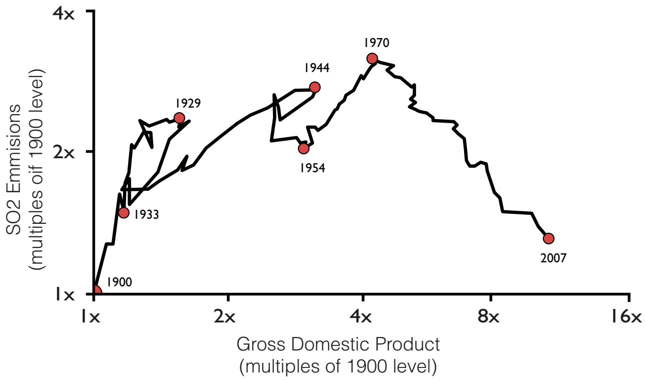

Fig 1.40
Empirically-observed Environmental Kuznets Curves tend to be far more irregular than the hypothetical smooth parabola, as in this chart depicting the sulfur dioxide emissions in the United States as a measure of wealth.

Alternatively, the philosophy most in line with the production-oriented intensive agriculture has an all-together different interpretation of the effect of growth. “Cornucopians”, such as economist Julian Simon, have suggested humanity’s sustained growth is ultimately a positive phenomenon, observing how “bottom-up” emergent technologies and behaviours (i.e. memes) have the capacity to reduce our reliance on natural resources and improve human society’s resilience.

Proponents of this viewpoint tend to note how symptoms of overpopulation, like resource scarcity, are not a product of the number of individuals a species may have but rather the efficiency with which the species interacts with its environment (resource consumption, waste production, etc). This is why in the late Pleistocene human population growth is believed to have been stifled at just 15 million individuals globally, owing to their inefficient resource collection methods.[13] This leads to the logical, though hypothetical proposition that the human population could continue to expand indefinitely as long as technology improves the efficiency of our interaction with the environment at an equal or faster rate.

Practically, however, there is a limitation to the extents to which resource use efficiency can be improved, creating an inevitable ceiling to demographic expansion on Earth. In response to this cornucopians turn to a recently observed trend known as the demographic-economic paradox, which indicates population growth is correlative to a society’s economic conditions. Though in Malthus’ era the most resource-advantaged societies had the highest population growth rates, modern human societies have evolved such that this is no longer the case. In fact, those countries with the most favourable economies today are the ones with the lowest fertility rates, while those in the initial stages of development have the highest.

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[13] Brown, A, *Feed or Feedback*, p.28

Acknowledging this trend cornucopian logic contends that, due to its associated social and technological evolution, the environmental impact of economic progress is not exponential but rather parabolic. Much like the example of fertility above, other instances of environmental impact (water pollution, air pollution, deforestation, ozone-depleting emissions, etc.) have been shown to rise and then subside throughout the process of economic growth. The theory, which is known as the Environmental Kuznets Curve (EKC), suggests reductions in environmental impact are actually emergent properties of developing economies, rather than in linear opposition as commonly perceived.

Critics of the theory point to those environmental impacts that have failed to subside along with fertility and pollution in the developed world, such as CO^{2} emissions and total material consumption. In response, supporters of EKC theory note that individual factors of environmental impact would likely have distinct economic thresholds before the inverted relationship begins to form. For instance, the conditions necessary to develop technology able to efficiently harness renewable energy is clearly more wealth-intensive than that required to impose dumping bans and emissions control.

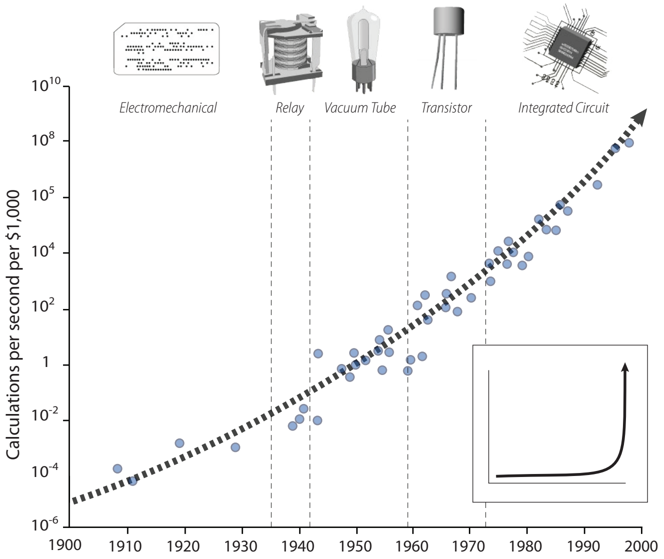

Fig 1.41
Graph depicting the progression of computing technology in relation to cost. Note the logarithmic scale on the Y-axis. The inset depicts the graph with a linear scale

Physical and Non-Physical Factors

Generally, the contrasting logic propounded in the Malthusian and cornucopian arguments are a product of their different departure points for observing human ecological sustainability. For the most part Malthusians approach the problem from the physical sciences, such as ecology, biology, or physics, where instances of perpetual exponential growth are physical impossibilities. Whether using audio feedback, nuclear reactions, or unchecked population growth as the example, invariably these systems will crash under the weight of their accelerating energy demands.

Contrarily, cornucopian viewpoints tend to originate from fields not purely rooted in the physical, such as economics. Non-physical measures of economics like knowledge can grow perpetually without the impediment of ultimate

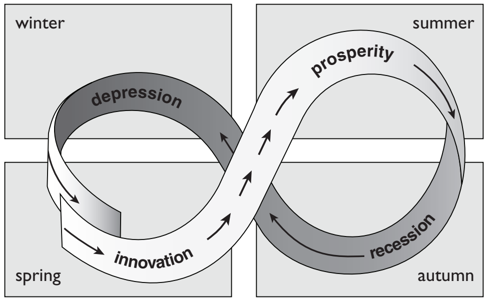

Fig 1.42
The above diagram is modified from one created by ecologist C.S. Holling to describe the four cyclical phases responsible for ecosystem resiliency. Similarly, the long-wave theory of economics describes four cyclical phases. Grouped into 'seasons', the Kondratiev Spring involves increased innovation, Kondratiev Summer involves prosperity, Kondratiev Autumn is marked by a recession, and Kondratiev Winter is a period of depression - priming the economy for further innovation.

physical restrictions. When knowledge is applied to a specific technology one can see how non-physical measures can overcome the suggested limitations presented by the physical world. Computing power, for instance, has doubled approximately every two years since the dawn of the 20th century.[14] Though it is believed the current technology for increasing transistor counts, called photolithography, will have reached its physical limitation by around 2019, the trend predicts a new paradigm will emerge – just as the existing integrated circuit board technology surpassed limitations of transistor-based technology, which surpassed limitations of vacuum tube technology, which surpassed limitations of punch card technology.

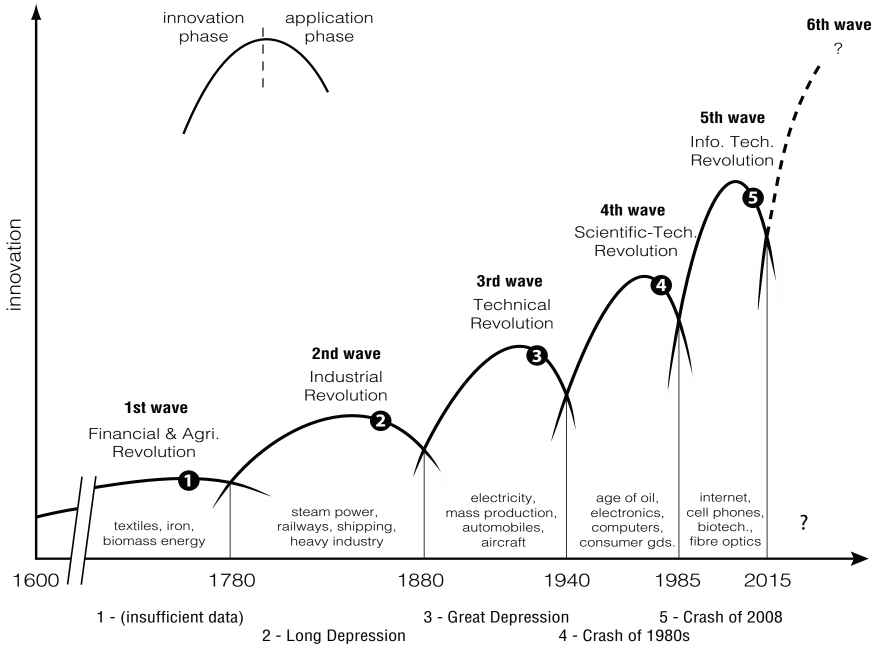

Fig 1.43 (right)
Hypothetical Kondratiev Wave progression.

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[14] Kurzweil, Ray. (2001). Essay: *The Law of Accelerating Returns*

A similar trend can be seen in long-term analyses of entire economies. It has been acknowledged for decades that technological progress largely occurs in waves – called Kondratiev Waves after the Russian economist Nikolai Kondratiev who first acknowledged their existence. According to long-wave theory, waves begin with a few pivotal innovations (e.g. steam power), which in turn spawn a vast array of other innovations (e.g. railways, steam ships, mechanization, etc.). This technological revolution leads to a period of economic boom, where new industries or commercial sectors emerge. Once the implementation of these technologies becomes saturated the economic bubble bursts, leading to the relative economic stagnation of recessions and depressions. During this period, the economic advantage of innovation returns – leading to a new 'wave' of initial innovations (e.g. internal combustion engines) and associated innovations (e.g. automobiles, airplanes, mass production, etc.).

Much like in the case of computing power, each wave of macroeconomic progression has helped liberate human initiative from presiding physical limitations. The transition from biomass burning to coal in the 18th century and coal to petroleum in the 20th century marks an exponential transition in energy density; coal is three to four times more volume-efficient than wood, and oil is three to four times more volume-efficient than coal.[15] Obviously, contemporary civilization would be physically impossible had this transition not occurred. It has been calculated that if the United States obtained all its current energy needs from burning wood, its forest cover – the fourth largest in the world – would be exhausted in just one year.[16] [17]

Although the transition to fossil-fuels is universally regarded as a primary cause of environmental impact today, it must also be acknowledged that it is currently facilitating the innovation of other energy-harnessing systems that will someday replace fossil fuels – lending support for the Environmental Kuznets Curve theory. Just as integrated circuit board computers will be central in realizing the

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[15] Young, H.E. (1980). Biomass utilization and management implications. *Weyerhaeuser Science Symposium* 3, Forest-to-Mill Challengers of the Future. Weyerhaeuser: 16

[16] Gibbs, Jeff. Green Nightmare: Burning Biomass is Not Renewable. (2009, December 17). *Huffington Post*

[17] Mongabay.com - *New study confirms continuing forest loss in most countries* http://news.mongabay.com/2006/1113-forests.html. Retrieved April 20, 2009

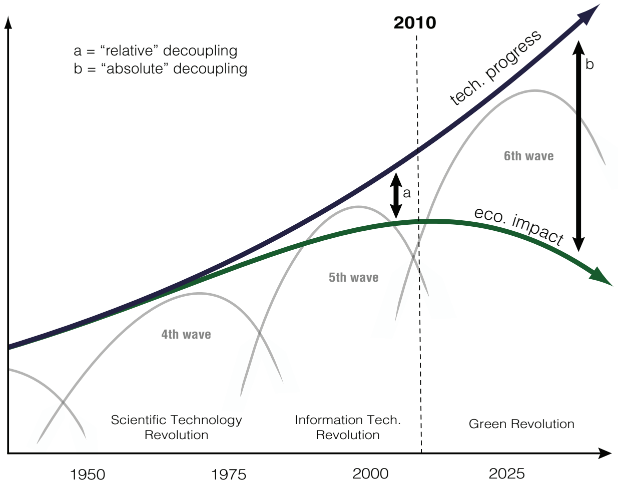

Fig 1.44
A comparison of the relationship between Kondratev Waves and the Environmental Kuznets Curve

next wave of computer power (e.g. quantum computers), fossil fuels have enabled the industrial, technological, and ironically, environmental conditions necessary for efficient ecologically-benign technologies to emerge.

Since the collapse of the global economy in 2008 and arrival of new resource limitations, many economists believe we are in the transition phase to a new Kondratiev Wave – the sixth since the 17th century according to political scientist Daniel Šmihula.[18] While speculation abounds on the character of this next wave, expectations of the end of cheap oil, water shortages, and increasing food insecurity suggest it will consist of innovations that will evolve our interaction with the natural world to better accommodate our exponentially progressing nature. Specifically this would involve technology that can disengage human productive chains from their dependence on the natural world's material resources and waste processing capacities – a process referred to as ecological "decoupling".[19]

Environmental Decoupling

The concept of decoupling first entered the modern environmental discourse in 1994 with the Factor 10 Club's *Carnoules Declaration*. The initiative called on industrialized nations to increase their resource productivity by, as the group's name indicates, a factor of ten – and presumably decrease their resource consumption by a similar magnitude. As the declaration states,

> *"It has been argued that economic activity is tied tightly to consumptive use of materials. To cut back on the one can only be accomplished by cutting back on the other. We challenge this notion. We believe that, while "traditional" economic growth is linked to materials and energy*

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[18] Šmihula, Daniel (2009). *The waves of the technological innovations of the modern age and the present crisis as the end of the wave of the informational technological revolution:*. Bratislava: Studia politica Slovaca

[19] This is also referred to as dematerialization.

> *use, many opportunities exist for increasing the productivity of materials and energy use without sacrificing real human welfare. In effect, we suggest that the productivity of materials and energy is the key."*[20]

Subsequently a series of influential publications have expanded on the concept by exploring hypothetical pathways to dematerialize human society. These include *Factor Four: Doubling Wealth, Halving Resource Use* (Lovins, Lovins, von Weizsäcker, 1997), *Cradle to Cradle: Remaking the Way We Make Things* (Braungart, McDonough 2002) and *Natural Capitalism: Creating the Next Industrial Revolution* (Lovins, Hawken 2003). At the heart of each publication lies the message that continued technological advancement can allow the dual benefit of an increase in material wealth and decrease in environmental impact.

The first fifteen years of dedicated study of environmental decoupling and its wider field of industrial ecology has introduced or advanced many potential technological leaps for the next Kondratiev Wave. These initiatives can be categorized as either, (a) synthesizing consumables, (b) increasing resource productivity, or (c) reprocessing wastes. Each category targets a different "trophic level" of industrial metabolism, namely (a) extraction/production, (b) consumption, and (c) waste processing, with the aim of converting their existing linear association into the more self-sustaining cyclical model of natural systems.

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[20] Factor 10 Club, Carnoules Declaration (1994), http://www.factorten.co.uk/

Fig 1.45
Israeli photovoltaic firm ZenithSolar has developed a system of rotating solar dishes capable of converting 75% of solar energy into electricity - a factor vastly superior to the conversion rate of conventional solar cells. Due its its inexpensive composition, primarily of mirrors, the cost per watt of the systems is comparable to that of fossil-fuel sources. Source: Christian Science Monitor, April 28, 2009

Synthesizing consumables is the process of substituting the natural capital that is demanded by society with an efficient engineered alternative with little or no environmental impact, in effect dematerializing production. The most recognized technologies in this initiative are the many emergent sources of renewable energy generation. Replacing fossil-fuel consuming, greenhouse gas emitting sources of energy with non-consumptive, non-emitting technology like nuclear, solar, and wind power would effectively disassociate human energy production from environmental impact.

The synthesis of consumables can also occur as an emergent property of other seemingly unrelated technologies. For instance, the maturation of computing technology has enabled an immaterial digital media to increasingly reduce the role of the material-intensive paper media.

Waste reprocessing technologies effectively mimic the role of "decomposers" in the resource metabolism of ecosystems by conditioning wastes into usable material inputs that sustain the 'producing' entities of the system. This reduces the environmental impact of economies by reducing both the demand for raw material inputs and the incidence of waste. An elegant example of this is biological wastewater filtration systems, which mimic the natural environment's water purification processes to redirect would-be waste water back into human use.

For solid materials, recycling has been the general path for recirculating resources within economies for millennia. Recently the emergence of "cradle to cradle" product design introduces a way to markedly increase the incidence of recycling within industrial economies. The concept involves creating a complete life-cycle map for every component and all packaging associated with a product to ensure each will either return to the natural ecosystem through biodegradation or be recycled indefinitely.[21]

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[21] McDonough, William & Braungart, Michael. (2002). Cradle to Cradle : remaking the way we make things. New York: North Point Press

An entirely different strategy has emerged in the form of plasma arc waste disposal. The technology, called plasma arc gasification, enables the conversion of all forms of refuse into electrical energy and usable base resources, like water, metal, and industrial aggregates – all with a minute fraction of the emissions that would otherwise have escaped from a landfill solution.[22] This advanced form of element recycling introduces the possibility of a zero-refuse society, where all material resources consumed by humans could easily be rechanneled back into industrial processes - in contrast to the logistical difficulties of cradle to cradle design.

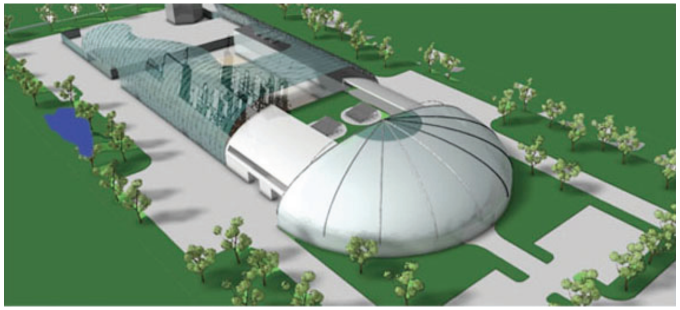

Fig 1.46
New plasma arc gasification plant proposed by Plasco Energy for the City of Los Angeles, California. Building exterior and landscaping designed by Douglas Cardinal

The initiative to improve **resource productivity** has been mentioned last due to the complexities surrounding its impact on economies. On the positive side, the philosophy of engineering products or services to do "more" with "less" has obvious benefits for a society trying to reduce its load on the environment. Initiatives like energy efficient buildings and electrical appliances, fuel efficient vehicles, and resource efficient fixtures beneficially reduce the resource-intensity of the services demanded by humans.

On the negative side, initiatives to improve resource productivity have often led to the counter-intuitive phenomenon known as "rebound effects". First described in his 1865 book *The Coal Question*, economist William Stanley Jevons explained how James Watt's improvements to the productivity of steam engines ultimately exacerbated the trend of coal depletion. Though Watt's design greatly reduced the consumption of coal per unit of steam power it also rendered steam power more economically viable. This increased utility of steam power led to a significant increase in the number of steam engines, which amplified the total demand for coal and ultimately expedited its depletion

When a rebound effect worsens resource depletion as in the above example it is often referred to as the Jevons' Effect. Generally rebound effects do not worsen depletion, but rather simply diminish the positive effect an improvement in productivity has on resource consumption.[23]

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[22] Plasco Energy Group, 2008

[23] Greening, Lorna; David L. Greene & Carmen Difiglio (2000), Energy efficiency and consumption - the rebound effect - a survey, *Energy Policy* vol.28: p.389–401

Rebound effects are caused by the tendency for improvements in resource productivity to reduce the cost of services that have adverse environmental impacts. For example, increasing the fuel efficiency of automobiles beneficially reduces the fuel intensity of driving; however, because this also renders driving less costly (due to reduced fuel consumption) it tends to be accompanied by an increase in the incidence of driving. This is an example of a direct rebound effect; an indirect rebound effect could come in the form of increased commodity consumption or travelling with the savings obtained from the reduced cost of driving.

In the discussion of environmental decoupling, it must be stressed that rebound effects only have meaning when the mode of the rebound effect directly harms the environment. In contemporary economies the primary modes of rebound effects, such as higher electricity consumption, use of transportation, and consumption of commodities, all have clear environmental impacts. The more an economy is able to disassociate the service in question with harming the environment the less significance a rebound effect of that service will have.

In reference to the above example, if electric automobiles become more economically advantageous to purchase and operate than combustion engine vehicles, they too would likely result in the rebound effect of an increased incidence of use. Yet, since electric vehicles don't involve the (direct) consumption of non-renewable resources or production of harmful waste emissions currently synonymous with driving, a rebound effect involving their increased use would likely be ecologically inconsequential.[24] Likewise, if an indirect rebound effect were to involve heightened commodity consumption from a manufacturing industry sourced primarily by recycled material and powered exclusively by renewable energy its environmental impact would also be minimal.

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[24] Electric vehicles could still be indirectly coupled to non-renewable consumption if the wider electrical grid was primarily fossil-fuel based. On the other hand, if de-materialized energy dominated electricity production (renewable, nuclear), electric automobiles could also achieve indirect decoupling from environmental impact.

Lastly to mention, the reduced cost of services that drive rebound effects can be avoided by increases in the price of resource consumption – achieved through natural market forces like scarcity, as well as government intervention through taxation. For example, if the cost of electricity were to double while the electrical efficiency of home appliances also doubles, the cost of utilizing electrical appliances will remain unchanged - thus no impetus for a rebound effect - while the environmental impact would be halved. Considering our current economic scenario is expecting a series of resource price increases due to expected scarcity (i.e. fossil-fuel, water), the incidence of rebound effects will likely be less in the future.

Decoupling Agriculture

Agriculture has long represented the physical "coupling" of human society and the natural world, owing to its hybrid disposition as part ecological process and part industrial production system. Though culturally this is often viewed as a harmonious union, the environmental impact of the productive disposition of agriculture rivals that of any other industrial sector. Humanity's dominance of material utilization in the biosphere is largely defined by agriculture - accounting for over 98% of human land use[25] , 72% of human water use [26], and 22% of human greenhouse gas emissions (the most of any industrial sector).[27]

Being the industrial sector most interconnected with natural systems, it is not surprising that agriculture has faced the greatest logistical hurdles in decoupling its production from environmental impact. The aforementioned initiatives of conventional agricultural reform both concede agriculture's dependence on

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[25] (1) Global agricultural land cover = 3,789,395,200 Ha (FAO Land Use and Human Settlement Tables) (2) Urban/Industrial land cover = 65,700,000 Ha (Schneider, A; Friedl, M & Potere, D. (2009). Monitoring urban areas globally using MODIS 500 m data: new methods based on urban ecoregions Remote Sens. Environ. in review)

[26] Rosegrant, et. al. *World Water and Food to 2025: Dealing with Scarcity.*

[27] (1) Agricultural by-products - 12.5%, (2) Deforestation for agriculture - 8%, (3) Fertilizer production – 1.2% = 21.7% Sources: (1) Emission Database for Global Atmospheric Research version 3.2, fast track 2000 project, (2) UN Framework Convention on Climate Change. (2007). Investment and financial flows to address climate change, (3) Wood, Sam & Cowie, Annette. A Review of Greenhouse Gas Emission Factors for Fertilizer Production. (2004, June) *IEA Bioenergy.* Note: does not include pesticide production, food transportation, or farm machinery contributions

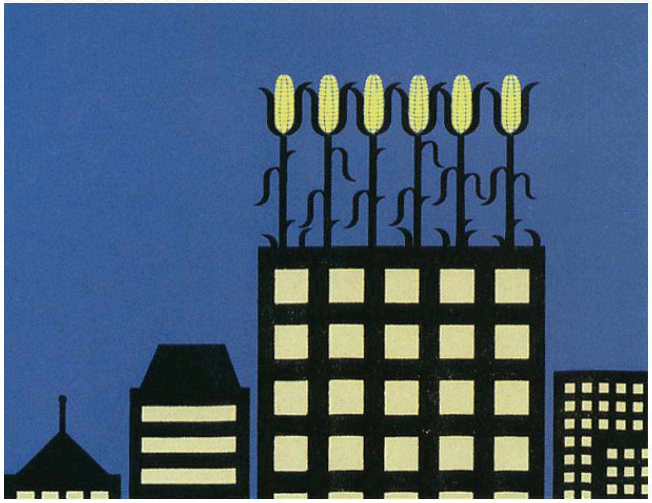

Fig 1.47
"Vertical farm" illustration by Yarek Waszul for Toronto Life magazine

natural systems, and as such fail to break the correlation between production and environmental impact. Agroecology's drive for a more harmonious integration of agriculture and ecology results in a greater dependence on land consumption, while intensive agriculture's drive for improved land productivity results in a greater material dependence on freshwater and fossil-fuels.

This unsatisfactory compromise suggests the logic of "conventional" agriculture, interconnected with natural ecosystems, may be becoming increasingly irrational; a product of a past age when the Earth's vast resource stocks were ample for human needs. Today the mounting conflict between our demographic demand for greater resource availability and ecological demand to avoid irreparably harming the biosphere presents the impetus for a new paradigm of agricultural production segregated from the natural world.

As mentioned previously, the key to decoupling industrial production from environmental impact is the substitution of natural capital with engineered alternatives, effectively absorbing former environmental externalities into the industrial realm. With the maturation of soilless/controlled environment agriculture (S/CEA) technology in the 1990s, largely due to stimulus provided by the space industry, the means to dematerialize food production finally found its technological bearings. S/CEA involves synthesizing the environmental conditions necessary for crop growth to occur, namely climactic conditions, nutrient delivery, and light energy. While S/CEA has largely been confined to a small number of food crops (e.g. tomatoes, cucumbers, peppers, and lettuce) and educational/research uses, the exponential growth of its associated technology[28] is increasingly improving the economic viability of large-scale indoor agriculture.

Springing forth from this technological milieu is the concept of vertical farming, which unites S/CEA technology with the architectural medium of multi-level buildings. Vertical farming introduces the possibility for large-scale agriculture

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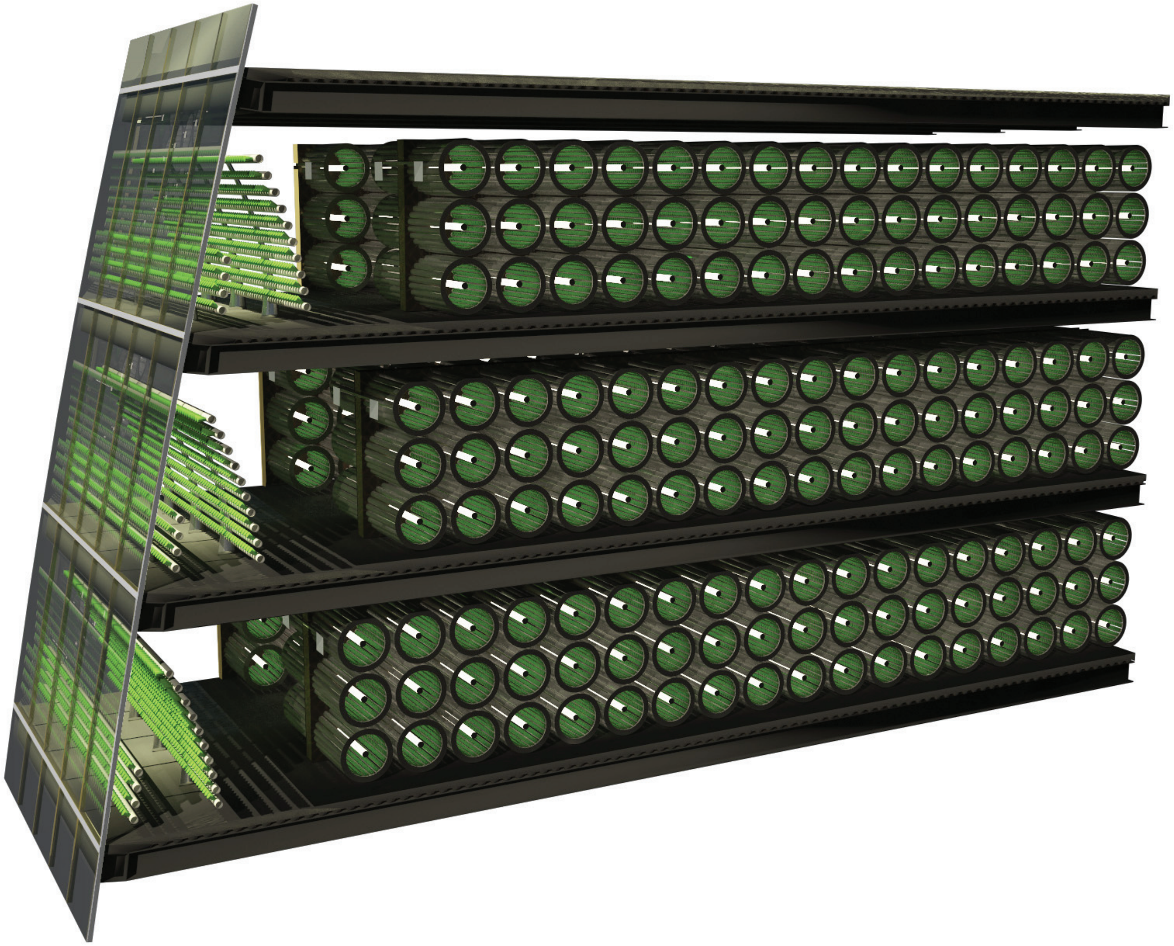
[28] Every decade since the 1960s improvements to light emitting diode (LED) technology have decreased the cost per lumen of LEDs by a factor of 10, and increased the amount of light generated per LED package by a factor of 20. This exponential development of LED technology, referred to as Haitz's Law, has dramatically reduced the cost of synthesizing light energy for indoor plant cultivation.

to exist within the confines of dense urban environments – effectively disconnecting food production from the Earth's fragile ecosystems and integrating it with the industrial ecology of urban centres. Requiring just a fraction of the resources of conventional agriculture, vertical farming represents the realization of an agriculture fully decoupled from environmental impact, and in this, one in touch with the exponentially progressing nature of human society.

PART II

THE VERTICAL FARMING CONCEPT



CHAPTER 6 - THE EMERGENCE OF VERTICAL FARMING

Though the concept of vertical farming has precedents that stretch deep into human history, the first publicized references to high-density indoor agriculture emerged from The Netherlands in 2001. After relentless agricultural expansion toward the end of the 20th century, The Netherlands was experiencing a series of adverse ecological trends that suggested its agricultural sector had breached its environment's sustainable production thresholds. Eventually the European Union and Dutch government were forced to impose restrictions on the country's pork production to help control the animal wastes that were polluting aquatic ecosystems and causing excessive soil acidification.

In response, the Dutch architecture firm MVRDV considered the harmonization of agriculture with architecture as a possible solution for its country's unsustainable pork industry. Entitled Pig City, the design comprised a network of soaring towers dedicated solely to pork production. The vast array of hog pens that compose the towers are envisioned with a highly industrialized and automated feed delivery and waste collection system. Though the design is not fully resolved it indicates the buildings could be powered by animal waste, and contains on-site facilities to slaughter and process the meat. Renderings of the project that depict the pens lifted hundreds of feet off the ground in configurations very similar to those of office cubicles reveal an obvious ethical dilemma and, in that, social critique of the project. As the firm's design statement reveals.

