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Future food-production systems: vertical farming and controlled-environment agriculture

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ABSTRACT
The unremitting trends of increasing population, urbanization, diminishing water supply, and continuing climate change have contributed to declining stocks of arable land per person. As land resources for agriculture decrease, policy makers are faced with the challenge of sustainability and feeding the rapidly growing world population which is projected to reach approximately 9.7 billion in 2050. Solutions for improving future food production are exemplified by urban vertical farming which involves much greater use of technology and automation for land-use optimization. The vertical farm strategy aims to significantly increase productivity and reduce the environmental footprint within a framework of urban, indoor, climate-controlled high-rise buildings. It is claimed that such facilities offer many potential advantages as a clean and green source of food, along with biosecurity, freedom from pests, droughts, and reduced use of transportation and fossil fuels. In this article, the issues involved are evaluated together with potential advantages and disadvantages. Possible implications are identified for consideration by policy makers and to facilitate further economic analysis.

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Introduction

An emerging global problem is the long-term decreasing stock of agricultural land per capita. Statistics on future growth of the world population from the United Nations Food and Agriculture Organization (FAO) reveal that arable land per person is projected to decrease by 2050 to one-third of the amount available in 1970 (FAO 2016). This decline is forecasted to continue due to the effects of climate change, the increasing geographic extent of drylands, the reduction in fresh water supply, and population growth (Fedoroff 2015). As shown in Figure 1, this trend means that the planet is running short of farmland to feed a growing number of people (Fedoroff 2015; FAO 2016; USCB 2016). A more complete list of prominent threats to the future supply of arable land would also include: climate change, declining fisheries (prompting a greater food burden on land-based products), increasing urbanization, rising costs of agribusiness (e.g. fertilizers, fuel, pesticides), rapidly increasing population, soil depletion, and degradation from over-farming and poor production practices.

There is increasing realization that primary producers such as Australia are too small to be the food bowl for Asia as current agricultural production would feed only about 60 million people (see Linehan et al. 2012; Fact Check 2014). At the present time, scaling up to provide for the region's entire population of 3 billion people is physically impossible. The comparative economic advantage of Australia is in providing so-called clean, green, and gourmet (CGG) foods for the rapidly growing middle and upper classes in Asia, particularly China, while expanding the current volume of production as fast as possible.

The practice of farming in Australia has evolved in the face of environmental adversity by careful planning, good management, and substantial research and development. Primary industries in the country, however, are encountering ongoing challenges due to uncertainties in climate, water supply, invasive pests, soil degradation, and transportation costs. The decline in arable land per person in Australia also mirrors the global pattern (Figure 2). Australian agriculture is competitive in the international economy, but may come under threat from disruptive new technologies, such as intensive urban farming.

Interest in vertical farming gained traction following publication of the book by Despommier (2010) who argued that the benefits of indoor greenhouse

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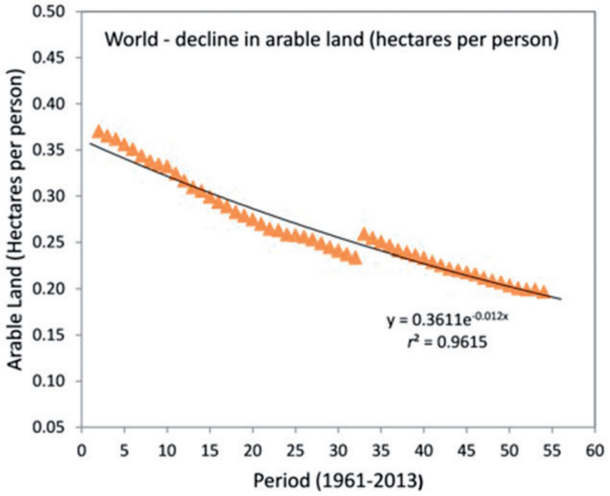

Figure 1. Decline of stocks of arable land in the world over the period 1961–2013. Indicative trend line calculated using data from the United Nations Food and Agriculture Organization (FAO 2016). The discontinuity coincides with the global recession in the early 1990s.

farming could be multiplied greatly by building high-rise buildings in urban environments. In the CGG food category, pilot farms have been established in various cities around the world including London, New York, Singapore, and Tokyo. In particular, China, Japan, and Israel are devoting resources to indoor factory farming due to issues relating to climate, pollution, and urbanization. The advantages and disadvantages of this approach have been the subject of continuing analysis at the industry level but more attention is needed with respect to planning, policy, and economics.

Despommier (2010) proposed that one approach to addressing the future trend of diminishing agricultural resources, changing climate, and other factors involves the concept of vertical farming. This approach is characterized by an urban, indoor, high-rise, climate-controlled factory with renewable energy and recycling of waste. The factory farms would be housed in the population centers of large cities or regional towns. Vertical farming has the potential for crop production all-year round in an air-conditioned facility, eliminating transportation costs, with greater control of food safety and biosecurity, and substantially reduced inputs with respect to water supply, pesticides, herbicides, and fertilizers.

In this article, we report on an evaluation pertaining to the claims, potential, and limitations of vertical farming and related food-production models. The intention is to offer an introduction to vertical farming and its derivatives, to assess the implications for future food production, and to provide a resource with information and recommendations to inform policy makers and economists. Some issues are underscored with a reference to the particular situation in Melbourne, Australia.

Vertical farming

In this section, we introduce vertical farming in the context of four issues: (1) drivers for farm innovation, (2) the potential advantages offered by vertical farming, (3) its origins in controlled-environment agriculture, and (4) reference to some technology issues, such as light-emitting diode (LED) illumination and genetics.

