System Dynamics Modeling of the Food-Water-Energy Nexus in Urban Areas, Focusing on Community Gardens

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A Thesis
In the Department
Of
Building, Civil and Environmental Engineering (BCEE)

Presented in Partial Fulfillment of the Requirements
For the Degree of
Master of Applied Science (Building Engineering)
At Concordia University
Montreal, Quebec, Canada

August 2023

CONCORDIA UNIVERSITY

School of Graduate Studies

This is to certify that the thesis prepared

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Entitled: System Dynamics Modeling of Food-Water-Energy Nexus in the Urban Areas, Focusing on Community Gardens

and submitted in partial fulfillment of the requirements for the degree of

Master of Applied Science (Building Engineering)

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ABSTRACT

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The urgent need to address sustainability challenges in food, water, and energy (FWE) has led to the FWE Nexus framework. Ensuring food security and sustainable urban agriculture are critical elements of sustainable development. Community gardens (CG) have gained prominence as they enhance food production, foster social cohesion, and mitigate environmental impacts. This study investigates CGs' land usage using a system dynamics modeling approach based on data from a case study at Concordia University's Loyola Campus Garden. Simulations were done using the Vensim Software. The objective is to analyze land usage in response to various CG scenarios: (1) harvesting ratio on dedicated CG land, (2) production efficiency by involving experienced farmers, and (3) cost considerations.

The findings reveal insights into CGs' potential for sustainable development. More CG land leads to increased local food production, impacting food security positively. Improving CG efficiency enhances their role in addressing food-related challenges. However, financial considerations must be balanced for long-term viability and scalability.

The study aligns with the United Nations Sustainable Development Goals (SDGs). Evidence supports CGs' contributions to SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-being), SDG 11 (Sustainable Cities and Communities), and SDG 12 (Responsible Consumption and Production). Policymakers, planners, and community organizers can leverage insights to promote sustainable urban agriculture and achieve development objectives.

Furthermore, this study highlights CGs' importance in the FWE Nexus framework and their potential for sustainable development. Understanding land usage dynamics allows informed decisions to enhance food security, foster communities' well-being, and promote responsible consumption in urban areas.

Keywords: Sustainability; Food Water Energy Nexus; Food security; Urban farming; Community gardens; System dynamics

Acknowledgments

I would like to take this opportunity to express my deepest appreciation and gratitude to my esteemed Supervisor, Professor Ursula Eicker. Her exceptional guidance, unwavering support, and invaluable expertise have been instrumental in the successful completion of this master's thesis, and I am forever indebted to her. I am grateful for the opportunity to work alongside the exceptional team at the Canada Excellence Research Chair (CERC). Particularly, I would like to extend my sincere thanks to Mr. Reiner Braun. I have to deeply appreciate Andrea Tremblay, creator and coordinator of the mind.heart.mouth, for sharing the unpublished data from the Loyola Campus Garden.

To my beloved mother, Jaleh, I express my heartfelt appreciation for her unlimited love, encouragement, and support. Though no longer with us, I want to pay tribute to my late father, Iraj. His memory, wisdom, and the values he instilled in me continue to inspire and guide my academic pursuits. I am also grateful for the mentorship and inspiration provided by my fantastic sisters, Sara and Tahereh. I am fortunate to have them as pillars of support in my life. Furthermore, I would like to express my heartfelt appreciation to my dear nephew, Aiden, with his bright spirit, whose innocent presence and contagious joy have brought immeasurable happiness to my life.

I extend my deepest gratitude to my loving and kind husband, Masoud. His understanding and encouragement have been vital to my academic pursuits. His belief in my abilities and the sacrifices made on my behalf have been a driving force behind my accomplishments.

Finally, it is with profound appreciation that I dedicate this thesis to my role model, Professor Ursula Eicker, whose guidance, and mentorship have been invaluable in shaping my academic and professional growth.