> *"In 2000, pork was the most consumed form of meat at 80 billion kg per year. Recent animal diseases such as Swine Fever and Foot and Mouth disease are raising serious questions about pork production and consumption. Two opposing reactions can be imagined. Either we change our consumption pattern and become instant vegetarians or we change the production methods and demand biological farming."*[1]

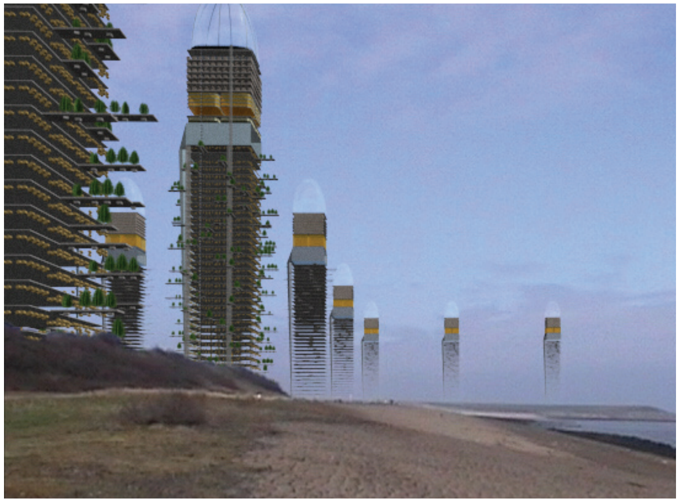


Fig 2.1
Perspective rendering of Pig City

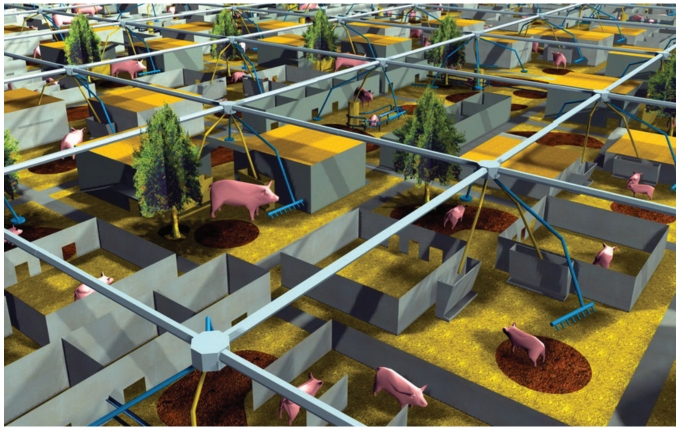


Fig 2.2
Internal rendering of Pig City

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[1] MVRDV Official website, www.mvrdv.nl. Retrieved March 3, 2009

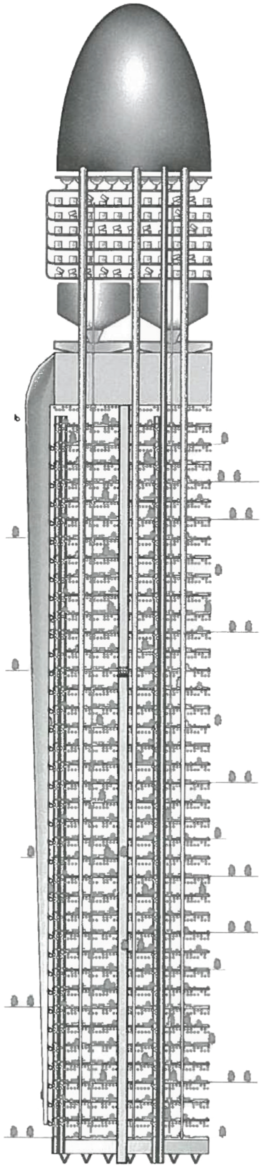

Fig 2.3
Elevation of Pig Tower - MVRDV

Despite its apparent tongue-in-cheek nature, Pig City received international attention as a novel, intuitive strategy for agriculture reform – borrowed from the vertical intensification pattern of human settlements. That same year another Dutch group received widespread attention for its proposal for a vastly intensified agricultural system, this time with a far more serious demeanour. Originating from the minds of a team of scientists from Wageningen University's Agrotechnology Research Institute, the proposal involved the creation of an enormous indoor agricultural facility called Deltapark. The aim of the project was to sequester agricultural processes within a controlled environment to maximize resource efficiency while eliminating the adverse ecological impact of farming. In the words of the project leader Dr. Jan Broeze,

> *"If you cluster various activities, like greenhouses, fish farming, and manure processing, then you create a sufficient scale for more sustainable food production...The idea is to use wastes from one industry to sustain another."*[2]

The planned form was a colossal six storey rectilinear box spanning roughly one kilometre long by nearly half a kilometre wide, totalling over 500 acres of usable floor space. Over a million chickens, 300,000 pigs, tens of thousands of fish, and an expansive vegetable garden were to call Deltapark home. Plants or fungi that require little light could grow in the centre of the building. Those that require more would be grown with hydroponics in greenhouses on the roof, whose nutrient solutions would be collected from the wastes created by animals elsewhere in the building. As the plant, fungus, or animal became ready for human consumption, it would simply be transported to the processing area or slaughterhouse on the main level. The project was primarily intended to generate discussion on the forms agriculture may have to take in its quest to become more resource efficient and ecologically benign.

As an interesting side-note, this strategy to improve agricultural resource efficiency by clustering farming with food processing and energy production was discussed by famed agronomist D. Howard Doane in his 1950 publication titled, ironically, *Vertical Farm Diversification*. Doane used the term 'vertical' to denote

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[2] Vidal, John. Farm of the Future? (2001, August 22) *Guardian Magazine*

a vertical hierarchy of resource flows created when a farm diversifies to include food processing and cyclical resource usage.[3]

The present definition referring to the use of the vertical spatial dimension in food production was introduced by Columbia University professor Dr. Dickson Despommier. A microbiologist by training, his involvement with the concept began after he presented his graduate students with the task of determining how much food could be grown on the vacant rooftops of New York City's buildings. The maximum viable yield they calculated was significantly less than what would be required to attain agricultural self-sufficiency within the city's borders. In response to this he questioned what yields could be attained from farming indoors within urban buildings – an inquiry that ignited the current interest in the vertical farming movement. Despommier's subsequent and continued involvement with the concept has been instrumental in delivering it from obscurity to widespread notoriety and increasing logistical relevance.

By 2006 designers began generating design concepts for vertical farms that provided the visual dimension necessary to capture the public's imagination with the possibilities of large-scale indoor agriculture. A watershed moment came in the spring of 2007 with the arrival of the global food price crisis, which saw the price of agricultural products breach the threshold of what some countries could easily afford. That April the first notable references to vertical farming appeared in the mass media, intended to satiate the heightened interest in emerging agricultural strategies that could improve food security in the future. Though the food price crisis has since subsided the viral spreading of references to vertical farming has continued unabated.

Fig 2.4
Living Tower by SPA Atelier was one of the earliest vertical farm designs

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[3] Doane, Howard D. (1950). *Vertical Farm Diversification: Added Income from Grading, Processing, and Direct Sell.* Norman, OK: University Of Oklahoma Press.

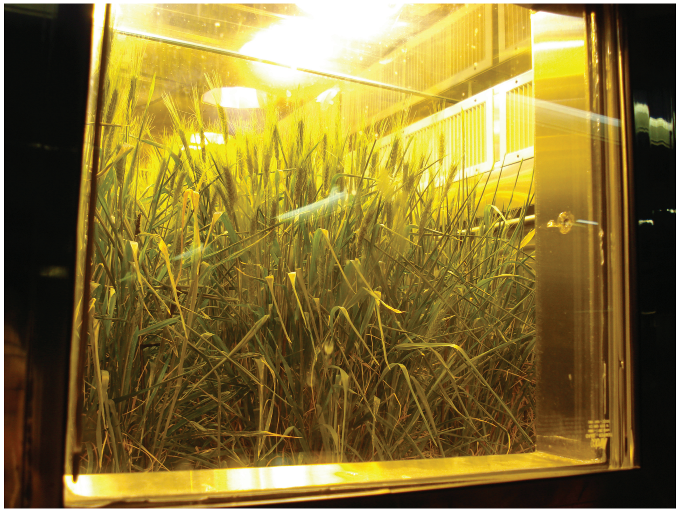

Fig 2.5
Dwarf wheat growing in a controlled environment chamber.
Controlled Environment Systems Research Facility, University of Guelph

CHAPTER 7 - VERTICAL FARMING EXPLAINED

Technically, vertical farming is the practice of soil-less/controlled environment agriculture (S/CEA) within the high-density confines of multi-storey buildings. As the name suggests, S/CEA consists of plant cultivation in contained environments where light, temperature, water, and nutrition can be finitely controlled. Until recently this high-tech form of horticulture was primarily utilized for plant study by universities and space agencies due to its high cost. In the past decade, however, improvements to associated technologies and increased awareness of the benefits of S/CEA have enabled it to expand into large-scale operations. Cornell University introduced the first commercial scale S/CEA facility in 1999, producing some 1,245 heads of high-quality lettuce per day.[4]

To appreciate the benefits of growing food indoors, consider the incompatibilities of human food production and the temperment of the natural world. Agriculture, whether industrial or organic, is structured to maximize the production of edible biomass (i.e. food), while natural ecosystems are structured to maximize their own stability.[5] These conflicting goals ensure that the success of one impedes the success of the other. Natural succession and climactic variability greatly impede food production worldwide, forcing billions to be spent on pest management chemicals and genetic modification of plant species. At the same time, the high rates of deforestation, desertification, soil erosion, and soil salinization noted previously are principally due to the expansion of farming, while the decline of aquatic ecosystems is largely the result of agricultural fertilizers, pesticides, herbicides, and antibiotics leaching into the water cycle.[6] [7]

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[4] Albright, Louis (2004) *CEA: Controlled Environment Agriculture* http://www.cornellcea.com/about_CEA.htm

[5] Holdren, John P & Ehrlich, Paul R. (1974) Human Population and the Global Environment: Population growth, risng per capita material consumption, and disruptive technologies have made civilization a global ecological force. *Use of Misuse of Earth's Surface*. ed. Brian J Skinner, Los Angeles: William Kaufmann Inc.

[6] Mazoyer & Roudart. *A History of World Agriculture*

[7] Brown, A, *Feed or Feedback*

By segregating crop growth within an in-door environment the temperature, light, water, humidity, and nutrient availability that dictate a plant's success can be finitely controlled, while the negative impacts of an ecosystem's natural succession can be eliminated. This two-fold benefit effectively permits the creation of each plant's ideal growing conditions year-round. Crops grow quicker, larger, and with many more harvests per year than external conditions permit; all without the use of fossil-fuel derived pesticides or fertilizers. Moreover, many agronomists have provided strong evidence indicating the nutritive value of S/CEA crops equals or surpasses that of the most successful field grown crops.[8] [9] [10] [11]

An additional point to consider involves the scourge of crop diseases. When conventional farms lose crops to invasive pathogens farmers must generally wait months for the next growing cycle to return their fields to productivity. For example, according to research conducted at the University of Georgia between 1998 and 2008 crop disease cost the state of Georgia an average of four hundred million dollars in lost revenue per year, with another one hundred ninety million devoted to controlling crop pathogens.[12] Together these costs reduce the yearly agricultural revenue of the state by approximately 13%.[13]

If properly designed, a vertical farm's contained growing environment would greatly reduce the risk of invasive pathogens impeding crop growth. For those pathogens that may take hold, a vertical farmer would have the ability to remove the diseased crop, clean the apparatus, and re-sow their growing medium within the same day – therein swiftly returning the system to productivity.

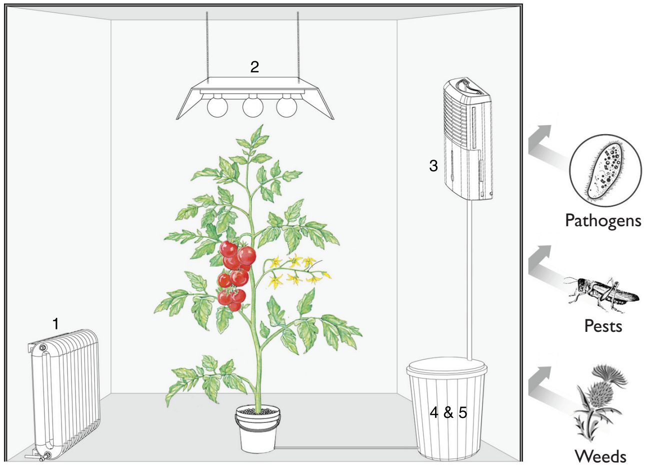

Fig 2.6
Simple diagram for a soilless/controlled environment agriculture system.
1. Temperature control, 2. Artificial lighting, 3. Humidity control 4. Irrigation,
5. Nutrient control

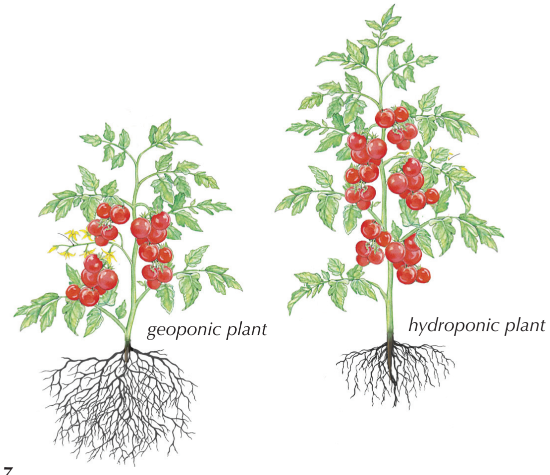

Fig 2.7
Due to the streamlined water-nutrient delivery of hydroponic systems, hydroponic plants do not have to develop the extensive root structures required by geoponic plants. This ensures the energy devoted to plant growth is maximized toward fruit production, therein increasing yields.

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[8] Wheeler, R.M., C.M. Mackowiak, G.W. Stutte, N.C. Yorio, & W.L. Berry (1997) Effect of elevated carbon dioxide on nutritional quality of tomato. *Advances in Space Research*, vol.2, no.10, p.1975-1978

[9] Wheeler, R.M., C.M. Mackowiak, J.C. Sager, W.M. Knott, & W.L. Berry (1996) Proximate composition of CELSS crops grown in NASA biomass production chamber. *Advances in Space Research*, vol.18, no.4/5, p.43-47.

[10] Nielsen, S.S., M.A. Belury, K.P. Nickel, & C.A. Mitchell (1995) Plant nutrient composition altered with controlled environments for future space life-support systems. *Proceedings of the Third National Symposium: New Crops, New Opportunities, New Technologies*. Indianapolis, IN: ASHS Press .

[11] Mitchell, C.A., C. Chun, W.E. Brandt, & S.S. Nielsen (1996) Environmental modification of yield and nutrient composition of Waldmann's Green leaf lettuce. *Journal of Food Quality.* vol.20, p.73-80

[12] Williams-Woodward, Jean L. (2009) *Georgia Plant Disease Loss Estimates, 1998-2002*. The University of Georgia Cooperative Extension, Colleges of Agricultural and Environmental Sciences

[13] Ibid

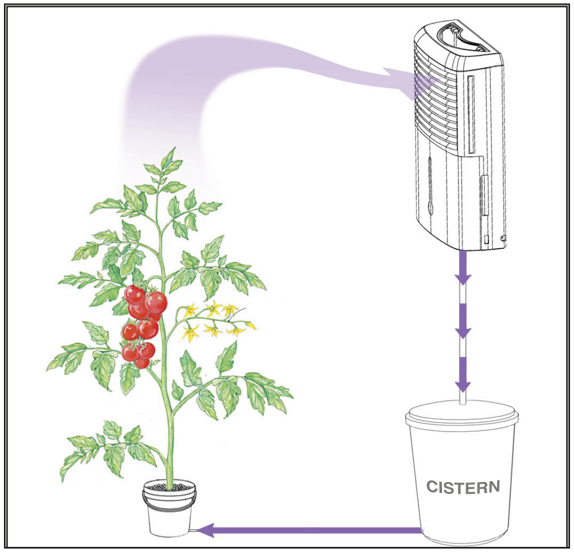

Fig 2.8
With a contained environment and a dehumidifier the large volume of water transpired through photosynthesis can be recaptured and returned to water circulation.

Reduced Reliance on Natural Capital

The most compelling argument in favour of vertical farming is its ability to disassociate food production from its current dependence on limited elemental resources and fragile natural capital. Consider the use of water in agriculture. The intake of water by conventional farms must account for the process of transpiration, wherein water is released during photosynthesis and evaporated into the atmosphere. Though the rate of transpiration differs for each plant species, agricultural crops tend to release between 200 kg to 1000 kg of water for every 1 kg of dry biomass produced by the plant.[14] Additional water loss occurs from evaporation directly from the soil and surface runoff – both of which are aggravated by the absence of natural weeds and grasses that would otherwise allow water retention.[15] It is this inefficiency that drives agriculture's unsustainable appetite for freshwater, which as mentioned accounts for 72% of all human water use.[16] [17]

When crop growth occurs within the contained environment of a vertical farm, all evaporated water can be collected by dehumidifiers and recycled back into the system. As a result, the only water to leave a vertical farm's circulation is that contained within the biomass of the saleable produce. Considering only water losses from transpiration a vertical farm would theoretically consume between 200 and 1000 times less water than a conventional farm to produce the same quantity of food.

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[14] Martin, J.; W. Leonard & D. Stamp (1976), *Principles of Field Crop Production (Third Edition)*. New York: Macmillan Publishing Co., Inc.

[15] Brown, A, *Feed or Feedback*

[16] Brown, L. *Plan B 2.0*

[17] Pimentel, David; Berger, Bonnie; Filberto, David; Newton, Michele; Wolf, Benjamin, et al. (2004). Water Resources: Current and Future Issues. *BioScience.* vol.54, p.909-18

The use of land by conventional agriculture is equally inefficient. Vertical farming addresses the land requirements of agriculture in three key ways. The first and most visually apparent is the farm's use of vertically stacked floors, each of which increases the area for crop production without increasing the farm's consumption of land.

Next, a vertical farm's aforementioned ability to perpetually generate the ideal growing conditions for each plant while protecting crops from harmful pests and weather-related disturbances ensures more harvests and less plant loss per acre than conventional farming. The effect of a contained environment is more difficult to quantify in terms of space efficiency, owing to the fact that some plant varieties offer more opportunity to improve their harvest efficiency than others.

According to agronomist James Douglas hydroponic greenhouses in Florida, which benefit from year-round production with ideal growing conditions, produce well over six hundred thousand pounds of tomatoes per acre - some thirty times the yield of conventional farming per acre.[18] Rice production in ideal hydroponic environments is over fourteen times higher than on traditional rice farms.[19] For lettuce, the yield equivalent of Cornell's S/CEA facility mentioned previously is 470 tons per acre per year - over twenty three times more productive than the typical California lettuce farm's yield for the same land area.[20]

Lastly, the light-weight hydroponic system permits plants to grow on vertically-oriented growing structures. As with any technology still within its infancy the efficiency and practicality of vertically-oriented hydroponic systems will likely improve in the coming years. Presently there are four basic typologies applicable to in-door crop cultivation on a commercial scale. These consist of:

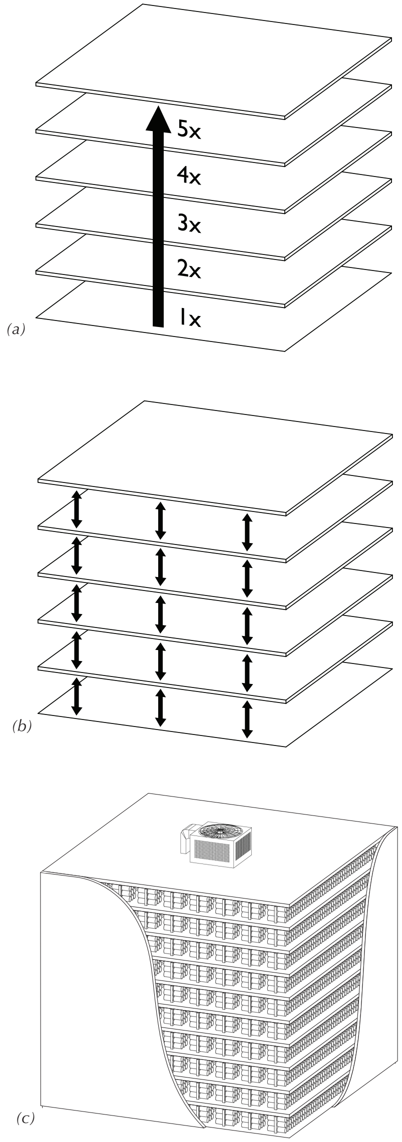

Fig 2.9
Three dimensions of vertical farm land productivity: (a) Multiple Levels, (b) vertically-oriented growing system, (c) controlled environment

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[18] Douglas, James S. (1975) *Hydroponics. 5th ed*. Bombay: Oxford UP,

[19] Ibid

[20] Friedlander, Blaine P Even in upstate New York's frigid winter weather, this lettuce harvest is crisp and bountiful. (1999, December 14) *Cornell New Service.*

Fig 2.10
An example of an A-Frame hydroponic system
Ricardoes Tomatoes & Strawberries - New South Wales, Australia.

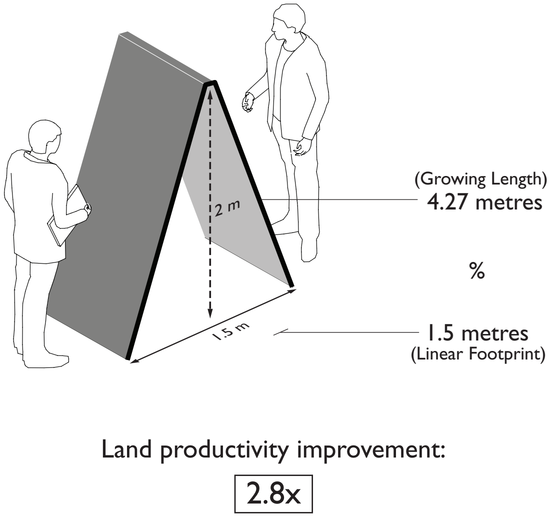


Fig 2.11
Space efficiency of the A-Frame design

A-FRAME TRELLIS

The A-frame “trellis” design was the first commercially successful hydroponic system to exhibit a vertical orientation. Varieties of this design consist of pipes configured either vertically or horizontally to form a triangular extrusion of its footprint, thus increasing the available growing surface without meaningfully reducing sunlight access. The primary advantage of the A-frame design is its simplicity, as it achieves a high degree of space efficiency while utilizing technology that has been standard in the hydroponic industry for decades.

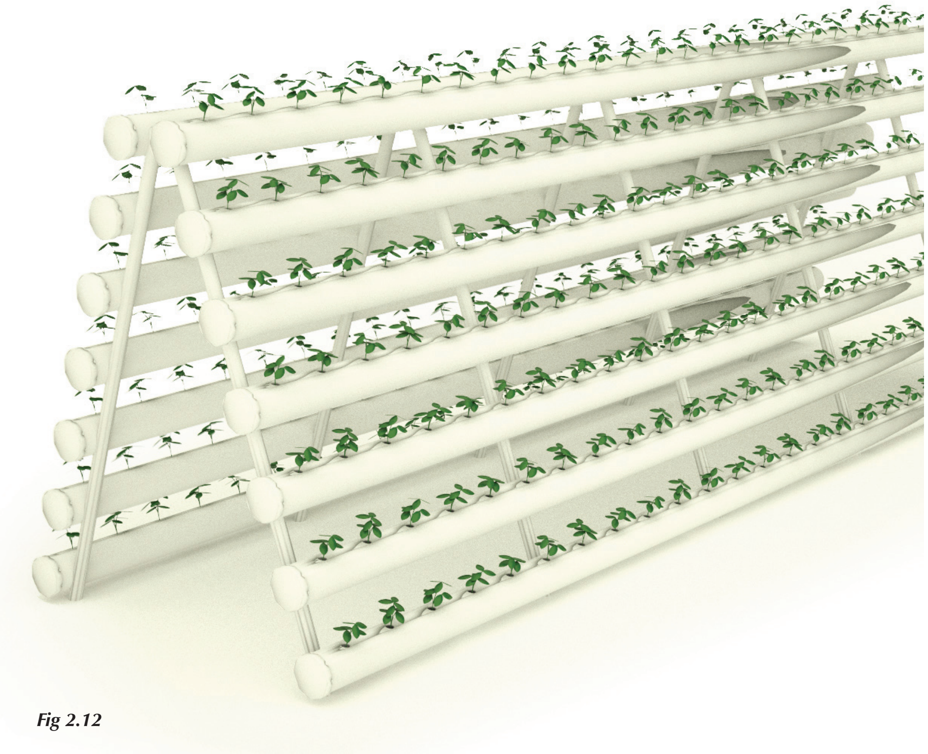


Fig 2.12

STACKED BEDS

Much like the A-frame design, the “stacked beds” configuration is extremely straightforward in concept and technology. The design is merely a stacking of the standard in-line pipe beds that continue to be the system of choice for commercial hydroponic farms. Much like the ramification of stratifying floors in a vertical farm, the design’s stacked configuration doesn’t allow sunlight to penetrate each layer, making artificial lighting a necessity. The best commercial example of the stacked bed approach is the design used by TerraSphere Systems, which has implemented systems with five tiers of growing surface within a 3 metre floor to ceiling height.

Fig 2.13

Fig 2.14
TerraSphere’s indoor farm, Vancouver, British Columbia

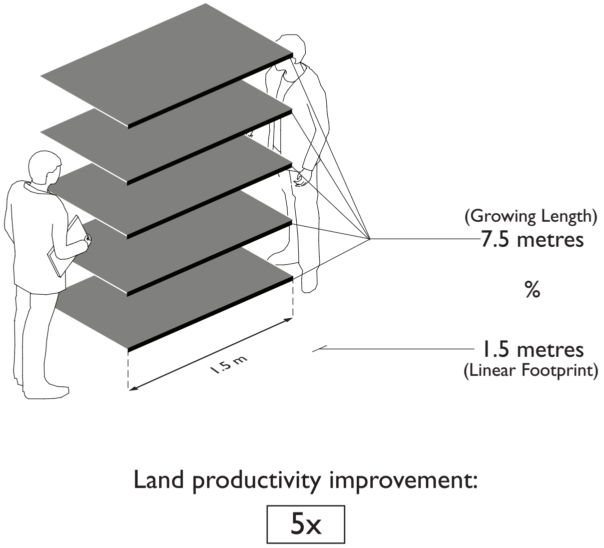


Fig 2.15
Space efficiency of the stacked bed design

Fig 2.16
Interior view of peas growing within a drum hydroponic system
Omega Garden - Qualicum Beach, British Columbia, Canada

STACKED DRUMS

Though it is the least common commercial hydroponic system listed here, the drum design likely offers the most promise for the future of indoor agriculture. It consists of growing plants within the interior of a drum structure positioned around a central artificial light source, resulting in an extraordinarily low space and energy use per unit of production. The first publicized example of this design emerged in the late 1970s from the Environmental Research Laboratory at the University of Arizona. Today the most popular variant is produced by Omega Garden™ of Victoria, B.C., which features a mechanism that rotates the drum through a tray containing nutrient solution.

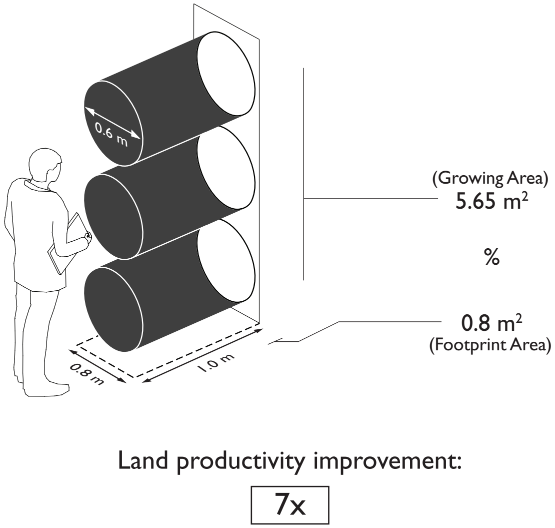


Fig 2.17
Space efficiency of the stacked drum design

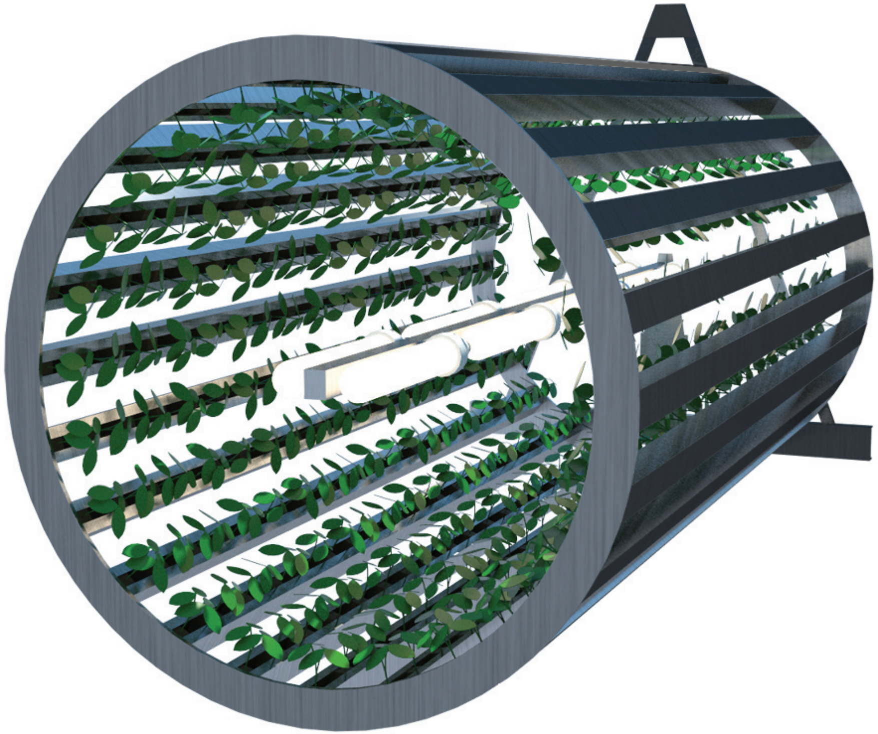


Fig 2.18

COLUMNAR SYSTEMS

The newest variant of vertical cultivation to emerge is the columnar design popularized by the English horticultural company Valcant. Their design, VertiCrop™, consists of a series of stacked trays arranged in a staggered pattern to increase light penetration. The "columns" are then cycled along a conveyor track to a central machine that delivers nutrient solution and removes the trays for harvesting. The design boasts the highest space efficiency among the sun-fed hydroponic systems available today, however, it is also the most limited in accommodating different plant varieties.

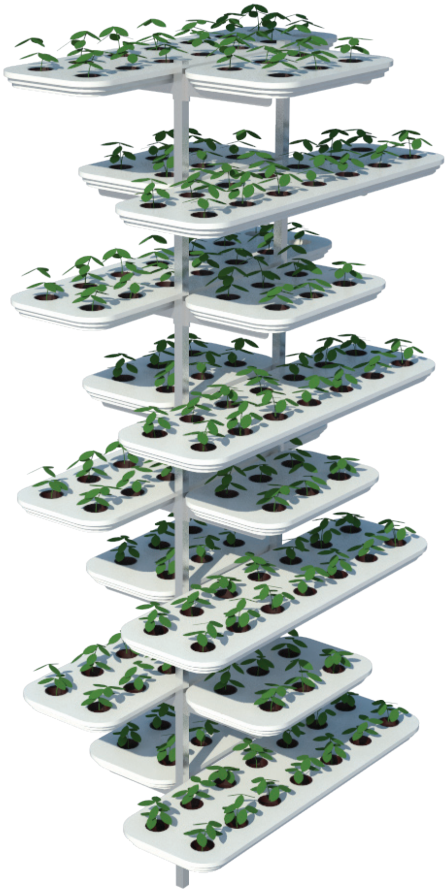


Fig 2.19

Fig 2.20
Valcant Product's VertiCrop™ system in operation at the Paignton Zoo. Paignton, Devon, England

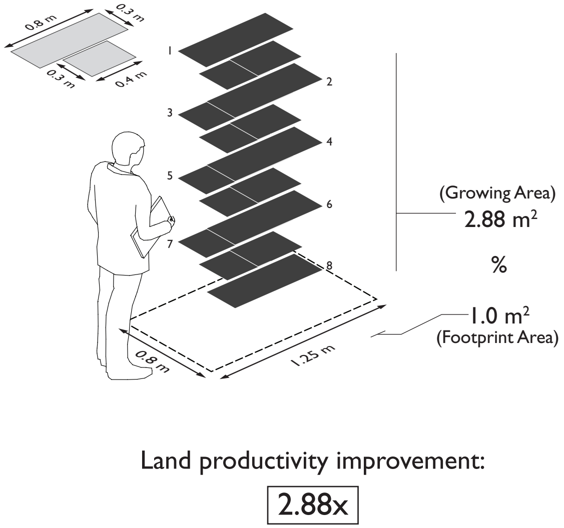
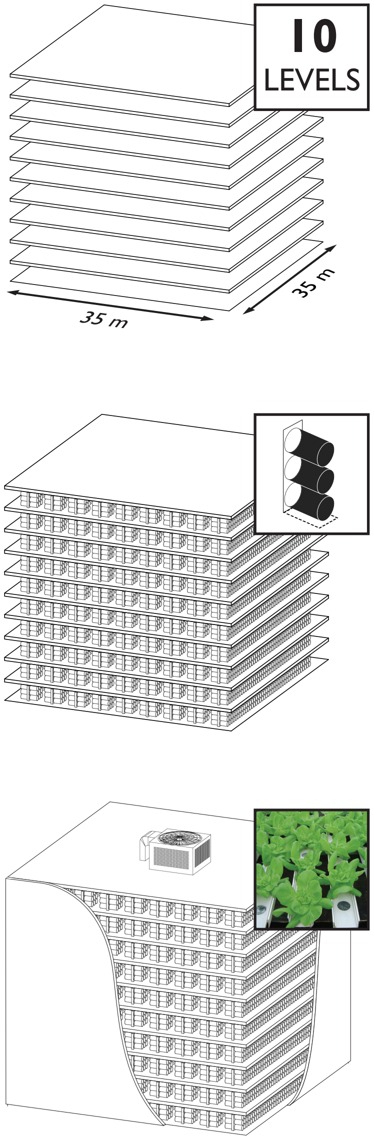


Fig 2.21
Space efficiency of the columnar design

To quickly estimate the land efficiency of vertical farm production one must simply multiply the usable area of the building's footprint by the three aforementioned variables of its design, namely its number of levels, the growing system productivity factor, and the S/CEA productivity factor for the variety of crop being grown. As depicted in Figure 2.22, on 1,225 m^2 of urban land a ten storey vertical farm (devoted totally to production) using the stacked drum hydroponic system could produce the same amount of lettuce as 1,577,800 m^2 of conventional arable land. With each square metre of usable floor area producing 161 times the yield of conventional lettuce farms for the same area, this sample vertical farm would reduce the land required for lettuce production by a factor of 1,288.