Drivers for farm innovation

A recent study released jointly by the University of Melbourne and Deakin University reported that in the absence of a change in policy planning, food self-sufficiency for Melbourne from the surrounding food bowl could fall dramatically as the urban population doubles to 7–8 million by 2050 (Carey, Larsen, and Sheridan 2016). The authors reported that the food bowl currently provides 41% of the total food supply for the city but this could drop to 18% due to climate change, population growth, and diminishing supplies of arable land and water.

There are many drivers for urban food planning and policy development. Morgan (2009) argues that food production is multifunctional and has widespread effects on public health, water, land, and economic development. The so-called new food equation refers to a combination of novel developments which are described as follows.

First, a surge in world-food prices in 2007–2008, when the international price of wheat doubled and the price of rice tripled, exacerbated food insecurity for two billion people and caused food riots in some parts the world. The global recession around 1991 is reflected in a sudden disruptive transition in annual data from the World Health Organization (WHO)

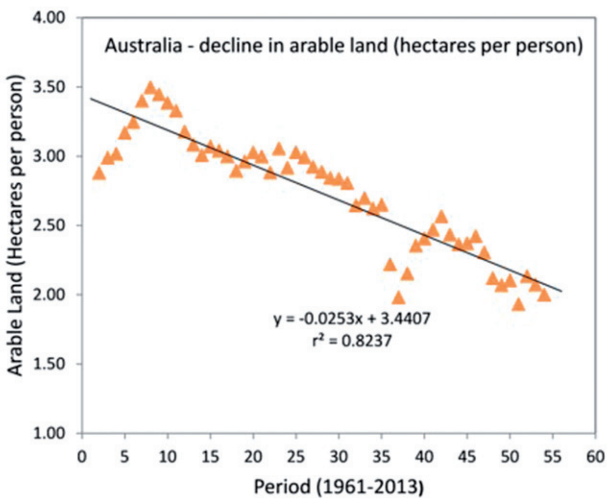

Figure 2. Decline of stocks of arable land in Australia over the period 1961–2013. Indicative trend line calculated using data from the United Nations Food and Agriculture Organization (FAO 2016). The discontinuity and recovery relate to the global recession in the early 1990s.

for arable land per person, which highlighted the importance of economics with respect to the trend in the availability of arable land (see Figures 1 and 2).

Second, climate change is intensifying heat stress, droughts, and damage to ecosystems. This is especially important in developing countries where food prices are already under pressure.

Third, land disputes and social tension increases when local land is purchased by cash-rich investors from Asia or the Middle East, often resulting in resentment and spiraling property prices. Purchases may be long term and not for immediate profit and above market prices, and also to evade domestic regulations on crop types (e.g. growing water-hungry crops in regions with droughts and water restrictions in the target market).

Finally, rapid urbanization is leading to resentment and unpredictable food shortages in some parts of Asia due to both depopulation of rural regions by job-seekers and increasing urban sensitivity to variability in the food-supply chain due to unstable labor availability.

These factors in combination are increasing complexity and uncertainties in planning sustainable food production (Morgan and Sonnino 2010). In Australia, additional drivers for change include government priorities aimed at increasing employment. New and emerging technologies, such as vertical farming and its derivatives, may provide new jobs in high technology, food processing, process maintenance, infrastructure development, and research and development. Note that urban farming also includes clusters around regional towns as well as central business district locations.

Another driver for change is that traditional food suppliers in Australia and Canada have recognized that they are too small to supply a large volume of produce to the global market and there is a public debate over the need to specialize in more profitable CGG food production for affluent clients in China, Japan, Singapore, and elsewhere. Finally, countries that are export destinations for Australian production, such as China and Japan, are also interested in greenhouse farming and are emerging as direct competitors to Australia in producing CGG foods using intensive indoor methods.

Potential of vertical farming

The vertical farming model was proposed with the aim of increasing the amount of agricultural land by 'building upwards.' In other words, the effective arable area for crops can be increased by constructing a high-rise building with many levels on the same footprint of land (Despommier 2010; The Economist 2010). One approach is to employ a single tall glasshouse design with many racks of crops stacked vertically. It is an extension of the greenhouse hydroponic farming model and addresses problems relating to the use of soils, such as the requirement for herbicides, pesticides, and fertilizers. Transportation costs can be eliminated due to proximity to the consumer, all-year-round production can be programmed on a demand basis, and plant-growing conditions can be optimized to maximize yield by fine-tuning temperature, humidity, and lighting conditions. Indoor farming in a controlled environment also requires much less water than outdoor farming because there is recycling of gray water and less evaporation. Because of these features, its wider adoption is likely to occur initially in desert and drought-stricken regions, such as some areas in the Middle East and Africa, and in small and highly urbanized countries such as Israel, Japan, and the Netherlands. Vertical farming is also attractive where there is a high demand for CGG food in countries that suffer from heavy pollution and soil depletion, such as parts of China.

Controlled environment agriculture

The vertical farming model is essentially an indoor farm based on a high-rise multi-level factory design. Typical features include innovative use of recycled water augmented by rainwater or water from a desalination plant, automatic air-temperature and humidity control, solar panel lighting and heating, and tunable 24-hour LED illumination. The LED equipment can be controlled throughout a growing season to emit a programmed spectrum of light that is optimal for photosynthesis for different types of crops. When coupled with regulation of temperature and humidity, the effects of seasonality can be minimized or eliminated.