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Chapter 1
(Introduction)

1.1 Introduction

The interdependence of climate change and food security poses a considerable threat to the future health and welfare of individuals worldwide. The agricultural sector is a significant contributor to climate change, accounting for approximately 11% of total anthropogenic greenhouse gas (GHG) emissions. When taking into account the complete value chain, this figure increases to between 26% and 37% of GHG emissions. The global reduction in agricultural land availability, the confluence of unfavorable weather patterns and heightened food spoilage due to global climate shifts are projected to substantially influence food production in the forthcoming year (Blom et al., 2022). The escalating global population and changing habits of eating require a surge in global food production by as much as 70% from 2017 to 2050, thereby presenting significant challenges (Hunter et al., 2017). For the purpose of successfully satisfying the growing demand for food by 2050 without causing additional harm to natural habitats through the creation of new arable land, it is imperative to mitigate the effects on the surroundings that food production methods have and explore innovative approaches to crop cultivation (Blom et al., 2022).

World Health Organization (WHO) presently advocates the consumption of a minimum of 400 grams of fruits and vegetables on a daily source. The recommended number of fruits and vegetables that an individual should consume depends upon their age, level of physical activity, and gender, as stated in the publication (*Fruit and Vegetables – Your Dietary Essentials*, 2020). This particular aspect holds significance in terms of adhering to a nutritious diet, as it constitutes a fundamental element within the context of this study.

1.2 Sustainability

Sustainable development refers to a form of growth that effectively fulfils the requirements of contemporary society while ensuring that the capacity of the forthcoming age group to fulfil their own appeals is not compromised, according to the World Commission on Environment and Development (WCED) (Wilkinson et al., 2001).

Sustainability was a topic of discussion as early as the 17th century. In 1713, H.C. von

Carlowitz was the first person to address sustainability when he proposed the philosophy of "nachhaltige Nutzung" (long-term use of future resources) for the German forest business (Knorr & Augustin, 2021). Throughout the subsequent half of the twentieth century, the ecological crisis and unequal wealth dispersal as a result of economic advances made it clear that traditional notions of progress, growth, development, and sustainability needed to be reexamined (Du Pisani, 2006). There was a heightened discussion on sustainability in the 1970s and 1980s (Knorr & Augustin, 2021). Among the many sustainability reproductions that have emerged (Spindler, 2013), the three-pillar model, which considers the environment, economy, and society in order to elaborate on subgoals for all components, depicts the interconnectedness of these factors (Regarding the environment: air, power, ecology, safeguarding the environment, waste; Regarding the economy: labor, geographical aspects, economic frameworks, pricing, public budget, consumer; Regarding the society: civilization, housing form, flexibility, and security).

The work published by Du Pisani, 2006, argues that sustainable development is an attempt to achieve a balance between expanding the economy and protecting the environment. Since, from a purist's perspective, sustainability and actual development are incompatible, this idea seemed to be at odds with itself.

1.2.1 Sustainable food production system

According to the existing body of research, the term "sustainable food system" describes an approach that simultaneously preserves the social, environmental, and economic foundations that make it possible for future generations to reach food security and nutrition. In other words, a food system that is environmentally friendly is one that ensures the provision of food security and nutrition to every individual, sources such as (HLPE, 2014; Neven, 2014) support this definition. According to the Brundtland Commission's concept of sustainable development (Brundtland, G H et al., 1987), processes that are considered sustainable (Tomas Norton et al., 2013) should have the following properties (a) use raw materials that can be produced on an ongoing basis with minimal negative effects on the environment, society, or economy; (b) do not rely on finite energy sources; and (c) do not negatively impact human health.

According to the (*Global Panel on Agriculture and Food Systems for Nutrition. 2020. Future Food Systems: For People, Our Planet, and Prosperity.*, 2020), a food system can be considered sustainable if it can continue providing food without harming the natural environment by causing problems such as pollution, soil degradation, biodiversity loss, or climate change. The definition given by the panel suggests that a sustainable food system should provide safe, nutritious, and environmentally friendly food for both present and future Europe (EU) citizens while also protecting and restoring the natural environment and its services. Additionally, the system should be economically strong, follow principles of justice and fairness, conform to societal norms and standards and be inclusive, and not compromise the availability of healthy food for those inside or outside the EU, nor destroy their environment.