FOOTPRINT
35 x 35 = 1,225 m^2

USABLE FLOOR AREA*
1,225 m^2 - 20% = 980 m^2

TOTAL FLOOR AREA
980 m^2 x 10 = **9,800 m^2**

*access/circulation (20%)

GROWING AREA (/w DRUMS)
9,800 m^2 x 7* = **68,600 m^2**

*ratio of growing area to footprint of triple-stacked drum design hydroponic system is 7:1

PRODUCTIVITY FACTOR
68,600 m^2 x 23* = **1,577,800 m^2**
= 390 acres

*estimated productivity improvement using Cornell Univ. CEA facility's lettuce production over conventional farms

Fig 2.22
Land productivity of a sample vertical farm explained

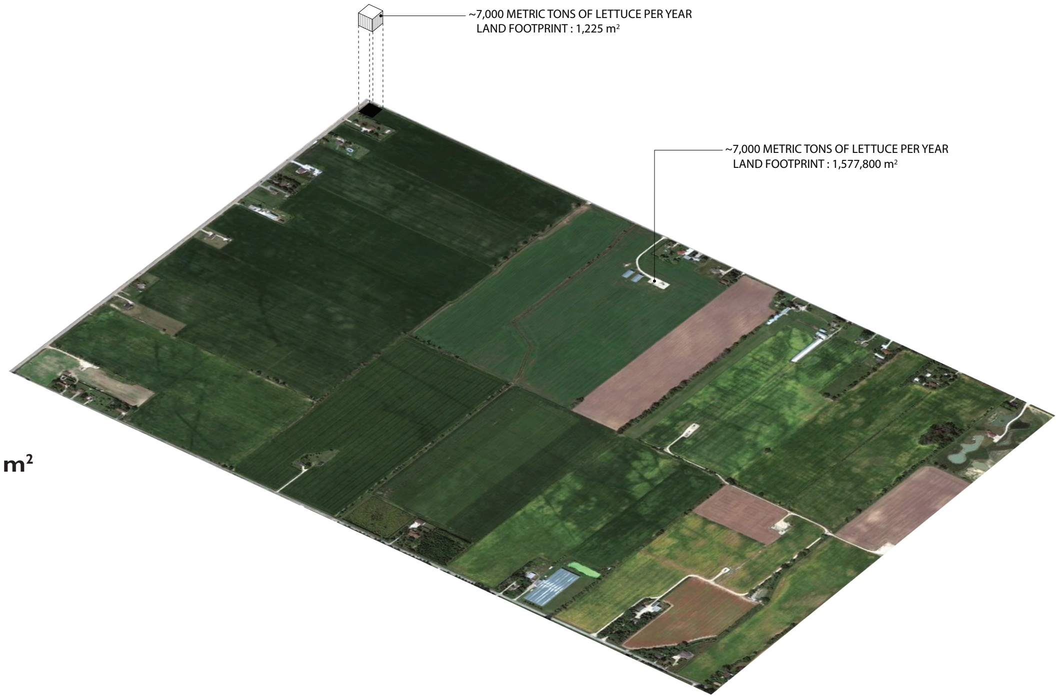


Fig 2.23

CHAPTER 8 - DESIGN DECISIONS

There are two basic categories of vertical farms – those geared to the education of advanced farming systems and those intended for the commercial production of food. Much like in the progression of soilless/controlled environment agriculture, educational applications of vertical farming will likely be the first to emerge. With funding opportunities from research grants and fees from those interested in exploring the novelty of advanced farming technology, this variety of vertical farm can be realized prior to the emergence of the economic conditions necessary for production-oriented initiatives. As a result of the reduced constraints on productivity, designs of "institutional" vertical farms are free to explore a wider array of architectural expressions.

However, if vertical farming is to meaningfully impact the way humanity produces food it must eventually become viable for commercial production in the free markets that dominate the global economy. To this end a vertical farm must be able to produce enough food to cover the cost of its day to day operations and, ultimately, the capital cost of the building's construction (or renovation). While this is clearly dependent on some factors outside the realm of architectonics, such as the market price of food and current state of grow-lighting technology, the physical arrangement of the building can have a profound impact.

For instance, to maximize yields a design must make optimum use of its internal space by accommodating the largest possible growing area. Generally this will result in a rectilinear floor plate due to its internal correlation with the footprint of most hydroponic systems and external correlation to most urban land allotments. It is also of vital importance that the building's design allows for the most efficient method for workers to tend the plants and, if designed for, animals. Though these decisions would depend heavily on the growing method used, generally it would involve the provision for manageably short ceiling heights and elevator-oriented aisles to minimize worker hours per area harvested. Such productivity and function-based constraints reveal the process of designing a vertical farm to be closer to the design of industrial factories, and to a lesser

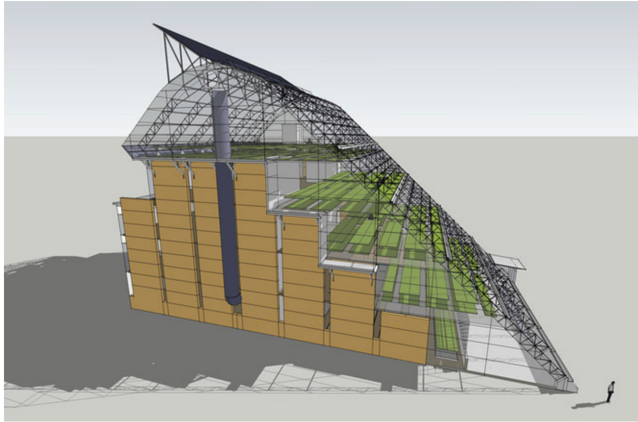


Fig 2.24
Vertical agriculture teaching facility planned for urban agriculture activist Will Allen's Growing Power project in Milwaukee, Wisconsin. The low density growing area is supported by the facility's educational uses and volunteer donations. Design by Kubala Washatko Architects

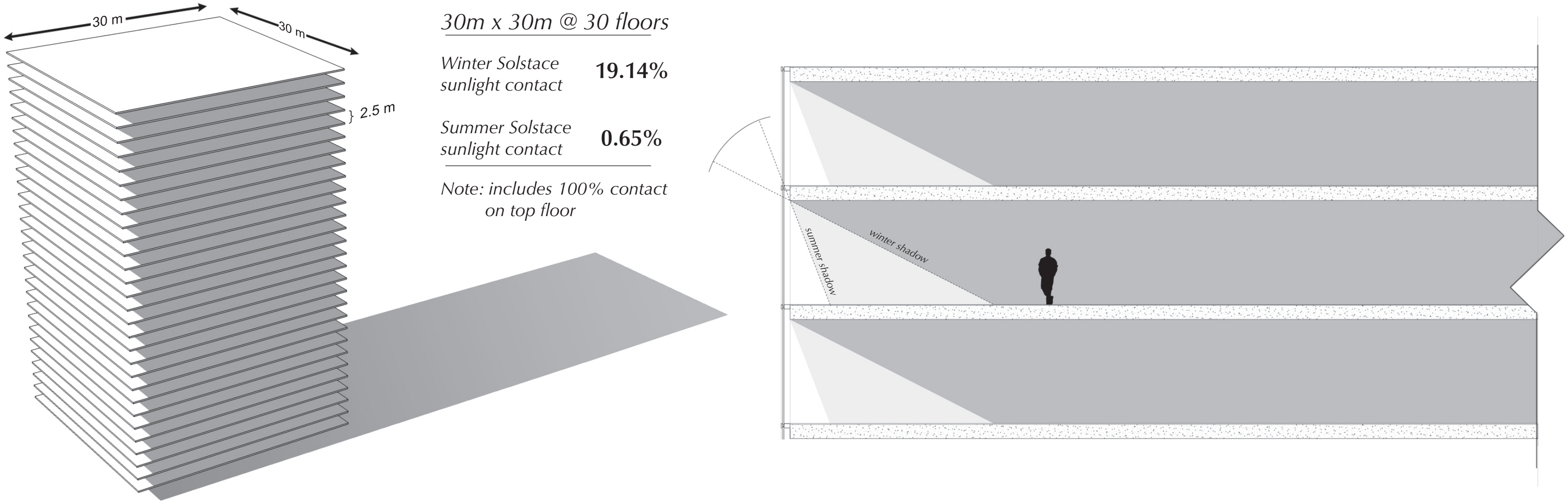
Fig 2.25
Image from the 'Living with the Land' attraction at Disney's Epcot Center. Epcot Center's hydroponic facility demonstrates the tourism potential for those interested in experiencing future agricultural technology

degree libraries, than the residential and commercial buildings the existing prototype designs often resemble.

Unfortunately, the design strategies that maximize crop yields also lead to higher potential operating costs due to the plants' reduced accessibility to solar energy. The dense growing configurations distributed throughout a vertical farm's multiple floors create far too many physical barriers for sunlight to penetrate. In fact, even if sunlight could somehow bend around these obstacles, the total sum of solar energy cast on a particularly dense vertical farm may be less than the farm's total energy needs. With tens of stories dedicated solely to productive plant cultivation, large vertical farms would likely realise the highest incidence of photosynthetic activity per acre on Earth. As a result, the vast majority of a vertical farm's crops must receive their light energy from artificial sources, creating an added economic burden over traditional forms of agriculture.

The battle between maximizing yields and maximizing solar penetration thus becomes the most important design consideration for architects, and ultimately will be the primary criteria from which the efficacy of a design will be determined.

Fig 2.26
Analysis of sunlight cast on floor area in multi-level buildings



30m x 30m @ 30 floors

Winter Solstace sunlight contact	**19.14%**
Summer Solstace sunlight contact	**0.65%**

Note: includes 100% contact on top floor

The unavailability of solar energy and subsequent reliance on artificial light sources serves as the primary disadvantage of vertical farming, as it necessarily leads to a high electrical energy load for services the sun provides for free to conventional farms. If this energy requirement were not accounted for by practical and renewable means it would undermine both the economic and ecological benefits of the concept.

Additionally, the inevitable production of agricultural by-products presents yet another disadvantage of high-yield farming in urban centres. In crop production biowaste is generated from the inedible leaves, stems, roots, and husks that humans do not consume, as well as from damaged or defective produce. If fish, meat (poultry) and egg production is included in the design additional biowaste is generated from animal feces and the carcases of deceased animals, all of which must be disposed of. If left for municipal waste disposal services to manage the facility would become counter-productive to the seemingly universal initiative to reduce the waste load cities generate.

Through a relatively simple technological process, however, the energy deficiencies and surplus biowaste can be reconfigured to become an advantage of sorts, where the excess of one becomes the subsidy of the other. Anaerobic digestion is a process that involves the accelerated biodegradation of organic material and subsequent capture of released methane – the main compound in natural gas. Once collected, the methane can be used to power electric generators that provide clean, renewable energy to the farm.

There are two main by-products to the process of anaerobic digestion – fibrous and liquid *digestates*. Fibrous digestate is composed of stable organic matter, primarily lignin and cellulose, while the liquid digestates contain most of the nutrients from the digested plant material.[1] When mixed together the digestates form a liquid slurry that can be applied to agricultural lands to improve both soil structure and fertility. Fibrous digestate can also be used independently as an environmentally friendly filler for composite plastics and fibreboard.[2]

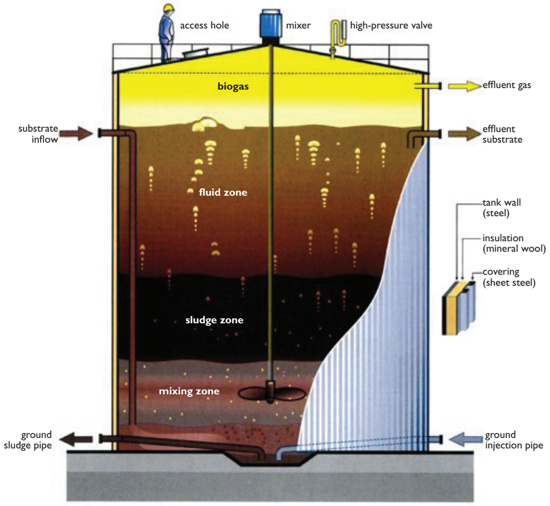


Fig 2.27
Diagram of a typical industrial-scale anaerobic digester.

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[1] Dagnall, Steve. (1995). UK strategy for centralised anaerobic digestion. *Bioresource Technology*, vol.52, issue 3, p.275-280.

[2] Marshall, Alex. (2006) Response to Consultation on the source segregation requirement in Paragraph 7A of Schedule 3 to the Waste Management Licensing Regulations 1994. Oaktech Environmental, February 5th, 2006.

Fig 2.28
Equipment used to apply digestate to fields as a soil fortifier. In this application, the digestate is applied under pressure to inject it deep into the soil structure, maximizing the improvement to soil fertility

The philosophy of uniting vertical farming with anaerobic digestion, as opposed to other viable strategies of renewable energy generation like photovoltaics, wind power, and bio-pellet combustion, responds to a fundamental conundrum of the agrarian lifestyle. As explored previously, the memetic emergence of agriculture shifted humans from a distributed nomadic lifestyle to one defined by sedentarianism and increasingly condensed settlements. This dramatically shifted the flow of nutrients in the environment, whereby localized settlements consumed nutrients produced by an entire region's fertility. The linearity of this arrangement resulted in two of the most prominently undesirable facets of urban life – excessive collections of nutrient waste (i.e. excrement/food waste) and the unsustainable plundering of regional soil fertility.

By reducing the biowaste an urban area's neighbouring ecosystems must accommodate and by processing that waste into a commercially viable soil fortifier, anaerobic digesters could significantly alter the linear nutrient flow that characterizes the unsustainability of urban settlements. Additionally, anaerobic digesters turn vertical farms into net exporters of organic material beneficial to the health and well-being of agricultural ecosystems, while simultaneously producing the food products that reduce the nutritional load of agricultural lands.

Yet another important benefit of uniting anaerobic digestion with vertical farming is the ability to use digestates as the nutrient source for a vertical farm's hydroponic system. While this is still a fringe practice in commercial hydroponic farms, likely due to the limited availability of digestates, it has been shown to produce qualitatively and quantitatively equivalent crop yields to conventionally derived nutrients.[3]

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[3] Liedl, B.E., Cummins, M., Young, A., Williams, M.L. & Chatfield, J.M. (2004). Hydroponic Lettuce Production Using Liquid Effluent from Poultry Waste Bioremediation as a Nutrient Source. *Acta Hort.* (ISHS) vol.659 p.721-728

According to calculations provided by On-Site Power Systems, an offshoot of UC Davis Anaerobic Phased Solids (ABS) initiative, one ton of plant waste produces around 22 therms of methane gas, equalling 2,200,000 BTUs. While varying with the waste patterns of selected plant species, a large vertical farm could easily produce plant waste measuring in the multiple hundreds of tons per day.

Comparing this capacity for energy production to preliminary research on the energy requirements of vertical farms has suggested the digestion of a vertical farm's waste could accommodate just over half of its total energy needs.[4] As this is short of the energy required to avoid using the existing fossil-fuel based grid, one strategy would be to increase the capacity of anaerobic digestion to accommodate outside sources of biowaste, such as the sewage and urban food waste.

The accommodation of food waste presents the opportunity for vertical farms to act as food waste depots for cities, consuming the material otherwise trucked outside of the city to decompose and contribute its methane to the atmosphere. Sewage has more embodied energy and requires less processing time than uncatabolized plant waste, making it a more efficient source of energy.[5] A downside of using sewage is that its digestate by-products would likely be unusable for applications involving plant growth for human consumption.

It must be mentioned that this focus on "on-site" solutions to the energy and waste processing requirements of a vertical farm is largely in response to the unsustainable nature of the existing energy and waste disposal grids – and thus may not be the most efficient strategy in the future. Should regional renewable energy generators like biogas plants and plasma arc gasification facilities emerge the economic viability of vertical farming may be improved by creating waste feedstock/energy transfer relationships with such facilities, as opposed to on-site solutions.

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[4] Energy In, Energy Out (2004) http://www.verticalfarm.com/presentations.html (Note: errors in the calculation of methane production by this reference was corrected by author and accounted for)

[5] Pyle, L. (1978). *Anaerobic Digestion: Technical Options in Biogas Technology in the Third World. A Multidisciplinary Review,* (Ed) A. Barnett,L. pyle,and S.K Subramanian. Ottawa: International development research center. p.47-52

CHAPTER 9 - ECONOMIC RATIONALE OF VERTICAL FARMING

In light of vertical farming's significant departure from conventional food production it is important to address the economic rationale through which the concept could be realized. Clearly, vertical farming involves a number of expenses not required for conventional farming; the burdens of internalizing the environmental externalities of conventional agriculture. Most of the added expenses are initial capital costs needed to synthesize an ideal growing environment, such as the construction (or renovation) of a multi-level enclosed building, installation of temperature and humidity control equipment, and assembly of a vast hydroponic system. Also, larger vertical farms that utilize artificial lighting would likely necessitate the installation of an on-site power generating system, such as anaerobic digesters with a methane-burning electric generator. These systems are considerable expenses to account for, and as such must be countered with an improved level of profitability to make the concept economically viable.

Fortunately, vertical farming's intensive method of cultivation offers many productivity advantages over conventional farming, presenting the possibility of offsetting elevated operating costs with increased yields of saleable produce. As mentioned Cornell University's CEA facility produces approximately 23 times more lettuce per acre than the average California lettuce field. This means the facility could be 23 times more costly to operate than a similarly scaled conventional lettuce field while matching its profitability - or 20 times more costly and achieve greater profitability.

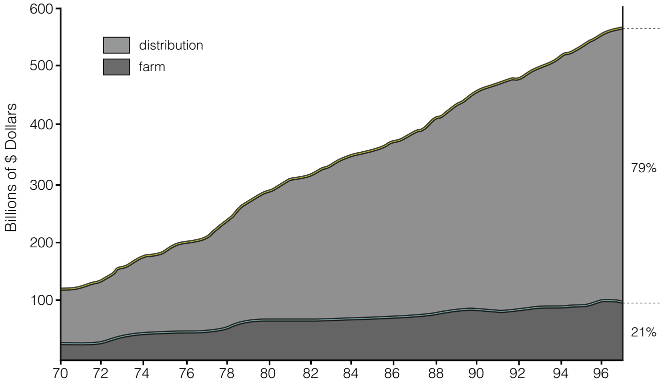

Fig 2.29
Food supply chain expenditures from 1970 to 1997. Note the increasingly diminishing share of food purchase profits being directed to farmers.
Source: USDA Agriculture Fact Book 1998

Another major advantage is the impact of the controlled environment cultivation method employed by vertical farms to protect crops from events that routinely disrupt conventional production. Such events include all instances of climactic variability and the majority of pest/pathogen infestations, each of which negatively impact a farm's profitability by reducing the volume of saleable produce and increasing its operating costs. A typical example of this impact occurred in 2010 when heavy rains in Saskatchewan, Manitoba, and Alberta caused crop losses valued at approximately $1.5 billion, for which the federal government pledged another $450 million in relief aid for affected farms.[21] [22] Additionally, in the aforementioned example of the U.S. state of Georgia losses and expenses associated with pests and pathogens average $590 million per year, approximately 13% of the yearly agricultural revenue.[23] Clearly, avoiding a large portion of these necessary costs of conventional agriculture would be another potential economic advantage for a vertical farm.

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[21] McFerron, Whitney & Greg Quinn. Canada's Wheat Crop to Shrink 17% From Last Year on Flooding in Praries. (2010, October 4). *Bloomberg.com*

[22] Nickel, Rob. Canada Farm Flood Loss Estimate cut to $1.5 Billion. (2010, December 1). *Reuters Canada*

[23] Williams-Woodward, *Georgia Plant Disease Loss Estimates,*

COST BREAK-DOWN

Regardless of vertical farming's macro-economic logic, support for a new concept such as this must inevitably be based on sound micro-economic principles. With the aim of placing the concept within a real-world economic context I have created a basic cost-analysis or "pro forma" for a hypothetical vertical farm. For continuity I have used the same 35m x 35m x 10 storey vertical farm used in Chapter 7, with slight modifications to conform to the rigour of this economic analysis. This primarily involves the addition of two floors to account for the packaging of harvested plants, re-sowing the drum module with seedlings, seedling growth chambers, and all ancillary mechanical equipment needed for a vertical farm to function. At 1,225 m^2 per floor the building's total area would be 14,700 m^2, 12,250 m^2 of which would be devoted to crop growth.

This hypothetical vertical farm will only produce one crop - lettuce. Though lettuce production in commercial hydroponic greenhouses is currently eclipsed by that of tomatoes, cucumbers, and bell peppers, lettuce has become the crop of choice for high-density S/CEA facilities due to its short growing cycle and light weight. Over the last decade hydroponic lettuce has found a niche in the global food market as a gourmet, high-quality item favoured by restaurants, specialty grocers, and fresh-conscious shoppers. When shipped with roots in-tact inside rigid water-holding containers the plants can maintain their freshness up until the moment of consumption, thus earning the moniker "living lettuce".

Hydroponic lettuce is also desired by restaurants for their clean, soil-free cultivation environment that produces plants requiring minimal preparation. With these considerations it is assumed the market for this hypothetical vertical farm's produce would be numerous downtown restaurants interested in local, high-quality organic lettuce, as well as regional grocery stores with specialty or organic food aisles.

Among the building's 10 levels of crop production an estimated 19,200 drum modules could be accommodated. Using the productivity statistics of an

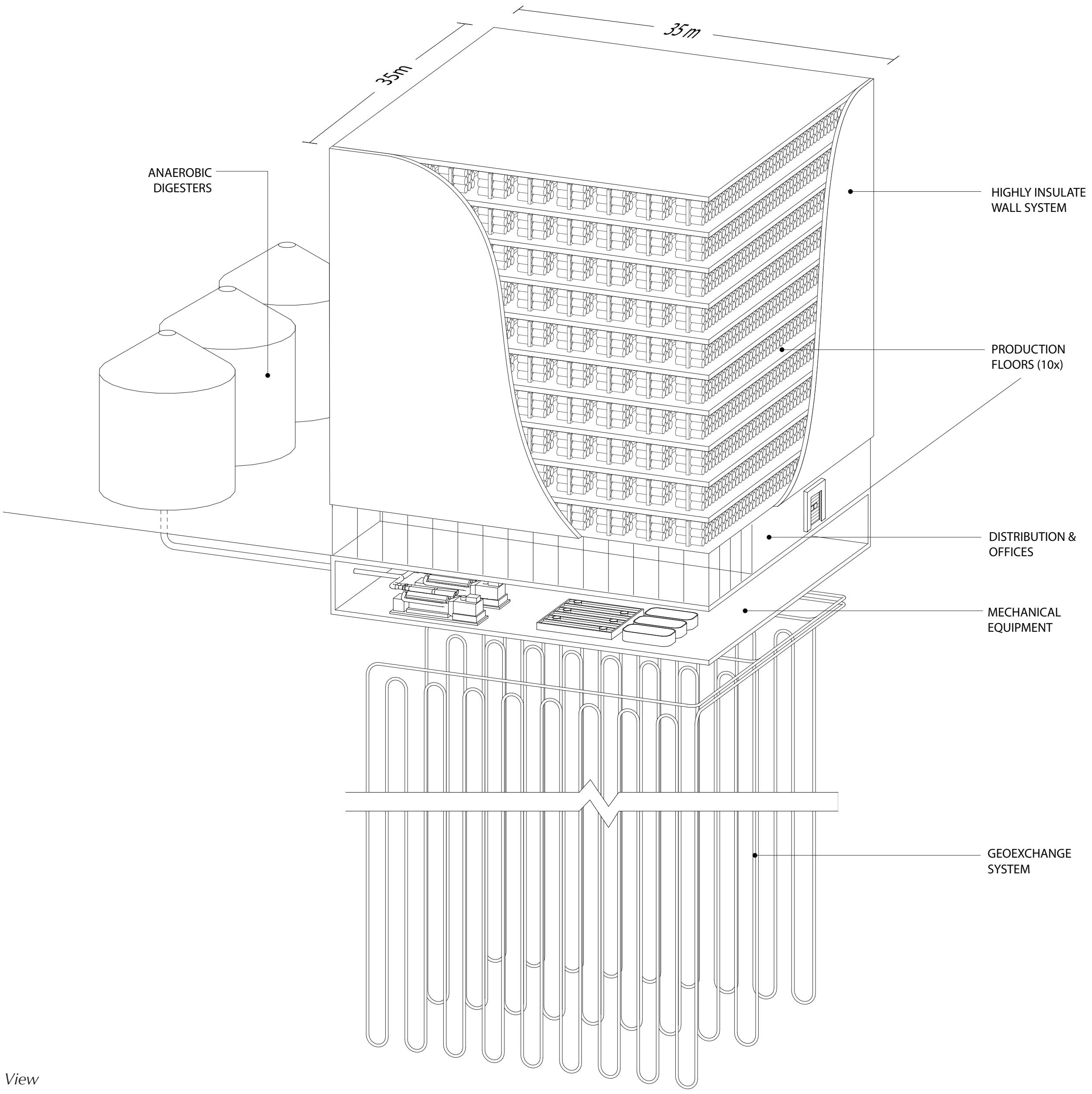

Fig 2.30
Vertical Farm, Axonometric View

identically-scaled hydroponic drum module currently sold by Omega Garden™, each drum could produce 80 half-pound lettuce plants within a 20 day growing cycle.[1] Conservatively assuming 10% of the yearly yield would be unsalable due to pathogen or physiological anomalies, the farm's total saleable output would be 25,228,800 lettuce plants per year.

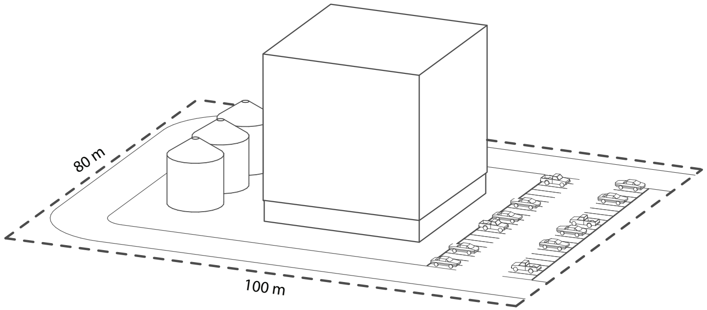

Fig 2.31

Site Axonometric, area = 8,000 m^2 */ 2 acres*

Capital Costs

(Building)

To quickly estimate a building's total construction cost one must multiply its floor area by the average price per unit of floor area for the same category of building in a similar location. Though no vertical farms are available for comparison it is assumed a purpose-built vertical farm would fall into the general price structure of conventional commercial urban buildings, given their standard structural and building envelope requirements. This comparison may prove to be too conservative as vertical farms would have very few interior partitions, doors, finishes, and hardware components, each of which command a significant portion of typical construction budgets. On the other hand the building will be designed with a minimum lifespan of fifty-years, which is a provision that would elevate construction costs. In downtown Toronto an accepted value for higher-end commercial buildings is $2,460 per square metre, giving the 14,700 m^2 vertical farm a total construction budget of $36,162,000.

(Land Cost)

In order to accommodate the building, the anaerobic digester tanks, and a small parking lot for employees the vertical farm will require 2 acres of land. According to Colliers International the average price of industrial land in the central zone of the City of Toronto for 2010 was $298,636 per acre.[2] Thus, the total estimated land cost for the vertical farm would be $597,272.

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[1] Omega Garden's unit actually produces 80 plants within 15 days in non-conditioned, showroom conditions. The extra five days were added to account for any possible inactive time between growing cycles.

