Urban Agriculture’s capacity to increase a city’s Food Security: A case study of Singapore vegetable production

by

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Submitted in partial fulfilment of the requirements for the degree of
Bachelor of Environment and Sustainability (Honours)
in the Fenner School of Environment and Society,
Australian National University
October 2020

Australian National University

Candidate's Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university. To the best of the author’s knowledge, it contains no material previously published or written by another person, except where due reference is made in the text.

Song Yu Min Andrea Date: 29 Oct 2020

Acknowledgements

First of all, a most sincere and heartfelt thank you to my main supervisor, Robert Dyball. Thank you for all the time you spent over Zoom call meetings with me and for being ever so patient with my questions. The breadth of knowledge you have never fails to inspire me and I really appreciate your guidance and support through all the ups and downs of this research journey. So once again, a huge thank you to you!

To Janice, thank you for so readily accepting the role of being my secondary supervisor. Thank you for the pointers and tips throughout and more importantly your ever-encouraging attitude and support.

To the other Fennerites, it was truly a pity that I could not get to know more of you better and learn from your expertise due to the COVID-19 pandemic. However, I believe that there will be more chances for us to meet again in the future to do so! A special thank you to Bronwyn Wilkes for always offering your encouragement and support and also for giving me incredibly detailed and helpful feedback. I would also like to thank Dr. Matthew Colloff for the feedback you gave me during the mid-semester review – it really helped me to think beyond the current scope I was working with and spurred new ideas. Finally, thank you to the Sem 1 2020 Honours cohort for always making Zoom tutorials fun and engaging (albeit being at 8am Singapore time) and Glenn Althor for being an amazing Honours Convener.

I would also like to thank my friends and colleagues from Edible Garden City and Ground-Up Initiative in Singapore. Thank you for spurring my interest in the topic of urban farming and for letting me get a glimpse of the ins and outs of this industry in Singapore.

Lastly, thank you to all my friends and family for your endless support and love throughout these few trying months. Thank you to my closest few for always willing to be my sounding board and for obliging to any "writing session over coffee" requests that I had. To my family, thank you for the silent but unwavering support and for always keeping me well fed and happy. Thank you for supporting me and my dreams, I will continue to strive to do my best and make you guys proud!

Abstract

Cities have developed ways of maintaining a secure food supply year-round by tapping into food grown in distant landscapes through trade and globalization processes. However, this security has been threatened as most agricultural yields around the world are predicted to decline under the impacts of global environmental change. This makes cities vulnerable to disruptions and shocks in the global food supply chain, prompting an interest in increasing local food production through urban agriculture. These urban agriculture systems are often a variation of indoor high-tech growing systems, with one of the more popular methods for growing vegetables being vertical hydroponics. This is a soil-less growing system where the roots of crops are suspended in a nutrient solution that is circulated throughout the system. Layers can be stacked on top of each other, resulting in it being called a "vertical" growing system.

One city that has been taking the threat of food security very seriously is Singapore. Being a city-state with a small land area and few natural resources, the city imports over 90% of its food. With increasing concerns over the resilience of its food system, the government has set a goal of producing up to 30% of its nutritional needs through local agriculture by the year 2030 – dubbed the "30 by 30" vision. In light of this, in this thesis I aim to critically assess the feasibility of using urban agriculture to contribute significantly to a city's food security.

From the results, it is estimated that Singapore would have to produce between 42,000,000kg to 125,000,000kg of vegetables locally to meet the target. Additionally,

the focus on increasing volumes of food produced locally overlooked the opportunity to incorporate more sustainable solutions from the beginning. One of these solutions include designing a more circular system where nutrients can be recovered and recycled. The shifting social-cultural dimensions of urban agriculture in cities and the educational role it can play in raising awareness for the well-being of farmers and their farmlands was also explored.

Thus, I argue that although urban agriculture can supplement imported produce to boost food security of cities, it would probably be unable to make a significant contribution towards the overall nutritional needs of city residents as its current form only targets a minor percentage of the vegetable component of a nutritionally adequate diet. The costs of increasing urban agriculture activities are also not very clear at the moment given the wide range of results gathered. However, as urban agriculture continues to play an increasingly important role in the food system developments of cities, it makes it even more important that we better understand how it affects different components within a city's system. This can help to lessen unexpected problems from

emerging in the future while increasing sustainability aspects, contributing to sustainable development of cities and their food systems.

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Chapter 1: Introduction

Ever since humans began settling down in one place and living together in increasing concentrations, there has been the challenge of providing sufficient amounts of food to satisfy the universal human need to regularly and reliably consume a nutritionally adequate diet (Despommier, 2013; Dyball and Newell, 2014). People overcame this challenge by augmenting what they could grow locally with food grown from distant landscapes, often procured through trade and conquest (Mazoyer and Roudart, 2006; Rimas and Fraser, 2010). This allowed such settlements to grow in size, wealth, stability, and power and beyond the natural carry capacity of the land they occupy (Mazoyer and Roudart, 2006; Rimas and Fraser, 2010). Over time, this process has been facilitated by globalization and developments in transport and storage technologies where fresh food can be delivered to cities from all around the world. These relations between food producers and consumers located in distant places, known as teleconnections (Seto et al., 2012), underpins the global food system today which many cities are entirely reliant on.

While these "telecoupled" food networks allow cities to exist and continue growing, they also make cities vulnerable to disruptions and shocks to the global food supply chain. This has become an increasing concern in recent years as the impacts of global environmental change have threatened the stable supply of agricultural yields (Ericksen, 2008a; Ray et al., 2019; Zhao et al., 2017). How unpredictable events have drastic consequences on the global food supply chain and corresponding food prices has also been further demonstrated in the global COVID-19 pandemic (Hamilton et al., 2020; Moran et al., 2020). Thus, in a bid to become more food secure, some cities have started taking steps to increase local food production.

One city that has been taking active steps in this direction is Singapore. Being a small city-state that imports over 90% of its food, this makes the country especially vulnerable to disruptions in the global food supply chain (Liu, 2020a; MEWR, 2020). In response, the Singaporean government has introduced a range of urban agricultural policies. The most notable one so far has been the "30 by 30" vision which envisions supplying 30% of the country's nutritional needs by 2030 through urban agriculture (SFA, 2019a). Hence, with a focus on Singapore, I aim to assess the feasibility of urban agriculture to contribute significantly to the city's food security. This will be done by

a) Estimating the volume of food that has to be produced locally to meet the "30 by 30" target. As discussed later in the chapter on Singapore's urban agricultural policies, this target actually consists of two food groups – with 20% of the target being vegetable intake and the remaining 10% being intake of animal protein (mainly fish and eggs). I will not be considering the animal protein target as it will require analysis and estimations of sustainable fishery management. Hence, I will be focusing on the feasibility of growing 20% of the population's vegetable needs.

b) Using available secondary sources on growing methods and technology on urban agriculture, quantify as far as possible what are the material and energy inputs and outputs of these systems. The extent of urban agriculture land area required to meet this target will also be estimated. This will be analysed using a Material Stocks and Flows Analysis (MSFA).
c) Discussing the sustainability implications of urban agricultural policy in Singapore. Although this is not the main aim the Singaporean government is trying to achieve, understanding the potential environmental benefits and disbenefits of increasing the use of industrial-technological growing systems is important. Its potential to operate within a circular economy nutrient recycling system will also be explored.
d) Discussing the social and cultural dimensions of food production and urban agriculture.

Although urban agriculture is not new, it has recently generated renewed interest in relation to its capacity to contribute to urban food security by increasing local food production (Despommier, 2009; Goodman and Minner, 2019; Sartison and Artmann, 2020). A report from the FAO (1996a) defined urban agriculture as "food production that occurs within the confines of cities. Such production takes place in backyards, on rooftops, in community vegetable and fruit gardens and on unused or public spaces.". Arguments put forward in favour of this practice include its ability to increase the localization of food production which reduces the carbon emissions associated with transporting food over large distances (Despommier, 2013). It also provides a source of fresher food for communities (Gross et al., 2016) while having the potential of creating a more circular food economy in cities as the loop between the start and end of the supply chains are tighter (Ferreira et al., 2018). Hence, many cities have deemed urban agriculture to be a sustainable approach towards enhancing local food production in comparison to the current industrial productivist food production narrative.

Food security was defined in 1996 at the World Food Summit as "when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food to meet dietary needs for a productive and healthy lifestyle" (FAO, 1996b). Though most wealthy, metropolitan cities do not seem to be "food insecure" by this definition, striving to maintain a stable and affordable supply of food to cities has always been a key concern of city governments. This comes with good reason, given how most cities do not have the space or resources to produce enough food to feed their residents. Hence, they are entirely reliant on external landscapes for their food supply, contributing to their vulnerability to any disruptions in the global food supply chain (Teng et al., 2011). This makes the role cities can play to improve the resilience of their food systems an essential part of the discussions around food security. This is also where urban agriculture comes into play, providing an option for cities to become more self-sufficient which in turn boosts the city's food security.

For Singapore's case, striving to have more control over their food supply has become one of the top priorities of the Singaporean government in the last two years (Singapore Food Agency, 2020). Although the country's food supply is secure due to the government's long-term efforts in diversifying their sources of food imports and actively investing in agri-tech research (AVA, 2012), the inherent vulnerabilities in the global food supply chain has prompted an increasing focus on local agriculture. The importance of this issue was again highlighted in the COVID-19 pandemic where some local farms harvested large batches of their crops, some prematurely, to cover the shortage of imported produce caused by delays in the supply chain (World Food Future, 2020). This urgency in exploring a higher degree of food self-sufficiency has led to a series of urban agriculture policies such as the "30 by 30" food target launched at the start of 2020 (Singapore Food Agency, 2020). The government's keenness, coupled with a newfound enthusiasm many have for high-tech urban farming systems, has made expanding the urban agriculture sector a key priority in the city's future development. As mentioned in a speech by the then Minister of Environment and Sustainability, Mr Masagos (MEWR, 2020):

> Our "30 by 30" vision is to grow enough food in Singapore to meet 30 per cent of our nutritional needs by 2030…It is a big challenge, as we are aiming to meet these needs using less than 1 per cent of our land area in Singapore…If successful, the "30 by 30" vision also means that we will own technologies and unique processes that will become the value-add our companies can bring to growing food overseas, which is the second leg of our food security. This will require a whole-of-nation effort.

Although this policy aims to increase the volumes of food produced through urban agriculture, the capacity of urban food systems being able to make significant contributions to a city's food security has not been explored in depth. Flow-on effects this rapidly developing sector may have in Singapore's system is also not well understood. Though many have lauded urban agriculture for its sustainability values, there has yet to be a study on how the different inputs and outputs will affect material flows within the city. Hence, the increase in the commercialization of agricultural activities in Singapore calls for a more critical assessment of the sustainability claims that many have made about urban agriculture. Furthermore, as having a resilient food system is important to the country, this suggests that its urban agriculture sector will continue to grow and expand over time. This makes it all the more important, and urgent, to understand the environmental and sustainability issues of this sector before it matures and creates problems that may be too embedded in the system to easily solve.

Besides the high level of enthusiasm and increasing uptake of urban agriculture technologies in Singapore, another reason for focusing on this city is to better understand what a relatively wealthy and technologically advanced city can achieve on this front. Having a relatively large budget and the required research and development resources to expand this industry is an advantage Singapore has over other less wealthy cities. Furthermore, the development of this sector has very much been a top-down approach, with the country's government dictating how and where the changes should take place. Thus, using Singapore as a case study can also serve as a proxy to other cities of similar wealth, development, and governing power (e.g. Hong Kong).