Some of the most important links in the food chain and the adjustments that may make it more resilient are included in Table 1. Many factors must be taken into account in order to optimize ensuring and availability, including initial manufacturing, post-harvest procedures, transportation and warehousing from farms to supermarkets, shipping and storing from supermarkets to consumers and food provisions, food preparation and waste, waste food after trade, and food policy (Knorr & Augustin, 2021). Sustainable processing, packing, delivery, and preparation strategies, as well as better management of resources (resources, goods, fluids, energy, waste, and expenditures), have previously been identified as crucial recommendations for a more resilient system (Augustin et al., 2016; Khoo & Knorr, 2014; Knorr et al., 2018). A phrase mentioned in Table 1 that should be defined is the PAN concept. The European Technology Platform; Food for Life (ETP 2007), a research vision document focusing on the European food industry, proposed the PAN (reverse engineering) framework within its processing group. This framework advocates for adapting food processes to meet consumer preferences, acceptance, and needs, thereby shifting the traditional approach of conforming raw materials to processing requirements (Knorr & Watzke, 2019).

Key food chain steps	Proposed needs and mitigation strategies
Supplies and Access	Re-evaluate access to raw materials and natural resources
	Re-evaluate needs for food production
	Harmonize production and access
Primary Production	Adopt agroecological approaches
	Consider alternative approaches to conventional agriculture (e.g. organic farming, small versus large farms, diversification of crops instead of monocultures, vertical farms)
	Optimize production based on nutritional yield
	Take on precision agriculture innovations
	Consider the pros and cons of genetically engineered crops to improve yields or build in desirable attributes
	Optimize harvest time for product quality and use real-time measurements for assessing produce attributes on farm
	Consider fermentation technology and culturing techniques as an adjunct to land-based agriculture for food production
Post-harvest processes	Improve grading practices
	Improve on-farm preservation, storage and transport
	Consider ensiling or drying excess/waste produce for animal feed
Transport and storage	Improve supply chain management
	Use appropriate packaging, preservation, and storage, transport to maintain quality (nutritional, microbial, functional attributes, including sensory, texture and color) and reduce losses
	Re-evaluate logistics systems and needs
	Introduce digital technologies to track and trace
	Transition to energy-efficient transport and storage systems
	Reduce, recover, and reuse loss and waste
Processing	Adopt more sustainable industrial food processing technologies (e.g. mild preservation, new fractionation and separation using greener extractants and membrane processes, emerging technologies such as high-pressure processing and application of ultra-sound in place of traditional methods)
	Use more energy-efficient home food preparation methods
	Introduce novel fermentation steps for producing value-added ingredients and food products
	Advance process-structure-function relationships for obtaining nutritionally optimized and sensorially appealing ingredients and food products

	Enhanced productivity in food manufacturing plants with the use of robotics
	Build “open access” processing facilities and regional processing hubs
	Reduce resource requirements for processing
	Reuse/regenerate and extract useful components from farm/food loss and waste (e.g. bioactives, chemicals, etc.)
	Tailor food processing to meet consumer expectations (PAN concept)
Retail	Improve training of personnel
	Educate consumers; Improve consumer information and dialogue
	Re-evaluate shelf life and use-by dates
	Develop safety/freshness indicators and rapid monitoring techniques
	Employ intelligent logistics practices
	Introduce digital management systems
	Introduce new categories for marketing of edible produce which do not meet cosmetic standards (e.g. ugly fruit and vegetables)
Consumer/Food service	Educate customers and improve communication and information
	Develop appropriately sized servings to avoid waste and overconsumption
	Rebuild consumer trust
	Promote sustainability education, including strategies for shifting to sustainable diets
	Develop consumer sharing networks/food banks for the re-distribution of foods to avoid waste
	Reduce, recover, convert, reuse and provide leftover use concepts and recipes
	Provide leftover use concepts and recipes
	Re-introduce the social importance of meals and the value of food
	Improve communication with and among consumers regarding appreciation/value of food
Trade and Food Policy	Advocate for fair trade
	Engage with governments to shape policy
Through Chain Practices	Develop sustainable food value chains that provide access to affordable food
	Develop and use real-time safety management systems
	Embrace the contribution of digital technologies to improve the safety and transparency of food chains
	Involve multi-stakeholders along the chain in the dialogue for improving the sustainability of food chains
	Ensure all players along the chain have equitable returns/benefits

Table 1. Needs and prevention methods for enduring and robust food value chains. The table comes from (Knorr & Augustin, 2021).