An indoor vertical farm may not even need soil if hydroponics is used. This cultivation technique involves growing plants in a soil-free culture with nutrient solutions. The plants are suspended in a medium, such as rock wool or perlite, and provided with nutrients, or the roots are directly bathed in the nutrient liquid using the nutrient-film technique (Jones 2016). Air conditioning provides a constant flow of air which can be enriched with carbon dioxide (CO_2) to further advance plant growth and development. Both ambient and nutrient temperatures can be held at specific levels that optimize the rate of plant growth. Any nutrients and water not absorbed by the roots can be recycled rather than lost to the system. The approach is consistent with CGG food production. It can be used to grow a wide range of crops, pharmaceuticals, or herbs.

A variant of hydroponics is aeroponics which involves spraying the roots of plants with atomized nutrient solutions or mists (Christie and Nichols 2004). There is reduced need for fertilizers, herbicides, and pesticides if there is effective isolation from a harsh external climate. Such a factory would essentially eliminate common constraints and risks to productivity, including heat and drought, pests, seasonality, and transportation costs from remote locations. Volatility in markets can be addressed because production can be planned according to demand. There are also implications for future food security and sustainability in the face of climate change and diminishing land and water resources.

The principal design elements of a vertical farm and its derivatives are shown in Figure 3. The use of wind turbines and storage batteries for solar panels add even further attraction to this approach. A multi-level vertical farm may take on many configurations including conversion from existing disused warehouses or apartment blocks. An example of a green building with similar characteristics to a vertical farm is shown in Figure 4. Conversion of building stock from office or residential use to vertical farming has potential for addressing the oversupply of inner urban high-rise developments.

The agricultural potential of LEDs has been the focus of research in greenhouse lighting (Yeh and Chung 2009). The much lower energy requirements of LED lighting in combination with photovoltaics has resulted in rapid deployment in factory applications. The photoreceptors in plants absorb the light energy for the purpose of photosynthesis and are affected by the wavelength and intensity of light. The spectral content of illumination, such as blue wavelength in LED lighting, has been found to change the concentrations of nutritionally important primary and secondary metabolites in specialty vegetable crops (Kopsell, Sams, and Morrow 2015). In particular, plant response to different wavelengths of light from LED sources suggests very significant improvements in productivity are possible.

In addition to wavelength, controlled lighting with respect to intensity and time duration is another area where potential optimization strategies are possible and requires further investigation. In particular, genetics research has a possible role to play in matching plants to the available light spectrum for improved yield. Spectral sensitivity may also extend beyond the visible wavelengths and into the ultraviolet and infrared bandwidths with potential effects on growth rates.

Genetic engineering may also be able to enhance growth of crops that are compatible with other controlled indoor environmental conditions. For instance, it might be possible to increase crop yield by fine-tuning variables such as temperature, humidity, and CO_2 levels. Determination of a dose– response model for light-sensitive cells would support system optimization (Benke and Benke 2013).

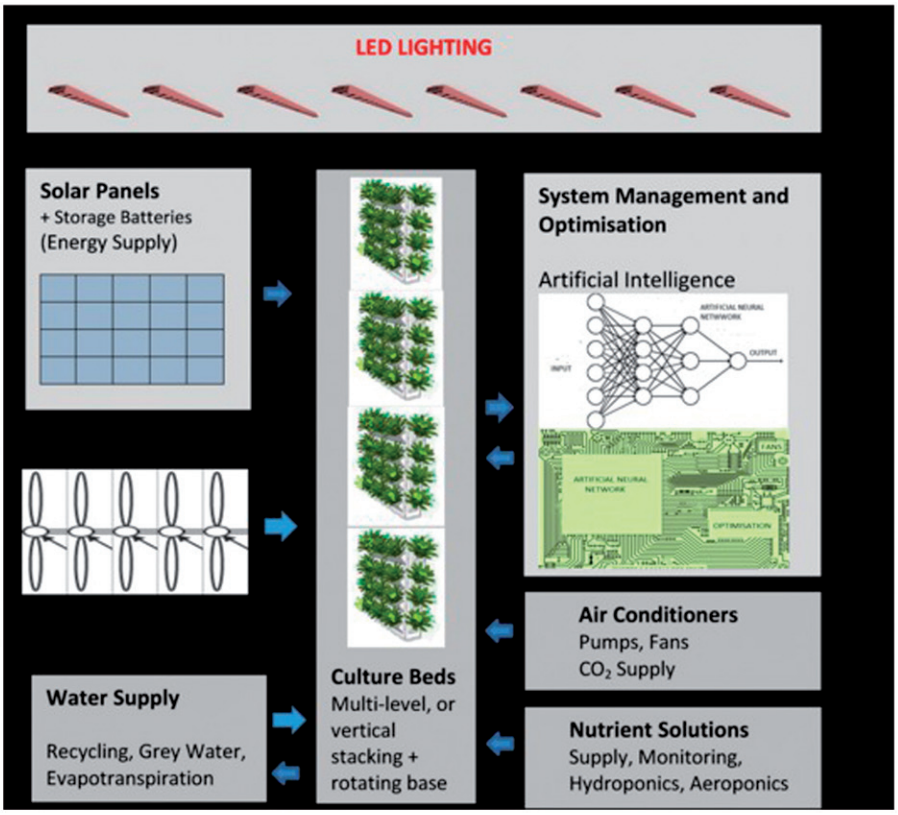

Figure 3. Components of a vertical farm and their interactions.