The main framework that I will use to explore these issues is through a human ecological lens with a systems thinking approach. Human ecology is mainly concerned with the social-ecological interactions which includes how societal demands and changes have an impact on the environment. As these interactions are often complex, a systems thinking approach provides an integrated framework that allows us to holistically look at the various dimensions that exist within human ecological systems. It also considers feedback mechanisms different interacting components of a system have on each other, in turn avoiding policy surprises and unforeseen outcomes (Dyball and Newell, 2014). Thus, using this concept to better understand Singapore's urban food sector will involve looking at the biophysical and energy flows the sector requires. This will be done using a MSFA where secondary literature and data is mapped into Singapore's context. It should be noted that the amount of data in this field is very sparse, varies widely between farming systems, and there are no uniform data reporting standards. Despite this, I still managed to gather a general reflection of the energy usage and external dependencies of these urban agricultural systems. While human ecology emphasizes both social and environmental dimensions in a system, I only brief comments on the associated cultural dimensions of Singapore's food system. My focus will be on the environmental dimensions increasing high-tech farming systems may have on cities. No attempts to analyse the economic feasibility of urban agriculture activities have been made either.

For this thesis, I first provide a literature review on the concept of sustainable food systems and urban agriculture in chapter 2. Chapter 3 will provide more context to the current urban agricultural policy developments in Singapore. This is followed by the methodology in chapter 4, which includes a more detailed explanation of an MSFA and the data collection process. The results and discussion follow in chapter 5, where the individual inputs and outputs are broken down in more detail with discussions around each of their environmental and sustainability issues. Discussions around the future potential of urban agriculture, the social dimensions of it, and how these aspects relate to the development of Singapore's urban agriculture sector are then conducted. Finally, chapter 6 presents the main conclusions gathered from this paper, including some limitations of this study while emphasizing the significance this topic has on the future development of cities and their food systems.

Chapter 2: Literature Review

2.1 Sustainable Food Systems

As mentioned in the introduction, having a resilient food system is of utmost importance to the stability of cities. Global food production systems have largely revolved around traditional agriculture and farming practices where humans have modified natural landscapes processes to grow food (Dyball, 2014). Prior to the industrialisation of agriculture, farming systems mainly relied on naturally occurring ecological cycles like the water cycle and biogeochemical cycles in the soil (Power, 2010; Zhang et al., 2007). To increase the productivity of these landscapes, humans have taken to manipulating ecosystems to produce more food in shorter amounts of time (Dyball, 2014). Over time and with further intensification, these landscapes affect carbon stocks and sequestration processes and nutrient cycles in the soil that were once regulated by natural ecosystems (Arden-Clarke and Hodges, 1988; Campbell et al., 2017; Verschuuren, 2017).

As the global population continued to increase, people tried to overcome the ecological limits of landscapes to produce even more food (Dyball, 2014). This subsequently resulted in the commercial food production systems we have today where monocropping practices and the quest for efficiency have disregarded many of the natural ecosystem processes that once determined landscape carrying capacity (Altieri, 2009; Kissinger et al., 2012; Sunderland et al., 2020). Producing ever larger volumes of food also demands more resources (FAO, 2018). This has resulted in environmental damage, such as the inability for soils to replenish nutrients faster than they can be taken up, rendering many farming practices now to be unsustainable (Despommier, 2009; Matson et al., 1997). Coupled with the impacts of global environmental change, land productivity is only projected to decrease over time which will result in a decline in agriculture yields (Ericksen, 2008a; Goodman and Minner, 2019; Ray et al., 2019; Zhao et al., 2017). If not managed properly, it may also result in increasing food prices globally (Moran et al., 2020; Teng et al., 2011).

These projections have a direct impact on the food supply of cities. Due to how cities rely heavily on global food production chains, the resilience of their food system is compromised by any shocks and disruptions on them (Hecht et al., 2019; Reddy and Singh, 2016). When the sustainability and affordability of this food supply is threatened, it in turn threatens the food security of cities. Hence, this has led to many city governments becoming increasingly concerned over their food supply chain while seeking ways to increase food security of cities.

In order to find solutions to increase food security of cities, we first need to understand the city's food supply chain. A framework that can be used for this is a food systems perspective. Food systems can be defined as "a set of activities and outcomes ranging from production through to consumption, which involve both human and environmental dimensions" (Allen and Prosperi, 2016; Ericksen, 2008b; Ingram and Zurek, 2016; Sundkvist et al., 2005). This framework is related to a human ecological systems thinking approach which accounts for the interactions between environmental, social, and human wellbeing aspects within a food system. It also accounts for the complex interactions and feedback processes between different components of the system. These feedback processes, or loops, are the "control devices" of a system, where negative feedback loops acts as has a stabilizing effect and positive feedback loops reinforces and amplifies a change (Dyball and Newell, 2014). Furthermore, when it comes to policy making, accounting for the systemic nature of these food networks also help to prevent misdiagnosing problems and implementing "solutions" that end up creating new problems along the feedback loop (Dyball and Newell, 2014).

With this framework, we can now take a deeper look into why urban food supply chains have been key discussion points around food security and food systems. Currently, more than half of the world's population are living in cities, with a projection that by 2050 the amount will rise to 68% (UN, 2018). This implies that most of the food produced globally will be transported and consumed within cities (Grewal and Grewal, 2012). This makes cities rely heavily on nearby and distant landscapes that span across regional and international boundaries (Friis and Becker, 2020; Millington et al., 2017). These transboundary relations are also known as telecoupling (Friis et al., 2016; Seto et al., 2012). A reason for this reliance is an underlying concept of how urban cities function. The priorities of cities have mostly been on concentrating economic, social and political activities within a certain area (Parnell et al., 2018). This concentration of many people within a smaller land area has also led to an increase density of infrastructure, not only to accommodate more people but also to use the limited land area more efficiently. Hence, this altered natural environment has resulted in a large amount of resources flowing into cities to keep them functioning (Bai, 2016). Just relying on the city's "natural" resources is insufficient to support the demands of their ever-increasing populations (Bai, 2016).

Many studies analysing the inputs, transformation, and output of materials from a city, often find that many environmental and sustainability aspects have been overlooked (APRU, 2017; Bai, 2016; Boyden et al., 1981; Warren-Rhodes and Koenig, 2001). This too applies to the food supply chains of urban cities that rely on agribusiness giants and global food distribution systems (APRU, 2017; Hecht et al., 2019). Although there are benefits of this system design, such as being able to produce large amounts of food at a relatively cheap price, it has also come at a cost to the environment (Deutsch et al., 2013; Sunderland et al., 2020; Zhang et al., 2007). Besides the damage to natural ecosystems mentioned above, the use of fossil fuels as an energy source has enabled landscapes to produce volumes of food that surpass what can be grown if we only relied on solar energy (Neff et al., 2011; Polack et al., 2008; Tittonell, 2014). These processes emit large amounts of carbon into the atmosphere, about 23% of anthropogenic GHG emissions according to a report by the Intergovernmental Panel on Climate Change (2019), which contributes to global warming (Francis et al., 2003; Pelletier et al., 2011; Vermeulen et al., 2012). Other environmental impacts include eutrophication of waterways due to excessive application of fertilisers, converting biologically productive land to farmland which has irreversible impacts on biodiversity, and draining rivers from excessive amounts of irrigation (Campbell et al., 2017; Deutsch et al., 2013; Matson et al., 1997). These negative impacts of industrial productivist agricultural systems that cities depend on have raised questions about their sustainability. Besides that, with food supply chains being so vulnerable to the effects of climate change, there has been a consideration for alternative food networks that can help cities reduce their dependence on the global food system.

A key idea that has surfaced to combat both sustainability and vulnerability issues of urban food systems has been to increase the localization of food production processes. An example of this are short food supply chains (SFSCs). SFSCs can be defined as "the re-localisation and re-socialisation of food production and consumption processes" (Kalfagianni and Skordili, 2018). Having a shorter supply chain can help to tighten feedback loops as there are fewer components and stakeholders involved in the system (Ferreira et al., 2018; Sundkvist et al., 2005). As the distance between the production and consumption of food is reduced, it also makes it easier to monitor changes and manage any flow on effects it can have within the system (Kalfagianni and Skordili, 2018). Hence, tighter feedback loops make the overall food system more sustainable as it makes it easier to track changes and impacts on environmental, social, and ecological processes (Galli and Brunori, 2013; Kalfagianni and Skordili, 2018; Kneafsey et al., 2013). Such local food production chains can allow cities to have more control over their food system. This in turn helps to increase food security of cities as they are able to be more food self-sufficient.

In light of this, many cities have turned to urban agriculture to increase local food production to improve their food security. Urban agriculture has been defined by the FAO (1996a) as "food production that occurs within the confines of cities". The definition has also been expanded to include peri-urban areas which use human and material resources in and around urban areas that ultimately supply that urban area with products and services (De Zeeuw et al., 2011; Kozai et al., 2016; Mougeot, 2000; Specht et al., 2014; Umesha et al., 2018). For this paper, I will focus on urban farming that occurs within the built environment of a city. Urban agriculture has become increasingly popular in cities as they are seen as part of the answer to the quest to increasing food self-sufficiency in a sustainable manner (Clinton et al., 2018; Despommier, 2013; Goodman and Minner, 2019; Sartison and Artmann, 2020). With this in mind, the following section will discuss what is urban agriculture with a focus on wealthy developed cities like Singapore. Cities that are less wealthy and less developed will not be considered as the challenges and potential solutions they face are very different from those in developed cities.

2.2 Commercial Urban Farming Systems

Although urban agriculture can refer to both livestock and crop farming, livestock farming is not as common due to space, financial costs, and pollution concerns (Kaufman, 2004; Mendes et al., 2008; Neville, 1992). Hence, "urban agriculture" in this paper will refer to the production of vegetables and leafy greens. There are two main forms of urban agriculture – community gardens and commercial farms. Community gardens are often valued for their social benefits, providing a sense of well-being and community spirit for city dwellers (Guitart et al., 2012; Pryor, 2017). To increase local food production, commercial urban agriculture farms have been on the rise in recent years. Often referred to as "industrial farming set-ups", these commercial farms are usually high-tech, climate-controlled vertical farming systems. They are usually located on rooftops, unused warehouses or buildings, or even discarded shipping containers, as in the case of Singapore (Lawrence, 2020).

Most commercial-scale urban farms often use hydroponics set-up to grow their crops. Hydroponic farming systems are generally defined as "the cultivation of plants without soil" (Sorenson and Relf, 2009). Growing mediums such as perlite or rockwool cubes are used in place of soil which hold the roots of the plant, which are then submerged in a nutrient solution to grow (Kaiser and Ernst, 2016). This results in more targeted and efficient nutrient delivery to the crops. The two most common commercial hydroponic systems are Nutrient-Film Technique and Deep Water Culture (which is also known as a floating raft system) (Gómez et al., 2019). Hydroponics growing environments can be set up both as a vertical farming system, where racks stacked horizontally on top of each other, or in a single layer. In urban cities, vertical hydroponic farms are more common as this increases the volume of crops that can be produced in a small area. These growing systems can be located both indoors and outdoors (see Figures 1. and 2.).