1.3 Nexus thinking and its effects on the food system

The occurrence of widespread problems with water supply, energy, and food industries has resulted in multiple challenges across various regions across the world. This has further exacerbated the interplay between supply and demand for these essential resources. Many nations have been grappling with issues such as water depletion and shortage, food security, ambiguities or indeterminacies related to energy matters, and ecological degradation. According to projections extending to the year 2050, there is a likelihood of a surge in the global population, with estimates indicating that it may reach around 9.8 billion. According to the projections, climatic interference is expected to cause a decline in agriculture output from 9% to 21%. Moreover, there is an estimation that the demand for water will experience a 55% surge (Fernandes Torres et al., 2019).

Various sectors that exhibit interdependencies support the global economy. These interdependencies are characterized by five significant aspects. Firstly, food, water, and energy are all interdependent on one another. Secondly, economic sectors are associated with at least one of these three elements. Thirdly, any modifications to these elements result in chain reactions in the related segments. Fourthly, the consumption of these elements generates negative impacts that are transferred to society. Finally, the interdependencies among these elements are becoming increasingly evident in the current scenario of resource scarcity and crisis (Fernandes Torres et al., 2019).

The nexus concept's recent unification and rising prominence may be attributed to concerns regarding the reliability of water, energy, and food provision. Additional factors that contribute to this phenomenon include the impacts of climate evolution, including worldwide heat waves and extreme temperatures, rising demands for natural resources, and inadequate planning and administration approaches (Fernandes Torres et al., 2019).

Safety occurrences possess the capability to trigger disturbances in social, economic, and environmental domains, as well as furnish prospects for devising remedies. The utilization of the nexus theme has garnered growing attention in academic discourse as a viable approach to addressing worldwide issues. The utilization of the nexus field has the potential to facilitate the attainment of ambitions stipulated in the Paris Agreement, which was concluded under the UN Systems Convention on Global Climate Change, the United Nations' goals for sustainability Goals (SDGs), and the UN (Fernandes Torres et al., 2019).

Following its consolidation, several authors have emphasized the difficulties involved with the nexus theme's approach. The absence of agreement in defining the notion of nexus can be observed initially. The term is commonly understood as a systematic approach to integrating and managing diverse sectors, aimed at fostering sustainable development through collaborative coordination. According to Fernandes Torres et al., 2019, some scholars view it as a novel perspective or an innovative integrated management paradigm that aims to face the global problems of transformation. However, this viewpoint is merely a modification of established ideas and frameworks in the scientific domain or a strategy for managing externalities across various sectors; among other principles, the emphasis is on improving system efficiency as opposed to the productivity of particular sectors (Fernandes Torres et al., 2019).

The application and operationalization of the conceptual aspect pose significant challenges. These challenges include: (a) the requirement of providing cutting-edge approaches and deliberative instruments that help manage interdependencies, protect investments, and boost profits, (b) additionally, there is a need for nexus modeling, (c) addressing institutional, legal, and governance issues, (d) considering spatial-temporal scales of operation, (e) it is also important that all the data be easily accessible and merged, and (f) observing the benefits attained through applying nexus concepts in practice when contrasted with the absence of these concepts in a non-nexus setting. According to Fernandes Torres et al., 2019, the nexus idea emphasizes resilience as a core principle for controlling the system's adaptability to various ecological problems, such as those brought on by the possessions of climate alteration (Fernandes Torres et al., 2019).

The literature indicates that nexus modelling is subject to five limitations. These limitations include (a) complexity when all three aspects and their changing interactions were taken into account concurrently in one model; (b) models that could translate into various kinds of metrics relating to the food, water, and energy arrangements and interrelated variables; (c) adequate databases to backing integrated examination; (d) the geographical bounds of the structure to be demonstrated, (e) the necessity for interdisciplinary demonstrating that incorporates qualitative and quantitative analyses (Fernandes Torres et al., 2019).