Figure 4. The Grocon Pixel building is an example of a green office building in Carlton near the Melbourne central business district. The multi-level building in the foreground has wind turbines on the roof and adjustable side panels for controlling exposure to solar radiation. If converted into a vertical farm, solar panels could be used on the roof and sidewalls and interior lighting would use high-efficiency LED sources. At nearby Lincoln Square there is a million liter holding tank under construction for local reuse of stormwater. The conceptual model illustrated is the twinning of a residential tower with a vertical farm.

Commercial derivatives

The following section outlines commercial examples of multi-level indoor urban farming. Common features are multi-rack climate-controlled enclosures with very high productivity, food security, and substantially less use of land, water, and energy. Another notable feature is rapid proliferation on an international scale (see Figures 5–7).

Sky Greens (Singapore)

In Singapore, the so-called Sky Greens 'A-Go-Gro' technology is based on A-shaped towers, over six meters high, consisting of up to 26 tiers of growing levels. These tiers rotate at one millimeter per second to provide uniform solar radiation as depicted in Figure 5 (Krishnamurthy 2014). The footprint of the system is only six square meters, making it ideal for urban environments. In Kranji, near Singapore's central business district, 120 towers have been erected and there are plans for an additional 300 to support daily production of two tons of vegetables. Current intentions call for building a further 2000 towers and for selling them overseas with a price tag of US$10,000 per tower. The cost of vegetables produced by these towers in Singapore is about 10% higher than imported product and the system supplies 10% of the vegetable market in Singapore. It provides the city-state with greater food security and CGG produce.

Valcent Company (North America)

The company Valcent Products (Verticrop 2016) has a technology that is a derivative of vertical farming that is now in operation. The system involves multi-level stacked plastic trays in a climate-controlled glasshouse enclosure (rather than multiple floors). The racks are rotatable (mechanized) and provide solar exposure.

The Vancouver-based company claims its vertical hydroponic farming technology can produce over an area of one standard residential lot (50 by 75 feet) the equivalent output of a 16-acre farm (Laylin 2016). In contrast to a traditional farm, the vegetables require only 8% of the water and 5% of the area. The produce is exported on a worldwide basis.

Highly efficient LED illumination is used to augment natural light from the glasshouse design. No harmful herbicides or pesticides are used. Three staff can oversee 4,000 square feet of plants and 2,000 square feet of space for germinating, harvesting, and packing. They can process as many as 10,000 plants every three days (Laylin 2012).

Mirai Company (Japan)

The Mirai company in Japan has developed and marketed indoor multi-level farms with impressive production statistics (Shimamura 2016). For example, one Japanese farm comprises 25,000 square meters producing 10,000 heads of lettuce per day (100 times more per square foot than traditional methods) with 40% less energy, 80% less food waste, and 99% less water usage than outdoor fields (Kohlstedt 2015; Shimamura 2016). New factories are now being planned for Hong Kong, Mongolia, Russia, and China.

Special purpose LED lighting allows plants to grow up to two and half times faster and has decreased the cycle of days and nights with optimized temperature and humidity conditions. At present, harvesting is still carried out on a manual basis but robots are planned in future upgrades. Mirai concentrates on fast-growing leafy vegetables that can be sent to market quickly.

Advantages of vertical farming

Despommier's original vision was a world full of skyscrapers with multiple levels cultivating crops

Figure 5. Racks of vegetables in a glasshouse design with hydroponics (Source: Sky Greens 2017).

throughout the year. In addition to generating more farmland on a single ground-level footprint, this would, according to a review by The Economist (2010), 'slash the transport costs and CO_2 emissions associated with moving food over long distances. It would also reduce the spoilage that inevitably occurs along the way.' In putting forth his pioneering conception, Despommier outlined a number of reasons why vertical farming could be highly attractive to policy makers: all-year-round crop production; higher yields (by a factor of six or more depending on the crop), avoidance of droughts, floods, and pests; water recycling; ecosystem restoration; reduction of pathogens; provision of energy to the grid through methane generation from compost; reduction in use of fossil fuels (no tractors, farm machinery, or shipping), and creation of new jobs. The closed environment could conceivably be also suitable for translation to other planetary environments in the context of space exploration (Giroux et al. 2006).

The claimed benefits of vertical farming can be categorized and summarized in terms of economic, environment, social, and political dimensions (see also Murase and Ushada 2006; Fitz-Rodriguez et al. 2010; Despommier 2010; The Economist 2010; Kozai 2013).

Economic advantages

The economic advantages of vertical farming are numerous and include the prestige of marketing premium CGG food with export-sales potential and a lower cost base due to protection from floods, droughts, and sun damage. There are essentially no requirements for fertilizers, herbicides, or pesticides. No soil is needed if hydroponics is used, only nutrients and a water supply.

There is no requirement for long-distance transportation due to localized production and no need for farm machinery such as tractors, trucks, or harvesters. There are no seasonality issues because continuous crop production occurs all-year round and can be programmed to match demand. An economic benefit may arise from reallocation of large rural farms to energy production from solar and wind sources.

Vertical farming could provide a competitive edge for Australia by combining extensive research and development with farming experience, big data, and modern technology to improve productivity.

Environmental advantages

The environmental benefits are significant, including providing healthy organic food not contaminated

Figure 6. A controlled-environment farm in Victoria showing tomato crop.

from chemicals. There is greatly reduced use of fossil fuels by avoiding transportation from rural zones to the urban customer base. Burning fossil fuels can be minimized by employing solar panels, roof-top wind turbines, and storage batteries. This will lead to a reduction in ecosystem-carbon levels.

Fresh water is augmented by evaporation of black and gray water to conserve water resources. There is also the potential to rejuvenate the national ecosystem so that rural land is reclaimed for vegetation. Most importantly, vertical farming supports environmental sustainability.