2.2.1 Indoor Hydroponics Systems

Indoor hydroponic systems refer to the plants being grown in an enclosed space. The size of these farms can range from just one room to entire warehouses and factories. These systems usually rely on artificial lighting, often light-emitting diodes (LEDs), rather than using natural sunlight (O'Sullivan et al., 2019). It also allows for a climate-controlled growing system where factors like temperature, humidity, and carbon dioxide levels can be kept at an optimum level for the plants (see Figure 1. for example). This makes indoor hydroponics an ideal urban farming system as it enables year-round production of crops (Despommier, 2009). These optimum growing conditions can help to speed up the growing process while maximizing the yield of crops harvested. Another benefit of indoor systems is that they can eliminate the need for pesticides and herbicides as the indoor conditions keep pests to a minimum (Despommier, 2013).

2.2.2 Outdoor Hydroponics Systems

Most outdoor systems are located on unused rooftop spaces. The main difference between outdoor and indoor growing environments is the former's inability to have climate-controlled growing conditions. The plants also rely on sunlight as their source of energy rather than the LEDs used in indoor systems. This translates to outdoor systems having a lower energy input requirement. An example of an outdoors, vertical hydroponics system is Sky Greens in Singapore (Sky Greens, 2014a) (see Figure 2.). Their growing structures are rotated throughout the day to ensure that the crops receive an equal amount of sunlight.


Figures 1. (left) and 2 (right). Figure 1. An indoor vertical hydroponics set-up. Plants are grown using LEDs and in a climate-controlled environment, with growing racks stacked on top of each other to create a vertical growing environment (Source: Pure Greens Arizona LLC (2020)). Figure 2. An outdoor vertical hydroponics set-up from Sky Greens, Singapore. These rotating growing structures are located on a rooftop and the plants rely on sunlight for their energy source. Growing racks have also been stacked vertically at angle to ensure all plants can receive sunlight (Source: Sky Greens (2014b))

There have been many studies that have outlined the benefits of using these high-tech vertical hydroponic farming systems in cities (Despommier, 2013; Goodman and Minner, 2019; Sartison and Artmann, 2020; Schnitzler, 2013; Sharma et al., 2018). Several authors have also conducted studies comparing these high-tech systems to more traditional farming methods (Barbosa et al., 2015; Beacham et al., 2019; Benke and Tomkins, 2017; O'Sullivan et al., 2019; Romeo et al., 2018; Van Ginkel et al., 2017). They found that vertical hydroponic systems require less water to grow each kilogram of vegetables. Van Ginkel et al. (2017) found that for Californian (USA) grown vegetables, hydroponic systems use 66 times less water than traditional farming. This is because hydroponic systems are able to deliver water more efficiently to the vegetables and less water is lost to percolation into the soil (Barbosa et al., 2015). Another benefit often highlighted is that these farming systems can produce more crops per hectare of land – an example cited by Lawrence (2020) claims that it can produce up to 200 times more. The first reason is the ability for continuous, year-round growing of crops in climate-controlled systems (Barbosa et al., 2015). Second, in the case of vertical farming systems, multiple racks of crops can be grown within a limited space which increases the volume of crops grown in a given land area footprint (Van Ginkel et al., 2017). Furthermore, as these crops are grown within the urban city, the transportation distance between farm to supermarket is greatly reduced which helps to reduce associated greenhouse gas emissions (GHG), assuming the produce is processed, retailed, and consumed locally (O'Sullivan et al., 2019). Hence, for the above reasons, many argue that urban agriculture is more sustainable than traditional farming systems. Moreover, if we manage to increase the commercial scale of urban farming, it can contribute to a city's self-sufficiency which in turn boosts its food security.

As these high-tech urban agriculture farming systems are become increasingly popular, many people have claimed that this is the "future of farming". A notable person that has been championing this view is Kimbal Musk (Elon Musk's brother). He started an urban farm called Square Roots which primarily sells herbs and other leafy vegetables (Square Roots, 2020). The goal he has is to be able to feed all of America with this farming system (Benveniste, 2020). A similar claim that "urban farming is the future of farming" was made in an interview with Sustenir Agriculture, a hydroponics farm in Singapore (VICE, 2020). Many new technology related enterprises have also jumped into this bandwagon, as illustrated by an article on Edgy Universe (2019) (a support center for technological advancement) titled "Why Urban Farms are the Future of Food Production". However, this brings about the question of to what extent can these farming systems actually substitute traditional vegetable farms and also how substantial is the amount of food that it can produce for cities.

2.3 The less talked about side of Urban Agriculture

While acknowledging the benefits of high-tech vertical farming systems and their ability to provide cities with a source of fresher food, the drawbacks of these systems are often overlooked or downplayed. One issue is that produce from urban agriculture alone is not able to make up a nutritionally adequate diet. Many countries have national dietary or nutritional guidelines under the Food and Agricultural Organisation (FAO). While these guidelines vary between countries, most of them state the importance of having a "varied and balanced diet" (Fischer and Garnett, 2016). Components often include fruits, vegetables, proteins, and carbohydrates (FAO, 1995; Fischer and

Garnett, 2016; WHO, 2020). However, the produce from urban agriculture are mostly leafy green vegetables and herbs (Feng, 2020; UMASS, 2020). Hence, although urban farming is able to contribute to a city's food supply, people often forget it only provides a small proportion of our nutritional needs.

One main disadvantage of high-tech growing systems is that they require much more energy to operate as compared to traditional agriculture systems. This is especially for indoor climate-controlled systems that require a large amount of electricity to power the LEDs and temperature and humidity controls (Barbosa et al., 2015; Martin et al., 2019; O'Sullivan et al., 2019). It was found that hydroponic systems use 30 times more energy than traditional systems to grow the same amount of vegetables (Van Ginkel et al., 2017). Some authors have argued that the energy required by urban farming systems and their associated GHG emissions are offset by the shorter transport distance between the farm and market (Benis and Ferrão, 2017; Despommier, 2013; Lee et al., 2015). However, most GHG emissions generated throughout the whole food system are actually generated during the food production phase, with transport making up only about 11% (Weber and Matthews, 2008). Others have also contested that if renewable energy sources were used to power urban farming systems, the GHG emissions would be much lower (Martin et al., 2019; Shamshiri et al., 2018). While this is true, we also need to keep in mind that not every city has the resources or the available infrastructure to do so. Thus, the energy cost and the associated GHG emissions generated by high-tech farming systems is also something that has to be considered when assessing its overall sustainability.

The source of water is also a factor that has not been widely considered. Although traditional farming methods require more water, they also have the advantage of being able to rely on rainwater in addition to irrigation. On the other hand, the location of urban farms usually means that they get their water from the city's water supply. This can add more stress to a city's water resources that already has many other competing demands for it (Gómez et al., 2019; Moglia, 2014; Shamshiri et al., 2018).

Another factor that has not been considered much is the inability of hydroponics systems to fix carbon in soils the way well managed agricultural systems do (Batjes and Sombroek, 1997; Farage et al., 2007; Kumar et al., 2006; Lal, 2008). In fact, hydroponic systems require additional carbon to be added, if not it can be a limitation to how fast the plants can grow in the system (Siddiqi et al., 2002). This suggests that not only are they unable to contribute to the regulation of carbon in the atmosphere, they in fact need bottled additives of it.

Though many large-scale traditional farms do use artificial fertilisers to supplement depleted soil nutrients, the difference is that hydroponic systems are wholly reliant on these nutrients to work (Kaiser and Ernst, 2016; Romeo et al., 2018). Traditional farms that engage in more sustainable farming practices, such as regenerative farming systems, can rely on the management of healthy soils for all their nutrients (Chenery and Gorman, 2020; LaCanne and Lundgren, 2018; Massy, 2017). As more fertilisers are being imported for hydroponics systems, there is also the possibility of a shift from importing vegetables to eat to importing nutrients to grow the same vegetables (though there is little to no literature on this yet). This can result in a new source of influx of nutrients into urban systems and we do not understand the consequences these influxes and accumulations can have on the city.

To conclude, though many authors have assessed the processes of high-tech urban farming systems, there is a need evaluate this trend using a systems approach that takes a multi-dimension perspective. It appears that these growing systems are more concerned with output yields and resource efficiency. We must also recognize that these high-tech farming systems are replacing natural ecosystem services with technological processes. As interest around these high-tech farming systems increases, the shift to using these systems on a larger scale has been largely unexplored in terms of doing a quantitative assessment of them to better understand what is cost of doing so. Additionally, the feasibility of urban agriculture to significantly contribute to a city's food supply and nutritional requirements is not well understood. This calls for a more thorough assessment of urban food growing systems that account for wider environmental, social, and sustainability dimensions. I will do this by quantifying the required inputs, stocks, flows and outputs of these systems in the context of Singapore's newly emerging urban agriculture industry.

Chapter 3: Singapore's Urban Agricultural Policies

Singapore is a city-state with an area of 725.7 square kilometers (Singapore Land Authority, 2020) and population of 5.7 million people (Department of Statistics Singapore, 2020). Having such a small land area in comparison to its population size has resulted the level of urbanization in Singapore to be almost 100% (The World Bank, 2020). This was necessary to accommodate housing requirements and the commercial building needs of its globalised economy. It also means that the amount of land available for traditional, open-air agriculture is almost non-existent. Hence, Singapore has relied heavily on importing its food source from around the world, making the country exceptionally vulnerable to price fluctuations and disruptions in the global food system (Liu, 2020a; MEWR, 2020; SFA, 2019a).

Currently, about 2 square kilometers (200ha) of land in Singapore is dedicated to farming activities. This makes up less than 1% of Singapore's total land area. There are currently 111 land-based farms, of which 83 produce vegetables (SFA, 2019b). It should be noted that some of these farms are located on rooftops or rooms in warehouses, hence not all of them may be considered in the 200ha farming area. Potentially due to the government's focus and preference for high-tech agricultural services as well as research and development in the 1990s (Neville, 1992), new farms that are more technologically advanced are usually favoured and are more likely to be granted the land lease for their farms (Begum, 2020; Nah, 2019). These high-tech agriculture farms that grow vegetables usually use vertical hydroponic growing systems, with an increasing number focusing on indoor climate-controlled systems. Furthermore, as discussed in the literature review section above, these farming systems are able to produce more food per area than traditional farms. In land scarce Singapore, this advantage makes such farming systems even more attractive to a government looking to increase local food production.

In more recent years, the Singapore government has shifted its focus towards expanding and developing the agriculture sector. Urban agriculture, once deemed to be incompatible with urbanization processes (Neville, 1992), was designated to be incorporated into the future development plans of the city. One of the main motivators for this shift was recognizing the importance of having to increase the country's food security as global crop yields were becoming increasingly vulnerable due to environmental change (MEWR, 2020). This led to the "30 by 30" food target which aims to locally produce 30% of Singapore's nutritional needs by 2030. This has been further broken down into 20% consisting of leafy green vegetables and 10% fish and eggs (Leow, 2019; Mahmud, 2019). For this paper, I will be focusing mainly on the leafy green vegetable production target. Protein production is not considered as it would involve another set of estimations requiring discussions on a different set of challenges and solutions.

There has been much ambiguity surrounding this target, with no quantified target volume specified. The term “nutritional needs” was not explained either. As mentioned in the literature review, nutritional needs comprises of vegetables, fruits, proteins (inclusive of dairy), and grains (carbohydrates) (FAO, 1995). In Singapore, the nutrition and food guidelines are presented as “My Healthy Plate” (MOH, 2020a) (see Figure 3.). It indicates that our diets should consists of 25% wholegrains, 25% proteins, and 50% of fruits and vegetables. Thus, if the vegetable production target is 20% of the 50% recommended fruits and vegetable intake, this only makes up 10% of the total nutritional needs (20% x 50% fruits and vegetables = 10%). As with the 10% protein target, this only makes up 2.5% of the total nutritional needs (10% x 25% protein = 2.5%). Altogether, this only makes up 12.5% of the 100% nutritional needs. It also does not add up to the 30% goal the government has set. In addition, since no carbohydrates and only a small percentage of fruits (some farms like Sustenir Agriculture are growing hydroponic strawberries) are locally produced, there appears to be a gap to fill in order to meet the 30% nutritional needs goal.