[2] Colliers International, Market Report & Forecast Greater Toronto Area Q3 2010

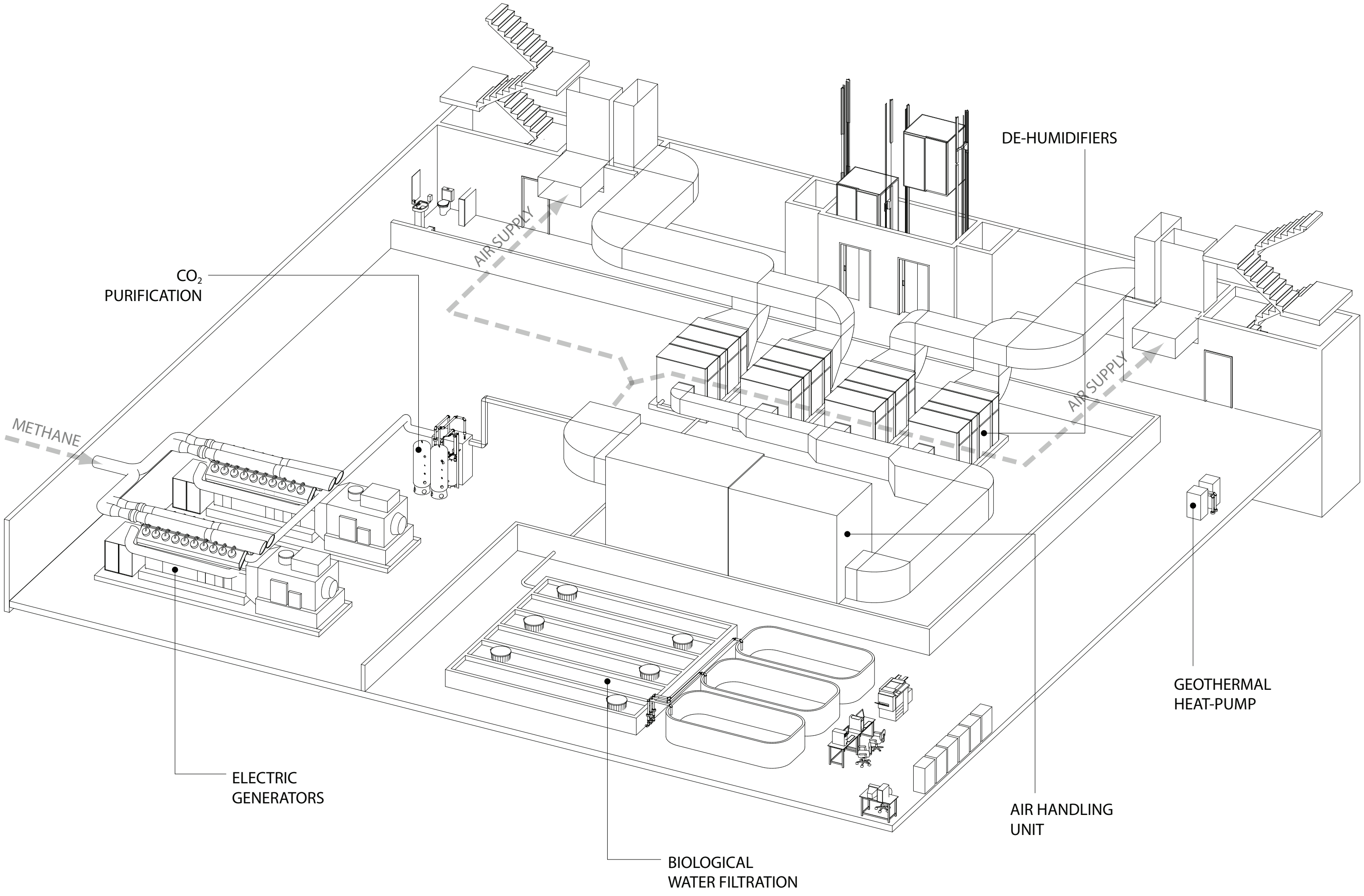

Fig 2.32
Vertical Farm, Basement

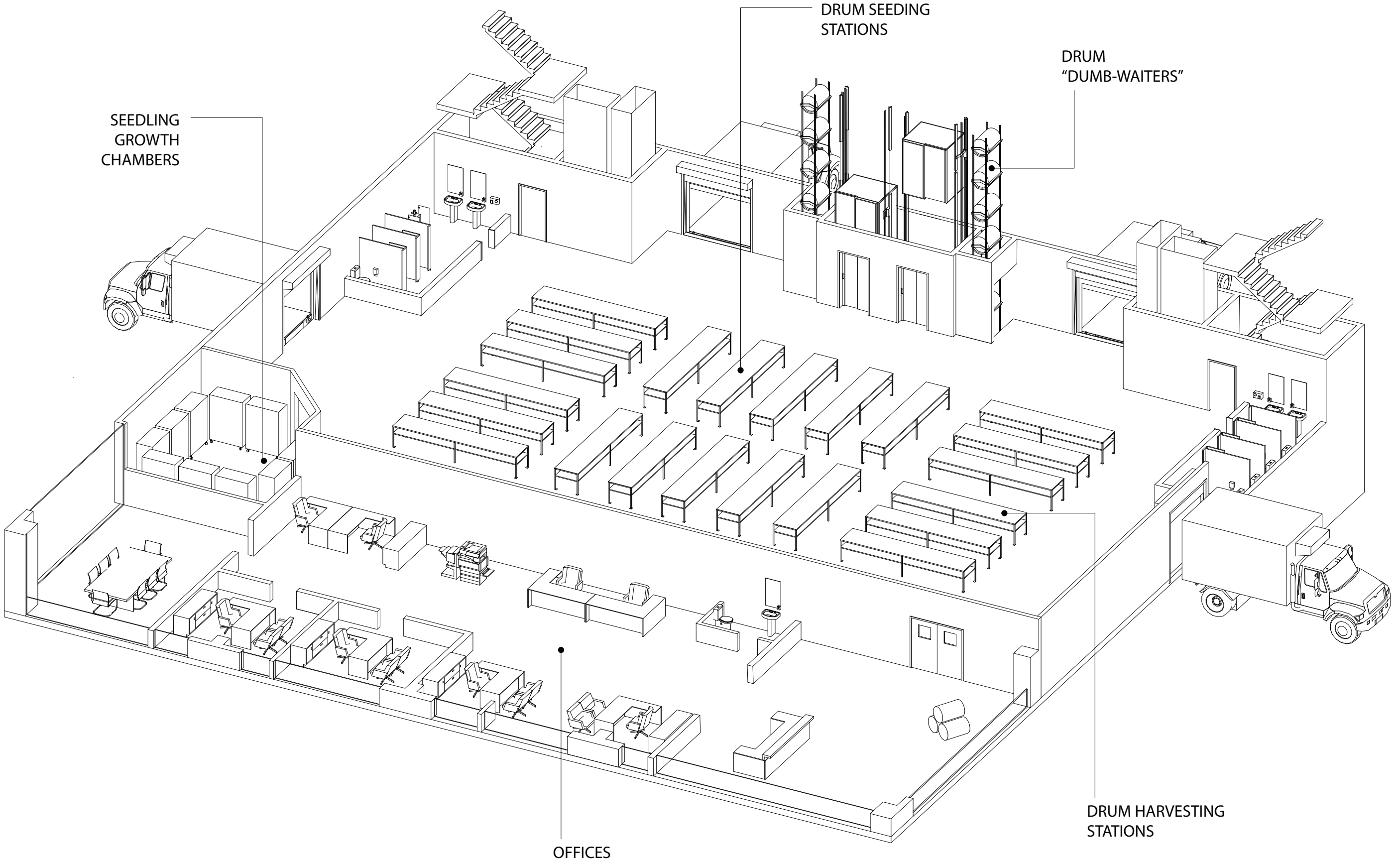

Fig 2.33
Vertical Farm, Ground Level

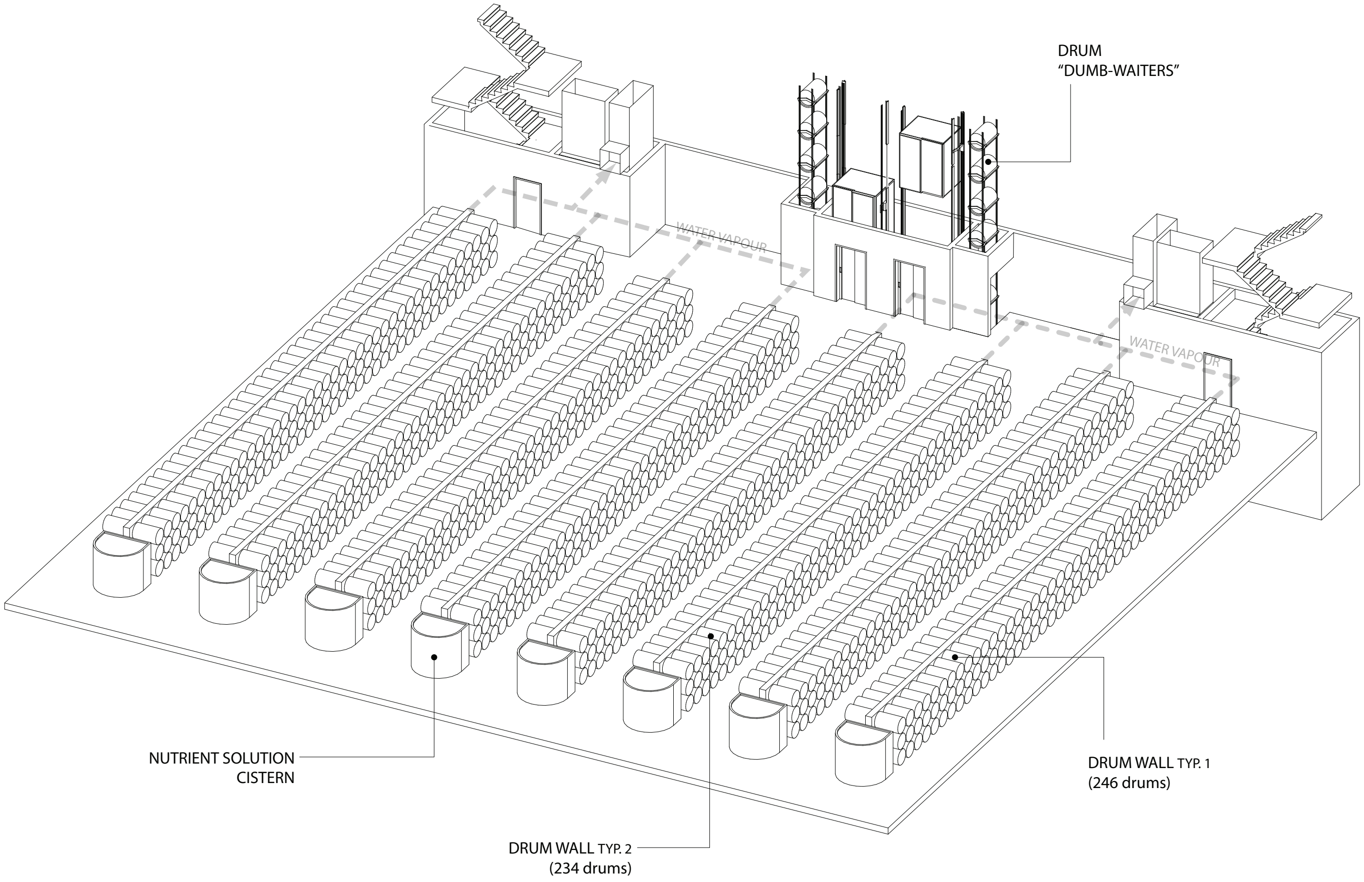

Fig 2.34
Vertical Farm, Typical Production Floor

(Building Systems)

The major building systems can be grouped into two categories – internal environmental control and electricity production. The former includes a geothermal heat pump for internal temperature control, an air handling system for ventilation, and industrial dehumidifiers, while the latter includes a bank of anaerobic digesters tanks and biogas-fuelled generators scaled to accommodate the vertical farm's exorbitant energy requirements.

The farm's base heating and cooling requirements will be accommodated by a geothermal heat pump. This system was selected both for its minimal long-term costs and its ability to beneficially utilize the temperature extremes produced by the building's mechanical components, specifically its electrical generators and dehumidifiers. Based on a projected requirement of 132 tons of geothermal capacity, Canadian Commercial Geothermal Inc. estimated a total cost from design to installation of around $1,200,000.

With temperature control provided by convection the building's ventilation system need only focus on maintaining desirable air quality and composition for the plants. Somewhat inverse to conventional buildings, this will involve replacing the oxygen-rich air emitted by the crop during photosynthesis with a mixture of fresh air and carbon-dioxide rich exhaust of the electric generators. Though not included in the productivity estimates for this hypothetical vertical farm CO^2 fertilization has been shown to significantly accelerate the rate of biomass production in lettuce and other agricultural crops in controlled environments.[3] [4] By compressing the crop's growth phase the farm would be able to achieve more harvests per year, thus increasing its economic productivity. For the hypothetical vertical farm a system that can ventilate 50,000 cubic feet per minute (CFM) was specified by Canadian Air Systems Inc. for approximately $70,000, with an additional $30,000 for installation.

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[3] Ikeda, A, S. Nakayama, Y. Kitaya, & K. Yabuki (1988), Effects of Photoperiod, CO^2 Concentration, and Light Intensity on Growth and Net Photosynthetic Rates of Lettuce and Turnip. *Acta Hort* (ISHS) 229. p.273-282

[4] Kramp, Dick. (2009) Making Green Energy Happen: Policy & Priorities. *Cogenration in Greenhouses: The Dutch Experience.* April 2009, GE Energy Jenbacher gas engines. http://www.ivey.uwo.ca/lawrencecentre/green/presentation_PDFs/Session3_Kramp.pdf

(Dehumidification)

Among the various systems specified for this vertical farm the provision to reclaim transpired water vapour is likely the most contentious. As mentioned previously, plants transpire considerable amounts of water vapour during photosynthesis. When large volumes of plants are grown in controlled environments this water vapour can build-up to a level that is detrimental to proper plant growth. Specifically, if humidity is too high plants have more difficulty transpiring, which reduces their rate of biomass production and can lead to physiological deformities, such as "tip burn" for lettuce.[5]

Conventional greenhouses and other indoor agriculture facilities currently avoid reclaiming transpired water, electing to simply expel it to the outside world and consume more water to replenish irrigation levels. This is a reasonable strategy since, generally speaking, freshwater is still an abundant and inexpensive commodity in the regions of the world engaged in advanced agriculture, thus rendering its costly reclamation an unnecessary economic burden.

The logic to include the recovery of transpiration in this cost analysis is to gauge the economic implications of realizing a form of food production that is maximally efficiency in its resource usage. Though the design's Southern Ontario siting may be one of the most freshwater-secure areas on Earth the incidence of water stress is widely projected to increase throughout much of the world in the coming decades. One study has calculated that if present trends continue 1.8 billion people will be living in absolute water scarcity by 2025, while a full two thirds of the human population will face water stress.[6] With agriculture currently accounting for some 72% of human water use it seems likely that such steps to reduce water consumption will become a desirable provision of vertical farming in the future.

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[5] Both, A.J. (1995). *Dynamic simulation of supplemental lighting for greenhouse hydroponic lettuce production.* Ph.D. Dissertation. Ithaca, NY: Cornell University Libraries. p.172

[6] United Nations Environment Programme. (2007). Globla Environmental Outlook - GEO4 environment for development. p. 97. http://www.unep.org/geo/geo4/report/GEO-4_Report_Full_en.pdf. Retrieved November 30, 2010.

With sufficient dehumidifiers a vertical farm would theoretically only lose water that is contained within the produce it sells, realizing maximum feasible efficiency of water use for agricultural productivity. The California lettuce fields that produce most of Canada's imported lettuce use between 1,800 and 3,500 cubic metres, or in weight metric tonnes, of water per acre harvested.[7] To produce the same yield of lettuce (~18 metric tonnes) a dehumidifier-equipped vertical farm would lose just 14.4 metric tonnes of water, assuming the standard 80% water content for the weight of lettuce. In other words a vertical farm could produce lettuce while consuming just 0.8% to 0.41% (i.e. 1/240th) of the water needed for conventional lettuce production.

Fig 2.35
Dehumidifier Corporation of America's DCA 14000T unit

To determine the total moisture load for the dehumidifiers to remove one must first establish the crop's maximum transpiration rate over a given unit of time. Due to the numerous variables that could impact such rates this estimate must be based on data from existing farms growing the same plant variety with a similar growing system. Though no commercial hydroponic farms utilize the drum style as of yet a similarly regulated S/CEA system is used by Cornell University's Controlled Environment Agriculture facility. According to program director Dr. Louis Albright the Cornell facility's hydroponic lettuce transpires approximately 1 mm of water per square foot, or 0.093 litres, per plant per day.[8] With a maximum daily population of 1,536,000 plants, the farm is expected to produce a staggering 7.135 metric tonnes of water vapour per day, or in industry-standard notation 655 pounds of water per hour.

To effectively remove this volume of moisture the farm will require a series of industrial-sized mechanical compressor dehumidifiers, as opposed to the more energy-consumptive desiccant technology. The 30-ton DCA 14000T sold by the Dehumidifier Corporation of America can remove 170 pounds of water per hour at the farm's desired relative humidity and temperature of 70% and 70° F, respectively. As four units are required to meet the moisture removal needs of 655 pounds per hour, and each unit is priced at approximately $60,000, the provision of reclaiming transpiration water will cost $240,000 for equipment and installation.[9]

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[7] Jackson, L., K. Mayberry, F. Laemmlen, S. Koike, K. Schulbach, & W. Chaney. (1996). *Leaf Lettuce Production in California*. Publication 7216, p.4 Oakland, CA: UC DANR. .

[8] Both, *Dynamic simulation of supplemental lighting for greenhouse hydroponic lettuce production*

[9] The Dehumidifier Corporation of America

CAPTIAL BUDGET

Building Construction	$36,162,000
Land Acquisition	$597,272
Geothermal System	$1,200,000
Air Handling Unit	$100,000
Dehumidifiers	$240,000

Fig 2.36
Typical cell of a Living Machine®

(Living Machine®)

In addition to losses due to transpiration, conventional hydroponic greenhouses must also consume freshwater to replace the nutrient solution which becomes pH-depleted after extended exposure to crops. Since we have established a commitment to achieve maximum conservation of water for this vertical farm the pH-depleted solution must be purified on-site and recirculated back into the system. To do this the building will require some form of wastewater treatment system, most appropriately one that utilizes no harsh chemicals and can be contained within a small footprint, such as a Living Machine®. A Living Machine® is a self-contained biological wastewater treatment system designed to purify water using microorganisms, algae, plants, snails, and fish. Physically it consists of a number of containers or cells housing the various biological entities, through which the water is circulated to increasing purity. Living Machines® were first conceived and implemented by Canadian ecologist John Todd, though today the trademark rights belong to Worrell Water Technologies of Charlottesville, North Carolina.

If we assume the hypothetical vertical farm's crops transpire 1/40th of their available solution per day it would result in a total solution capacity of 285,400 litres. If we also assume the farm would need to replace the solution every two weeks - a standard solution cycle duration for commercial hydroponics – the farm would require some 10,200 litres, or 2,694 gallons, of wastewater purified daily. After consulting with Worrell Water, their Living Machines® require approximately 150 square feet per 1000 gallons of daily purification, resulting in a total size of 808 square feet (75 square metres). The cost of all initial engineering, assembly, and on-site installation was specified at $400,000.

(Growth Chambers)

The farm will require a series of commercial-scale propagation chambers to grow the plants from the seed to seedling stage, during which the plants lack the internal structure necessary to thrive in the hydroponic drum module. The seedling growth stage will last between 15 to 20 days, roughly the same time span required for transplanted seedlings to develop into saleable lettuce plants. Given these similar cycles the vertical farm's seedling growth capacity must be the same as its maximum daily crop capacity - 76,800 plants.

The greenhouse and nursery equipment manufacturer Pro-Grow Supply Corp. produces an energy and water efficient growth chamber called the PC-46 that holds up to 46 standard "1020 flats" (a.k.a. trays).[10] With 200 cells per flat a single PC-46 can propagate 9,200 lettuce seedlings at a time, meaning the vertical farm would require a minimum of 9 chambers. Adding an extra chamber for redundancy, the 10 PC-46s priced at $3,000 per unit would cost a total of $30,000.[11]

Fig 2.37
The PC-46 growth chamber produced by Pro-Grow Supply Corp.

(Electricity Demands)

Given that vertical farming relies on artificial lighting instead of sunlight it should not be surprising that one of the most important variables for the economic success of a vertical farm is the performance of its grow lamps. A less efficient variety of grow lamp would not only increase the electricity load required to provide sufficient light energy for the plants, it would also produce more waste heat, resulting in increased loads for the temperature and humidity control systems to manage.

Fortunately grow lighting technology has rapidly advanced over the past decade, and is expected to experience similar significant advancement throughout the coming decades. Light-emitting diode (LED) technology, for instance, progresses under what is called Haitz's Law, which observes and predicts that the cost

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[10] Pro-Grow Official Website, http://progrosup.info/prop_cham.html, Retrieved Dec. 18th, 2010

[11] Greenhouse Megastore, www.greenhousemegastore.com, Retrieved Dec. 10, 2010

Fig 2.38

Omega Garden's™ Volksgarden® with a 200W Compact Fluorescent grow lamp supplying a crop of chard with light energy

per lumen (useful light emitted) of LEDs falls by a factor of 10 every decade.[12] This means in 2020 LEDs will be ten times less costly than contemporary LED technology, which has already crossed the threshold of being a cost effective option for certain applications of indoor horticulture. Other emerging technology, like electrodeless 'magnetic induction' lamps, offer still greater watt-per-lumen efficiency and overall cost effectiveness for grow lighting applications. As a result, the economic limitations using artificial light will undoubtedly become less significant as this exponential trend of grow lamp efficiency continues.

Omega Garden's™ identically scaled hydroponic drum module unit currently uses a 200W compact fluorescent (CLF) tube light to produce the aforementioned yield of 80 plants over a 20 day growing cycle. Operating year-round with an 18-hr lighting day period, the 19,200 drum modules in the hypothetical vertical farm would require an astonishing 18,921,600 kWh per year. As a comparison, this is more than the electricity requirements of one thousand typical North American homes.[13] It should be noted that, while the estimates have been based on the 200W CFL, Omega Garden™ is currently planning to convert to a more efficient 100W magnetic induction lamp – a change that would cut the total electricity load of the grow lights in half.[14]

The next most significant energy load comes from the building's four industrial dehumidifiers. Requiring 38 kW each, the four units under constant operation would consume approximately 1,331,520 kWh of electricity per year. The ventilation system's 60 hp motor running at an expected 80% efficiency would require around 470,328 kWh per year. The specified geothermal heating and cooling unit operates with a small heat pump and two circulation pumps, together using approximately 53,240 kWh. If the KONE EcoDisk® brand were selected for the building's two elevators each unit would consume around 7,000 kWh each per

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[12] Haitz's Law, *Nature Photonics*, p.23. vol.1, (2007, January) Nature Publishing Group

[13] Silverman, Dennis. *Southern California Household Energy Savings*, (2007, October). U.C. Irvine

[14] Given the ability of magnetic induction lamps to dim to better conform to the varying lighting requirements of a plant's growing cycle they would likely use less than 50% of the electricity consumed by 200W CFLs to produce the same harvest

year.[15] Assuming the building's two custom drum transporting 'dumb-waiters' would require half that amount the yearly elevator electricity load would be just 21,000 kWh.

Initial estimates for water pump needs include ten high discharge head pumps to supply each floor with fresh irrigation and eighty 3000 gallon per hour (GPH) pumps for inter-floor distribution to each drum wall. The Deep Well Submersible Pump sold by Wayne® costs $350 and uses 559 W, while its 3000 GPH Continuous-Duty Pump costs $50 and uses about 124 W.[16] Together the ninety pumps would cost $7,500 to purchase and consume just less than 147,000 kWh if operating continuously for a year.

Finally, the farm's PC-46 growth chambers require 875 watts per unit, creating a yearly electricity load of 76,650 kWh for ten units at continuous operation.[17] Together the vertical farm's total energy requirements are just over 21 million kWh per year.

(Electricity Production)

Due to the stated desire to realize a form of agriculture that does not rely on non-renewable resources this hypothetical vertical farm will utilize anaerobic digesters connected to methane-burning electric generators to account for its complete electricity needs. In large, multi-crop vertical farms significant amounts of plant waste would be generated to cover a potion of the digester's required feedstock, thus providing a secondary benefit in the productive use a would-be waste material. However, in this simplified hypothetical vertical farm the sole crop variety, lettuce, can be sold with its roots in tact, leaving the only on-site source of biowaste to be the infrequent occurrences of diseased or otherwise unsalable plants. As a result the entire feedstock for the anaerobic digesters will arrive from external sources, most desirably from food waste from the urban vicinity.

Energy Demand Summary

Grow lamps (19,200 CFLs @ 18hr/d) =	*18,921,600 kWh*
Dehumidifiers (4 unites @ 38 kW) =	*1,331,520 kWh*
Ventilation System (one 60 hp motor) =	*470,328 kWh*
Geothermal Heat Pump (as spec.) =	*53,240 kWh*
Elevators (2 standard, 2 "drum waiters) =	*21,000 kWh*
Water pumps (90 pumps) =	*147,000 kWh*
Growth Chambers (10 @ 0.875 kW) =	*76,650 kWh*
TOTAL	**21,021,338 kWh**

Fig 2.39
Onsite Power System's demonstration Anaerobic Phased Solids digester system located at University of California at Davis.

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[15] *KONE elevator ecoefficiency.* KONE official website. Retrieved Nov.29, 2010

[16] Wayne corporate website, www.waynepumps.com

[17] Pro-Grow Official Website, http://progrosup.info/prop_cham.html, Retrieved Dec. 18th, 2010

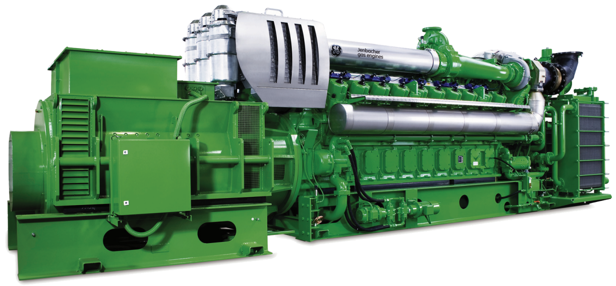

Fig 2.40
General Electric's 620 Jenbacher gas engine

Energy Production Summary

1 imperial ton food waste = 22 therms of biogas
1 therm = 100,000 BTU, 1 BTU = 0.000293 kWh

100 tons of food waste = 2,200 therms
= 220,000,000 BTU
= 23,527,900 kWh

Designing a vertical farm to accept municipal food waste has two important advantages, the most immediate of which are economic. Urban food waste is not only a free, abundant energy feedstock from which a vertical farm can generate electricity, it would also become an added source of revenue since municipalities pay for the processing of their waste – usually around $100 per ton.[18] The second advantage being that it redirects wastes from landfills that would otherwise contribute to atmospheric greenhouse gas emissions to become an energy source that reduces the carbon-footprint of a production facility.

The standard methane (i.e. biogas) production rate from food wastes its 22 therms per ton of waste feedstock, or the equivalent of 645 kWh. To produce enough methane to generate at least 21,000,000 kWh per year required for the farm's major systems the building would need a series of digesters that could process up to 100 tons of food waste per day.

Onsite Power Systems Inc., a spin-off of University of California at Davis' Anaerobic Phased Solids (APS) research, designs and builds APS digester systems at and above the 100 ton per day scale. Their design to this specification consists primarily of three large tanks measuring 10.6 metres in diameter by 12.2 metres in height, equating to around 1,080 cubic metres of volume each. In addition the system would require some small monitoring equipment, stairs and catwalks for observation, and screw pumps and piping needed to transmit material through the tanks. In total the design and installation of this system would cost approximately $10,000,000, and generate a methane stream capable of delivering 23,527,900 kWh per year.

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[18] Glysson, E.A. 1990. Chapter 8. Solid Waste, *Standard Handbook of Environmental Engineering*. Ed. R.A. Corbitt, New York: McGraw-Hill, Inc. p. 8-36.

The actual electricity generation would occur by feeding the collected methane to a gas-fuelled electric generator. General Electric's Jenbacher series of engines is the most likely candidate, as they can process biogas directly without the costly step of treatment or refining. According to GE Canada the design and installation of Jenbacher engines costs between $1,200 to $1,500 per kW of electrical generation capacity. Since the farm requires an engine system that produces 2686 kW, the Jenbacher gas engines are expected to cost approximately $4,078,750.[19] In addition, the system would also require a transfer switch to enable the transmission of power to and from the regional electricity grid. This piece of equipment, estimated to cost around $50,000, is necessary should the building's digester system or generators need to go offline or, more advantageously, if the building happened to produce excess electricity.

(Availability of Urban Biowaste)

The most comprehensive study on urban food waste to date emerged from the United Kingdom in 2009. It discovered that the U.K. produced approximately 8,300,000 tons of household food waste in 2009, or 136 kg per capita. As the specified vertical farm design requires 90.7 metric tonnes (100 U.S. 'short' tons) of biowaste daily to cover its electricity needs it must collect the food waste from approximately 243,422 residents. Utilizing Canada's average lettuce consumption rate of 11 kg per capita, the farm's 5,721,795 kg (12,614,400 lbs) of lettuce production per year would satiate the lettuce demand for 520,163 people. At this ratio the estimated food waste of the City of Toronto could support vertical farms that would produce 100% of the lettuce needs for 5.8 million people.

This estimate does not include other key sources of urban biowaste like restaurant and institution food waste, yard trimmings, and sewage. Looking just at the later, a study conducted by engineers from the Queen's-RMC Fuel Cell Research Centre found that the City of Toronto (excluding GTA suburbs) could generate

CAPITAL BUDGET

Building Construction	$36,162,000
Land Acquisition	$597,272
Geothermal System	$1,200,000
Air Handling Unit	$100,000
Dehumidifiers	$240,000
Living Machine®	$400,000
Growth Chambers	$30,000
Anaerobic Digester System	$10,000,000
Jenbacher Gas Engines	$4,078,750

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[19] 23,527,900 kWh / (24 hours x 365 days) = 2,686 kW; 2,686 kW x $1,500 = $4,028,750

Fig 2.41
Organic waste collection programs have successfully diverted a significant percentage of urban waste from landfills. Unfortunately most cities merely deposit their collected organic waste in feilds to enable decomposition, which allows methane to escape into the atmosphere.

310,000 kWh of electricity per day from its existing sewage waste. If directed to the anaerobic digesters of vertical farms this waste stream would be sufficient to extend a city's self-sufficiency for lettuce to an additional 2.76 million people. Together this suggests just two biowaste streams of the City of Toronto's 2.7 million people could support enough vertical farms to produce all the lettuce needs for 8.5 million people.

It should be noted that an urban network of vertical farms would undoubtedly produce a wide variety of vegetable and fruit crops, rather than focus purely on lettuce. Though the data necessary to confidently estimate vertical farming's production of other crops by weight is unavailable, the above statistics suggest a significant portion of a city's fresh vegetable demand could be supplied by vertical farms powered by local biowaste. Also to note, when vertical farms produce crops like tomatoes and peppers that generate significantly more plant waste than lettuce the requirements for external urban biowaste would be reduced. Furthermore, these values are based on the use of 200W compact fluorescent grow lights in the vertical farm, a technology that is relatively old and energy intensive. If one assumed the use of the more efficient 100W electrodeless induction lamps or a future iteration of LEDs the vertical farm would require a small fraction of the biowaste feedstock to produce the same yields.

In the future, as demand for biowaste as an energy feedstock increases vertical farms will have to compete with other energy providers for access to this resource. While this may seem like a complication to the vertical farming model proposed here one should note the advocacy of on-site biowaste processing was intended primarily to circumvent the existing fossil-fuel based electricity grid, as well as encourage the emergence of cyclical urban resource metabolism. If cities begin to generate electricity from their biowaste at a regional scale it would enable vertical farming to shed the on-site power generating requirement while achieving the same environmental goals.

(Hydroponic System)

Few hydroponic growing systems are designed specifically to accommodate grow lamps, even fewer have been used in applications with the scale and density required for vertical farming. In this absence I have designed the three-tier drum wall advocated throughout this chapter as a logical evolution of the existing drum-based concepts.

The Volksgarden® unit produced by Omega Garden™ includes a rotating mechanism, an exterior frame, and a trough for the nutrient solution, each of which are not included in this three-tier drum wall system. On the other hand, the drum wall would require additional plumbing, duct work, and structural members not included in the Volksgarden®. Given these seemingly offsetting costs, the per-module price of the drum wall system is assumed to be comparable to that of the Volksgarden®, which currently retails for $2,000.[20] With 19,200 drum modules within the vertical farm the total cost of the hydroponic system is estimated to be $38,400,000, making it the largest expense of the project.