Social advantages

Vertical farming will provide new jobs in engineering, biochemistry, biotechnology, construction, maintenance, and research and development opportunities for improving the technology. Enhanced productivity can lead to lower food and energy costs and improve discretionary incomes. The oversupply of high-rise apartments and disused warehouses in capital cities can be reduced by using empty buildings for multi-storey farms close to the consumer, rejuvenating neglected neighborhoods. The model may help to address isolation in remote rural communities by re-skilling workers in technology for vertical farms in local towns and cities.

Political advantages

A key political advantage of vertical farms is that climate-change commitments are more easily satisfied and the technology supports adaptation and mitigation. The closed-system approach supports biosecurity because of greater protection from invasive pest species. A distributed network of vertical farms has lower blackout risks and there is also reduced dependence on a few large power stations that are vulnerable to earthquakes or terrorist attacks.

Challenges to vertical farming

There have been critics of the original vision of vertical farming as described by Despommier (2010). For instance, Cox (2016) claimed that there are a number of problems including the limited range of crops suitable for this business model (originally mostly vegetables such as lettuce, strawberries, and tomatoes), together with the small proportion of the population that could be serviced and the expensive energy requirements. Furthermore, he contends that only the plants on the top level would benefit from solar radiation in a greenhouse environment and energy supplied by photovoltaics is limited because plants cannot be stacked in vertical arrays.

The arguments advanced by Cox have become less relevant due to continuing advances in technology. For example, solar panels are now more efficient for energy generation and light exposure is more cost-effective due to the advent of new cheap and energy efficient LED lighting. Additional sun exposure is possible using rotatable stacked arrays of plants inside a single high-rise enclosure (Morrow 2008; Massa et al. 2008). The cost of storage batteries is decreasing rapidly by analogy with Moore's Law in electronics. The new LED sources have potential for greatly increased yield in greenhouse settings due to matching spectral characteristics with plant type and physiology (Massa et al. 2008; Trouwborst et al. 2010).

The challenges to vertical farming may be summarized as follows (Alter 2010; The Economist 2010; Cox 2016). Start-up costs can be high if land is purchased in central business districts. The number of crops grown is not as great as for rural farming. Production volumes are also not as large as broadacre farming and scaling-up may add cost and complexity. More specific challenges are the need to manage disruption to the rural sector, to raise investment capital, and to train a skilled workforce.

Key performance indicators

Key performance indicators (KPIs) are metrics that can be used to support the evaluation of vertical

Figure 7. Example of a large-scale indoor farm in Singapore (Source: Sky Greens 2017).

farming. The KPIs may be quantifiable or qualitative assessments based on modeling, analysis, literature review, and expert opinion. The factors making up the KPIs are itemized in Table 1. The tabulated values are discussed in greater detail in the following subsections. Note that each KPI identified as satisfied may still be improved in future. An advantage of the KPI table is that it highlights and ranks issues of importance. This methodology also provides the foundations for further analysis if there is a quantitative dimension to the performance indicator.

Table 1. Vertical farm – key performance indicators (KPIs).

	Key performance indicator	Satisfied	Partial	Not satisfied
1.	Start-up costs			✓
2.	Energy consumption		✓	
3.	Number of crop types		✓	
4.	Production volume			✓
5.	Scaling-up issues		✓	
6.	Venture capital		✓	
7.	Skilled workforce for maintenance		✓	
8.	Disruption to the rural sector		✓	
9.	Transport savings	✓		
10.	Clean, green and gourmet food	✓		

Start-up costs

In many cities, such as Melbourne or Sydney, startup costs relate mainly to very expensive real estate in urban areas compared with rural land and also depreciation costs on plant and machinery. While disused warehouses may be available and land reclamation might be possible, in the main this cannot be regarded as a large-scale solution. A key question for an investor is how many years to the break-even point. A disadvantage of farming in built-up inner city areas near the central business district is the very high cost of property in some cities. For the purpose of conversion to commercial use, the relevant reported apartment values for Melbourne were in the vicinity of US$349,000 median for the lowest quartile in 2016 (REIV 2016). A recent Victorian government report has set standards of 65 square meters minimum for human comfort and habitability (Design Standards 2016). Assuming, conservatively, a figure of 100 square meters for notional apartment size then the potential cost for urban arable land would be around US$3,491 per square meter.

For a hypothetical 10-level vertical farm, the land cost would be reduced by an order of magnitude to US$349 per square meter per 'arable' unit. In contrast, rural values for Victoria were in the vicinity of US$3,967 per hectare in 2015, or US$0.40 per square meter (using data from Kuchel 2016). These calculations are approximate only and subject to modifications due to fit-out in the buildings but clearly reveal the huge cost disparity in land values. The history of property prices indicates a trend of greater divergence between urban land and rural land in the future suggesting that this will be a continuing challenge to the cost base of an urban farm. A startup urban farm may well be saddled with an initial cost in the order of US$317 per square meter for arable area, without construction and fit-out, which would be reflected in the price of the product.

Beyond land values, a traditional single-level greenhouse outside the inner urban area has been estimated to cost around US$317 per square meter in Victoria and as little as US$0.79–1.58 per square meter in developing countries (Tomkins 2016). According to calculations by Tomkins, one can grow five times as much in an indoor setting relative to the field, so therefore the cost reduces to US$70 per square meter. Therefore, potential productivity improvement on the same geometrical footprint of land could be 50-fold. A derivative of vertical farming is a single-level high-ceiling greenhouse enclosure with multiple stacked racks, up to 10 levels or more, which represents a further improvement in infrastructure cost.