Figure 3. My Healthy Plate. A visual representation of the food and nutrition intake guidelines recommended by Singapore’s Health Promotion Board. It suggests diets should comprise 25% of wholegrains, 25% of proteins (meat and others), and 50% of fruits and vegetables. (Source: MOH (2020a))

Besides the “30 by 30” goal, the government has also signaled the importance of this industry by increasing funding and grants for urban agriculture related activities. For example, the National

Research Foundation has committed SGD$144 million (approximately AUD$149 million) to agri-food research (Leow, 2019; Ministry of Trade and Industry, 2019). Most of these funds go to farms that engage in agri-tech activities, especially those with automated and climate control functions to improve the yield, resource use efficiency, and sustainability of agriculture production. This shows the government's preference for research and development and its believe that technological advancement is the way forward for progress.

Current research around urban agriculture in Singapore has mainly focused on its financial viability (Montesclaros et al., 2018) and how local farms should develop to minimize local competition while maximizing benefits (Montesclaros and Teng, 2018; Rut and Davies, 2018). A study by Kosorić *et al.* (2019) on the social acceptance of integrating vertical farming systems into public housing estates has also found that many Singaporeans are receptive to the idea of having vertical farms near their homes. A common theme throughout most of these studies is also the role the government plays in driving the development of urban agriculture (Low, 2019; Montesclaros and Teng, 2018; Rut and Davies, 2018). They cited how many farms rely on government funding during their initial start-up period and the importance of the government's support when it came to acquiring land and space for agricultural activities (Low, 2019; Montesclaros and Teng, 2018).

Hence, although we have some understanding around the economic, social, and governance aspects of urban agriculture in Singapore, we do not have much information on the actual agriculture production systems. This includes looking at the resources required to run these systems and their wider environmental and sustainability dimensions. We also do not have much understanding around how these inputs flow throughout the system and the rate at which they accumulate. This makes understanding these processes and flows of Singapore's urban agriculture systems all the more important in order for us to identify potential problems that may arise.

Chapter 4: Methodology

In this thesis I seek to critically assess the potential contribution of urban agriculture to increase food security for the population of Singapore. To do so, I first aim to quantify as accurately as possible the amount of vegetables that have to be grown per year to meet the Singapore government's "30 by 30" target. In order to better estimate the amount of inputs required by these systems, I will first calculate the total amount of vegetables that have to be produced. As there is no one specific vegetable that is grown in the hydroponic systems, the yield will be estimated using recommended daily vegetable intake data found on the Singapore Health Promotion Board's website.

Based on the estimated quantities calculated, I will then estimate to the best of my ability what are the biophysical and energy requirements needed to meet this quantified target. The land area required will also be estimated. This will be done through an MSFA which I will further elaborate on below.

4.1 Material Stocks and Flow Analysis (MSFA)

At its core, a MSFA is a tool that can be used to assess the sustainability of an area ranging from farms to cities or even countries (Fischer and Garnett, 2016). As the name suggests, an MSFA analyses the flow of materials and energy inputs and outputs of the natural and built environment of a defined area (Hendriks et al., 2000). Between these inputs and outputs, it examines the stocks and flows of these materials within the area and how they are transformed (Hendriks et al., 2000). It also allows us to better understand how different stocks and flows can interact within the system.

A MSFA can play an important role in helping us better understand the impacts urban agriculture can have on cities. By enabling a more rigorous and accurate measurement of the stocks and flows, it allows us to quantify the specific inputs and outputs of high-tech hydroponics systems in a city. From this, it can also identify specific targets and leverage points for making changes which policy makers can benefit from. In addition, it can be used together with the systems thinking approach I have taken (described in the *Sustainable Food Systems* section) to illustrate the material and energy processes that are transferred into, within, and out of the city.

MSFAs have also previously been used in many diverse studies. Examples include assessing the urban metabolism of cities (Boyden et al., 1981; Warren-Rhodes and Koenig, 2001), looking at the environmental risks of agriculture run-off (McDougall et al., 2019) and assessing the stocks and flows of specific elemental materials like lead (Hendriks et al., 2000) or infrastructure materials of a city (Huang et al., 2006). More specifically for food production systems, MSFAs have underpinned the analysis of studies conducted in indoor farms located in Chicago (Chance et al., 2018), production of crops in the desert of the Arava region in Israel (Wyngaard and Kissinger, 2019), and also the food production to consumption chain in Feliz, Brazil (Kuhn et al., 2017). Data obtained can also be used by transdisciplinary teams for environmental policy decision making which allows for consideration of sustainability principles in the system (Dyball and Newell, 2014). Sustainability principles have been defined as (Newell, 2014):

> A process that consumes a *non-renewable resource* is sustainable as long as the rate at which it uses that resource does not exceed the rate at which a renewable resource (used sustainably) is substituted.
>
> A process that consumes a *renewable resource* is sustainable as long as the rate at which it uses that resource does not exceed the rate of regeneration of the resource.
>
> A process is sustainable as long as the rate at which it generates a *pollutant* does not exceed the rate at which that pollutant can be recycled, absorbed, or rendered harmless in the environment.

These principles also underpin the need for a circular economy as the common linear economic system where materials are transformed, used, then disposed does not account for these principles. This makes a MSFA a suitable tool for this study as it can effectively map the interactions in the system and find opportunities to create more circularity within it.

4.1.1 Study Area

The study area I will be focusing on is Singapore, making the city the system boundary. The farming systems based in Singapore sit within the system and can influence the amount of inputs and outputs that flow throughout the system. Although there are many material components that go into farming system, example being the infrastructure materials required to build the hydroponics racks, this study is mainly concerned with the basic materials that go into growing leafy green vegetables. I will also be only considering the material and energy flows of hydroponic growing systems as they are the most common in the industry.

4.1.2 Inputs

The input components that are required to transform a seed to an edible plant are i) water and carbon, ii) light energy, and iii) nutrients. This thesis will only be looking at the material and energy flows of these 3 inputs. As mentioned above, other material inputs like the growing structures will not be considered in this study although they can also make up a significant amount of material stocks and flows in the system.

4.1.3 Transformation

The transformation process refers to how the energy and materials that entered the system are changed. This includes looking at material accumulations within the system and the amount of time a material remains in the system (residency period). For this study, a simplified description of transformation is the process where the metabolism of a plant transforms water and carbon into carbohydrates via photosynthesis, as depicted the photosynthesis equation below:

$$6\ CO_2 + 6\ H_2O \text{ –(solar energy)} \rightarrow C_6H_{12}O_6 \text{ (glucose)} + 6\ O_2$$

In urban farming systems, we need to recognize that this natural process is mediated by technological processes in an artificial system.

4.1.4 Outputs

The main output from the farming system are the vegetables produced. Other outputs that are also significant, but not considered in this study, are the waste generated and carbon emissions. Nutrients that flow out of the system also have the potential to be recovered and reused though not many are currently doing it. This will be further discussed in the sections below.

4.2 Data Collection

Input and output flows of urban farming systems were collected from secondary sources. Water, energy, and nutrient inputs and yield outputs were adopted from previous studies that looked at similar hydroponics systems. It was also supplemented with data that could be obtained from the websites of Singapore-based urban farms. Visiting urban farms in Singapore to talk to local farmers was initially part of the plan as well. However, this could not be done in the end due to COVID-19 restrictions.

As I was unable to find much data on Singapore's urban farms, studies from other countries had to be used. A few reasons for the difficulty in obtaining such information are i) many urban farms in Singapore are relatively new, hence the inputs and outputs still vary between growing cycles (M Lavoo 2020, personal communication, 8 June), and ii) most farms do not publicly release data on volume inputs (S Chua 2020, personal communication, 2 January). Thus, for this project, the studies that I obtained data from were based in the USA (Barbosa et al., 2015; Chance et al., 2018; Cropbox, 2017; Mendez Perez, 2014; Van Ginkel et al., 2017), France (Romeo et al., 2018), and Japan (Techno Farm, 2020). Although there may be differences in the energy requirements due to the different climate control settings between different countries, having a wider range of sources should give an indication of the upper limit and lower limit of the amounts required.

Data related to the inputs and outputs of the farming systems were compiled into a table. The units of these different inputs and outputs were then standardized. These processed data inputs were then used to estimate the quantities required to produce enough vegetables in Singapore to meet the "30 by 30" target, now understood to mean 20% of the recommended intake of the vegetable fraction of a nutritionally balanced diet. This resulted in a possible range of values for each input needed.

Chapter 5: Results and Discussion

5.1 Quantifying "30 by 30"

Since the production target is so ambiguously worded, I will just assume it is 20% of the vegetables that Singaporeans consume annually. As there are many ways to define what "nutritional needs" are, in this paper I used Singapore's dietary guidelines as a reference for my calculations. According to Singapore's Health Promotion Board (HPB), we would need 2 servings of vegetables per day to fulfill our nutritional needs (MOH, 2020b). HPB also has various serving recommendations depending on the type of vegetable. The 3 "vegetable recommendations" selected for this study are

i) 150grams of raw leafy vegetables (MOH, 2020b),

ii) 50grams of raw pale leafy green vegetables (HPB, 2020a) (such as lettuce and bok choy), and

iii) 68grams of raw generic dark green non-leafy vegetables (HPB, 2020b) (such as broccoli).

These 3 categories were selected as they cover most of vegetable types recommended by HPB. Recommended servings of raw vegetables were chosen over cooked ones as vegetables tend to lose water, and hence weight, when cooked (Péquignot et al., 1976). Hence, recommended servings of cooked vegetables will not be reflective of the actual weight and nutritional values of the vegetable (Miglio et al., 2008). This difference is also reflected in Australia's serving size guidelines where recommended serves of raw and cooked vegetables differ (Australian Government Department of Health, 2015).

The calculations are as follow:

<u>Raw Leafy Vegetables</u>

150g x 2 servings per day = 300g per day.

5.7 million Singaporeans x 300g/ day = 1,710,000,000g = 1,710,000kg per day.

1,710,000kg/ day x 365 days in a year = 624,150,000kg/ year.

624,150,000kg x 20% = **124,830,000kg** of vegetables to be locally produced per year.

<u>Raw Pale Leafy Green Vegetables</u>

50g x 2 servings per day = 100g per day.

5.7 million Singaporeans x 100g/ day = 570,000,000g = 570,000kg per day.

570,000kg/ day x 365 days in a year = 208,050,000kg/ year.

208,050,000kg x 20% = **41,610,000kg** of vegetables to be locally produced per year.

<u>Raw Generic Dark Green non Leafy Vegetables</u>

68g x 2 servings per day = 136g per day.

5.7 million Singaporeans x 136g/ day = 775,200,000g = 775,200kg per day.

775,200kg/ day x 365 days in a year = 282,948,000kg/ year.

208,050,000kg x 20% = **56,589,600kg** of vegetables to be locally produced per year.

Based on these calculations, Singapore will need to locally produce an estimate of **42,000,000kg – 125,000,000kg** of vegetables per year in order to meet 20% of its vegetable nutritional needs.