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[20] Omega Garden official website, www.omegagarden.com

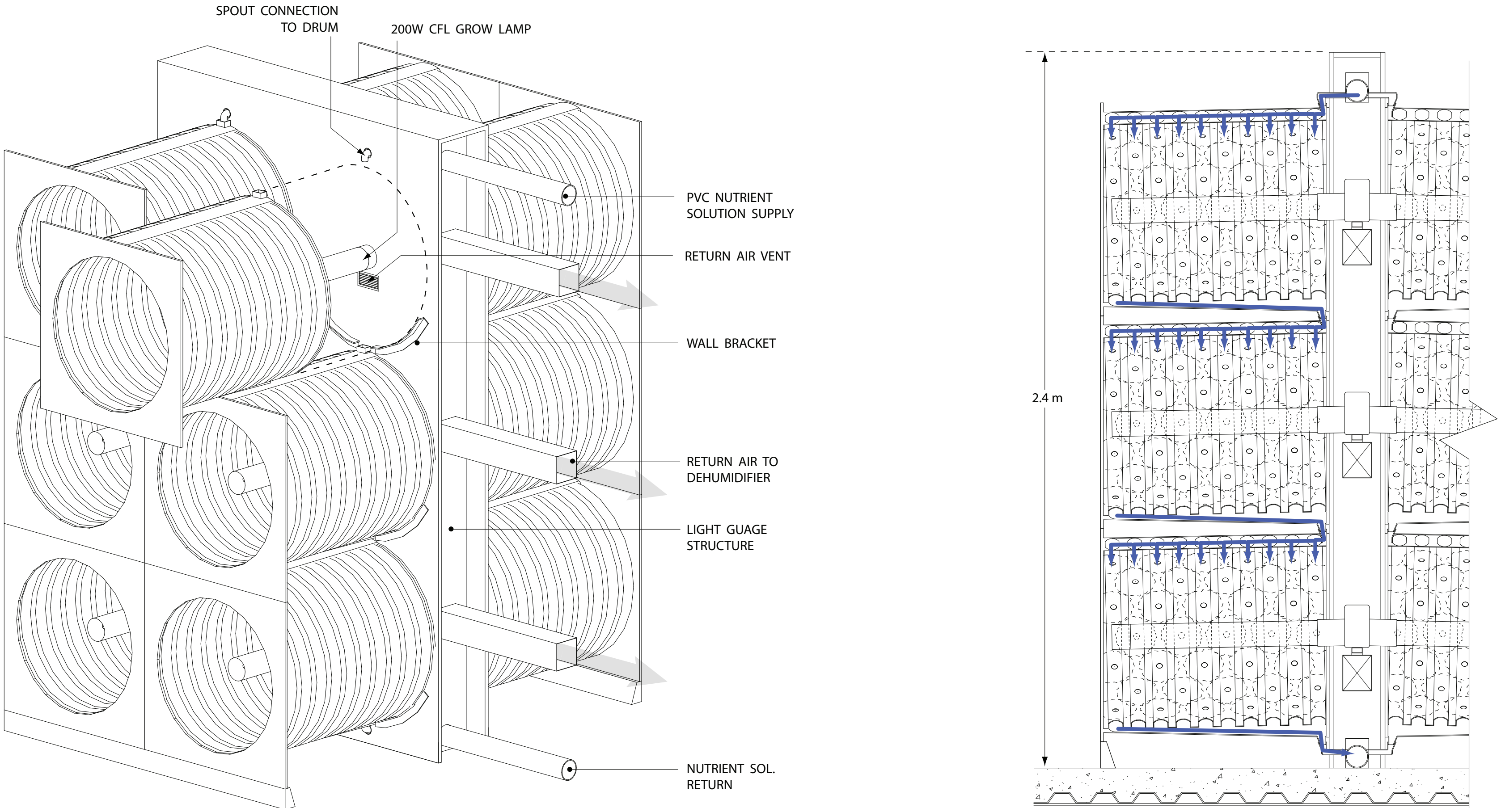

Fig 2.42
Stacked drum hydroponic system

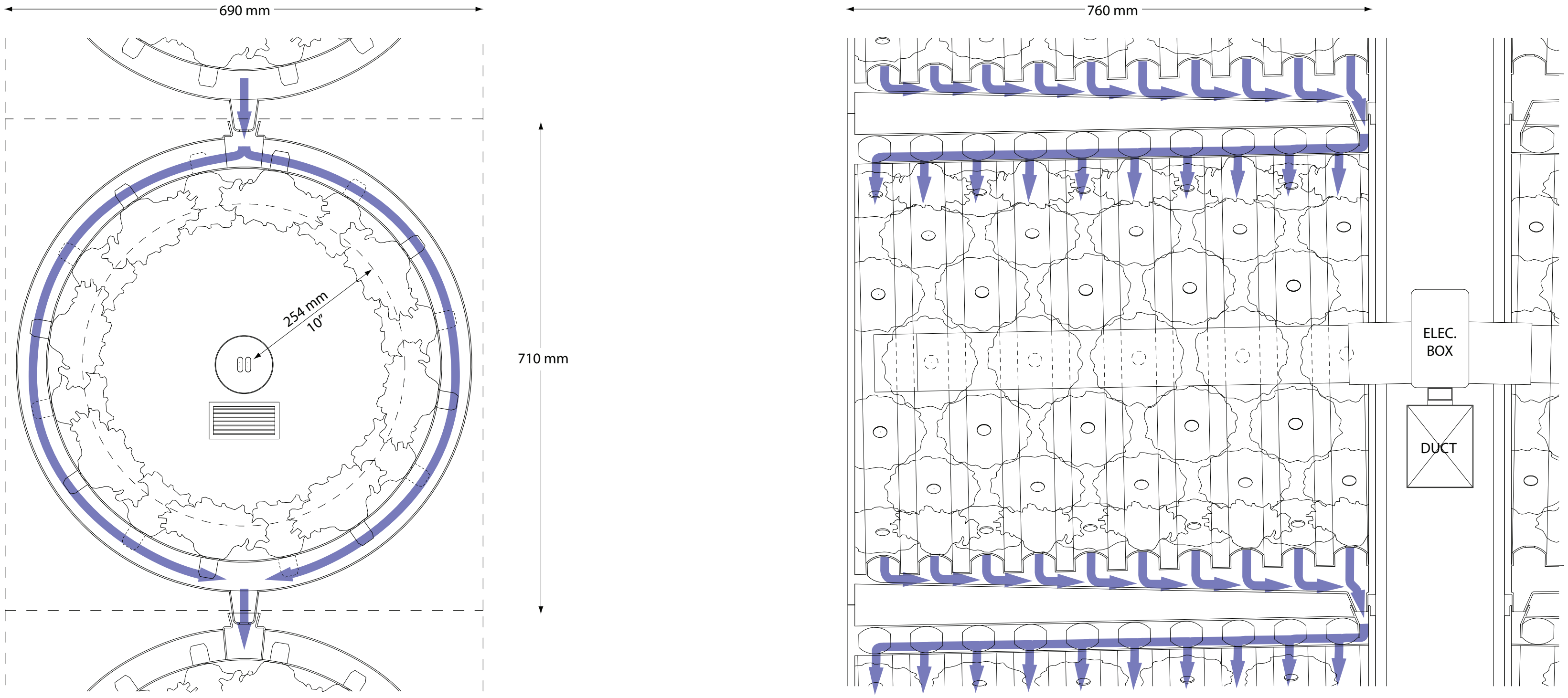

Fig 2.43
Stacked drum hydroponic system, details

CAPTIAL BUDGET

Building Construction	$36,162,000
Land Acquisition	$597,272
Geothermal System	$1,200,000
Air Handling Unit	$100,000
Dehumidifiers	$240,000
Living Machine®	$400,000
Growth Chambers	$30,000
Anaerobic Digester System	$10,000,000
Jenbacher Gas Engines	$4,078,750
Water Pumps	$7,500
Hydroponic System	$38,400,000
Working Capital	$9,121,552
Contingency Allowance	$9,121,552
TOTAL	**$109,458,626**

(Contingency Allowance & Working Capital)

A contingency allowance is required to cover possible expenses not accounted for in the initial capital budget, such as increases in the price of materials, construction delays, equipment failure, and inflation. The contingency allowance is generally expressed as a percentage of the initial capital budget, with the value being determined by the project's complexity and estimated degree of risk. Considering a vertical farm is specialized, highly complex building the preliminary estimate for a contingency allowance is 10% of the initial capital budget, or $9,121,552.

Since the farm will not immediately generate income the budget must also include the provision for capital to cover expenses between the end of construction and the achievement of maximum productivity. Like the contingency allowance, "working capital" is generally represented as a percentage of the initial capital budget in preliminary cost-analyses such as this, and likewise is estimated as 10% for a total value of $9,121,552.

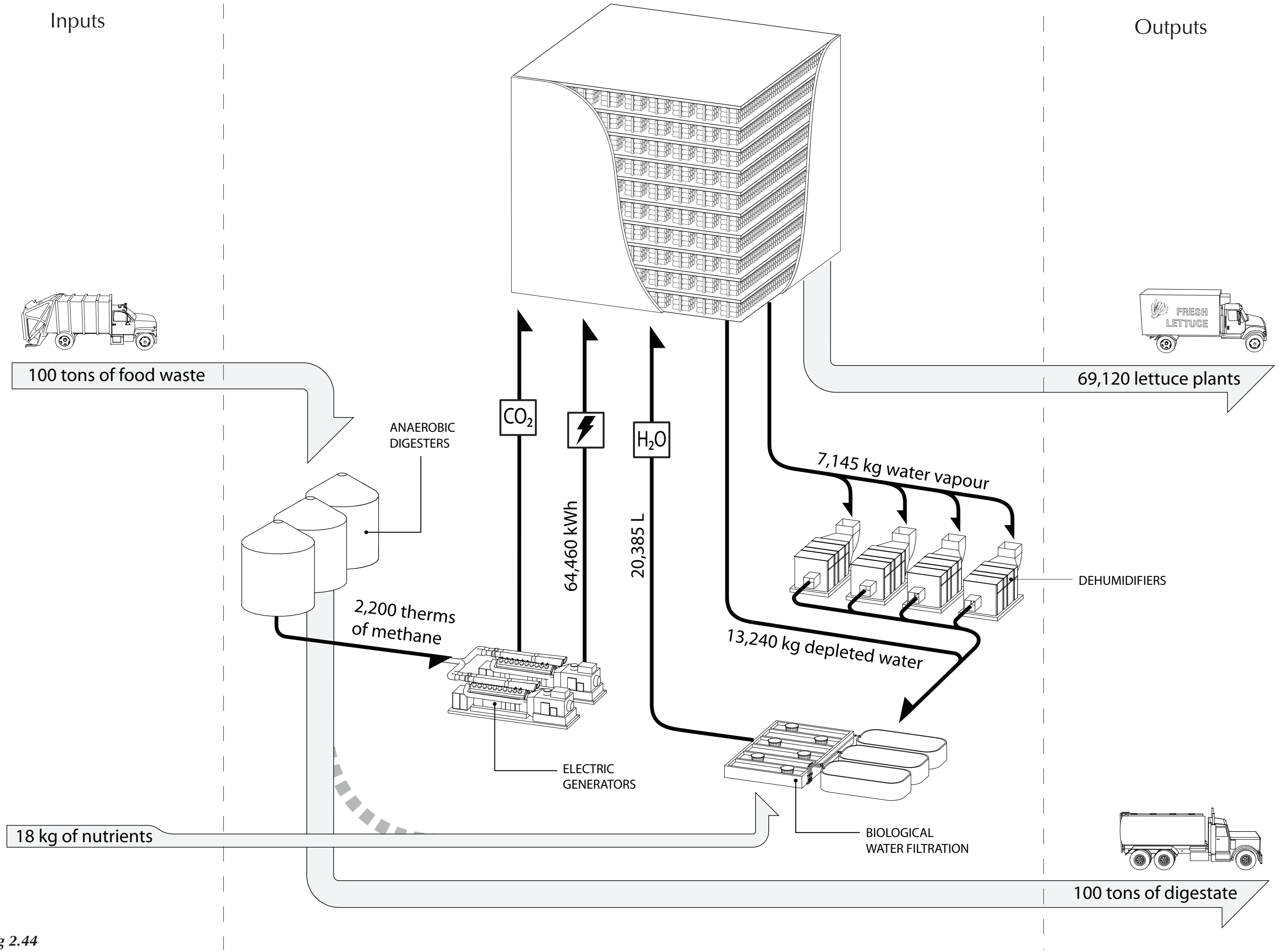

Fig 2.44
Vertical farm system diagram

Operating Costs

(Labour Needs)

Estimates for the expected labour costs of a vertical farm were attained through scaled comparisons to the labour requirements of Canada's commercial greenhouse vegetable industry. The available data indicates every 10,000 m^2 of cultivatable greenhouse space requires an average of 8.65 labourers to tend crops and 2.60 employees devoted to packing, distribution, and marketing operations.[21] Applying this to the 68,600 m^2 of productive growing surface available in the hypothetical vertical farm would result in a total labour requirement of 78 employees - 60 devoted to managing crops and 18 to the ancillary operational tasks. From another study the average salary for commercial greenhouse employees in Ontario was calculated at just $15,507.[22]

A few important differences between commercial greenhouses and vertical farms must be taken into consideration. Firstly, vertical farms would operate year-round at full productivity with daily harvesting and crop sowing tasks, as opposed to the oscillating work load of conventional greenhouses that enables the use of temporary workers. As a result the listed labour estimate must be multiplied by a 'productivity coefficient' to account for the year-round working conditions. Likewise, salaries must be increased to a more reasonable rate for full-time employment in Ontario. On the other hand, modular hydroponic systems would enable a vertical farm to introduce the labour efficiency of assembly-lines to agricultural production by concentrating the harvesting and sowing duties in a single location.

As it is currently difficult to quantify the labour impact of a vertical farm's increased productivity and the organizational efficiency of modular growing systems, an estimated productivity coefficient of 1.25 will be used. Based on the listed data the vertical farm would then require 75 employees devoted to managing the plants and 23 devoted to marketing and other ancillary tasks. In addi-

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[21] *Factsheet: Overview of the BC Greenhouse Vegetable Industry.* Ministry of Agriculture, Food and Fisheries, Industry Competitiveness Branch. Revised November 2003.

[22] The Ontario Greenhouse Alliance (TOGA). *The Greenhouse Sector in Ontario 2009 Update*,

tion, Onsite Power Systems estimates the 100 ton digester system will require four employees; two shifts of two workers per shift. With an average yearly salary of $45,000 for each of the listed divisions of employment, the total yearly labour cost of the vertical farm would be $4,245,000.

Employers must also pay for certain benefits and insurance coverage for their employees. In Ontario these generally include the Canadian Pension Plan (CPP), statutory worker's compensation (WC), and employment insurance (EI). The national rate for employer CPP contributions is 4.95% of an employer's gross labour costs, while WC and EI contribution rates tend to be around 0.60% and 2.49%, respectively.[23] From the listed gross labour costs of the farm these ancillary labour costs would total $341,298 per year.

(Depreciation & Maintenance)

As the farm's equipment and building assets will depreciate in value over time the budget must allocate funds to cover their respective replacement costs. This analysis will use the straight-line method of depreciation estimation, which involves subtracting the asset's residual value from its initial cost and then dividing the sum by its useful life in years.

The farm's building has a construction budget of $36,162,000 and an estimated lifespan of fifty years, resulting in an annual depreciation expense of $723,240. The primary elements of the anaerobic digester have an expected lifespan of fifteen years, resulting in a depreciation cost of $666,667 per year. The Jenbacher engines twenty-five year replacement interval would require a depreciation expense of $163,150, while the geothermal system's estimated thirty year lifespan would result in $40,833 of amortized expenses.

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[23] Estimate of Mandatory Benefits Costs, University of Saskatchewan. http://www.usask.ca/hrd/investigators/benefit_estimates.php, retrieved December 29, 2010.

With an expected lifespan of ten thousand hours, the 19,200 grow lamps would need replacing every 1.2 years. At $55 per bulb the yearly grow lamp replacement expense would total $880,000. The hydroponic drums have an estimated lifespan of ten years; conservatively assuming each drum costs $1,000 the yearly depreciation expense would be $1,920,000. The remaining principle components, namely the water pumps, air handing system, dehumidifiers, and Living Machine®, would require just $32,600 in depreciation expenses combined. Together the farm's depreciation costs total $4,426,490 per year.

Building and equipment maintenance is another necessary expenditure for facility operation budgets. According to Onsite Power Systems the anaerobic digester's annual maintenance expenditure is approximately 4% of the system's initial capital cost – a standard ratio for mechanical equipment. The $10,000,000 system would thus require approximately $400,000 in yearly maintenance expenditures. The GE Jenbacher engines require major maintenance overhauls every 60,000 hrs, or just under 7 years of continuous use. While the first overhaul is included in the initial price, the final two would cost approximately 75% of the initial purchase price each – just under $3,060,000 combined. Split evenly over the 25 year lifespan of the engine results in an average yearly maintenance expenditure of $244,725.

The building's estimated maintenance and repair expenditures were obtained from a study conducted by facility cost forecasters Whitestone Research for The National Research Council (U.S.). The study found the sustainment costs for robust fifty-year lifespan buildings to be around $3.50 per square foot, or $37.67 per square metre.[24] With 12,250 m^2 of gross floor area the expected building maintenance is $461,458 per year.

The maintenance expenditures for the farm's remaining equipment are comparatively insignificant. The geothermal system would require not more than $2,000 for periodic heat pump filter replacements, while the conventional 4% of capital cost estimate can be applied to the farm's remaining mechanical components – resulting a total of $31,600.

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[24] Lufkin, Peter, *Life Cycle Cost Models for Federal Facilities*, (2010, February 18). Whitestone Research.

(Packaging)

When purchased in bulk standard wax-lined cardboard cartons cost between $0.80 and $1.70 at online distribution markets.[25] Using the average price the farm could expect to pay approximately $1,314,000 for the 1,051,200 24-head cartons per year. Though the "living lettuce" plastic clamshell containers were discussed earlier as a more qualitatively desirable packaging option they would notably increase the farm's operating costs. With a typical price of $0.39 per container and a capacity of just 1 head per container the yearly cost to package the farm's 25,228,800 saleable lettuce heads would be $3,784,320.[26] As a result, this analysis will assume the use of cardboard packaging.

(Nutrients)

Ideally the nutrients required by the vertical farm's crops would be derived from the nutrient-rich digestate of the anaerobic digester. Research into the use of digestate as a nutrient source has shown it to be an effective alternative to conventional fossil fuel-derived inorganic fertilizers.[27] Financially this would have two advantages; it would reduce the expenditures on both externally-derived nutrients and the transportation of digestates off-site. However, since too few hydroponic facilities have published costing data on the use of digestate as a nutrient source this analysis will only consider the application of conventionally derived nutrients and minerals.

According to Cornell's CEA facility the ideal hydroponic solution recipe for lettuce involves dissolving 0.97 grams of Peters Professional Hydro-Sol® (a standard nutrient formulation) along with 0.15 grams of Magnesium Sulphate and 0.64 grams of Calcium Nitrate for every litre of liquid solution desired.[28] At the aforementioned solution capacity of 285,400 litres the total nutrient require-

INCOME STATEMENT

Operating Costs	
Labour - base salaries	$4,245,000
Labour - benefits, insur.	$341,298
Depreciation	
Building	$723,240
Anaerobic Digester	$666,667
Air Handling Unit	$244,725
Geothermal System	$461,458
Living Machine®	$8,100
Water Pumps	$1,500
Dehumidifiers	$16,000
Grow Lamps	$880,000
Hydroponic Drums	$1,920,000
Maintenance	
Anaerobic Digester	$400,000
Jenbacher Engines	$244,725
Building	$461,458
Other	$35,600

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[25] Retrieved from Alibaba.com, Dec.30, 2010

[26] Retrieved from Plastic Container City on December 29, 2010, product no. LBH-756-1.

[27] Liedl, et. al., *Hydroponic Lettuce Production Using Liquid Effluent from Poultry Waste Bioremediation as a Nutrient Source.*

[28] *Lettuce Handbook*, Controlled Environment Agriculture website, www.cornellcea.com. Biological and Environmental Engineering, Cornell University. Retrieved Nov. 17, 2010

Fig 2.45
Sample plastic "clamshell" container

ments for each solution cycle would be approximately 138 kg of Hydro-Sol®, 21 kg of Magnesium Sulphate, and 91 kg of Calcium Nitrate. With a two week solution cycle duration the vertical farm's yearly nutrient requirement would be 3,613 kg of Hydro-Sol, 556 kg of Magnesium Sulphate, and 2,390 kg of Calcium Nitrate. Interestingly, the cost of this vital input resource is nearly irrelevant among the facilities many other exorbitant expenses. Hydro-Sol® sells for approximately $3.00 per kilogram from online markets[29], while Magnesium Sulphate sells for $2.21 per kilogram[30] and Calcium Nitrate a mere $0.25 per kilogram.[31] With a bi-weekly replacement rate for the listed nutrient mass requirements, the vertical farm's yearly expenditures for nutrients would be just under $13,000.

(Digestate Transport)

After biowaste traverses the multi-stage digestion process the remaining material, digestate, must be removed to accommodate more waste feedstock. Assuming the cost to transport the digestate away from the farm would match that paid by the city to deliver the raw biowaste, estimated at $100 per ton, the yearly removal cost would be $3,650,000.

(Property Taxes)

In most municipalities property taxes are determined by multiplying the property assessment value by the building's categorical tax rate. Assuming the vertical farm's property value equates to the cost of the land acquisition and building construction its assessed value would be $36,162,000. For the proposed site location of downtown Toronto the industrial property tax rate is 3.69%, giving the project a yearly property tax of $1,356,417.[32] It should be noted that both these estimation variables are likely overestimates, as similarly scaled buildings in the central GTA tend to be valued around $20 million, while the other possible property tax category, farmland, has a rate of just 0.21%.

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[29] HGI Worldwide Inc., www.hydro-gardens.com/51126.htm, retrieved Dec.30, 2010

[30] Salt Works® Website, www.saltworks.us/ultra-epsom-salt-wholesale.html, retrieved Dec.30, 2010

[31] Retrieved from Alibaba.com, Dec.30, 2010

[32] 2010 Property Tax Rates, City of Toronto website, www.toronto.ca, Retrieved Dec. 30, 2010

Revenue

With 19,200 drum modules yielding 80 plants every 20 days with a 10% failure rate this vertical farm would produce around 25,228,800 saleable lettuce plants every year. In the wholesale produce market small vegetables tend to be sold in units of transportable containers rather than by weight or individual plant; for lettuce the standard is cartons of 24 plants. With the above production the farm would introduce a yearly total of 1,051,200 cartons to the wholesale lettuce market.

A quick note about the production scheduling of a vertical farm; unlike conventional agriculture that has seasonal planting and harvest phases a vertical farm's production would be staggered to achieve a stable revenue stream. Since lettuce has a 20-day growing cycle the farm would likely be divided into twenty production units, which for this design would each consist of 960 drum modules or roughly half the contents of a single production floor. Once a production unit's modules were harvested they would be cleaned, re-sown, and transported back to their original location within the same day. The process would then be repeated the following day with the next production unit on the queue, and so on into perpetuity.

Information on the pricing of lettuce was obtained from the Canadian Ministry of Agriculture's most recent summary of weekly wholesale prices for hydroponic "Boston" lettuce. Ranging between a stable high of $25.00 and a low of $18.50, the average price for the twelve month period was $20.86 per carton of 24 plants. At this price the vertical farm's daily revenue from produce sales would be $60,076, while its yearly revenue would be $21,928,032. For comparison purposes it should be noted that this yearly average for the hydroponic Boston variety was less than both field-grown romaine lettuce and all varieties of organic lettuce, which cost an average of $21.68 and $27.75 per 24-head carton respectively.

As mentioned the other source of revenue, biowaste processing, would draw an expected $100 per ton. With an anaerobic digester capable of processing 100 tons of biowaste per day the vertical farm could earn $3,650,000 per year.

CAPITAL BUDGET

Building Construction	$36,162,000
Land Acquisition	$597,272
Geothermal System	$1,200,000
Air Handling Unit	$100,000
Dehumidifiers	$240,000
Living Machine®	$400,000
Growth Chambers	$30,000
Anaerobic Digester System	$10,000,000
Jenbacher Gas Engines	$4,078,750
Water Pumps	$7,500
Hydroponic System	$38,400,000
Working Capital	$9,121,552
Contingency Allowance	$9,121,552
TOTAL	**$109,458,626**

INCOME STATEMENT

Operating Costs	
Labour - base salaries	$4,245,000
Labour - benefits, insur.	$341,298
Depreciation	$4,426,490
Maintenance	$1,131,783
Packaging	$1,734,480
Nutrients	$25,600
Transport	$3,650,000
Property taxes	$1,334,377
TOTAL	**$16,923,000**
Revenue	
Produce Sales	$21,928,032
Biowaste processing	$3,650,000
TOTAL	**$25,578,032**

Pro-Forma Analysis

With operating expenses totalling $16,917,000 and gross operating income projected at $25,578,032 the farm's annual net operating income would be $8,661,032. Compared to the capital budget of $109,578,626 the project has a projected rate of return of 7.91%. At face value this appears to be a satisfactory investment opportunity on-par with the global average return for diversified funds, and higher than the average mutual fund in the United States.[33] However, since business development ventures such as this carry significantly more risk than mutual funds most investors in business development set their minimum acceptable rate of return at 10-12%. Additionally, since vertical farming is an unproven industry utilizing new technology the project would involve more risk for investors than the average development venture. As such the project would likely require an annual rate of return between 15% and 20% to be considered a desirable investment in the current market.

Qualifying the analysis' result to current market conditions is important because economic variables change over time in ways that can significantly alter a business venture's financial feasibility. As one would expect, the analysis's deduced 7.91% rate of return is markedly higher than what a vertical farm could have achieved when commercial-scale hydroponics, compact fluorescent lighting, and A.P.S. digestion techniques were still in their infancy. In the same respect, as these technologies continue to mature one could expect vertical farming to continue its path toward economic viability. Using the analysis as a departure point it is worthwhile to briefly examine the major internal design decisions and external market forces that could impact vertical farming's investor interest.

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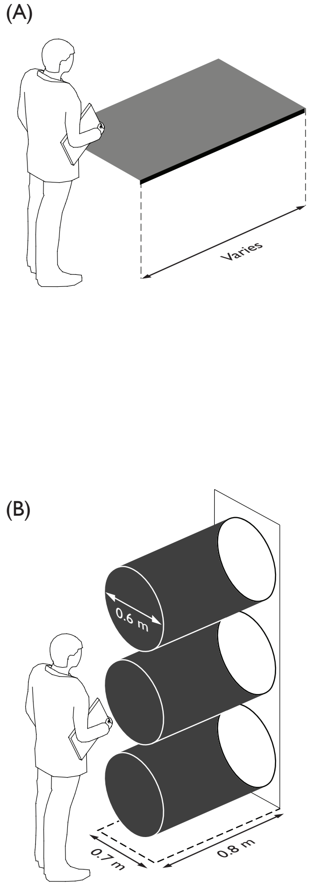
[33] The average rate of return for diversified funds in the global economy from 2000-2006 was 7.9%, while the average rate of return for U.S. stock funds was 5.37%. Source: Boudreau, Denis O, S.P. Uma Rao, Dan Ward, Suzanne Ward, Empirical Analysis Of International Mutual Fund Performance. International Business & Economics Research Journal, Volume 6, Number 5. May 2007

Improvements to Revenue

The most obvious way to improve the vertical farm's return is to increase its operating income, and to this end there are many factors to consider. One strategy could involve establishing a niche market for vertical farm produce for which consumers would be willing to pay a price premium. Selling points to this end could include hydroponic lettuce's superior quality and cleanliness to conventional lettuce, as well as its beneficial impact on the environment (diverting biowaste from landfills and returning organic fertilizers and soil fortifiers to rural lands). Organic produce, which merely boasts a 'reduced' impact on the natural world, currently enjoys a healthy price premium over non-organic produce. Organic lettuce imported from California into Ontario had an average price of $27.75 per 24-head carton for the same period as the Boston variety used in the analysis. If the vertical farm could match this price premium it would generate over $7.3 million more in net operational income and increase the rate of return to just over 15% - likely meeting the projected minimum return to attract investors.

The farm's operating income could also increase by diversifying its production with other food services, thus consolidating the multi-step food distribution system. The modern food supply chain currently involves many off-farm sectors, such as wholesalers, processors, and retailers, each of which command a certain portion of the profit from food sales. For example, using the typical 20-30% markup for wholesalers and 40-50% markup for retailers, every $1.00 of food sold by a farmer to a wholesaler would be sold for $1.30 to a retailer, who would in turn sell it for $2.42 to the consumer. These price mark-ups account for the expense of the services offered by each distribution stage (transportation, marketing, refrigeration costs, etc.), as well as their respective profit margins.

Given their ability to be situated within an urban context vertical farms have the opportunity to circumvent the standard food-distribution chain in a way not available to conventional food producers. If vertical farms were designed with on-site markets, "satellite" markets, or other forms of local distribution they could amass a portion of the profits normally collected by other food-trade sectors.



Cornell CEA Facility's productivity of 470 (U.S.) tons per acre per year
= 232.28 lbs per m^2 per year

= ~465 plants (1/2 lb) per m^2 per year

@ $0.87 per plant ($20.86 per 24 ctn)

= $404.55 per m^2 per year

With 10% failure rate, each drum produces 72 plants every 20 days, resulting in 18.25 harvests per year. (Based on the performance of the similar Omega Garden Volksgarden®)

216 plants x 18.25
= 3,942 plants per drum stack per year

Footprint is 0.7m x 0.8m = 0.56m

= 7,039 plants (1/2 lb) per m^2 per year

@ $0.87 per plant ($20.86 per 24 ctn)

= $6,124 per m^2 per year

Fig 2.46
A comparison of the revenue generating potential of (a) conventional greenhouse hydroponics with (b) space-efficient hydroponic systems designed for artificial light.

Crop Suitability for Vertical Farming

VEG. by consumption*	
~~Potatoes~~	~~35.2 lbs/pp~~
Onions	18.0 lbs/pp
Head Lettuce	15.7 lbs/pp
Tomatoes	15.7 lbs/pp
Romaine	10.3 lbs.pp
Peppers	9.1 lbs/pp
~~Sweet Corn~~	~~8.5 lbs/pp~~
Carrots	7.8 lbs/pp
Cabbage	7.6 lbs/pp
Cucumbers	6.2 lbs/pp
Celery	5.8 lbs/pp
Broccoli	5.5 lbs/pp
Sweet Potatoes	4.5 lbs/pp
~~Pumpkins~~	~~4.4 lbs/pp~~
~~Squash~~	~~3.8 lbs/pp~~
Mushrooms	2.3 lbs/pp
Garlic	2.2 lbs/pp
Snap Beans	2.0 lbs/pp
Spinach	1.4 lbs/pp
Artichokes	1.4 lbs/pp
Cauliflower	1.4 lbs/pp
Asparagus	1.1 lbs/pp
Eggplant	0.8 lbs/pp
Radishes	0.5 lbs/pp
Okra	0.4 lbs/pp
Collards	0.4 lbs/pp
Kale	0.3 lbs/pp
Brussel Sprouts	0.3 lbs/pp
Mustard Greens	0.3 lbs/pp
Turnip Greens	0.3 lbs/pp
Escarole	0.2 lbs/pp
Lima Beans	0.02 lbs/pp
TOTAL	173.42 lbs/pp

FRUIT by consumption*	
~~Orange~~	~~56.02 lbs/pp~~
~~Apples~~	~~48.62 lbs/pp~~
~~Bananas~~	~~25.06 lbs/pp~~
~~Grapes~~	~~20.72 lbs/pp~~
Watermelon	15.45 lbs/pp
~~Pineapples~~	~~13.47 lbs/pp~~
~~Peaches~~	~~9.06 lbs/pp~~
~~Canteloupe~~	~~8.88 lbs/pp~~
Strawberries	8.22 lbs/pp
~~Grapefruit~~	~~7.55 lbs/pp~~
~~Pears~~	~~5.36 lbs/pp~~
~~Lemons~~	~~5.14 lbs/pp~~
~~Tangerines~~	~~4.09 lbs/pp~~
Avacados	3.90 lbs/pp
~~Limes~~	~~3.22 lbs/pp~~
Cranberries	2.56 lbs/pp
~~Plums~~	~~2.28 lbs/pp~~
~~Mangoes~~	~~2.11 lbs/pp~~
~~Cherries~~	~~1.88 lbs/pp~~
Honeydew	1.65 lbs/pp
Blueberries	1.20 lbs/pp
~~Papayas~~	~~0.98 lbs/pp~~
~~Appricots~~	~~0.92 lbs/pp~~
~~Olives~~	~~0.87 lbs/pp~~
Raspberries	0.62 lbs/pp
~~Kiwi~~	~~0.46 lbs/pp~~
~~Figs~~	~~0.22 lbs/pp~~
~~Dates~~	~~0.20 lbs/pp~~
Blackberries	0.10 lbs/pp
TOTAL	250.81 lbs/pp

Currently suitable	
Vegetables - 67.5 lbs/pp (38.9%)	Fruits - 8.22 lbs/pp (3.3%)
Likely to be suitable	
Vegetables - 54.02 lbs/pp (31.2%)	Fruits - 25.48 lbs/pp (10.2%)
~~Req. modification for suitability~~	
Vegetables - 51.90 lbs/pp (29.9%)	Fruits - 217.11 lbs/pp (86.56%)

* Source: Economic Research Service, USDA

Additionally, due to its compact and industrialized configuration vertical farming serves as an ideal diversification partner for packaging facilities, wholesaling warehouses, and processing plants – therein amalgamating food production with the growing "value-added" sector of the food industry.

Crop Selection

Lettuce was used as the sample crop for this economic analysis as it had the most comprehensive dataset available to enable accurate predictions of yields and operating costs for the selected hydroponic system – the stacked drum design. Lettuce is one of the less caloric and nutrient efficient crops, however, which raises the question of which other crops are applicable to vertical farming.

Though it has been stated that the technology necessary to realize a vertical farm is generally well established, certain component technologies have yet to fully embrace the peculiarities of vertical farming. This is most prominently the case for hydroponic systems, as they tend to be designed for sunlight-fed applications and best suited to grow those crops which have developed a robust hydroponic market, namely lettuce, cabbage, bell peppers, strawberries, eggplants, tomatoes, cucumbers, and herbs. These lighter herbaceous plants with comparatively small space requirements have been the most successful hydroponic varieties to-date because they offer a density of production that can offset the heightened operating costs of hydroponic production. Given that lettuce is no better suited for S/CEA than the other staple hydroponic crops we can assume these other crops would achieve a similar profitability as was demonstrated in this economic analysis. Should these prove to be the only crops vertical farming were able produce profitably, it would mean the concept is only applicable to 39% of a developed nation's vegetable consumption and 3% of its fruit consumption by weight.[34]

Alternatively, plants with thick woody stems (e.g. fruit trees, thick vines) and those that require large growing zones per unit of saleable produce (e.g. wheat, corn, squash) are not well suited for commercial high-density soilless cultivation,

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[34] Percentages from the United States' food consumption by weight in 2008, Source: United States Department of Agriculture, Economic Research Service

and would likely require significant genetic modification to be an economically viable crop for vertical farms. From the same data set from the USDA, plants of this description which are not applicable to vertical farming constitute 30% of the USA's vegetable consumption and 87% of its fruit consumption by weight.