Australia has very expensive real estate in the capital cities, which presents a planning difficulty at the commercial scale (Parkinson 2016). In particular, the high property prices may mean some investors will see vertical farming as a proxy for the property market. Nevertheless, several Japanese companies are investing heavily in the infrastructure side to support this approach (Parkinson 2016).

In summary, infrastructure depreciation and improved productivity will eventually lead to parity with the annual running cost of outdoor farming, but it is not clear when this will happen. If the yield per hectare for indoor farming is much higher than rural outdoor farming, perhaps as much as up to 50 times, this factor will eventually outweigh the initial cost of land acquisition. The break-even point is the number of years from startup, and this will largely determine when the availability of CGG food is not hampered by the cost structure. In the case of Victoria, comparing the previously stated urban and rural prices, and assuming 50-fold improved productivity, the break-even point may well be an estimated 6–7 years.

In contrast to Melbourne or Sydney, in some areas in the United States, there is no shortage of affordable properties in former industrial districts located near major cities, such as New York and Chicago, which are suitable for reuse for vertical farming. This is not a matter of expensive land near the central business district, but old industrial buildings standing vacant for decades and highly amenable to conversion to vertical farming without the need for major investment. For instance, AeroFarms in 2015 converted a former lumberyard in Newark, NJ, into one of the largest vertical farms in the world, with racks stacked twelve layers tall, in order to grow kale, bok choi, watercress, lettuce, and other baby-salad greens (Frazier 2017).

Energy consumption

Energy requirements are based on whether there is a need for stand-alone off-the-grid farming or not, which is not in itself a critical factor. Some researchers have developed a rule of thumb that the area of solar panels required would need to be a factor of twenty times greater than the arable area on a multi-level indoor farm, which was impossible for rooftop solar at that time (The Economist 2010). Since then, project sponsors have submitted plans for a new high-rise residential tower in Melbourne that is sheathed in high-efficiency photovoltaics and new generation LED lighting. The proposed *Sol Invictus* building is described as an 'off-the-grid' 60-level residential tower that will have rooftop-wind turbines, doubled-glazed windows, and battery storage from the solar panels (Johanson and Pallisco 2016). It was reported that the facade would have an area of 3,000 square meters of photovoltaics plus 300 square meters of similar equipment on the roof. This represents technology that is already two years old and further improvement is likely by the time construction begins two years from now. The external energy requirements of an indoor farm have diminished greatly and are likely to approach off-the-grid operation at some time in the near the future.

Number of crop types

Despommier (2010) and others claim that, in principle, any crop can be grown in a vertical farming greenhouse. Most current production involves lettuce species, plus tomatoes, and strawberries. Other crops, including grain, grape, and tree fruit, are also feasible options. Soy products would provide a protein substitute and could have an impact on the meat industry. It is to be noted that soy–protein replacement for chicken is already available in supermarkets. Aquaculture and pharmaceutical production may also be suitable for this type of farming, as is legal cannabis cultivation.

Frazier (2017) reported that a reason for leafy greens being very popular as a crop is that they provide a premium profit margin, rather than any inherent limitations in crop types. Supplying proximate restaurants with fresh local produce has been a successful marketing strategy by local urban farms. Potatoes, sweet potatoes, and bulb onions have been grown in a glasshouse by the second author using hydroponics. Production of tree crops may require more thought and effort but can be achieved by growing mini-trees or on dwarfing rootstocks. This form of cultivation may need more space between the growth modules to allow taller crops but with fewer vertical layers in the farm.

Production volume and scaling-up

Vertical farming does not as yet, in terms of production volume, pose a risk to traditional agriculture.

This threat is likely to be some years away following the extant trends cited earlier. It needs to be noted that greater production volumes can be achieved by vertical expansion in multi-rack systems, horizontal expansion, or more construction sites around country towns.

The question that needs more research and analysis is the degree to which vertical farming could undermine broad-acre production. Hamm (2015) estimates that three facilities the size of the Empire State Building could produce enough wheat to feed New York City. The question is, would wheat and other relatively low-value agricultural commodities make economic sense given the high capital cost of establishing and running a vertical farm. Low-value field crops are not economically viable at present, but this may change in the future with an ever changing climate, scarce arable land, and diminishing and intermittent resources such as water.

Once established, vertical farming expansion would tend to be incremental in cost. Multi-floor systems, however, may have the same limitations which are evident with residential high-rise buildings, such as regulated height limits or fire security. Production volume is not yet regarded as a limiting factor in the special case of CGG food destined for affluent clients. Implementation of the vertical farming model may be more pronounced toward the year 2050 due to climate change and rapidly declining availability of arable land per capita. Volume production and application to broad-acre crops remain current limitations to vertical farming.

Venture capital

Venture capital could be attracted from local investors or from investors located overseas where there is keen interest in CGG food, where land is at a premium, or where there is land contamination and air pollution. Cost of food for affluent consumers is not a major deterrent. Indoor farming is likely to be an attractive target for funding or co-investment from government, industry, and universities, due to the nature and potential of the projects.

Skilled workforce for new jobs

Farming in high-rise buildings will generate new careers for technologists, project managers, maintenance workers, marketing, and retail staff. There will need to be workers to manage planting, cultivation, monitoring, harvesting, and research and development (Despommier 2010). Consulting engineers will be required to install and manage air-conditioning, water recycling, and lighting controls. In industrialized economies, there are few problems in providing skilled labor or scientific resources due to the supply of university-educated workers.