5.2 Vertical Hydroponic Farm Data

For this study, I looked at data of input material, energy, and output yields collected from papers and publicly available information on websites of vertical hydroponic farms. A total of 10 sources were found. These 10 sources were on farms that produced leafy green vegetables with a substantial amount of information collected of these systems. I found a disproportionate amount of data available between indoor and outdoor farms, with 8 sources on indoor vertical farms. Indoor farms analysed consisted of growing systems in shipping containers and those located in a room or buildings. The 2 outdoor vertical hydroponic farms are both located in Singapore and are built on rooftop spaces.

Water, energy, and nutrient requirements of each growing system were collected. The primary output measured was the amount of crops produced in kilograms (kg). Something to note is that most of these studies focused on lettuce production, hence the data collected may not be representative of other crops. I also found that most studies focused primarily on the yields and water inputs of vertical farms. Very few studies had data on energy and nutrient inputs.

Input and output data collected from all the studies varied greatly (see Appendix 1 for data collected from all studies). The units the data was presented in also differed between studies, hence I converted them to similar units for better comparison (see Appendix 1 for original to converted data). Overall, there did not appear to be any obvious trend or clear indication of any one value. It was surprising to see as I initially thought the amount of material and energy inputs would be quite similar per kilogram of produce. This suggests that different hydroponic systems require quite varying amounts of material and energy inputs. Out of all the sources, the study conducted by Barbosa et al. (2015) stood out from the rest. It accounted for all inputs, except nutrient usage, and outputs of the hydroponic systems and these values were calculated using engineering equations supplemented with data from other literature on similar systems (Barbosa et al., 2015). As these figures appear to be a better reflection of the average inputs and yields, the estimations in the following sections will be calculated using the results from this study (except for the nutrient component). I will also further discussions around their environmental and sustainability dimensions.

5.3 Water Usage

For the indoor farms, water used in terms of litres per kilogram of lettuce produced ranged from 0.77 L/ kg (Techno Farm, 2020) to 7.11 L/ kg (Mendez Perez, 2014). Cropbox (2017) states that each of their shipping container growing systems uses about 102,206L of water per year. The average amount calculated by Barbosa *et al.* (2015) is **20±3.8 L/ kg/ year**. Data on water usage from the outdoor vertical farms was mostly non-existent.

To produce 42,000,000kg – 125,000,000kg of vegetables every year, using the 20±3.8 L/ kg/ year figure, my calculations for water demand ranged from **840,000,000L to upwards of 2,500,000,000L per year**. Putting things into perspective, the lower estimation is about the same amount of water all Singaporeans use in a day. On average, a Singaporean uses 148L of water a day, amounting to 843,600,000L a day in total (gov.sg, 2020). If the larger estimation is used, this is about 3 times the amount of water all Singaporeans use in a day.

Although hydroponic systems do require much less water than traditional farming systems as demonstrated by multiple studies (such as Barbosa et al., 2015; Van Ginkel et al., 2017), the source of the water also needs to be considered. In Singapore, the water used comes from the country's domestic water supply. If we consider traditional farming systems where their water source is rainwater, we can argue that hydroponic farms are replacing "free" ecosystem services with human-engineered systems. Hence, the notion that hydroponic systems use irrigated or domestic water supplies more efficiently does not quite hold if we are comparing this efficiency against rainwater that is originally "free". Furthermore, Singapore is considered to be one of the most water scarce countries in the world (Maddocks et al., 2015). Although its national water agency is continuously researching new ways to address the country's water challenges (PUB, 2016), the projected increase in urban agriculture would eventually still require a sizeable amount of water in the future.

One of the suggested ways to reduce the stress urban agriculture places on a city's water supply is to use waste water (Gómez et al., 2019; Moglia, 2014; O'Sullivan et al., 2019; Shamshiri et al., 2018). Since wastewater also contains nutrients crops require such as nitrates, using domestic waste water can provide both water and nutrients to urban farms. However, recycling wastewater for urban farming purposes is not widely practiced. Not only is the use of domestic waste water for farming highly regulated, the cost of treating the water is also high (Moglia, 2014; O'Sullivan et al., 2019). Waste water has to be treated to remove pathogenic and chemical contaminants while keeping a sufficient amount of nutrients for the plants to grow (Moglia, 2014; O'Sullivan et al., 2019). Hence, as the process of treating wastewater is quite costly on a farm level and there is the potential of contaminating the crops if pathogens and harmful chemicals are not removed, this form of waste water recycling has not been widely adopted.

However, the above argument is slightly different in Singapore's case. The country has created a "water loop" system (see Figure 4. below) where much of its wastewater is already treated and being reused within the system. This means that the water being used in the hydroponics systems would have already been "recycled". Within Singapore's water system, there may be a possibility of directing "direct non-potable use" (DNPU) water (see Figure 4. arrow between "5 NEWater factories" and "Industries") straight to urban farms. NEWater, where DNPU water comes from, is used water that is treated through microfiltration, reverse osmosis, and ultraviolet disinfection (PUB, 2020a). This produces a high-grade reclaimed water that is delivered to industries. The treatment process ensures DNPU water will be safe for agriculture as pathogens and bacteria will not be passed on to the crops and subsequently humans (PUB, 2020b). By allowing farms to use DNPU water, it can help to shorten the recycling loop between wastewater to farms. However, this possibility is currently not being explored as building new transmission networks to specific farms is not worth it, especially given the short land tenure leases which means farms may shift locations every few years. Hence, relying on the current distribution network that also contains "recycled" water would make the most sense for urban farms in Singapore.

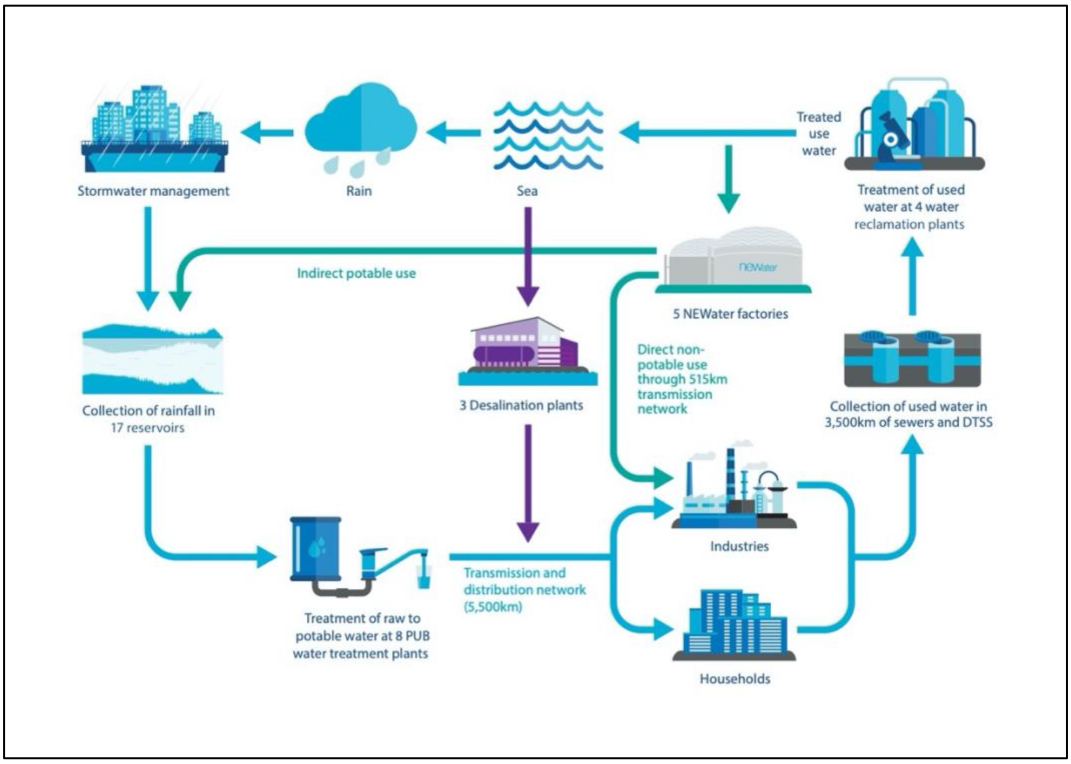

Figure 4. Singapore's "Water Loop" system. The figure shows how potable and non-potable water is collected, treated, and distributed in Singapore. It also shows how wastewater is collected, recycled, and reused within the system. (Source: PUB (2020))

Another possibility that has been raised is using harvested rainwater in indoor hydroponics systems. Rainwater harvesting and storage practices are common in traditional agriculture settings, especially in areas where water is scarce (Velasco-Muñoz et al., 2019). However, there is relatively little literature on using harvested rainwater for urban agriculture and even much less so on its use for hydroponics systems. One study that focused more on roof rainwater harvesting for urban farm gardens stated that using rainwater can help to reduce urban run-off and may be a significant contribution to the overall sustainability of urban agriculture (Amos et al., 2018). The same study also highlighted the current lack of research and information around this topic. It notes that urban rainwater harvesting and urban agriculture have emerged independently with a lack of understanding and research on how to combine them. One reason why rainwater has not been used may be because hydroponic systems require a high quality of water – the "cleaner" the water the better the yield (Das and Sing Majhi, 2009; Schwarz et al., 2005). Another reason is that rainwater can also be too acidic for plants to grow. A study by Balasubramanian et al. (2001) stated that around 88% of precipitation samples collected in Singapore registered a pH value of 5.0 or lower with the lowest value of 3.49. Despite this, rainwater harvesting is something that is still worth looking into as it has the potential to reduce the demand urban agriculture may put on Singapore's water system and also reduce urban runoff.

Since urban farming activities will probably increase in the future, the use of water is something that we should be more aware of when looking at this topic. Though hydroponics systems require much less water compared to traditional farms, the increasingly commercial scale at which these systems will be operating on will still require a significant amount of water. As Singapore's water resources are scarce, this may emerge as a problem in the future. Looking into roof rainwater harvesting systems that directly transport rainwater to the hydroponic growing systems is a potential solution to help reduce the water drawn from Singapore's local supply.

5.4 Energy Usage

Out of the 10 studies, 6 had data on the energy usage of their farm operations. 5 of these studies were conducted on indoor farms. The figures have been converted to megawatt-hour (MWh). At Cropbox (2017) 0.14MWh of energy was used per day. 3 other studies had figures ranging from 0.004MWh/ kg (Techno Farm, 2020) to 0.0195MWh/ kg (Van Ginkel et al., 2017). The average amount given by Barbosa et al. (2015) was **0.025±0.003MWh** of energy per kilogram of produce per year. The outdoor vertical farm data is from Sky Greens (2014), where they only stated 0.04-kilowatts (0.0004 megawatts) of electricity is required to power each growing tower.

In order to produce 42,000,000kg – 125,000,000kg of vegetables per year, multiplying by 0.025±0.003MWh, this would require between **118,000MWh to 3,500,000MWh** of energy. If we take the higher figure, this equates to about 3.5 terawatt-hours (TWh). Putting this into perspective, the total amount of electricity used by all households in Singapore in 2018 was 7.2TWh (EMA, 2019). Hence, if Singapore was to use only indoor vertical farming setups to achieve the vegetable production goal, the energy cost of doing so will be at least half as much as all the energy used in households in a year.