As the incidence of indoor agriculture continues to increase with the passage of time it is inevitable that new hydroponic systems will emerge to cater to a wider selection of crops. Therefore, the plant varieties that account for the remaining 31% of the USA's vegetable consumption and 10% of its fruit consumption (each of which are occasionally grown by commercial hydroponic farms presently) are very likely candidates for vertical farming in the future. Furthermore, the exponential growth of indoor hydroponic agriculture will undoubtedly increase the incentive to invest in genetic research tailored to improve agricultural crops suitability to confined cultivation environments. For instance, should agronomists be able to create a super-dwarf variety of wheat or corn, with a short stalk suited for an adjacent light source rather than the sun, it could vault these vital crops into economic viability for vertical farming.

Reductions in Operating Costs

The farm's annual rate of return could also be improved by reducing its operating expenses. One opportunity to accomplish this would be to establish a market for the farm's abundant digestates, which the analysis assumed to be a valueless commodity that must be shipped off-site at the farm's expense. This assumption was made due to the complications that have arisen with the use of digestates as fertilizer over the past decade. Some groups have pressured food wholesalers and retailers to boycott crops grown with digestates due to the possibility of household chemicals, heavy metals, and e-coli bacteria being transferred to edible crops.[35] Unfortunately for the anaerobic digester industry this blanket objection should only apply to digestates created from sewage or manure feedstocks. Conversely, digestates created solely from food and plant waste contain no materials foreign to natural ecosystems, making them an ideal organic fertilizer and soil

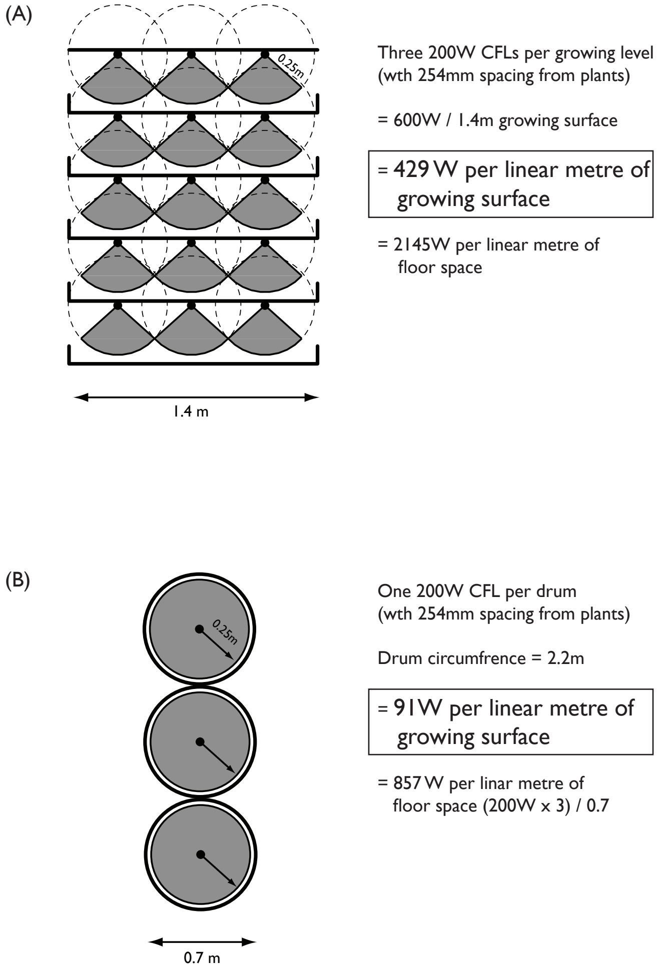

Fig 2.47
A comparison of the energy efficiency of (a) the stacked bed hydroponic design (as employed by TerraSphere), which is based on conventional greenhouse hydroponic systems and (b) the three-tier drum concept, which was designed specifically for artificial light

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[35] Supermarkets Unwilling to accept crops grown with digestate, (2010, April 12). *New Energy Focus,*

“Simplified” Vertical Farm Pro-Forma

CAPITAL BUDGET

Building Construction	*$36,162,000*
Land Acquisition	*$597,272*
Geothermal System	*$1,200,000*
Air Handling Unit	*$100,000*
~~Dehumidifiers~~	~~*$240,000*~~
~~Living Machine®~~	~~*$400,000*~~
Growth Chambers	*$30,000*
~~Anaerobic Digester System~~	~~*$10,000,000*~~
~~Jenbacher Gas Engines~~	~~*$4,078,750*~~
Water Pumps	*$7,500*
Hydroponic System	*$38,400,000*
Working Capital	$7,649,277
Contingency Allocation	$7,649,277
TOTAL	**$91,795,326**

INCOME STATEMENT

Operating Costs

Labour - base salaries	*$4,245,000*
Labour - benefits, insur.	*$341,298*
Depreciation	$3,572,573
Maintenance	$467,458
Packaging	*$1,734,480*
Nutrients	*$25,600*
~~Transport~~	~~*$3,650,000*~~
Property taxes	*$1,334,377*
Electricity	$1,471,494
Water	$6,382
TOTAL	**$13,220,634**

Revenue

Produce Sales	*$21,928,032*
~~Biowaste processing~~	~~*$3,650,000*~~
TOTAL	**$21,928,032**

italic = unchanged

fortifier. With anaerobic digestion becoming increasingly common in North America it is inevitable increased public education on the distinction between sewage and food waste digestates will create a greater demand for the latter. If the farm could sell its digestates for the cost of their transportation off-site, an estimated 100 per ton or $3,650,000 per year, the farm’s rate of return would jump to 11.2%.

It is also important to examine the impact of the initial design’s energy self-reliance and water conservation provisions. If these were not included it would remove the anaerobic digestion system, Jenbacher gas engines, Living Machine®, and dehumidifiers from the list of required components, totalling $14,718,750 in savings from the initial capital budget. This in turn would reduce the required working capital and contingency allowance by $1,472,275 each, the depreciation expenses by $853,917, maintenance expenses by $670,325, and digestate transportation requirements by $3,650,000. The farm’s operating costs would include an additional $1,471,494 to account for the off-site electricity and water consumption, and would also have $3,650,000 less revenue due to the lack of accommodating municipal biowaste processing.[36] Nevertheless, this simplified vertical farm would yield an improved annual rate of return of 9.49% if implemented in current market conditions.

However, prudent investors may deem this design even less satisfactory for investment due to its increased sensitivity to external economic impacts, specifically changes in the price of electricity. As most industry experts agree the cost of electricity will increase in Canada, the United States, and much of the world in the coming years, this design would experience proportionally increasing operating costs that would likely unhinge its economic feasibility.[37] More immediately, the current price of electricity in all but a handful of countries (which include Canada and the United States) would eliminate this simplified vertical farm configuration as an economically feasible option. In Europe the weighted average price of electricity for industrial consumers was $0.14 per kWh as of

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[36] Electricity price estimated at $0.07 per kWh, water price estimated at $0.86 per 1,000 L

[37] *Canada’s Electricity Future*, Canada Energy http://www.canadaenergy.ca/index.php?hydro=future&direct=of&electricity=electricity

2009,[38] a price that would increase the simplified design's electricity bill by $1.5 million per year and drop the rate of return to 7.88%, below that of the initial design. In contrast, the initial design's resource self-reliance ensures its operating costs would be insulated from such fluctuations in commodity prices.

External Factors

Like the price of electricity's identified impact there are many other external factors that could influence a vertical farm's profitability. The most commonly discussed of these is the impact rising oil prices could have on the market price of food products in the coming years. In 2007 and 2008 the global economy suffered a 'food price crisis', during which the price of the world's staple crops doubled, or in the case of rice, tripled.[39] Though many factors have been blamed for this event, an increase in the price of oil from $45 per barrel in January 2007 to $134 in July 2008 was clearly a central factor.[40] During this period farms in the United States producing corn, wheat, and soybeans saw operating costs rise by 63%, 57%, and 42% respectively since 2006, primarily due to a doubling of the cost of fertilizer and near-doubling of the costs of fuel, lubricants, and electricity.[41]

From the last quarter of 2008 through the end of 2009 food prices nearly returned to their pre-crisis levels thanks primarily to the massive deflation of

Fig 2.48
Global price index for wheat from 2000-2008. Source: FAO

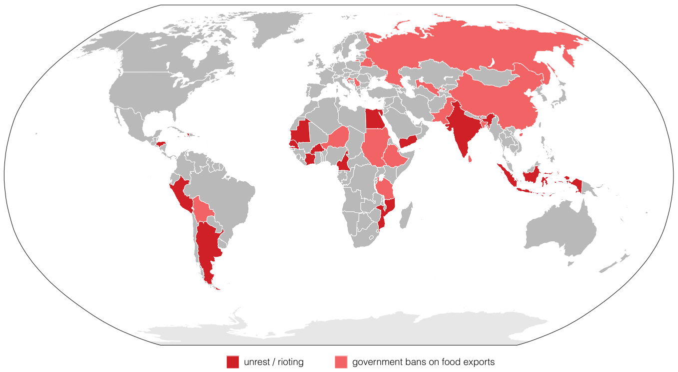

Fig 2.49
Countries most affected by the 2007-2008 Food Price Crisis. Countries with notable bouts of unrest include (from west to east) Honduras, Haiti, Peru, Argentina, Mauritania, Senegal, Ivory Coast, Burkina Faso, Cameroon, Egypt, Mozambique, Yemen, India, Bangladesh, and Indonesia

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[38] International Energy Agency, *Key World Energy Statistics - 2010*, www.iea.orgf&electricity=electricity

[39] Steinberg, Stefan. Financial Speculators reap profits from global hunger. (2008, April 24). Retrieved on June 10, 2010 from http://globalresearch.ca/index.php?context=va&aid=8794

[40] U.S. Energy Information Administration, *Weekly United States Spot Price FOB Weighted by Estimated Import Volume*, http://tonto.eia.doe.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=wtotusa&f=w

[41] USDA Economic Research Service, Commodity Cost and Returns. (2010, October 1). www.ers.usda.gov/Data/CostsAndReturns/

oil prices during the subprime mortgage crisis and subsequent global recession. However, with conventional agriculture still heavily dependent on fossil-fuel and the effects of dwindling oil reserves widely expected to surface within the next decade, the food price crisis may have been a brief glimpse of the economics of conventional agriculture in the 21st century. Requiring none of the pesticides and fuel for machinery used on conventional high-yield agriculture, and at worst minute fractions of their inorganic fertilizers, the production costs of vertical farming can be effectively insulated from volatility in oil prices. Should oil prices increase as widely expected vertical farming will be able to increase its market competitiveness amidst the inflating prices of conventional farm produce.

Finally, the economic viability of vertical farming will undoubtedly benefit from improvements in grow lighting technology. As LEDs and magnetic induction lamps continue their trend of decreasing wattage and cost per lumen generated they will inevitably replace compact fluorescent technology as the grow lamps of choice for vertical farms. Once this threshold is met vertical farms will be able to downsize their energy production requirements and reduce bulb replacement costs while maintaining their level of productivity.

CHAPTER 10 - VERTICAL FARM TYPOLOGIES

It has been previously established that vertical farming's likely path to realization will occur by way of diversification with other food-related land uses, given its physical opportunity and economic advantage to do so. Yet another motive for such unions to occur can be found in the distributed food network of modern cities. Urbanites consume food in many environments, such as individual homes, restaurants, hotels, cafeterias, schools, hospitals and other institutions. For in-home consumption food is generally procured from retail grocers, while the other listed food providers tend to be supplied by separate intermediaries like wholesalers. As such, if vertical farming is to be relevant to the full spectrum of a city's food needs it must be able to engage both a city's residential and distributed food streams.

Depending on which stage of the food distribution network a vertical farm wishes to intervene the resultant hybrid building is expected to exhibit characteristics specific to its merging partner. For example, a vertical farm paired with a retail market would have a much different operational structure and impact on its urban vicinity than one paired with a processing plant or a residential building. Such categorical idiosyncrasies suggest it may be more advantageous to group vertical farms into general typologies referring to their specific use and expected urban impact, rather than simply generalize the concept's application universally.

In this chapter I will examine three such typologies through three respective design projects. Each of the addressed design typologies represents vertical farming's impact at a different stage of urban food distribution, specifically the retail sector, the residential point of consumption, and the wholesaling sector.

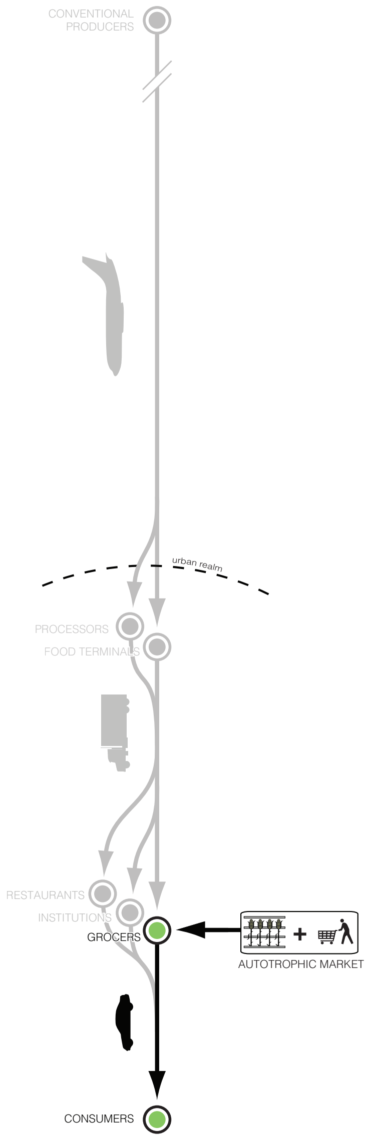

Fig 2.50
Simplified urban food distribution diagram identifying the intervention of the autotrophic market

Autotrophic Market

The first typology to list is the one most often discussed – a vertical farm whose sole purpose is to produce and sell food products on-site or within its immediate urban vicinity. With the aim of delineating this type I have proposed the name autotrophic markets. In biological parlance an autotroph is a species, such as a plant, that generates its own food from its environment's elemental resources, as opposed to heterotrophs like humans and other animals that obtain their food by consuming other organisms. An autotrophic market would thus refer to a market whose food stores are replenished through its own internal processes – an analogy to the internal photosynthesis that drives the biomass production heterotrophs depend on.

Architecturally an autotrophic market could range from a low-rise building that supplies a small grocery store to a skyscraper that supports a major urban market or network of local grocery stores accommodating tens of thousands of people daily.

There are many benefits to this variety of vertical farm. By producing food mere floors above a pedestrian-accessible point of sale autotrophic markets can reduce an urban area's dependence on food importation. Considering food imports tend to arrive by way of heavy transport in modern cities these vertical farms could have a significant impact on the traffic signature of the urban area it serves. Fewer trucks equates to qualitative improvements like reduced traffic congestion and noise, environmental improvements via reduced emissions, and financial improvements by way of reduced infrastructure stress.

The major drawback of this typology involves the logistics of supplying a retail market solely with the produce generated from a vertical farm. In the best-case scenario a vertical farm could supply two varieties of meat (chicken and fish), eggs, and around a dozen fruit and vegetable crops. While this may be enough to satisfy a person's basic dietary needs, it pales in comparison to the extensive variety of product categories and brands of modern grocery markets. Furthermore, intuitively it seems far more advantageous for a vertical farm to focus its production on a select few high-revenue crops rather than include additional varieties with decreased revenue-generating potential.

(SkyFarm)

The SkyFarm concept was my first introduction to vertical farm design, and among the first attempts in general to create a resolved architectural solution for a vertical farm. Consequently, the design takes on the simplicity and impracticality common of designs with limited precedents that are rooted largely in the conceptual realm. Nevertheless, owing to the small collection of vertical farm designs to emerge to date SkyFarm still serves as one of the more illustrative examples of the autotrophic market typology.

Fig 2.51
SkyFarm rendering

The design is envisioned on a 1.34 hectare site located at the northwest corner of King St. and Widmer St. in downtown Toronto. It consists of 58 floors of agricultural production, 56 above ground and 2 below, initially scaled to accommodate the basic dietary requirements of 40,000 people year-round. The design also includes space uses integral for a vertical farm and market to function, such as a preparation and packaging area, offices, and parking. A bank of anaerobic digesters intended to suffice most of the farm's electrical needs was envisioned to consume four floors along the basement's northern edge, however, the planning logistics of this are now understood to be questionable.

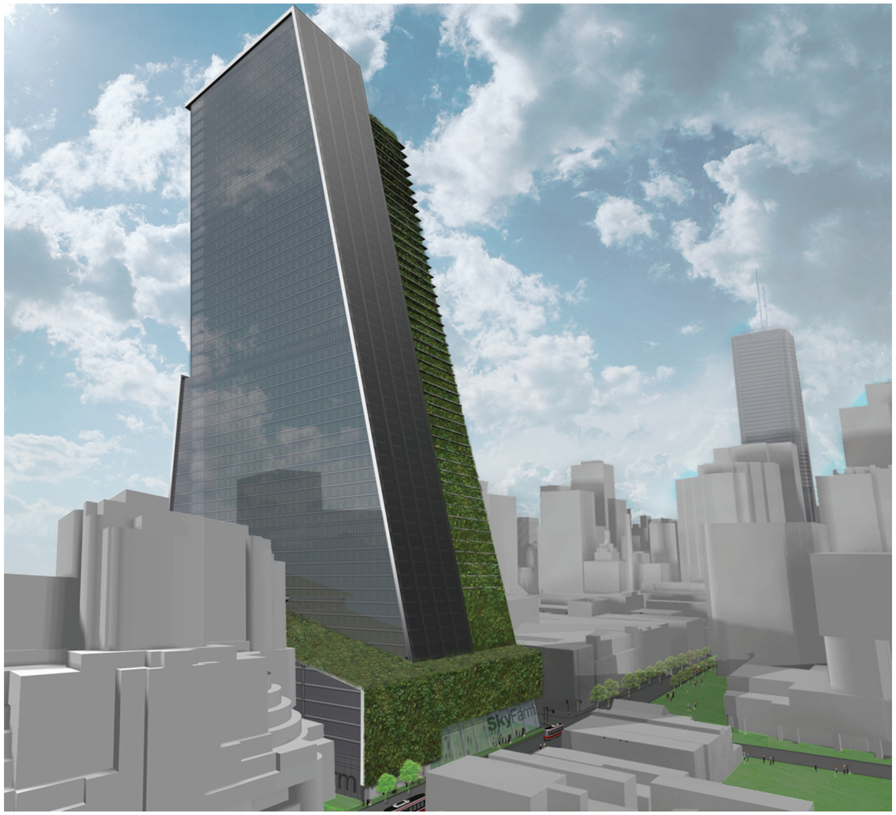

Fig 2.52
SkyFarm rendering

The tower form was broken into two halves with the intention of visually expressing two renewable energy generation options for vertical farms. The western half is dedicated to solar energy, consisting of a simple photovoltaic panel cladding. The eastern half, along with the podium roof, is dedicated to the growth of silage to be harvested and used for methane production. As the design was intended primarily for general concept communication, rather than site-specific concerns, the silage exterior was explored more as an option for climates with more favourable growing conditions year-round than those of Southern Ontario.

The first three levels are dedicated to a massive urban market fashioned after the popular St. Lawrence Market located on the eastern edge of downtown.

Fig 2.53
SkyFarm rendering

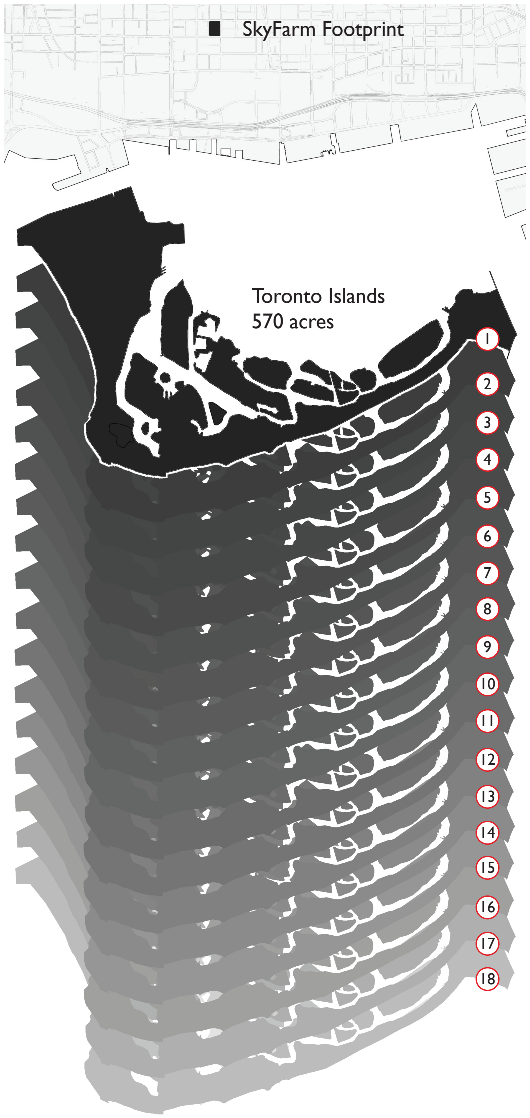

Fig 2.54
SkyFarm contains approximately 256,000 m^2 of growing space. Applying the productivity of the drum hydroponic system (7x) and that of S/CEA lettuce production (23x), SkyFarm's productivity would be equivalent to 10,180 acres of conventional farming - 18 times the area of Toronto Island

It must be mentioned that the initial calculation for a serviceable population of 40,000 people was based on a rule-of-thumb that hydroponic systems tend to triple the growing area available per floor. Subsequently the three-tier drum design has emerged with a growing area to floor footprint ratio of seven to one within a 2.5m ceiling height, rendering the potential serviceable population much larger.

Also, as eluded to previously I have since abandoned the notion that a single vertical farm should sustain all the basic nutritional needs of its serviceable population due to the economic disadvantage of growing low-revenue varieties that require heavy processing, such as wheat. A more realistic crop selection would concentrate on a few varieties with high retail value and demand – thus serving a much larger population, yet supplying only a portion of their diet. In removing the total-diet provision vertical farming also extracts itself from the potentially disconcerting ethical grounds of introducing animal husbandry to urban buildings disconnected from the natural environment – as exhibited by MVRDV's *Pig City*.

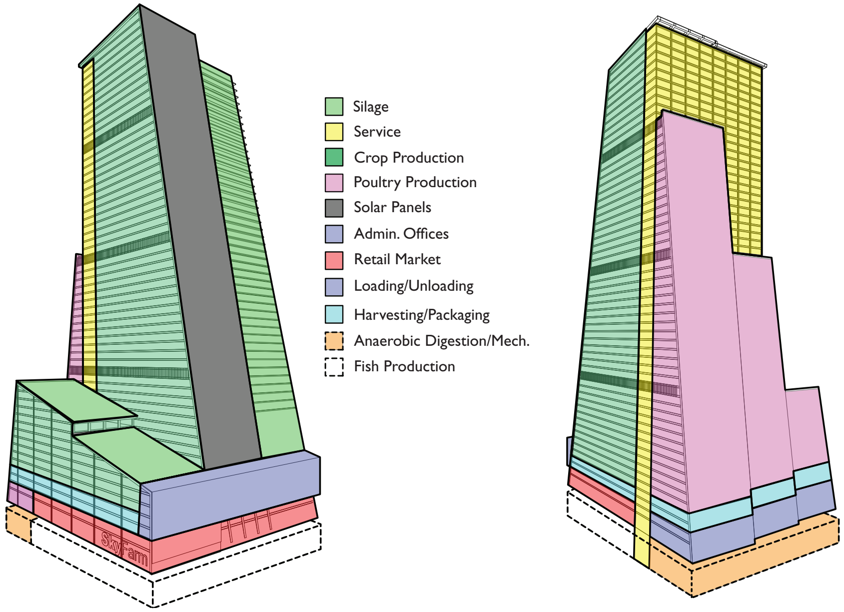

Fig 2.55
SkyFarm space use organization

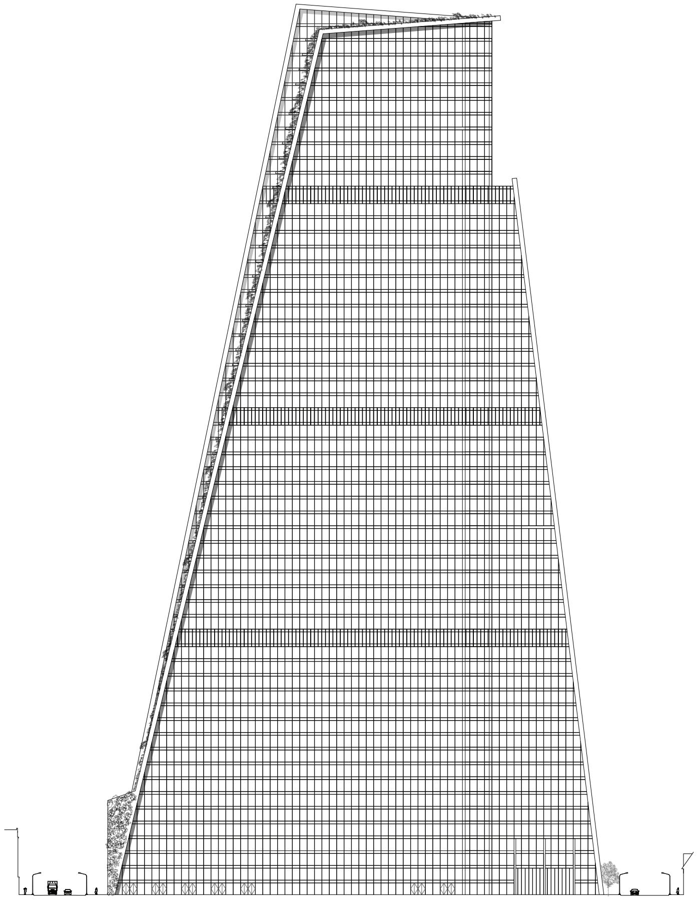

Fig 2.56
SkyFarm, east elevation

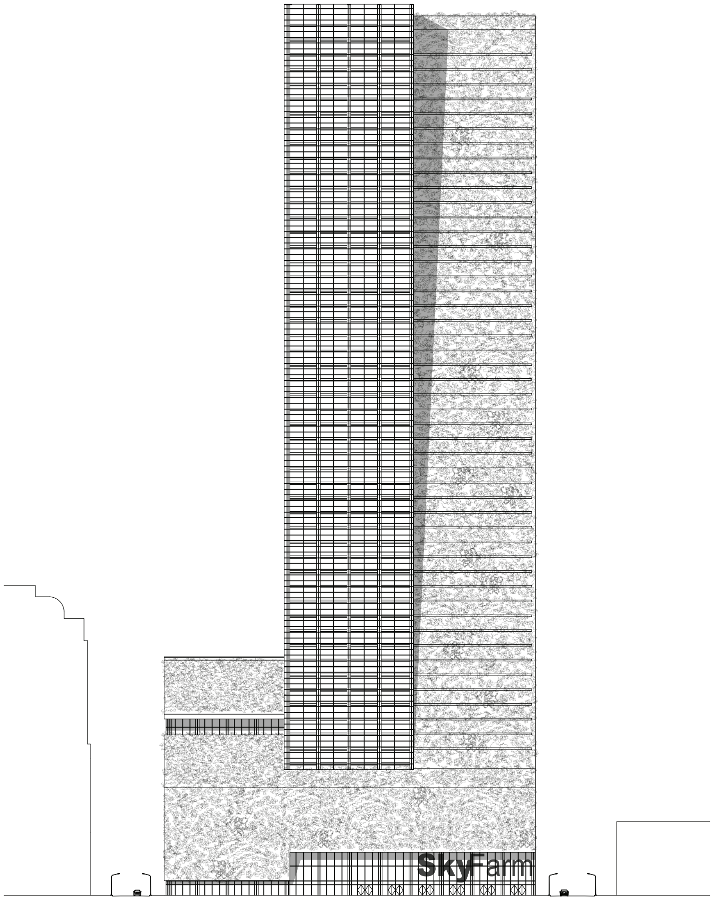

Fig 2.57
SkyFarm, south elevation

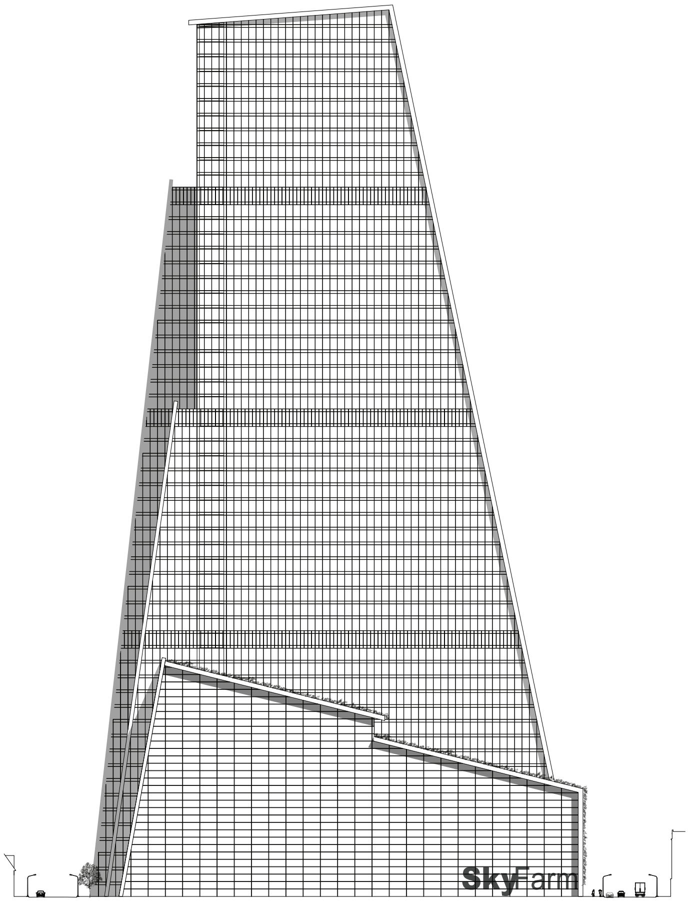

Fig 2.58
SkyFarm, west elevation

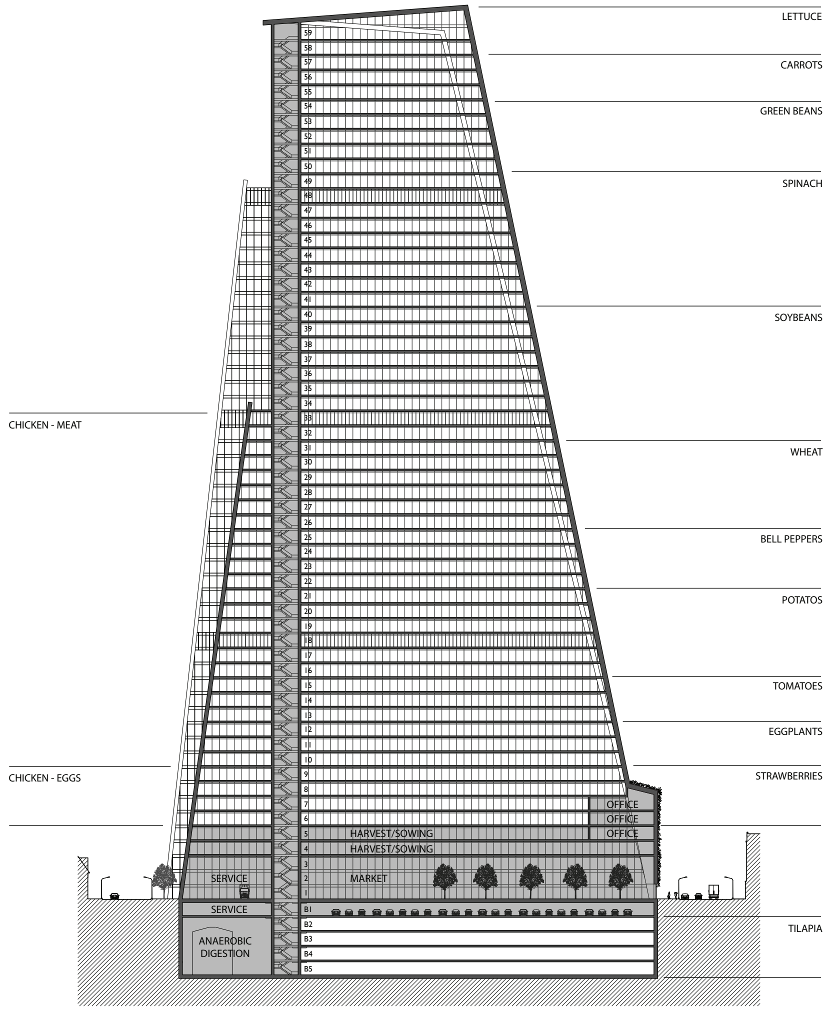

Fig 2.59
SkyFarm, section

Vertical Farm Arcology

Perhaps the most intriguing application of vertical farming technology is its integration with a residential building to form an *arcology*. The notion of arcologies has long been used in science fiction as conceptual solutions to overpopulation and ecosystem degradation - dating at least as far back as H.G. Wells' *When the Sleeper Awakes* of 1899. The word itself is a portmanteau of the words "architecture" and "ecology", and describes a self-sustaining building with an internal cyclical flow of resources that mimics the metabolism of natural ecosystems.