At the same time, novel industries may develop to provide advanced electronic instrumentation and services with consulting professionals advising on derivatives of the vertical farming concept, such as rooftop gardens on apartment buildings, office blocks, restaurants, hospitals, and a technology-driven resurgence of the backyard greenhouse (Despommier 2010). The new jobs created may prove to be more highly skilled and diverse and probably increase overall employment in the food-production sector. The semi-automation of some aspects of the food cycle will also provide opportunities for robotics and software engineers for process improvement.

It is also possible to conceive of social benefits that may accrue from the vertical farming model of food production. It is well established that rates of depression and suicide are higher in remote regions and part of this problem relates to isolation and lack of a vibrant social network, especially for males (Roy, Tremblay, and Robertson 2014; Fontanella et al. 2015). Vertical farming has elements of a collective enterprise with social interactions among activities, providing meeting places for socially isolated staff with opportunities for new friendships.

Disruption to the rural sector

Potential disruption to the rural sector is an emerging issue but contained in the short term by high startup costs associated with vertical farming. The future outlook entails the emergence of other less benign challenges to the sustainability of traditional farming models. Costs for vertical farming are decreasing rapidly due to advances in automation and greenhouse technology. Strategy and planning are needed to address the transition to controlled-environment agriculture, including education of government officials and farmers to familiarize them with the new technologies and support for infrastructure development.

Transportation savings

The location of food production in urban areas in closer proximity to consumers is an attractive notion and will likely result in dramatic reductions in transportation costs. Vertical farming also cuts greenhouse-gas emissions from trucks and therefore supports adaptation and mitigation with respect to climate change. It has been reported that 20% of carbon emissions in the United States originate from the farming sector (Despommier 2010). Marked reduction in agricultural emissions is also plausible for Australia.

Clean, green, and gourmet (CGG) food

The possibility of CGG food production is easily the most attractive feature of the vertical farming model. This aspect is less price sensitive to affluent consumers in high-demand countries such as China. All-year-round crop production without seasonality, in a climate-controlled environment (including both temperature and humidity), will produce fresh produce virtually on demand. There would be no weather-related crop failures due to drought or flooding if hydroponic and aeroponic technologies are employed.

Using recycled water and nutrients in a closed, indoor, climate-controlled environment adds to food security and can reduce or even completely eliminate the need for pesticides and herbicides. Contamination by pathogens or heavy metals will no longer be an issue as occurs in rural farming. There is scope for marketing the product in this respect. Strict hygienic practices must still be observed to minimize the risk of introduction of pathogens and biological contamination into the growing space. However, in a vertical farming situation, one can closely monitor the crop for signs of pest or disease both manually and automatically using sensing technologies. This mode of cultivation is very well suited to adopting new and emerging robotic technologies as well as remote-sensing procedures. This means that outbreaks are detected early to enable diseased and infested plants to be identified and disposed of appropriately. Any residual contamination can be cleaned up when the crop is harvested using strict hygienic practices.

One possible obstacle to vertical farming is that some consumers may regard the products as 'Frankenfoods,' as discovered by managers of a giant underground farm supplying London's restaurants (Curtis 2016) and another business that supplies between 8% and 12% of the British output of tomatoes, peppers, and cucumbers (Fletcher 2013). For this reason, some enterprises may not publicize growing conditions for fear of alienating consumers and destabilizing sales potential. To minimize this issue, it can be stressed that growing conditions are not different from existing hydroponic facilities with respect to germplasm, nutrition, and other cultural and production practices. Furthermore, the plants are derived from natural breeding programs with normal nutrients supplied. There is an advantage that plants are grown in a hygienic environment with reduced need for pesticides and are in a closed system so there is no environmental pollution from nitrogen leaching or run-off.

Triple bottom line categories

Using the framework of the triple bottom line (TBL) as described by Slaper and Hall (2011) allows us to summarize the impacts associated with vertical farming in Table 2. This assessment is based on a combination of claimed advantages, cited literature, and the KPI framework discussed previously and presented in Table 1. Evaluation of these metrics cannot be easily monetized but a statement of effects supports qualitative evaluation and identifies issues for later quantitative analysis. In the category of *Economics*, impacts include improved productivity, lower costs for farm chemicals, reduced losses from floods and droughts, decreased transportation costs, and all-year-round production. In the category of *Environmental*, key impacts are export potential of CGG foods, no soil required, reduced carbon levels, and sustainability. In the category of *Social*, impacts include employment, social interaction, and a more holistic lifestyle where apartments and food can be co-located in many cases.

Conclusion

The global megatrends of decreasing water supply, increasing population, urbanization, and unabated climate change have contributed to globally decreasing stocks of arable land per person. Under these circumstances, the sustainability of the traditional farming model based on large rural farms is likely to come under threat in coming decades. One approach for engaging with this challenging problem is vertical farming, which is based on controlled-environment agriculture and greenhouse designs suitable for urban settings.

This article describes vertical farming and its derivatives and highlights the implications for future food production. A number of the advantages and

Table 2. Triple bottom line – potential impacts of vertical farming.