The high energy demand of indoor agriculture systems is something that many authors have raised before (as discussed in the literature review). Some also say that the energy requirements and its associated costs is the largest limiting factor that prevent large scale adoption of these systems (M Lavoo 2020, personal communication, 8 June). In Singapore, where most of its energy comes from burning natural gas (EMA, 2020a), the energy draw will also contribute to the country's carbon emissions. Again, this brings about the argument of such growing systems replacing free ecosystem services with artificial or human-made sources. On conventional farms, the source of energy for plants to grow comes from the sun which is considered to be "free" energy. However, indoor systems rely on energy from power generation plants to power artificial light sources and climate controls. This means that we end up paying for energy that is free in conventional agriculture systems. Although many enthusiasts of high-tech farming systems look to technology for solutions to increase the efficiency of resources used, we need to acknowledge that in the process we are replacing free ecosystem services that occur naturally. This goes to show how under-valued free ecosystem services are and how they are not often considered when discussing the sustainability of the inputs into urban agriculture systems.

One of the most common suggestions to improve the sustainability of urban agriculture's energy source is the use of renewable energy sources. However, though renewable energy sources are becoming more common now, the amount of energy they can produce is still far too little to generate 100% of the energy a commercial scale indoor farm requires. In Singapore, a 10-kW rooftop solar photovoltaic (PV) system can produce between 12.5MWh – 14.5MWh of energy annually (EMA, 2020b). This means that each day an estimate of 0.0343MWh – 0.0397MWh of energy can be produced. Using the upper range of 3,500,000MWh of energy required per year I calculated above, this means that 8550MWh of energy would be required per day. This would require at least 102,000,000 10-kW rooftop PV systems. Hence, the question is to what extent can renewables cover the energy demands. The consensus so far is that the development of renewable energy sources and power storage technology has not yet reached a level where larger farms can solely rely on this energy source (Centre for Liveable Cities, 2020; World Food Future, 2020). Furthermore, with the high initial start-up costs of indoor vertical hydroponic farms, bringing in renewable energy sources from the beginning would only drive up this cost. Hence, many farms only start considering using renewables later on (World Food Future, 2020). Thus, although renewable energy sources may help to supplement part the farm's energy requirements, renewable energy technology has to further advance before it can be effectively incorporated into growing systems.

An alternative option to reduce energy demands is through setting up more outdoor vertical farms, eliminating the need for energy-guzzling artificial lighting and climate-controlled systems. As land space is scarce in cities, these outdoor vertical farms are usually located on rooftops (examples cited by Al-Kodmany (2018), Despommier (2009), and Pryor (2017)). There are already quite a few rooftop farms in Singapore such as SkyGreens (as mentioned above) (Sky Greens, 2014a), ComCrop (Comcrop, 2020), and Citiponics (Citiponics, 2020). Setting up vertical farms on rooftops also turns unused spaces in cities to productive areas (Gasperi et al., 2016; Thomaier et al., 2015). Furthermore, since the energy cost of such farms are lower, they can grow vegetables that are usually cheaper and more widely consumed by the public (e.g. producing bok choy that is more widely consumed in Singapore as compared to kale). This will also help to increase the consumer market of locally produced vegetables.

However, there is an upper limit to the amount of vegetables that can be produced from rooftop farms. For one, there is a limited amount of rooftop space in cities. Due to weight considerations, the number of growing structures on each rooftop are also limited (Pryor, 2017; Walters and Stoelzle

Midden, 2018). Hence, the productivity of rooftop farming will probably be lower compared to an indoor farm. Besides that, there are also competing needs for rooftop space in Singapore. In order to increase cleaner sources of energy into Singapore's energy mix, the government has identified solar energy to be a key source of renewable energy they want to focus on, making rooftop area prime real estate for solar panel installations (EMA, 2020c; Tan, 2019). This will limit the amount of rooftop space that can actually be used for farming. Hence, though rooftop farming has potential to reduce the energy demands, it also comes with its own set of challenges. It can definitely be carried out together with indoor farming, however due to its lower productivity just relying on outdoor, rooftop farms alone would erode the capacity of Singapore to meet its vegetable production targets.

Overall, though energy is used to maintain optimum growing conditions which increases crop productivity, it still begs the question of whether this is enough to justify the energy costs of these systems. Renewable energy sources may be better utilized in the future as renewable energy technologies, battery storage, and its affordability improves. Although rooftop farms can reduce energy demands and turn unused areas in cities into productive spaces, it also comes with its own set of limitations and challenges. Therefore, given the scale of the problem, looking at ways to reduce the energy demand of indoor vertical farming or to increase the capacity of renewable energy sources may be the most pressing issues the sector currently faces if it wants to become more sustainable.

5.5 Nutrient Usage

Nutrients are usually delivered to crops in the form of a soluble nutrient solution added to the main water tank. This solution is made up of a mix of macro nutrients [Nitrogen (N), Phosphorus (P), Potassium (K)], micronutrients, and trace elements. Only 3 studies had data on nutrient inputs. Data from Chance *et al.* (2018) simply stated that a total of 0.0907kg of nutrients were used in their farm, no specific values were given for each type of macronutrient and the total amount did not correlate to any weight. Meanwhile, Cropbox (2017) stated that their system uses 0.00202kg N/ m^2, 0.00392kg P/ m^2, and 0.00224kg K/ m^2. La Petite farm in Lyon required 0.0026kg N, 0.0013kg P, and 0.0036kg K per kilogram of lettuce (Romeo et al., 2018).

For this study, I will focus more on the macro nutrients (N, P, and K) as these minerals make up the main component of the nutrient solutions. As it is unclear of the volume produced per square-meter in Cropbox, I will not be using their data. Using data from La Petite's farm, approximately **109,000kg – 325,000kg of N; 54,000kg – 163,00kg of P; and 94,000kg – 280,000kg of K per year** will be required to produce 42,000,000kg – 125,000,000kg of vegetables. Though this amount may be small compared to conventional commercial size farms, the significance here is that hydroponics systems are entirely reliant on nutrient solutions in order for the vegetables to grow. Not taking into account the commercialisation of agriculture, in traditional agriculture systems these macro nutrients come from natural biogeochemical processes in the soil that are just enhanced by human interventions. At its core, the nutrients required for plants to grow also come from free ecosystem services. However, in hydroponics systems, plants are unable to do this. As water sources also do not contain sufficient amounts of nutrients plants require, they rely on these synthetically produced minerals for nutrients.

One nutrient input often not mentioned in farming systems as a fertiliser is carbon. In traditional agriculture systems, it is drawn from the atmosphere in the form of carbon dioxide where it exists in overabundance due to anthropogenic GHG emissions. Furthermore, well-managed agroecosystems have the capacity to draw carbon dioxide from the atmosphere and fix it in plant and soil organic matter. This is a significant ecosystem service these landscapes can provide, as discussed earlier in the literature review. In indoor farms, carbon is an artificially regulated input in the form of an industrially produced gas. The energy and material costs of artificial carbon input was not estimated in this study. Furthermore, not all indoor systems use it. However, this is again an example of a naturally occurring, “free” input that high-tech systems have to augment with industrial technology.

One reason for the lack of discussion around the nutrient inputs of hydroponics systems is that many industrial farms also use large amounts of synthetic fertilisers. A report from the FAO (2016) projected that globally 199 million tonnes of fertiliser would be needed for agricultural activites. Hence in comparison, the nutrient requirements of hydroponic systems are actually much lower (AlShrouf, 2017; Despommier, 2009). An advantage of hydroponics is that the nutrients put into the system are in a soluble form, enabling the plants to directly absorb it. This direct delivery of nutrients also means that less is wasted. In conventional farms, fertilizer added to the soil may be lost due to run-off and not all the nutrients are taken up by the plants (Despommier, 2009; Gillingham and Thorrold, 2000; Hart et al., 2004). Hydroponic systems also allow unused nutrients to be recycled – a main water tank, which also contains the nutrient solutions, feeds water into the system and whatever is not absorbed by the plants returns to the same tank. Furthermore, studies have also identified that nutrient management of hydroponic systems can contribute to circular economy efforts and improve environmental aspects (Calabria et al., 2019; Martin et al., 2019; Rufí-Salís et al., 2020). In Singapore, this nutrient loop system also relates to its “water loop” system (see Figure 4. in Water Usage section 5.3 above). At the point where collected wastewater is treated, nutrients can potentially be recovered here and redirected to urban farms. Thus, considering the overall efficiency of resource use and the potential of creating a more circular system, hydroponic systems are more sustainable in regards to nutrient inputs.

Although hydroponic systems do make use of nutrients more efficiently, this discussion also brings about the question of where these nutrient solutions are coming from. For Singapore’s case, though there are a few Singapore-based companies that have developed special nutrient formulas for hydroponics (e.g. LushGro), the source of these primary materials are currently imported. Though this area has not been thoroughly researched, there may be a possibility that instead of importing food we are beginning to import the nutrient solutions to farm our own food. Hence, “carbon emissions” saved from the transportation of food may end up getting transferred to importing nutrients. This gives a false sense of “sustainability” as impacts are being shifted to other parts of the system. Furthermore, as the urban farming industry in Singapore continues to grow, the amount of imported nutrient fertilisers will increase. This will also result in an influx of new nutrient flows into the city. How these nutrients will accumulate and move through the city system is also something that is not very well documented. However, given Singapore’s small geographical scale, with a good system design, nutrients should be able to be recovered from municipal waste streams or the sewer system. The potential to recover nutrients from the system is discussed further in section 5.7 below.

Overall, though nutrient inputs are an essential component of hydroponic systems, there is relatively little information surrounding this particular input. However, we are still replacing natural processes with technological ones, making it important to weigh the costs and benefits of doing so. Other aspects such as where the nutrients are coming from and the potential for nutrient recovery within city systems to create a more circular economy are also areas worth exploring. Advancement in these areas will only serve to further improve the sustainability of such systems and highlight components of the system that can be bettered.

5.6 Yield and Land Area

The main output of hydroponic systems are the crops. For this study, yield is presented in the weight (kg) of crops produced by the farming system. All the studies had data for the yields. The yields of the indoor farms ranged from about 60kg/ m^2 (Kriwangko, 2018) to 332.85kg/ m^2 (Cropbox, 2017) of lettuce. Other indoor farm that presented yield data in kg/ m^2/ year ranged between 44.7 kg/ m^2/year (Romeo et al., 2018) to 197.5kg/ m^2/ year (Van Ginkel et al., 2017). The average amount calculated by Barbosa *et al.* (2015) was **41±6.1 kg/ m^2/ year**. As for the outdoor farms, the data obtained from Citiponics (2020) is 26.64kg/ m^2/ year whereas Sky Greens (2014) simply claimed that its facilities can produce up to 5000kg – 10,000kg of vegetables per day when their farms are running at full capacity.

To produce 42,000,000kg – 125,000,000kg of vegetables per year in Singapore, this will require a minimal of **900,000m^2 and up to 3,600,000m^2** of land area depending on the yields of different farms.

Currently, less than 1% of land in Singapore is used for all agricultural activities (inclusive of fish farming, chicken farms etc.) (SFA, 2019b). Given the scarcity of land in Singapore, it does not seem likely that the amount of space allocated to agriculture will increase drastically. This is where the interest of vertical, indoor farming spaces stems from as they are more productive per m^2. Such farms can also be located within built-up warehouses that already exist (e.g. Artisan Greens in Singapore) or on rooftops (e.g. Sky Greens, Comcrop, Citiponics) which means the government does not have to allocate "land space" to such farms.