The purely theoretical view of the arcology concept has been largely due to the logistical complications of removing an urban populace's food requirements from conventional usurpation and destruction of natural ecosystems. Architect Paolo Soleri's extensive work with the arcology concept in the latter half of the 20th century largely sidestepped this issue, owing to the lack of a technological means to apply urban self-containment to agriculture. Thanks to the emergence of the technologies associated with vertical farming we now have the means to provide all essential resources for urban living – food, fresh water, fresh air, and energy – from on-site processes disconnected from natural ecosystems.

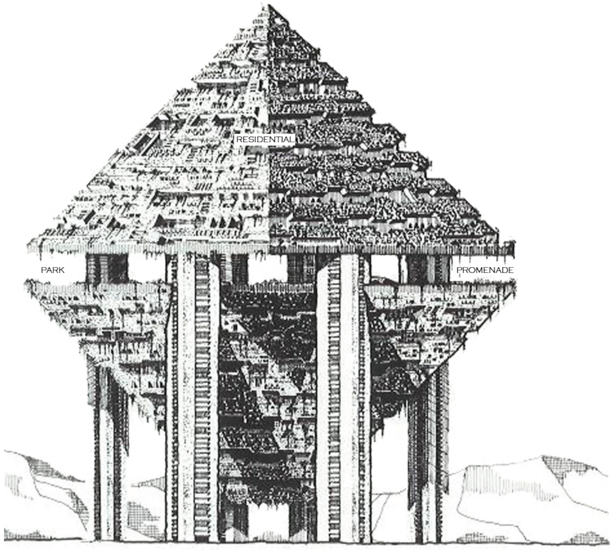

Fig 2.60
This iconic arcology, called Hexahedron from Paolo Soleri's book **Arcology: City in the Image of Man***, elegantly expresses the concept's motive for urban life to persist without encroaching into the natural environment. Though the desirability of arcologies of this scale is likely minimal, vertical farming's decoupling of food production from the enviornment makes such self-reliant urban environments possible.*

Analogous to the resource metabolism of natural ecosystems, the arcology variant of vertical farming is composed of three trophic levels, a 'producer' vertical farm, a 'consumer' residential building, and two 'decomposer' processes, an anaerobic digester and a biological water filtration system (also known as a Living Machine®). Together these elements form a web of symbiotic resource flow relationships that enable the building to operate with a self-sufficiency similar to that of ecological systems.

The residential units demand food, water (both potable and non-potable), fresh air, and electricity, while expelling biowaste, waste water, and carbon-dioxide rich air. The vertical farm produces food, potable water, oxygen-rich air, biowaste, and waste water while demanding non-potable water, carbon-dioxide rich air,

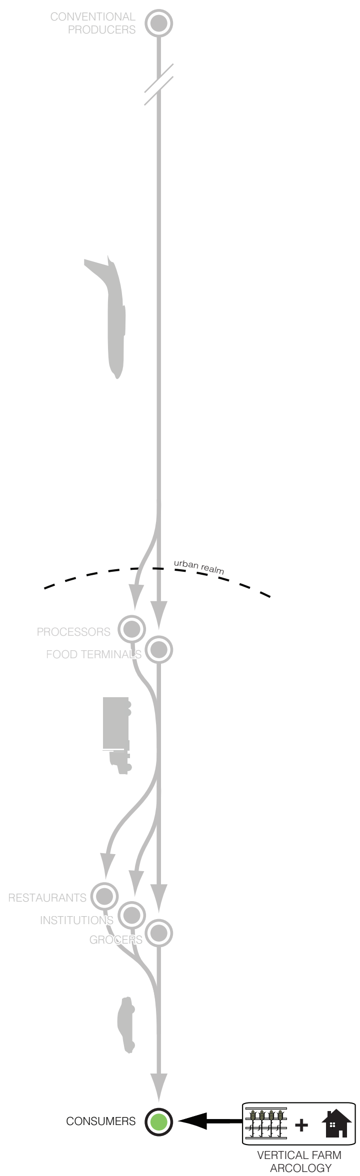

Fig 2.61X
Simplified urban food distribution diagram identifying the intervention of vertical farm arcologies

elemental nutrients, and electricity. Anaerobic digesters would consume the dual streams of biowaste to produce the dually demanded electricity, as well as the elemental nutrients needed by the vertical farm. The Living Machine would consume the dual streams of waste water to produce the dually demanded non-potable water, as well as food (in the form of tilapia) to the residential units.

(Agro-Arcology)

The design for Agro-Arcology was commissioned in 2008 by the Green Party of Canada to conceptualize a revitalization of Toronto's Moss Park neighbourhood. The building site, which is bordered by Queen Street, Jarvis Street, Shuter Street, and the park itself, is undoubtedly one of the most eclectic neighbourhoods in Toronto's urban tapestry. The 3.3 acre site is currently consumed by the Moss Park Armoury – a building whose largely windowless façade and bordering barbed-wire fence does little to abate the criminal activity that has come to define the neighbourhood.

Fig 2.62
Agro-Arcology Site-plan

Fig 2.63
Agro-Arcology, axonometric

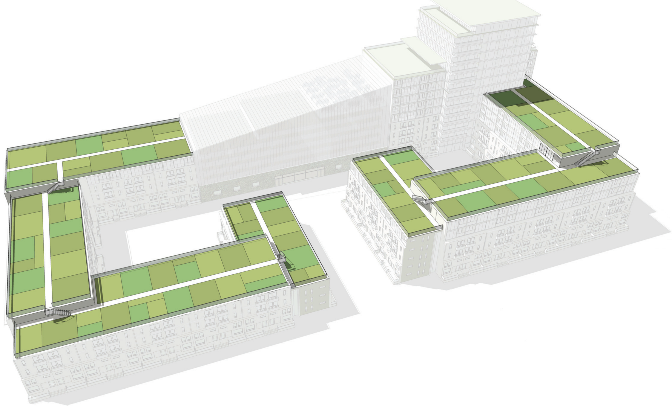

Fig 2.64
Agro-Arcology - rooftop gardens

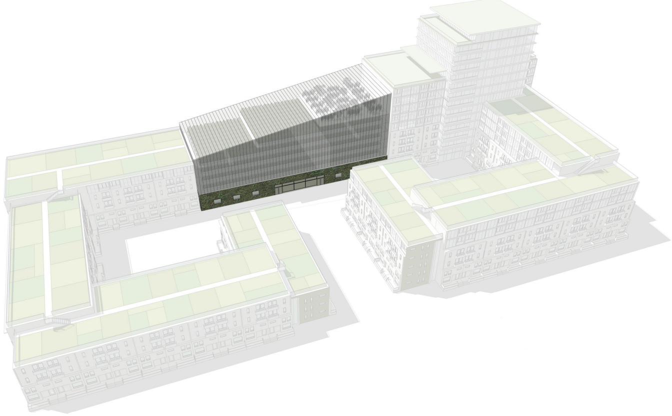

Fig 2.65
Agro-Arcology - vertical farm

The form of Agro-Arcology is largely that of the mixed-use condominium typology, bifurcated by a glazed vertical farm. Ranging from three to fifteen storeys, the size of the building's eight residential 'wings' have been designed to maximize access to sunlight, while also achieving the high densities warranted by a proximity to the downtown core. The building's inventory of unit types consist of 75 townhouses, 310 condominiums, and 170 loft-style apartments – along with 30 commercial storefronts located along the busy thoroughfare streets.

The roofs of Agro-Arcology have been designed for community garden plots, measuring a combined 5,200 m^2. The elevated position ensures excellent light throughout the growing season, while nutrient-rich digestates supplied by the anaerobic digester offer a readily available source of soil fortifier. In addition to further maximizing the nutritional productivity of the building the gardens offer a forum for social interaction with the neighbourhood community, as well as a coveted source of outdoor activity for dense urban areas.

The 6 1/2 storey vertical farm is oriented along the north-south axis to maximize uniform sun penetration. The scale of the farm was determined by the space required to produce a high percentage of the basic caloric needs for each of the 1,000 residents year-round, with sufficient saleable surplus to cover the vertical farm's cost of operation. With respect to demand and retail value the most advantageous selection of crops would likely be tomatoes, lettuce, peppers, cucumbers, and green peas – however this could vary with the consumption patterns of the residents and/or the flux of market prices.

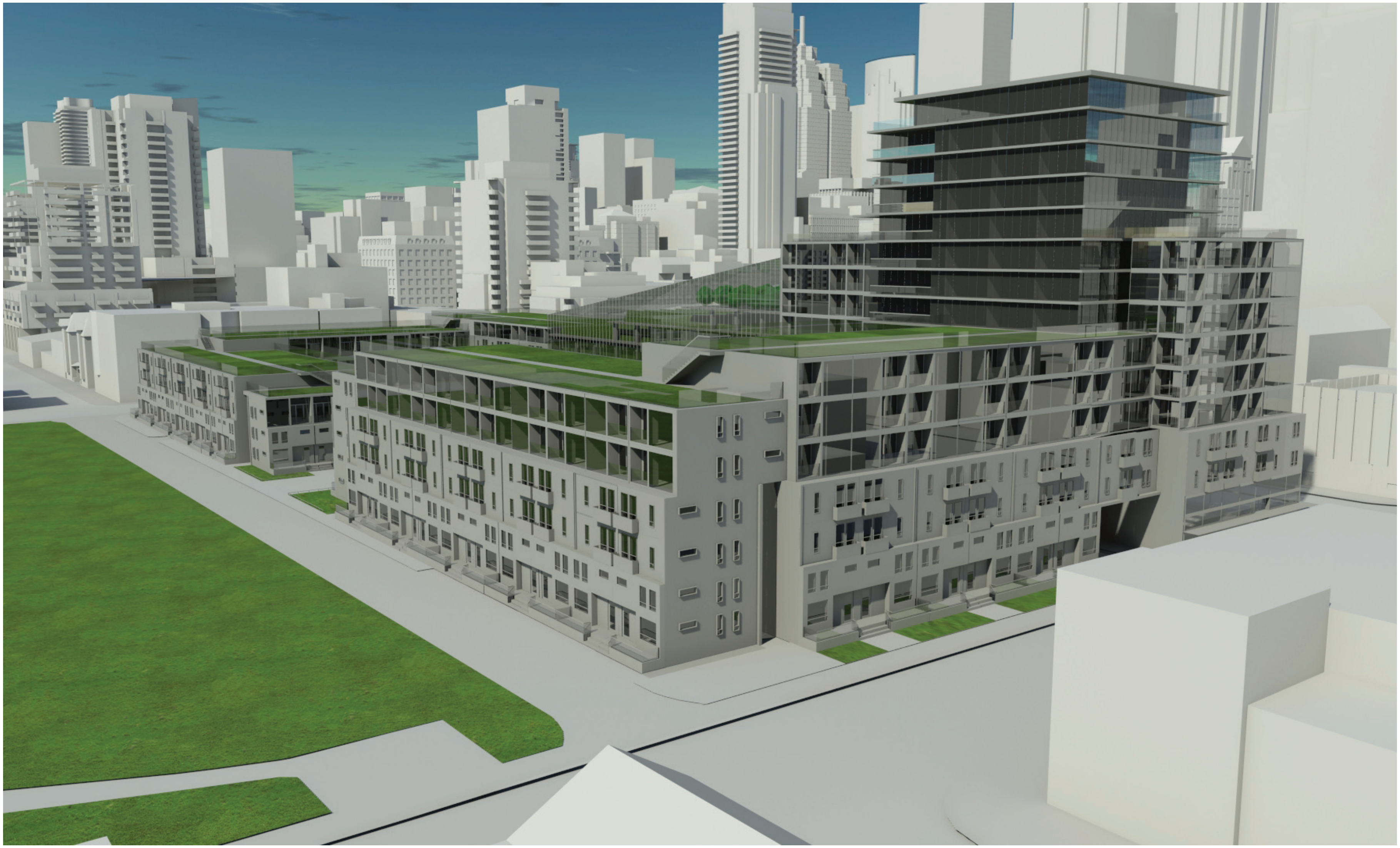

Fig 2.66
Agro-Arcology, north view

The vertical farm also plays a central role in Agro-Arcology's water metabolism. Since most of the water consumed by agricultural plants is expelled as water vapour, dehumidifiers within the farm can collect an abundant supply of potable water for residential use. This takes advantage of a symbiotic resource relationship not available in stand-alone vertical farms, as the purity of dehumidified water is well beyond that required for plant irrigation.

As mentioned Agro-Arcology employs the use of a biological wastewater treatment system, commonly known as a Living Machine®, rather than externalizing its waste water like typical urban buildings. Originally conceived by John Todd in 1976, Living Machines® consist of a multi-phase network of beneficial microorganisms, plants, and fish intended to mimic the natural water filtration process of wetlands.

In Agro-Arcology the Living Machine® would be configured to filter all wastewater generated from the residential units, as well as the pH-depleted irrigation water of the vertical farm. Though not quite potable the purified water of a living machine is ideal for the non-potable water needs of the residential units, as well as the irrigation water for the vertical farm - by far the largest water consumer on site. Along with the collection of external rain water, Agro-Arcology's cyclical water metabolism introduces the possibility of urban living with a zero "water footprint".

Fig 2.67
Agro-Arcology, section perspective

Yet another symbiotic resource relationship within Agro-Arcology can be found in the air circulation between a contained farm and the adjacent residential units. Mimicking the relationship between the world's photosynthetic and oxygen-breathing organisms, plant growth within the vertical farm would produce fresh oxygenated air for the residential units while readily consuming their carbon dioxide rich waste air. While not drastically affecting the environmental impact of Agro-Arcology, the benefit of this symbiosis involves alleviating urban living from a reliance on urban air quality – which tends to be drastically worse than that of rural environments.

Fig 2.68
Agro-Arcology elevations

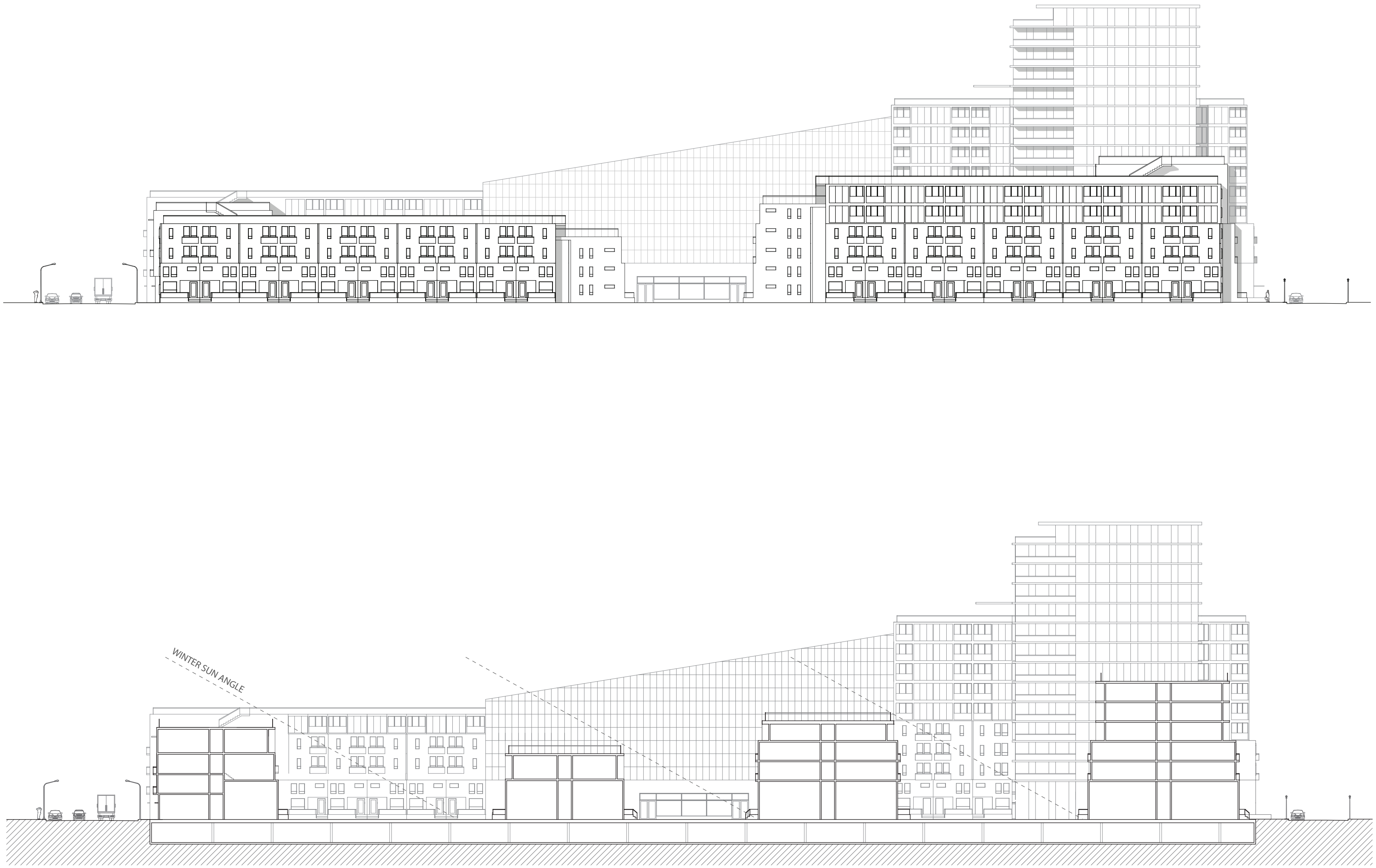

Fig 2.69
Agro-Arcology elevation & section

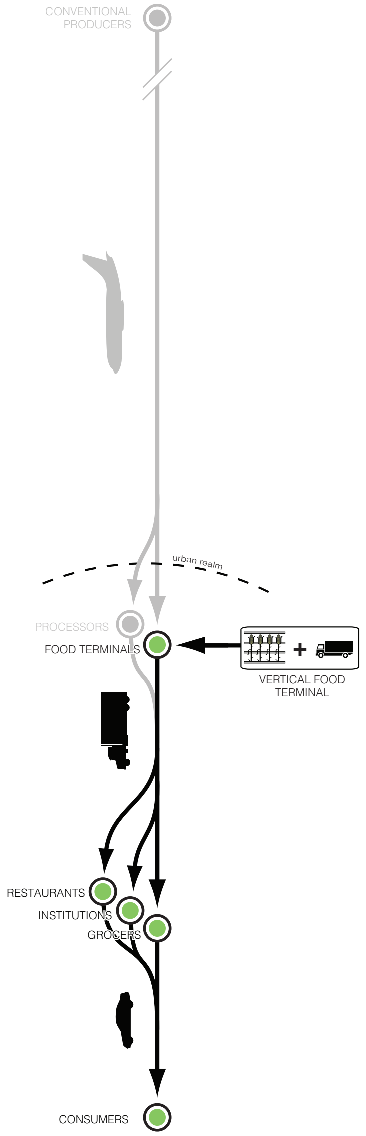

Fig 2.70
Simplified urban food distribution diagram identifying the intervention of the vertical food terminal typology

Vertical Food Terminal

Food distribution terminals are extremely important buildings in the modern food trade, as they are the primary interface between urban food proprietors and rural producers of fruits and vegetables. There are three key functions of a food terminal; receive bulk volumes of produce via heavy transports, store the produce during the negotiation of its sale, and offload the produce to smaller transports for distribution to grocers and restaurants in the city. Usually these stages are administered by food brokers or wholesalers, who along with safety inspectors, truck brokers, and financial services form a terminal's permanent community. With respect to the aforementioned diversity of a city's food network, the application of vertical farming to food terminals is essential if the vertical farming concept is to be relevant to the full spectrum of a city's food needs.

The terminal variety of vertical farm has two distinct advantages over the previously addressed typologies. Firstly, since food terminals can be located on less expensive land near the urban periphery their partnership with a vertical farm offers an immediate economic advantage over the more costly urban siting of the market-based typology.

Also, food terminals tend to be situated advantageously near major transportation infrastructure. This is a vital asset for vertical farms that either utilize anaerobic digesters as their energy solution or focus on a small selection of high-valued crops – both of which are likely required for the economic viability of large-scale vertical farming. The anaerobic digester's resultant by-products must be regularly removed and shipped off-site, while large volumes of biowaste must be imported to account for the inadequate energy feedstock produced by the farm itself. Additionally, the production of large volumes of a select number of crops would likely greatly surpass the local demands for such produce, meaning it would require off-site distribution to reach a sufficient consumer base. Therefore, a food terminal's interconnectedness with a city's transportation network offers a notable logistical advantage for vertical farm operations.

Unfortunately, since food terminals are at the wholesale stage of food distribution a merged vertical farm would be resigned to collect wholesale-level profits rather than the retail profits collected by market-based vertical farms.

(Ontario Vertical Food Terminal)

The Ontario Food Terminal is the largest wholesale fruit and produce distribution centre in Canada, and the third largest in North America after those in Chicago and Los Angeles.[1] The building's 40 acre site accommodates more than twenty five thousand transport trucks annually that supply the majority of fresh produce sold or served outside of Toronto's major grocers.[2]

The new design consists of three key elements, a podium base, three towers, and a shelter for a bank of anaerobic digesters. The design's footprint is roughly the same shape and area (35,000 m^2) as that of the existing structure, though it has been rotated 17° clockwise to align with the cardinal directions. The ground floor configuration has been designed in an H-shape rather than the existing U-shape due to structural considerations for the building's towers, yet its capacity for facilitating food distribution and cold storage remains the same.

The design also preserves the segregated docking stall arrangement of the existing building, with 76 stalls accessible to heavy transports along the building's exterior and 96 stalls for smaller transports within the internal courtyards. Though these 76 heavy transport stalls are less than the 120+ of the existing terminal, the new design would produce a large volume of the produce that was previously imported, thus reducing its requirement for such stalls.

The building's form has also been designed to maximize sunlight penetration while maintaining the compact scale warranted by its food-trade and agricultural functions. The roofs and south-facing walls are entirely glazed, while the towers curve backward and taper upwards to increase light penetration and reduce

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[1] Mintz, Corey .The Mother of All Fruit Markets. (2008, May 7) *Eyeweekly.com*. Retrieved June 10, 2010

[2] Ontario Food Terminal Board Website – Statistics. http://www.oftb.com/stats.htm. Retrieved July 1st, 2010

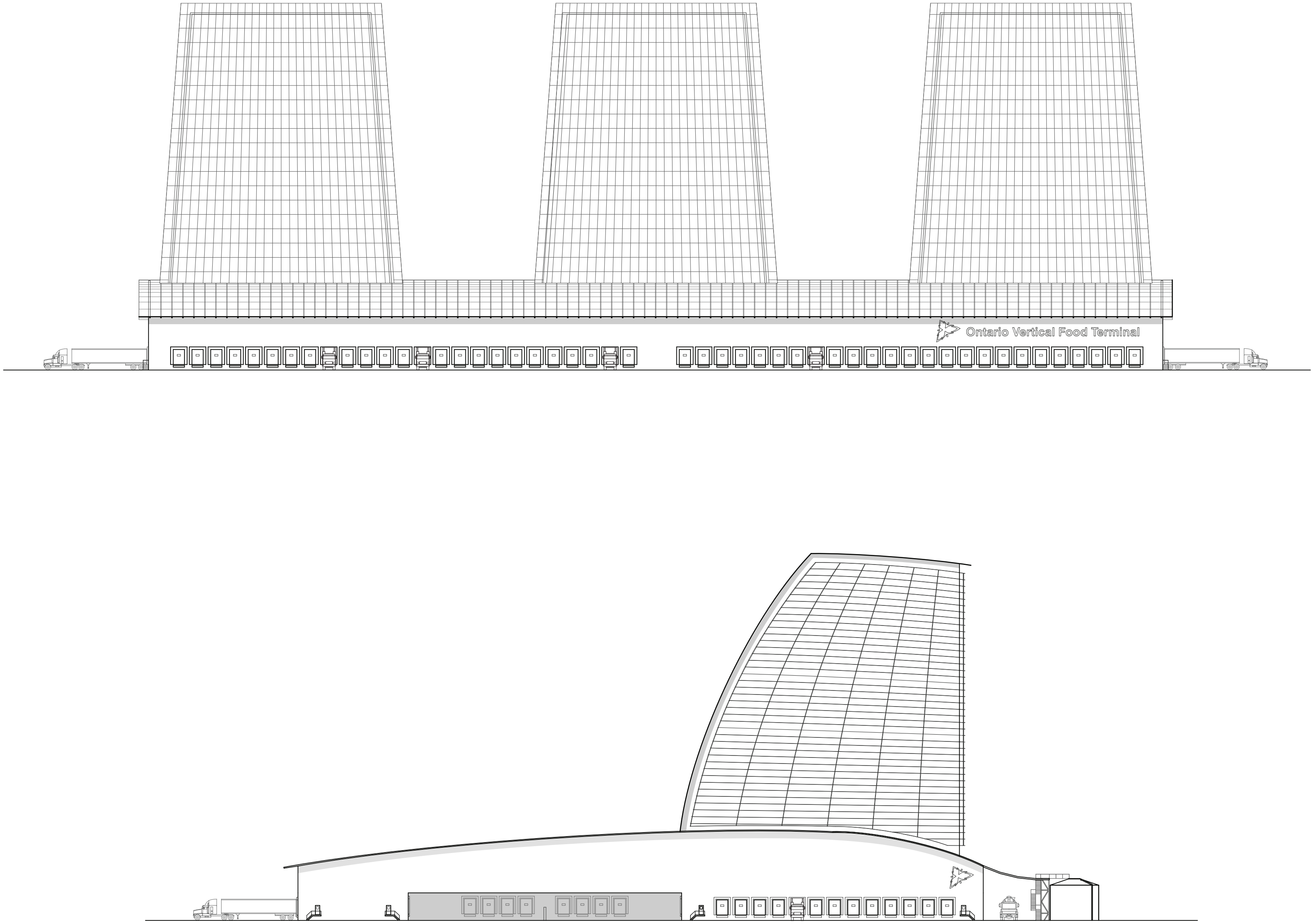

Fig 2.71
Ontario Vertical Food Terminal elevations

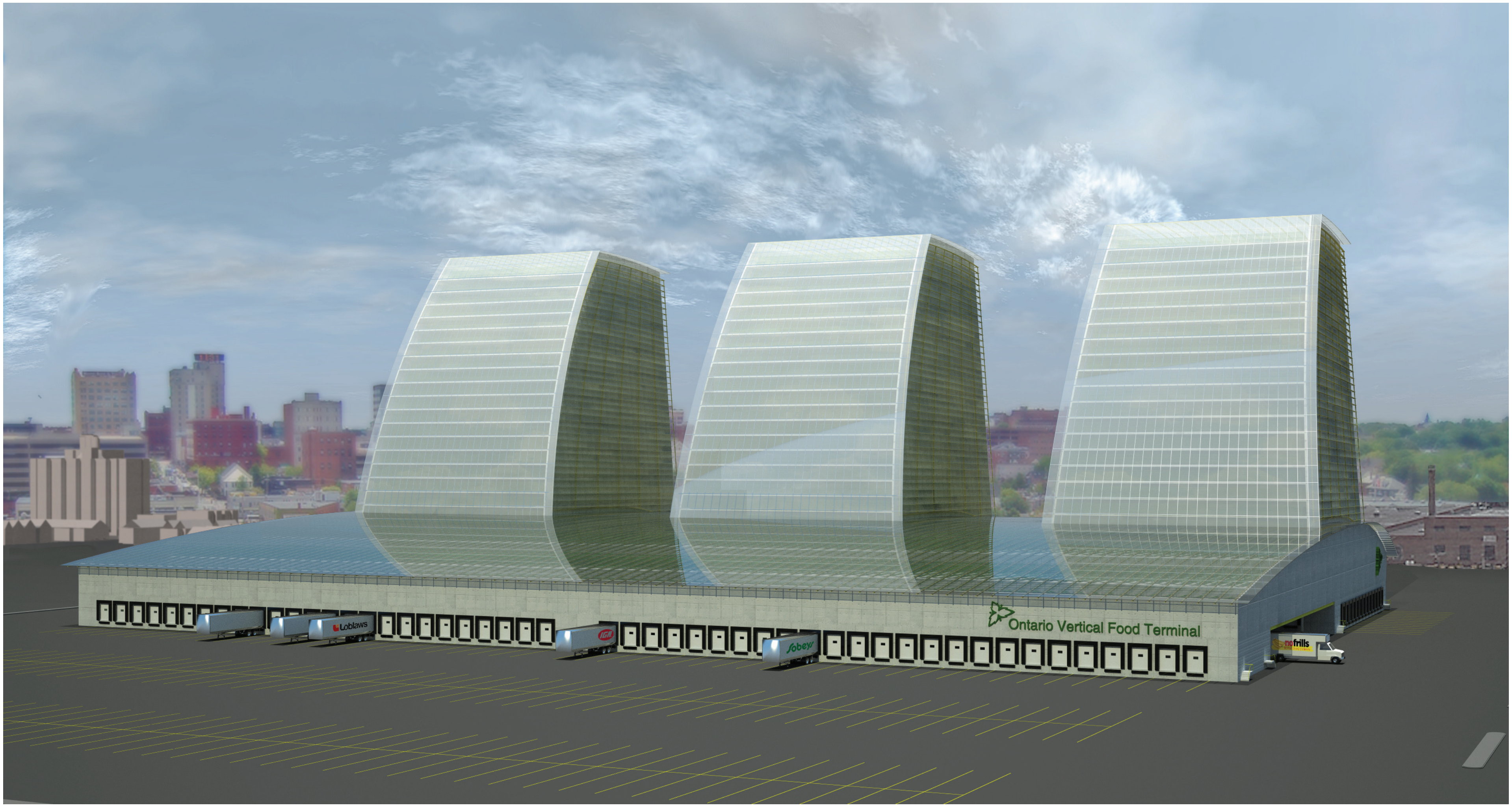

Fig 2.72
Ontario Vertical Food Terminal rendering

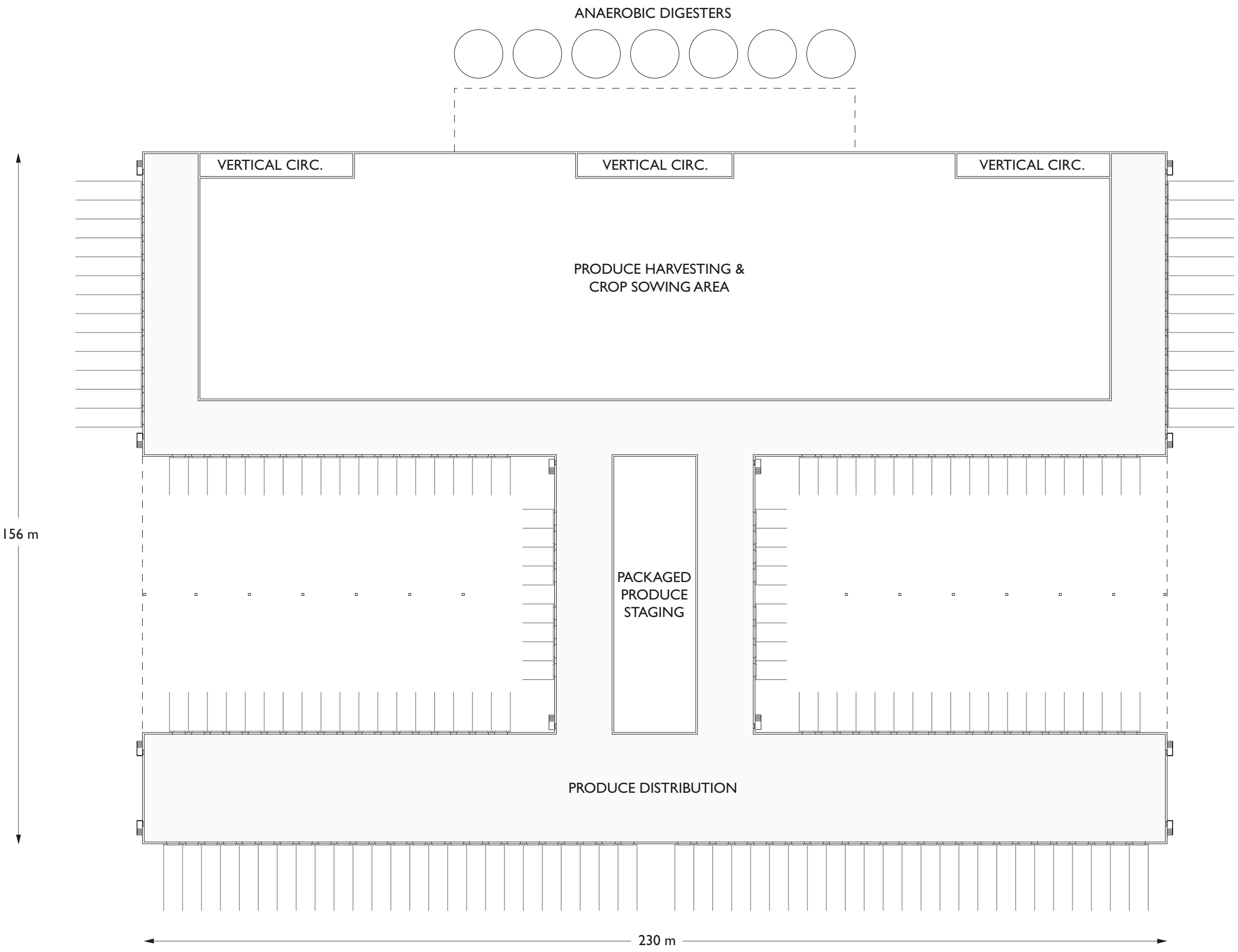

Fig 2.73
Ontario Vertical Food Terminal plan

shadowing on the podium, respectively. Yet, while these provisions dictate the aesthetics of the building just 9.5% of its total floor area receives direct sunlight, meaning the vast majority of the OVFT's produce would be grown with artificial lighting

Due to the large area of non-glazed exterior wall on the north, east, and west facades it has been designed with an expansive trellis intended to support an appropriate variety of 'climbing plant' – thus acting as a vegetative cladding to the otherwise blank walls. A possibility also exists to collect any biomass that the vine may shed due to seasonal shift for processing in the anaerobic digesters, therein beneficially contributing to the building's function as well its aesthetics.