Category	Impacts
Economics	• Improved productivity • Reduced cost base for fertilizers, herbicides, and pesticides • No losses due to floods, droughts or sun damage • Reduced transportation costs • No requirement for farm-rolling stock • Production can be programmed to match demand because no seasonality issues
Environmental	• Export potential of clean, green, and food • No soil is required if hydroponics is used • Reduces fossil fuel use by employing renewable energy sources • Reduction in carbon levels • Rejuvenation of the ecosystem • Environmental sustainability
Social	• Provides employment in regional areas • Addresses social isolation in remote rural communities by providing jobs in towns • Increases demand for trade workers in construction, renovation, and ongoing maintenance • Provides new jobs in engineering, biochemistry, biotechnology, construction and maintenance, and research and development • Encourages a more holistic lifestyle where apartments and food production are localized and therefore reduces need for vehicles and transport

disadvantages associated with these cultivation methods are identified and investigated.

Vertical farming has been demonstrated at the pilot scale and also at the production level and has potential advantages over rural farming, including the use of hydroponics, which challenges the need for soil-based farming for a range of crops. Under this mode of cultivation, productivity scales up with the number of levels in a high-rise building or number of racks in a single high-rise enclosure. Many of the supporting technologies have been explored in past variations of greenhouse farming but are now coalescing into commercially viable systems due to rapid recent advances in electronics, engineering, solar power, wind power, storage batteries, LED lighting, water recycling, and computing power.

The challenge to traditional agriculture will occur initially with the multi-rack mechanized system within a single high-rise greenhouse. Multi-rack systems are already in operation globally and expanding rapidly. For example, these technologies are marketed by several major Japanese firms and supported by research at a number of universities (Kozai 2013; Pantaleo 2014). There are also commercial counterparts in the United States, Canada, China, Israel, South Korea, and the Netherlands. In time, funding for indoor-farming research will compete with field hydrology and soil science, or even against outdoor 'smart agriculture' which uses the Internet of Things, drones, and satellite imaging. In the distant future, there is the prospect of fully automated urban farms based on vertical farming and controlled-environment agriculture.

The potential benefits of vertical farming include a sustainable food-production model with all-year-round crop production, higher yields by an order of magnitude, and freedom from droughts, floods, and pests. The approach is compatible with water recycling, ecosystem restoration, reduction of pathogens, energy production by methane generation from compost, decreased use of fossil fuels (no tractors, plows, or shipping), generation of new jobs for many years, and low or no requirement for pesticides.

The construction industry could receive a boost with rising demand for new vertical farming factories in urban areas and perhaps on the fringes of regional towns. Future employment spurred by this mode of cultivation and its derivatives has the potential to provide new careers because engineers will be needed to design and manage air conditioning, water recycling, and lighting, as well as the overall optimization of complex systems. There will be employment opportunities in maintenance, seed planting, monitoring, and harvesting. In time, as process automation proceeds, new job requirements will include systems analysis and software development.

A current problem is the high startup costs due to land prices in inner urban areas in some global cities (as described in the case of Melbourne). This situation may be improved by recycling old buildings or using sites on city fringes and around regional towns. In some 'rust belt' states in the United States, there is no shortage of vintage structures and disused factories in outer suburban areas. Another issue is energy consumption if full off-the-grid production is required (which is being addressed with evolving technology related to renewable energy and battery storage). Infrastructure depreciation will eventually lead to parity with the annual running cost of outdoor farming, although it is not clear when this crossover point will be reached. Yields per hectare in a glasshouse are claimed to be much higher than rural outdoor farming, by an order of magnitude at least, and this factor will help to compensate for the higher cost of land.

The volume of output and biodiversity in vertical farming is not yet a threat to the sheer scale of agriculture in regional broad-acre crops, such as wheat, but this is changing. Production from indoor farms continues to increase while the trend in regional farming is toward ever lower levels of arable land per person. The current dominating theme with indoor agriculture is premium CGG food for export, rather than production volume.

Important policy issues addressed by vertical farming are food security and response to the effects of climate change. Some urban centers, such as Singapore, already produce 10% of leafy green vegetables by indoor farming because of a commitment to enhance domestic food security. The closed-environment model can also be translated to remote polar or desert regions, or even space exploration, where food production on spacecraft or other planets may be necessary (Giroux et al. 2006).

In light of these circumstances, we proffer several recommendations. First, there needs to be more accurate quantification of the economics of vertical farming and its derivatives using computer simulation and detailed analysis of new commercial installations. Requirements for the business case include analysis of cost base and profitability by investigation of full life-cycle analysis (LCA) with a traditional farm as a benchmark. There is also a need to estimate the number of years to reach parity with a traditional farm with respect to return on investment (ROI), and a tradeoff study on key cost drivers including land, plant depreciation, market demand, and reduced transportation costs.

Second, the research needs to focus on investigation of vertical farming derivatives, such as single-level greenhouse designs in novel urban configurations, including underground, on rooftops in cities, or in disused warehouses. The economic proposition will likely vary with these options.

Third, we suggest greater in-depth exploration of multiple-rack stacked designs that can be rotated according to optimum solar exposure in a single high-rise greenhouse enclosure. This derivative is already in operation in some countries and represents an entry point to vertical farming technology.

Fourth, policy makers may consider development of change-management strategies for future transition of affected parts of the field-horticulture industry. This could entail education of farm workers with new skills more suited to controlled-environment agriculture. Business and management skills could also be addressed with education and professional assistance.

Fifth, it is necessary to begin to identify employment opportunities in technology, monitoring, maintenance, customer service, and research and development surrounding vertical farming. The job mix may change in time with increasing levels of process automation. For example, manual handling and routine hardware maintenance may be replaced by engineering skills in process control and monitoring, emergency repairs, and software development.

Finally, there is a need for increased funding for research in plant genetics for yield optimization, extending the range of crop types, and fine-tuning for optimal response to controlled variables such as wavelength of LED lighting, temperature, humidity, and CO_2 levels.

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