All the produce from vegetable farms in Singapore are destined for consumption in the local market. According to SFA (2019a), a total of 83 vegetable-producing farms currently produce up to 14% of the country's leafy vegetable requirements (there was no mention of how this figure was calculated). However, due to the high costs of setting up and running indoor hydroponic farms, many choose to grow higher-value crops. These crops, most notably kale or herbs like basil, though have higher nutritional value, are not traditionally part of the vegetables consumed in Asian cuisines which primarily make up Singaporean diets (American Overseas Dietetic Association, 2011). Although more people are starting to purchase these vegetables, it brings about the discussion of whether an increase in urban hydroponic farms will directly increase the volume of culturally appropriate crops produced locally.

Besides this, there are also some issues around the accessibility of locally produced vegetables. Though more farms are starting to sell their produce in supermarkets, a large majority are still doing it through online stores or through their own websites. Many local farms also offer subscription services to their own produce boxes (e.g. Citizen Box by Edible Garden City, Vegetable Baskets by The Little Red Farm). This suggests that their presence in supermarkets or wet markets appear to be lacking. Based on my personal observations, I usually only find produce from one or two local farms on the shelves. Although there has been a push to bring more local produce to supermarkets (Liu, 2020b), the accessibility to these products are still quite limited. It also limits the market to those who do their grocery shopping online, making it even more difficult to get locally grown vegetables to the community.

Another issue with accessibility is the price of locally grown crops. Though the quality of produce may be better and fresher than imported vegetables, many people who do not know this difference will still first focus on the price. Most of the products from these farms come at a premium cost in supermarkets and some are only available in high-end stores that the average Singaporean would not visit. For example, on a local online grocery shop "Redmart", 100g of locally grown chinese cabbage (or choy sum) costs between \$1.18 - \$1.56. On the other hand, 100g of imported choy sum costs \$0.50

- $0.70 (Redmart, 2020). The fact that they are almost double the price may deter consumers from choosing local options.

With an increasing amount of resources being put into developing indoor farming technologies, achieving the 20% food production goal appears to be feasible. However, we also see that this system is currently highly targeted to a particular end user. In Singapore's case, it is usually people who have the purchasing power to buy the higher priced produce or those who make a conscious decision to buy local. Many of the crops produced by indoor farms in are also not part of the average Singaporean's diet, suggesting the need to transition indoor farms to more widely consumed produce.

5.7 Future Potential of Urban Agriculture

Though urban agriculture can definitely contribute to the city's food supply, it cannot provide all the nutritional needs people require. Hence, cities like Singapore will still need to continue sourcing for nutrients and food beyond its boundaries. Based on the MSFA conducted, we can see that the main excess stock entering the system are nutrients. These nutrients are entering the system not only in terms of food but also fertilisers that are used in high-tech urban farms. If we look at this from an MSFA and sustainability perspective, this can potentially become a problem, especially if excess nutrients accumulate and remain in the system. Furthermore, excess nutrients that flow out of the system have no way of being recovered which is quite a waste of resources.

This can present a problem if cities are not prepared to handle large influxes of nutrients. Conversely, this also presents an opportunity. If nutrients can be captured at the end of the system, there is the potential to create a more "circular economy" within the city (Manríquez-Altamirano et al., 2020; Richa et al., 2020). This would require increasing the capacity of the system to process effluents and other sources of food waste. Furthermore, since most of the phosphorus consumed by humans ends up being excreted primarily through urine and, to a lesser extent, feces (Cordell et al., 2013), a considerable amount could be recovered and reused in urban agriculture systems (Cordell et al., 2011; Mihelcic et al., 2011). Recycling these nutrients back into urban agriculture systems in the city can also offset chemical fertilizer imports, maintaining an overall balance between nutrient inputs and outputs of agriculture systems. Creating this circular economy also helps to improve the overall sustainability of the system as it enables nutrient inputs to be recycled in the Singapore environment. Given that, out of necessity, Singapore will continue to import almost 100% of its carbohydrates, 90% of animal protein, most of its fruits, and 80% of vegetables, the volume of nutrients brought in will be more than enough to cover the nutrients required to locally grow 20% of its vegetables if imported nutrients is recovered. If infrastructure is built to recover these nutrients for its own urban farms, surplus nutrients recovered could also be re-exported back to countries of the food's origin, creating a circular nutrient economy on a larger scale.

Another advantage that can arise from urban agriculture besides creating more closed loop systems are finding synergies between different industries. Synergies refer to how efforts to improve the sustainability of Singapore's urban agriculture sector can also improve and draw on other industries. It is definitely something the Singapore government can embrace to further the sustainability dimensions of urban agriculture.

A possibility is the use of industrial waste from Singapore's chemical manufacturing sectors as fertilisers for indoor hydroponic farms. This is known as industrial symbiosis, where waste from one industry can be a resource to another (JTC, 2020; MEWR and NEA, 2020). The practice of converting waste from chemical industries into resources for fertilizers production is already being researched in other countries like Poland (Biskupski et al., 2015; Gorazda et al., 2017). Though there are concerns over whether toxic minerals can be filtered out effectively from chemical waste, improvements in nutrient recovery techniques may make this a viable solution for industrial symbiosis between chemical and farming industries. For Singapore, although there is no relation between these 2 industries at the moment, the maturing of its chemical industries and the newly emerging urban agriculture sector provides a good chance to develop this area. Although it is not clear whether fertilisers produced from chemical waste can be used in hydroponic systems, it presents a new frontier for Singapore to spearhead its research and development.

Besides that, another synergy that can occur is with the renewable energy sector. As mentioned in the energy section, the largest sustainability issue with indoor urban agriculture systems is how energy intensive it is. Renewable energy technologies are not a viable option at the moment as they are unable to provide a sufficient amount of energy the systems require. Thus, this limiting factor may serve as motivation to rapidly improve renewable energy technologies that can be used by indoor agriculture systems. As the capacity of electricity produced from renewable sources increases and the overall cost of installing the systems are lowered, more farms can incorporate it into their growing systems. Although it is not clear to what extent this will help to speed up overall developments and improvements of the renewable energy sector, it can potentially contribute to Singapore's goal of increasing renewable energy generation in the long run (EMA, 2020a).

Overall, while it is not possible to satisfy all the nutritional needs of Singaporeans just through urban agriculture, there are also other benefits that come with it. These include opportunities to form more closed loop, circular economies within the city's food system, and the creation of synergies between different industries. Thus, urban agriculture will still play an important role in the future development of cities. As this sector continues to grow, it can hopefully bring more focus to sustainability efforts in cities.

5.8 Social Dimensions of Urban Agriculture in cities

Urban agriculture has also often been lauded for the social benefits it adds to cities. Though we have touched on some social aspects in the yield section above – specifically on culturally appropriate diets and accessibility to local produce – there are still many social and cultural dimensions that can be addressed. Even though social aspects are not the main focus of this paper, it is still a crucial component of human ecology as it seeks to explore "the interactions between humans, their environment, and culture" (Dyball and Newell, 2014). Hence, in this section I will be highlighting a few key issues that have the potential to be further looked into in future research.

One social benefit that has resulted from the increased attention given to the urban agriculture sector in Singapore is job creation. Recently, Singapore's Minister for Sustainability and the Environment announced that up to 55,000 jobs related to sustainable development are to be created in the next 10 years, which includes skilled jobs in high-tech agriculture and aquaculture sectors (Tan, 2020).

However, there have also been some drawbacks. As urban farms are becoming more commercialized and the farm processes are becoming increasingly automated, it results in diminishing social values. An important aspect of open plot urban agriculture has always been the social and community values it brings (Davila and Dyball, 2015; Lawrence, 2020; Pryor, 2017). Many urban farms provide a common space for city residents of different walks of life to come together. Examples of such spaces are community farms that are located within neighbourhoods (Lawrence, 2020). This allows residents to build community spirit and bond with each other (Guitart et al., 2012; Ober Allen et al., 2008; 'Yotti' Kingsley and Townsend, 2006). Another important aspect urban agriculture brings is its ability to engage city residents in farming activities. It serves an educational purpose, teaching city residents that are far removed from food production processes how the food they consume is grown. With the commercialization of urban farms, especially indoor high-tech farm factories, these values and community interactions are reduced as the public are usually not allowed to enter these facilities. Though there are some commercial urban farms in Singapore that strive to account for better social and community values through employing members of marginalized communities (e.g. ComCrop) or offering volunteering opportunities (e.g. Edible Garden City), newer high-tech farms are unlikely to provide these opportunities. The main social value urban agriculture is providing to the city is shifting from community building to consumers being able to buy fresh, local produce. Given the unique social and educational value urban farms can bring to cities, attention should also be given to non-commercial farms to ensure that these values are not diminished.

Another social dimension that many city dwellers often do not think about, much less talk about, is the co-dependence urban dwellers and farmers have on each other. Since is it not possible for Singapore to be 100% self-sufficient, it means that we are still going to be dependent on the capacity of foreign agricultural lands and the farmers who manage those lands. As Singaporeans continue to rely on them, extending our care to their health and well-being should be of concern to us (Davila and Dyball, 2015; Dyball, 2015; Porter et al., 2014). That is easier said than done, given how removed we are from these landscapes and people. Despite that, it also presents an opportunity for local agriculture initiatives to play this educational role first. Local agriculture initiatives can engage Singaporeans with local farmers and teach them how and why they should care about the people that produce their food first. As local farmers are closer to home, it may make it easier for consumers to relate to them and their experiences. Once we have fostered this relation between consumers and local farmers, we can then extend this care and awareness to the different regions where the rest of our food comes from (APRU, 2017).

Thus, though Singapore's food goals appear to be less focused on social dimensions, it is an important aspect that we should not ignore. Besides job creation, the urban agriculture sector will need to find more ways to increase its social values. Maintaining engagement with local communities is a key factor that has to be addressed. Balancing the presence of commercial and non-commercial farms may help in this aspect. Urban agriculture can also play an educational role – making consumers more aware of how their food is grown and connect them with the farmers, both local and overseas, that do so.

5.9 Where does Singapore currently stand?

Having touched on the future potential urban agriculture can provide and concerns over maintaining its social dimensions, then comes the question of where does Singapore currently stand with regards to the development of its urban agriculture sector? Based on results gathered from the MSFA and looking at the different studies, the primary outcome Singapore's government wants from its food system is to increase the volume of local food production. Though sustainability is a key word that keeps resurfacing whenever urban agriculture is brought up, upon closer look, sustainability principles were never quite integrated into the system's initial design. Although focusing on increasing the local capacity for food production has its benefits, it also comes with some trade-offs.

Since the local agriculture system is focused on the outputs, it has not fully accounted for the material and energy sources needed if Singapore is to increase the number of indoor high-tech farms. It also has not accounted for sinks such as the influx of nutrients into the system. Although it may be part of the plan to address these issues after the sector is more developed, Singapore missed the chance to create a more sustainable system by designing these aspects into the projects from the beginning. The current local farming system is built with the idea of "sustainability", however there is still much that has to be done before it is truly sustainable. Developing this new sector also presented the opportunity to establish a close loop farming system. Though we can work towards or incorporate these closed loop systems later, it will be more difficult after the system is established as changes in the system is bound to cause disruptions.