The design also strives to facilitate the two aforementioned functions critical to maintain a vertical farm's production, namely the filtration of water and production of electricity. For the former the design incorporates three large biological water filtration systems (i.e. Living Machines®) located on the base level of each tower. As envisioned, the building's vast network of isolated hydroponic solution circuits would periodically be directed to the tower's biological filtration system. Once there the water would pass through a series of stations populated by microbes, flora, and fish that would replenish its pH level and purify it to irrigation grade. Upon exiting the filtration system the purified water would then serve the next hydroponic circuit's irrigation needs.

For electricity production the farm has been designed with a bank of seven large anaerobic digesters located 16 metres beyond the building's northern edge to comply with most building codes. The system's design is based on the anaerobic phased solids digesters developed at UC Davis, and scaled to provide the entire estimated electricity needs of the farm. The digester tanks would receive two streams of biowaste, one from the farm itself and the other imported from the city. As envisioned, inedible leaves and stems collected in the produce packaging area would be directed to the tanks via an underground conveyor system. Urban sources of biowaste arriving by truck would be dumped into a bin connected to a similar conveyor system, which is the method conventionally employed for biowaste plants. The collected methane would then be directed back into the building where it would fuel electricity generators located in the building's basement along its northern wall.

A final point to mention regards the design's incorporation of a variety of hydroponic systems, some of which are original modifications from the standard prototypes listed in Chapter 7. There are three basic hydroponic systems employed, the A-frame style, the bed style, and the drum style. The areas that have access to sunlight have been designed with the A-frame system, both in the conventional design for the podium levels and a modified design for the towers – owing to their lateral, rather than vertical, sunlight access.

The other two systems have been employed for their respective benefits to growing specific crops. Bed-style systems are ideal for growing root crops, like carrots, as well as heavier crops, like cucumbers. The drum style is ideal for all smaller and lighter crops, and due to its much higher space-productivity is envisioned as the primary growing system for the building.

As a closing note it must be mentioned that, while these designs for the OVFT's hydroponic, water filtration, and energy generation systems are the product of careful contemplation and research, they must be viewed as conceptual solutions intended primarily to explore the architectural implementation of such technologies. The immense complexity of such buildings would unquestionably require the expertise of a wide array of specialists, most notably systems designers, plant biologists, and bioengineers.

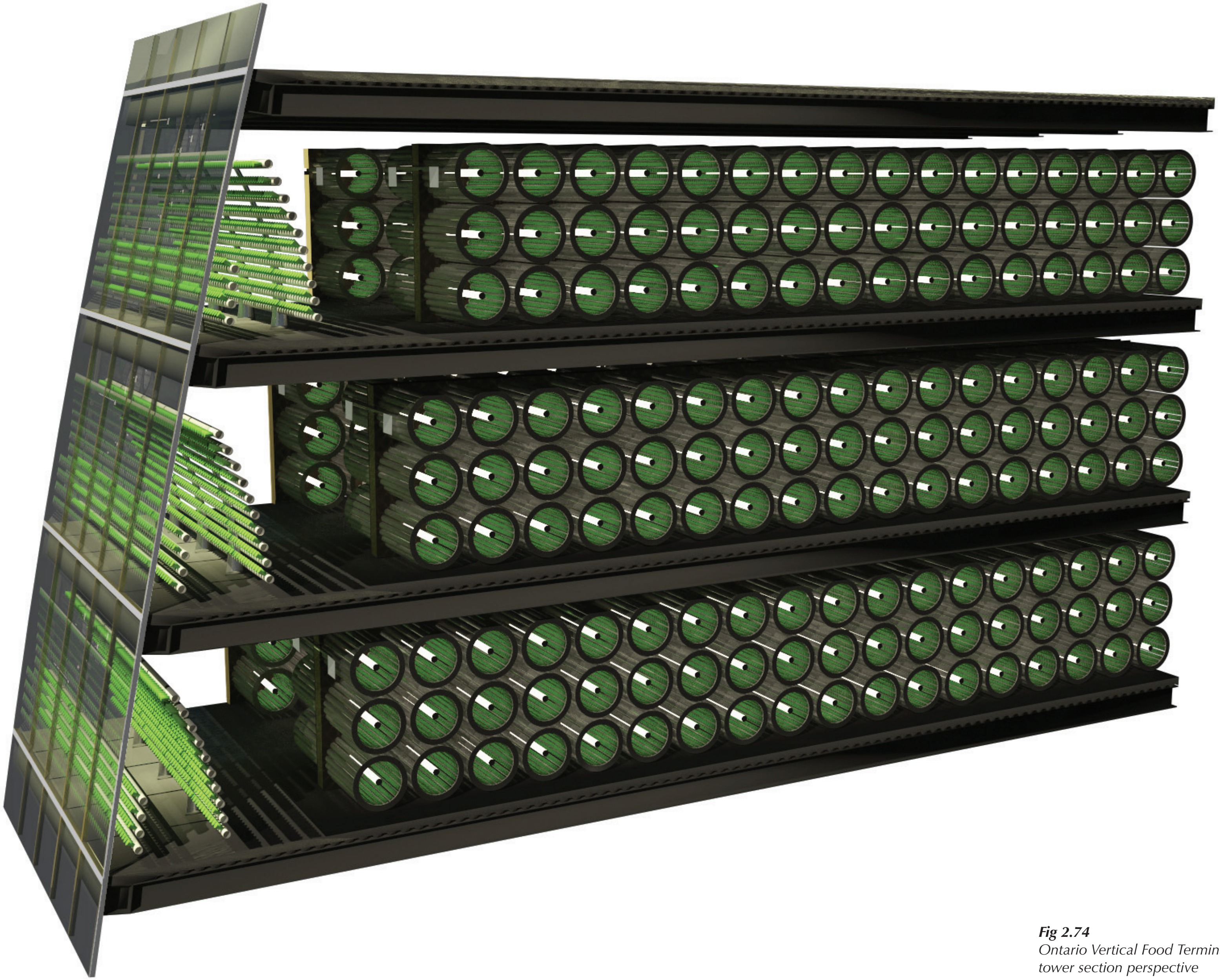

Fig 2.74
Ontario Vertical Food Terminal tower section perspective

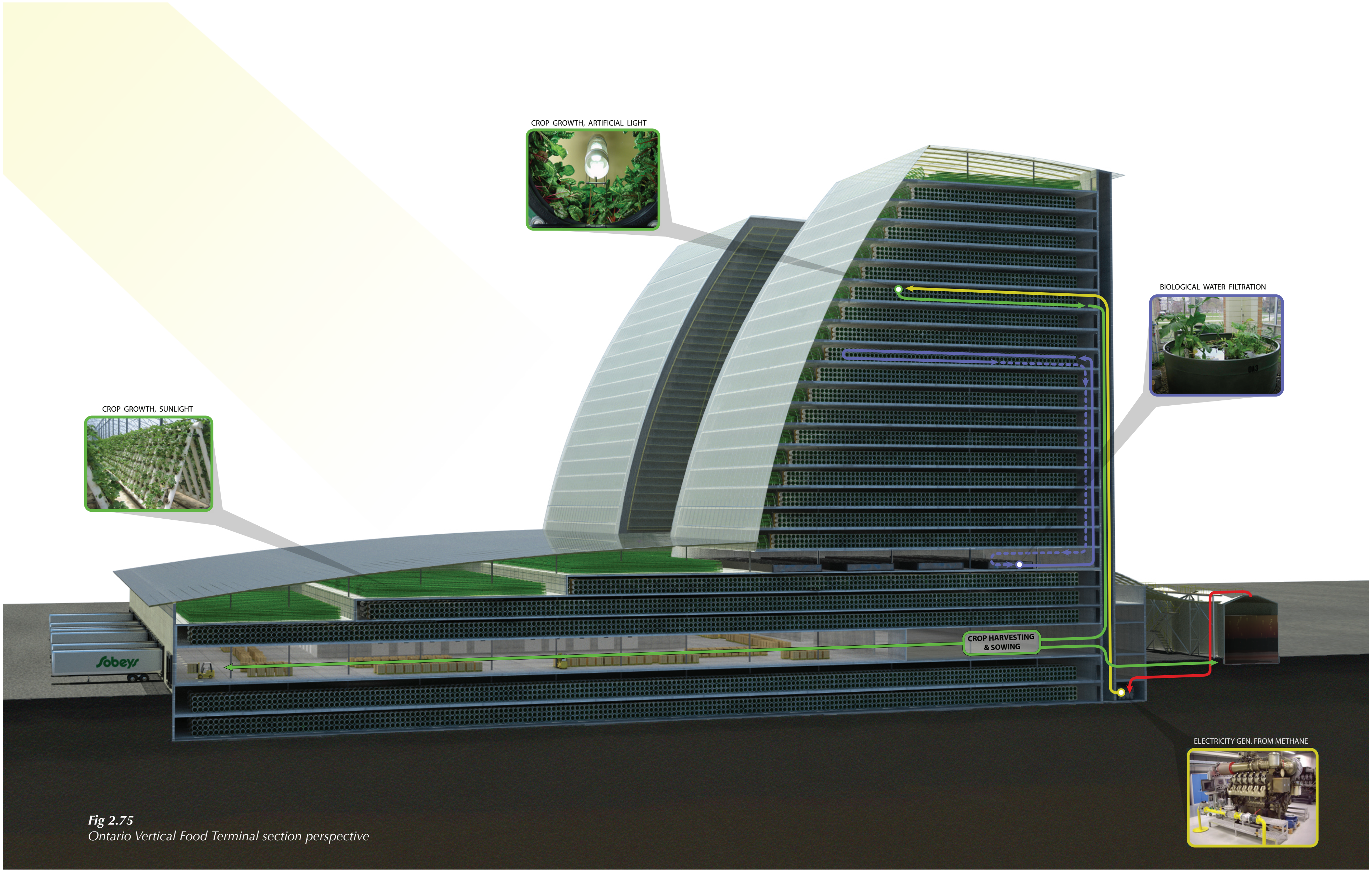

Fig 2.75
Ontario Vertical Food Terminal section perspective

CONCLUSION – THE IMPLICATIONS OF VERTICAL FARMING FOR A RESILIENT URBAN ECOLOGY

The analysis of the concept of environmental decoupling that culminated Part I was largely presented from an ideological perspective, with broad explanations of how an environmentally-decoupled economy could arise. Such generalization is to be expected when examining complex self-organizing systems at their macro-scale, just as referencing specific local ecosystems is generally unnecessary in discussions on the biosphere as a whole. Yet, considering complex systems like the global ecology and economy evolve primarily by way of bottom-up phenomena, rather than top-down directives, it is ultimately essential to understand their behaviour at more immediate scales. With this sentiment in mind this thesis will conclude by examining how vertical farming can encourage a more resilient, cyclical resource metabolism to emerge in the microcosm of human society, the city.

To effectively explain vertical farming's impact on urban resource metabolism it is important to address the underlying systematic behaviour of cities in relation to that of their sustaining natural ecosystems. Like ecosystems, cities are classified as "complex adaptive systems"; complex in that they are diverse and composed of multiple interconnected agents, and adaptive in their capacity to evolve in response to stimulus.[1] Both can be described as emergent phenomena wherein their overall form and behaviour are determined not by the sum of their constituent parts, but rather the patterns that emerge from the *interactions* of their constituent parts. Both are also strongly influenced by their contextual forces: the hydrological and thermodynamic signature of a region for ecosystems and the regional economic, demographic, and environmental forces for cities. Urban systems will expand or contract, evolve or become stagnant over time, just like ecological communities.

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[1] For cities, 'agents' would include the entities that constitute an industrial ecology, such as buildings, vehicles, and infrastructure, while an ecosystem's 'agents' would include the many organisms of which it is composed.

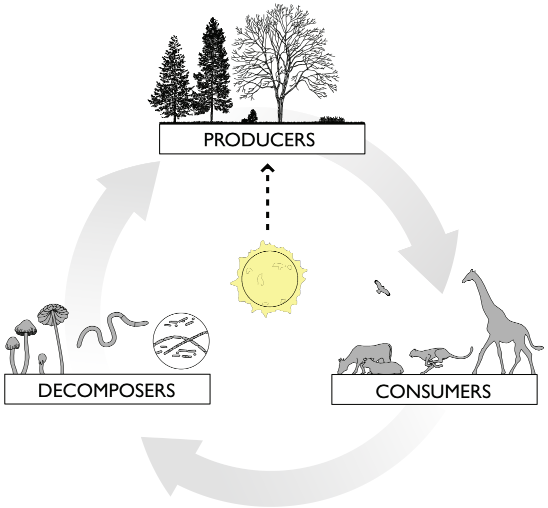

Fig 2.76
Resource metabolism of natural ecosystems

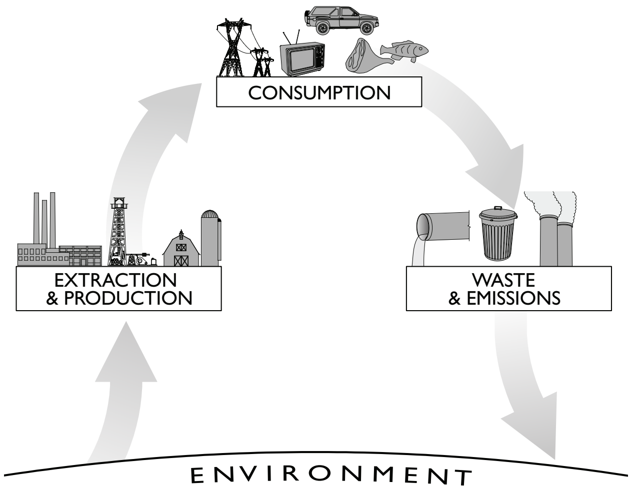

Fig 2.77
Resource metabolism of industrial society

The evident behavioural distinctions between cities and ecosystems can be explained primarily by the differing levels of diversity among their respective constituent agents. It is widely understood that ecosystems exhibit a complex cyclical metabolism. This is enabled by the heterogeneous array of organisms that compose ecosystems, where the waste material discharged by one organism can become the nourishment for another. As the typical cycle goes, autotrophs *(producers)* like plants and algae manufacture energy-rich molecules from sunlight and basic elements, a function known as primary production. Heterotrophs *(consumers)*, which comprise the remaining complex organisms on Earth, depend on primary production either directly or indirectly for nutritional sustenance. At the end of each organism's life cycle the nutrient content of their bodies is broken down by detritivores *(decomposers)* into the basic elements used at the onset of the cycle. This metabolic structure is astonishingly self-reliant, requiring few inputs beyond sunlight and externalizing no material output waste.[2]

On the other hand, modern cities have overwhelmingly linear metabolisms distinguished by their insatiable appetite for natural resource inputs and substantial production of waste outputs. This simplistic resource usage pattern is a product of the homogeneity of a city's composition. In contrast to the internal diversity of ecosystems, cities are largely composed of entities fulfilling the role of heterotrophic consumption. Urban citizens consume food, water, and other commodities, their buildings and appliances consume electricity, and their vehicles consume fuel – the latter two also involving the consumption of raw materials in their manufacture. Without the complimentary metabolic functions of producers or decomposers urban agents must obtain these resources from sources found outside the community, while also creating wastes of little use to the community, forming the traditional input and output externalities of urban life.

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[2] For non-terrestrial ecosystems, such as those of the deep oceans, the energy input may be other than sunlight.

This contrast in the agent diversity is also a significant factor in determining the long-term stability of complex, adaptive systems like cities and ecosystems. In ecology stability is described in terms of an ecosystem's *resilience*, which refers to its ability to tolerate external perturbations without shifting to a qualitatively different state.[3] An ecosystem's stability is enhanced when the important ecological functions (i.e. seed dispersal) are executed by a diversity of species, each with different responses to environmental stimulus.[4] Conversely, when important ecological functions are executed by a single "keystone" species an ecosystem can quickly destabilize as a result of events detrimental to that species.

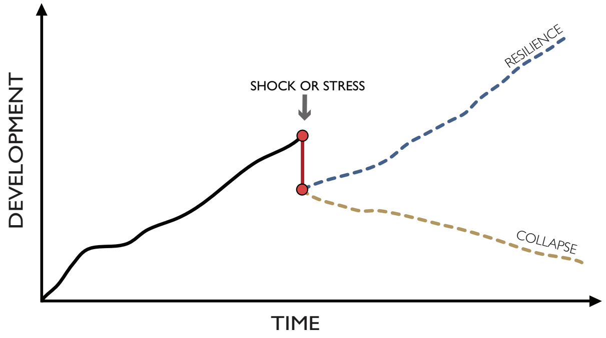

Fig 2.78
Graphic depiction of systematic vulnerabilty and resilience

The resilience of urban systems is defined analogously as the measure of a city's ability to absorb disturbance while still being able to continue functioning, and likewise is determined by factors of systemic diversity. One of the more established modes of analysing urban resilience concerns the diversity of a city's economy. If a city's economy is poorly diversified, meaning that it relies disproportionately on a single network of industries or economic generators, it becomes extremely vulnerable to the market fluctuations of that keystone industry. The regression of Flint, Michigan in accordance with the decline of the U.S. automotive industry is an often referenced example of the danger of overspecialized urban economies. When a city's economy is supported by a diverse web of economic generators the failure of any one sector would inflict far less damage on the city's overall prosperity, rendering it more resilient to routine market fluctuations.

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[3] Definition retrieved from Resilience Alliance, http://www.resalliance.org/576.php

[4] Walker, Brian. Conserving Biological Diversity through Ecosystem Resilience. (1995, August) *Conservation Biology*, Vol.9, No.4, p.747-752.

Yet, while economic diversification is a property common to many urban areas, diversity of *metabolic function* within a city's economy is not. As discussed, the metabolic functions that populate conventional cities are disproportionately represented by the consumer trophic level, which must be subsidized by the external environment to persist. Logically one must then acknowledge that the long-term viability of conventional cities is contingent on the resilience of the Earth's biotic and abiotic services that cities depend on. Paradoxically, the city's rapacious dependence on these natural services is the major force expediting their depletion.

If cities hope to achieve economies that are meaningfully resilient to the effects of ecological decline and exhaustion of limited material resources they must reduce their existing dependencies on natural capital and become accountable for a larger portion of their metabolic needs. In other words, cities must diversify to become producers of the resources that sustain urban life and reprocessors of the wastes traditionally thrust into the natural environment.

Interestingly, cities have a long history of facilitating the local synthesis of formerly demanded natural processes through the phenomenon of "import-replacing". Import-replacing was first identified by Jane Jacobs in *Cities and the Wealth of Nations* to describe the tendency in free urban economies for emergent industries to replace external imports. Though this generally involved the replacement of imports that originated from other cities, Jacobs notes that some of the most profound examples of import-replacing involve goods and services formerly supplied by nature.

> *"A few examples from the past are replacements of natural ice with the city-originated work of manufacturing mechanical refrigeration equipment; replacements of cotton, flax, silk, and furs with artificial, city-devised fibers; replacements of ivory and tortoise shell with plastics. No doubt in such cities as continue to be creative at replacing imports in the future, there will be many other such instances, like city-devised replacements for fossil-fuels which already have a head start in Japanese cities, where hundreds of thousands of dwellings are now successfully using solar heaters."*[5]

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[5] Jacobs, Jane. (1984). Cities and the Wealth of Nations. New York: Random House. p.41

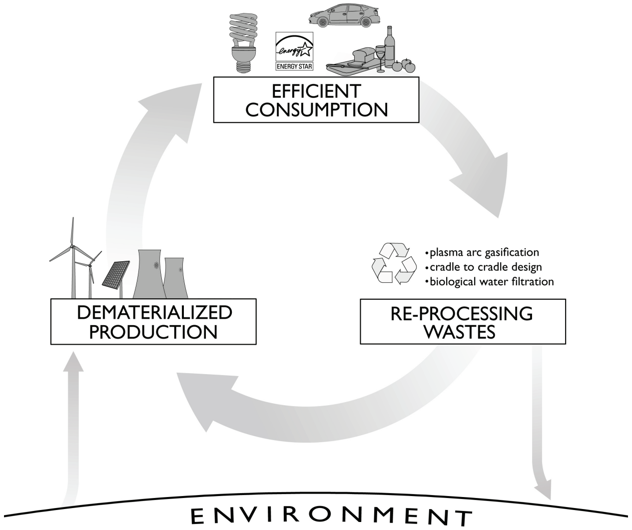

Fig 2.79
Resource metabolism of industrial society decoupling from environmental impact

Stated simply, vertical farming is the urban replacement of imported rural agriculture. It introduces the possibility for large-scale agriculture to exist within the confines of dense urban environments, enabling cities to achieve greater self-sufficiency in their nutritional demands.

The impact of this transition on the resilience of urban economies is hard to overstate. For example, a network of vertical farms would protect cities from the temporary instances of volatility that can disturb the importation of vital commodities, such as extreme weather and social unrest. Increased commodity security is particularly important for food, since most food products have a limited shelf life and must travel thousands of miles to reach urban markets.[6] A measure of this vulnerability can be found in a study published by Toronto Public Health which claims the city would be unable to meet its population's food needs in just three days if it were cut off from external imports.[7]

Additionally, vertical farming would increase a city's resilience to the more long-term, systemic alterations that human society is widely expected to experience in the coming decades. With vertical farming's maximally efficient resource use and functional segregation from the natural world, cities could achieve food security amidst the environmental transformations and resource shortages that would cripple a conventional urban food network.

It must be stated that urban resilience could also be obtained through much different initiatives. If urbanites were successfully encouraged to resume the depression-era practice of preserving locally produced fruits and vegetables for winter consumption and/or significantly reduce their demand for meat the city would also become far less dependent on external food imports. The elegance of the vertical farming concept is that it reduces the ecological impact of food production by harnessing the existing momentum of technological innovation, rather than requiring the resistance of humanity's instinctual desire for improved material comfort and convenience. By disconnecting food production from the

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[6] Xuereb, M. (2005). *Food Miles: Environmental Implications of Food Imports to Waterloo Region.* Region of Waterloo Public Health.

[7] Toronto Public Health, *The State of Toronto's Food: Discussion Paper for a Toronto Food Strategy*, November 2007.

Earth's fragile ecosystems and integrating it with the industrial ecology[8] of urban centres vertical farming could help establish a new paradigm for urban resource metabolism characterized by improved resource productivity and the cyclical exchange of materials.

With respect to its advantageous material input demands and output yields, vertical farms would fill two vacant roles in conventional urban ecologies : autotrophic production and detritivoric decomposition. In perfect contrast to the consumption of food products and production of sewage and organic wastes that urban life necessitates, a vertical farm (designed to the specifications advocated in this thesis) would serve as a consumer of organic waste and a producer of the food cities require. In doing so vertical farming would allow the metabolic mutualism[9] synonymous with cyclical resource flows to become a regular phenomenon in urban ecology.

The metabolic impacts of the discussed vertical farm typologies would be clearly visible at the neighbourhood scale. Agro-Arcology's most visible impact would be the establishment of a mutually beneficial resource interaction with its adjacent urban vicinity, as the building would collect the biowaste generated from its neighbours and offer a stable supply of fresh fruit and vegetables in return. Beyond this its metabolic impact would be largely commensal in nature, as its on-site production of electricity and purification of water and air would likely only benefit the building's residents.

However, to fully appreciate the building's affect on urban resource metabolism one must look more broadly at the potential impact of the typology in general. The vertical farm arcology is a unique variant of a very prevalent, existing building type – the multi-unit residential building. If vertical farm arcologies were adopted by developers and urban planners as a more advantageous residential model they would allow multi-unit housing to evolve from its

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[8] Industrial ecology is the flow of materials and energy within industrial systems like cities and regional economies

[9] In biology the word symbiosis defines a wide range of biological interactions, typically separated into three categories. Mutualism is an interaction that benefits both entities involved, commensalism benefits one without impacting the other, and parasitism benefits one while harming the other.

existing parasitic requirement for external resources to one defined by resource self-reliance. This memetic mutation of multi-unit housing could enable the world's cities to accommodate the massive population growth expected in the 21st century without significantly increasing its dependence on the external environment.

In contrast, large vertical farms like SkyFarm and the Ontario Vertical Food Terminal represent entirely new building types that could reconfigure the resource metabolism of entire regions of existing urban fabric. In addition to displacing existing external food importation with an urban alternative, large-scale vertical farms could function as regional biowaste processing facilities. This metabolic role would enable urban ecologies to productively utilize biowaste, a provision that could ultimately reduce municipal waste impositions on the natural environment by over 34%.[10] Moreover, as the soil fertilization and fortification benefits of the resultant anaerobic digestates are desirable commodities in rural areas, such vertical farms would allow urban ecologies to help replenish the natural lands they have relentlessly consumed for millennia.

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[10] Environmental Protection Agency, *Wastes – Non-Hazardous Waste – Municipal Solid Wastes*. http://www.epa.gov/epawaste/nonhaz/municipal/index.htm

Given the immense scale of many vertical farm designs, SkyFarm and the Ontario Vertical Food Terminal included, questions about the concept's relationship to its wider economic context have arisen. Using the economic analysis as a benchmark, both SkyFarm and the Ontario Vertical Food Terminal would undoubtedly cost well over a billion dollars to construct. At this scale vertical farms could only be realized by developers with virtually endless capital and the capability of operating massive, logistically complex buildings. The only two candidate developers for such projects are the governments of centrally planned economies and, if it is shown to be sufficiently profitable, large multinational corporations within liberal economies. If vertical farming were only applicable to these organizations, the hope for the concept to meaningfully impact world food production would require a great wave of centralization of economic power, which is neither a likely nor desirable scenario.

My response to this problem is two-fold. Firstly, one must realize that vertical farming can exist at a wide range of scales like conventional farming. Designs like SkyFarm and the OVFT should be understood as conceptual explorations of the concept at the extremities of its potential realization, much in the same way Frank Lloyd Wright's *Mile High Illinois* served as a provocation for super-tall skyscrapers. In contrast, the simplified vertical farm designed for the economic analysis was shown to be profitable at just 5% of the size of the Ontario Vertical Food Terminal, with which it shares the function of being a productive food terminal. Within the economic model constructed there is nothing to suggest vertical farming would experience acute economies of scale that would significantly benefit larger operations, meaning projects a fraction of the size of the design used in the economic analysis would likely achieve a similar rate of profit.

With the projected trends of rising food prices and the improving efficiency of grow lights in mind, it appears the vertical farming model advocated in this thesis can expect its gross revenue per unit of production to rise while its major capital and operating costs will shrink. Therefore, vertical farming will likely be an accessible venture for community-scaled businesses in the future; a scenario that would enable vertical farming to infiltrate the food production system of liberal economies through the phenomena of bottom-up, emergence.

The second point to mention is that vertical farming is a technology that can exist within many different economic and political environments. Just as intensive farming was practiced identically in communist USSR and capitalist United States, vertical farming will likely proliferate irrespective of its wider economic context. Historically, centrally planned economies have the advantage of avoiding the necessity for immediate profitability which exists in liberal economies. On the other hand, liberal economies have the advantage of self-organization, which can allow for a much more rapid evolution of markets and greatly increase the efficiency of distribution. With these distinctions in mind it may be logical to assume centrally planned economies will develop fewer, larger vertical farms, and likely be the first developers of commercial-scale vertical farms, while liberal markets will see more numerous, yet smaller vertical farms emerge that operate with greater economic efficiency.

An example of the flexibility of the concept can be seen in the potential operational variability of the arcology variant of vertical farm. Agro-Arcology, for instance, could operate as a high-end condominium development, where the appended vertical farm could sell its produce for the price premium garnered by organic agriculture on the open market. Alternatively, it could operate as a co-operative housing development where residents would be engaged in the cultivation of the crops and serve as their sole consumers. Though one's political philosophies may favour one model over the other, from a macro-scale perspective both encourage a city's food needs to decouple from their existing negative impact on the Earth's ecosystems by way of integrating food production with urban industrial ecology.

With vertical farming's metabolic impact in mind one can envision how other import-replacing technologies could arise to further the city's transition toward a cyclical metabolism. The steady growth of renewable energy technologies provides hope that urban energy needs will eventually be derived from sources with negligible environmental impacts, such as solar and wind power. As with vertical farming, energy production from these technologies can be scaled to practically indefinite extents to allow for the continued growth and progression of cities without harming the biosphere.

At the other end the material life-cycle a decomposer trophic level has begun to form in cities with the emergence of municipal recycling over the past decades. Though current practices only allow recirculation of select materials, new technologies like plasma gasification appear poised to significantly increase the spectrum of wastes a city could effectively re-process into desired commodities. A city that utilizes such technology would be able to reduce the impact of waste disposal on natural ecosystems while simultaneously reducing the volume of raw materials necessary to sustain economic development.

Moving forward, the question of how best to facilitate this shift to a more resilient, self-contained urban metabolism presents itself. After acknowledging the obvious necessity for the continued advancement of the technologies that improve resource productivity, one interesting development could see an expansion to the scope of urban planning to include the adaptive management of urban metabolism. If armed with a thorough understanding of the science of system's theory and the mechanics of industrial ecology, urban planners could introduce informed by-law amendments and zoning changes to encourage metabolic attractors like vertical farms to gain a foothold where they are needed most. Through this practice we may ultimately learn that effective stewardship of the natural environment begins with the stewardship of our own industrial ecology.

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