Looking at the whole food system in a more holistic manner could have resulted in designing a more circular food economy in Singapore. Instead of just focusing on the yield, if the inputs were given the same priority, the whole system could be developed to be more sustainable. However, given that this sector is still relatively new, it may not be too late to change the behaviour of the system without causing too much disruptions. There is definitely the opportunity to explore more closed loop sustainability outcomes in nutrient recovery. More research and development for industrial symbiosis between chemical manufacturing industries and nutrient provision can be done as well. There is also potential to explore other sources of water inputs such as rainwater harvesting. As for energy inputs, we can enhance the development of renewable energy technologies and find ways to integrate them with indoor farming systems. New ways to increase the productivity of rooftop farms can also be developed as they require less energy. Overall, if we want to change the behaviour of the system, we would need to redesign it. By shifting some of the focus towards addressing the sustainability of the inputs and closing material loops, it will benefit the whole system in the long run.

Chapter 6: Conclusion

In a bid to increase food security in cities around the world, urban agriculture activities are likely to increase over time. Hence, I set out to estimate the feasibility of using urban agriculture to contribute towards the "30 by 30" food target Singapore has set for herself. I did so through i) estimating the quantity of food that has to be produced under the "30 by 30" goal, with a focus on leafy green vegetables, and ii) estimating the extent of land area required by urban agriculture to meet this target and quantify as far as possible the inputs and outputs that will be needed.

For the first aim on quantifying the "30 by 30" goal, I found that the goal was quite ambiguously worded with no specific method to calculate how much vegetables it would need to produce locally to meet this food production goal. Thus, the calculations made in this paper were based on nutritional and food guidelines from the Singapore Health Promotion board. This resulted in the eventual amount having quite a large range from 42,000,000kg to upwards of 125,000,000kg.

As for the second aim of estimating the biophysical and energy requirements to meet the food production goal using mostly indoor vertical hydroponic systems, I also found a very wide range of results. From the MSFA conducted, Singapore would require

i) 840,000,000L – 2,500,000,000L of water;
ii) 118,000MWh – 3,500,000MWh of energy;
iii) 109,000kg – 325,000kg of Nitrogen; 54,000kg – 163,00kg of Phosphorus; and 94,000kg – 280,000kg of Potassium fertilisers;

of inputs per year to produce enough crops to meet the "30 by 30" goal. It would also minimally require 210,632m^2 and up to 2,792,617m^2 of space. There was also a general lack of information on the inputs required for indoor hydroponic systems and the way data is reported is inconsistent between studies. Furthermore, many studies have only reported on water usage and yields with a minority doing more detailed analysis on energy and nutrient inputs. Most of the growing systems in the studies were also different variations of hydroponic systems which required vastly different amount of inputs. These factors all contributed to the wide range of results I ended up with.

My third aim of this study was to explore the sustainability implications of Singapore's urban agricultural policy. Although the main objective of its policies is mostly to increase local food production to boost national food security, the "sustainability" aspects also cannot be ignored. The overall "sustainability" claims of indoor hydroponic farming systems are defendable in terms of how efficiently they use resources. However, sustainability dimensions go beyond this. It encompasses the input sources such farming systems require and their effects on the wider system they sit in. From the discussion section, some key issues that the sector can improve on include i) advancing renewable energy technologies to bring down the intensive energy demands of indoor farming, ii) exploring rainwater harvesting systems to reduce drawing water from urban water supplies, and iii) recovering nutrients at the end of the system. The idea of a circular economy around nutrient recovery was also raised. In principle, there is the capacity to capture nutrients at the end of the system and recycle it. This changes the linear flow of nutrients through the system into a circular pathway, resulting in cities having a more sustainable food economy. In Singapore's case, it was a missed opportunity to incorporate this circularity into the system right from the beginning. However, given the country's relatively small size and how localized its system is, there is potential in the future to recover and circulate these materials. A drawback of incorporating circularity into the system later would be that we are retrofitting a solution into the system that is already set up. Finally, more speculatively, when there is the capacity and infrastructure to recover nutrients from Singapore's waste stream, surplus nutrients could feed into a circular economy operating at a more international scale which allows for nutrient recycling with international landscapes Singapore imports nutrients from. Being an international trade hub, ships already sailing to relevant ports can carry these nutrients with them.

My final aim of this thesis was to discuss the social and cultural dimensions of food systems in cities. Though primarily focused on environmental and sustainability dimensions, food systems and their societies are also closely interlinked. Thus, a brief discussion on the associated social-cultural dimensions tied my findings back to the wider context of urban cities. Whilst urban agriculture has always been strongly associated and lauded for the community values it brings to cities, we may need to rethink how commercial high-tech indoor farms add to this. As farms become increasingly commercialized and automated, the social values have shifted from community building to just purchasing locally produced foods. There is a need to balance these shifting social values as the urban agriculture sector in Singapore develops. Another social dimension regarding the wider food system is Singaporeans' concern for the well-being of the overseas farmers and lands much of their food comes from. Currently, there is little to no discussion about this issue in Singapore. Urban agriculture can play an educational role in fostering better relations between local farmers and consumers which could eventually extend to more awareness of these overseas farmers.

In light of these results and discussions, attaining the 20% vegetable target of the "30 by 30" food production goal set by the Singapore government appears to be feasible. The cost of doing so, however, is much less clear due to how widely the figures range for each input and output. Another thing that should be noted is that this paper is mainly looking at the nutritional needs vegetable production can contribute to the country. Though local vegetable production is on the rise, there is a limit to the other types of agricultural activities that can operate in Singapore. This means that Singapore is unlikely to become 100% nutritionally self-sufficient. In addition, many indoor farms in Singapore choose to grow higher value crops to cover the costs of running an indoor farm. Hence, although the amount of vegetable production may eventually be able to contribute more significantly towards food security efforts, the city would still very much have to rely on imports from other countries to satisfy other nutritional needs, notably animal proteins and carbohydrates.

Returning to the human ecology framework, we see how our increasing dependance and reliance on technology can influence social and environmental dimensions of cities. High-tech indoor urban agriculture systems do increase the capacity to produce more food locally. As this technology continues to develop, the overall economic cost needed to run these systems will most likely decline over time as well. While this prospect paints a somewhat bright future for an increase in localized agriculture, we need to keep in mind that these solutions to the urban food system challenge remains in the high-tech industrial space. This means that it is also subjected to related risks of the current technological and industrial food production systems. It is not to say that high-tech innovations are generally bad, however we should also give more consideration towards how systems can make use of the natural ecosystems they sit in in a more benign way rather than pinning all our hopes on technological developments. This may be more difficult in Singapore's case as it does not have the land area for agricultural systems that can allow for more natural ecological processes. However, it also creates new opportunities to implement circular economies and develop new ways to make better use of the free ecosystem services.

While my study makes important contributions to the discussions around urban agriculture and food security of cities, these discussions also sit in the wider context of the justice and social aspects of food systems. Hence, there are also some limitations to what I could cover. Crucially, the lack of standardized and reliable studies into the inputs and transformations required per unit of output needs to be addressed. I relied heavily on Barbosa et al. (2015) as these were the most transparent data I could find. Further studies can consider exploring the economic efficiency and desirability of local food production systems. More details around the new social-cultural dimensions commercial-scale urban agriculture brings to cities are also worth exploring. Besides this, I also found that there was a lack of information on outdoor hydroponic systems. This gap can be looked into as outdoor vertical farms may help the sector address one of the key drawbacks of indoor farming systems which is the high energy usage. Food waste was also not estimated for in this MSFA, although some principle comments were made about recovery and reuse

By focusing on Singapore's food production system in this paper, I hope that it can provide a useful comparison for other cities with similar social-ecological systems that are looking to increase local agriculture production. Similar cities can learn from the successes and different measures

Singapore has used to increase local production while also identifying missed opportunities (e.g. increasing nutrient recycling efforts) that can be implemented earlier. If we are looking to increase the sustainability values of food production systems in cities, a fundamental shift from the traditional linear economic framework to a more circular one is required. Even if food production becomes more localized, it will not be truly "sustainable" unless these new industries are built on the foundations of a circular economy within the wider systems they sit in. As high-tech urban agriculture activities in cities are likely to increase in the future, it is imperative that we gain a deeper understanding of how their materials and energy flows interact within the city. Identifying related costs of doing so will also benefit the city's development in the long run. My overall findings suggest that urban agriculture is a feasible, and even essential, venture for cities. However, there has to be a better understanding of how significantly it can contribute to the nutritional needs of a city's residents while developing more concrete solutions of how it can add to the sustainability aims of a city.

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Appendix 1: Table of collected data with processed values

O: Original data from source

C: Converted data to more standardized units

<u>Indoor vertical farms</u>

Farm/ Company	Yield	Water	Energy usage	Nutrient
Cropbox (company selling shipping container vertical farms)	O: 1347 tonnes/ 320 sq ft (lettuce) C: 332.85kg/ m^2 of lettuce	O: 27,000 gallons/ year C: 102,206.12L/ year	O: 140 kWh/ day C: 0.14MWh	O: 18lb N/ acre 35lb P/ acre 20lb K/acre C: 0.00202kg N/ m^2 0.00392kg P/ m^2 0.00224kg K/ m^2
Sustenir Agriculture (Singapore)	O: 3.2 tonne of lettuce/ 54sqm (Source from Kriwangko (2018)) C: 60kg lettuce/ sqm	Unknown	Unknown	Unknown
La Petite Ferme du Grand Lyon (Lyon) Study by Romeo et al. (2018)	O: 44.7 kg/ m^2/ year (conversion not required)	5.96 L/ kg (conversion not required)	Unknown	0.0026kg N/ kg 0.0013kg P/ kg 0.0036kg K/ kg (conversion not required)
Nick Greens (Chicago, USA) Study by Chance et al. (2018)	O: 36.0 lbs lettuce (area of farm not stated) C: ~16.33kg of lettuce	O: 30 gallons C: 113.56L	Unknown	O: 0.2lbs (total) C: 0.0907kg (total)
Atlanta shipping container farm (Atlanta, USA)	197.5kg/ m^2/ year of lettuce (conversion not required)	1.65 L/ kg (conversion not required)	O: 19.5 kWh/ kg C: 0.0195MWh/ kg	Unknown

Study by Van Ginkel et al. (2017)				
Figures from Barbosa et al. (2015) paper	41 ± 6.1 kg/ m^2/ year of lettuce (conversion not required)	20 ± 3.8 L/ kg/ year (conversion not required)	O: 90,000 ± 11,000 kJ/ kg/ year C: 0.025±0.003MWh/ kg/ year	Unknown
Techno Farm, Japan	O: 648 heads/ m^2/ year C: 97.2 – 103.68kg/ m^2/ year (assuming each head of lettuce weighs between 150g – 160g (Perez, (2014))	O: 0.11L/ head C: 0.77 L/ kg	O: 0.57kWh/ head C: 0.004MWh/ kg	Unknown
Indiana Vertical Farming Analysis Study by Mendez Perez (2014)	O: 8482 tonnes/ year, grown in a 10-storey vertical farm of 100m x 100m = 100,000 m^2 C: 84.82kg/ m^2/ year	237L/ kg	O: 133 million kWh (for all the lettuce produced on the farm) C: 0.0175MWh/ kg	Unknown

<u>Outdoor vertical farms</u>

Farm/ Company	Yield	Water	Energy usage	Nutrient
Citiponics (Singapore, Aqua Organic System)	O: 4000kg/ 1800sqm/ month C: 26.64kg/ m^2/ year	Unknown	Unknown	Unknown
Sky Greens (Singapore, low carbon vertical	5000kg – 10,000kg of vegetables can be produced per day	Unknown for crop growing	40W (0.04 kW) of electricity required to power a 9m tall growing	Unknown

hydraulic farming system)	when the farm is at full capacity	0.5 litres of water is required to rotate the 1.7 ton vertical structure	tower that holds 38 troughs	