1.4 Problem statement and research questions

A significant gap concerning the application of system dynamics in urban farming and its outcomes has been found. While more studies are being conducted on urban agriculture, few have used system dynamics to model the interactions of the main factors that determine whether urban farming initiatives succeed. For academics and stakeholders, this knowledge gap represents an opportunity to understand urban agriculture dynamics better and devise evidence-based policies for fostering its expansion and sustainability. Simulation of the effects of urban agricultural systems, determining crucial leverage points for intervention and empowering stakeholders can be achieved by using system dynamics to make more well-informed decisions regarding resource allocation and policy formulation. In the long run, this may lead to urban agricultural practices that are more efficient and long-lasting, which is a sustainable action for city dwellers and the food system.

The problem addressed in this study is the urgent need to address sustainability challenges in food, water, and energy and the potential role of community gardens in mitigating these challenges. While community gardens have gained prominence as a form of urban farming due to their potential to enhance food security, foster social cohesion, and mitigate environmental impacts, there is a need for a comprehensive understanding of the behavior and dynamics of community gardens regarding land usage. Additionally, the strategies for maximizing the productivity and impact of community gardens while considering factors such as production efficiency, cost considerations, and land allocation require further investigation. Therefore, this study aims to analyze the performance of community gardens concerning land usage and explore the potential of these initiatives to contribute to sustainable development, addressing key research questions related to sustainability, food security, urban farming, and achieving Sustainable Development Goals.

The following research questions have been considered to fill this gap:

1. How can system dynamics be utilized to simulate the interaction of the effective parameters that determine whether or not an urban farming initiative succeeds?
2. How can system dynamics be utilized in models to determine which policies and interventions will most impact the development and long-term viability of urban agriculture?
3. Using system dynamics, what are the social, economic, and environmental advantages and trade-offs of urban farming?
4. How can urban farmers, politicians, and community members work together to improve sustainable cities to represent the intricacies and problems of actual urban agriculture accurately?
5. How does the ratio of land dedicated to community gardens impact local food production and food security in urban areas?
6. What are the key factors that influence the production efficiency of community gardens, and how can they be optimized to enhance their productivity?
7. How do community gardens contribute to social cohesion and community engagement in urban neighborhoods?
8. What are the barriers and challenges in implementing and scaling up community garden initiatives, and how can they be overcome?
9. How do community gardens align with and contribute to achieving the Sustainable Development Goals outlined by the United Nations?
10. How can community gardens be integrated into urban planning and development strategies to promote sustainable urban agriculture and sustainable communities?

Chapter 2

(Literature Review)

2.1 Food-water-energy nexus

There has been a lot of discussion in academia and policy circles about the Food-Water-Energy (FWE) Nexus in recent years. In this framework, FWE is all seen as interconnected in terms of production and consumption (Mahlknecht et al., 2020).

The FWE Nexus was initially proposed during the Bonn 2011 Nexus Conference, although this nexus existed from the beginning (Mahlknecht et al., 2020). According to the nexus concept, FWE is interdependent, with effects in one sector affecting the performance of the others; as a result, there is a pressing need to combine their governance and management (Mahlknecht et al., 2020).

The World Economic Forum Nexus is an effort to understand better the interplay between several factors that have traditionally been treated independently. Water services, fisheries, irrigated agriculture, and food production exemplify how water is essential to economic stability. Hydroelectric power generation and biofuel production are two examples; water is also used in nuclear and geothermal power plants for cooling systems, crucial to gasoline and shale gas extraction and is used in mining operations. Long-distance pumping, water delivery, filtration, sewage treatment, and evaporation require energy from water for human consumption and irrigation. Globally, 70% of freshwater withdrawals go towards agriculture (Food and Agriculture Organization of the United Nations, 2017).

According to a report published in 2016, about 10% of water extractions are used for primary energy production and electricity generation (Energy and Air Pollution - World Energy Outlook 2016 Special Report, 2016), which is allocated towards the primary manufacturing of energy and the production of electricity. Additionally, 30% of the output is directed towards food production and its associated supply chain, while 8% is allocated towards removing (Mahlknecht et al., 2020), transportation, and sewage treatment. A visual representation of this distribution can be observed in Figure 1.

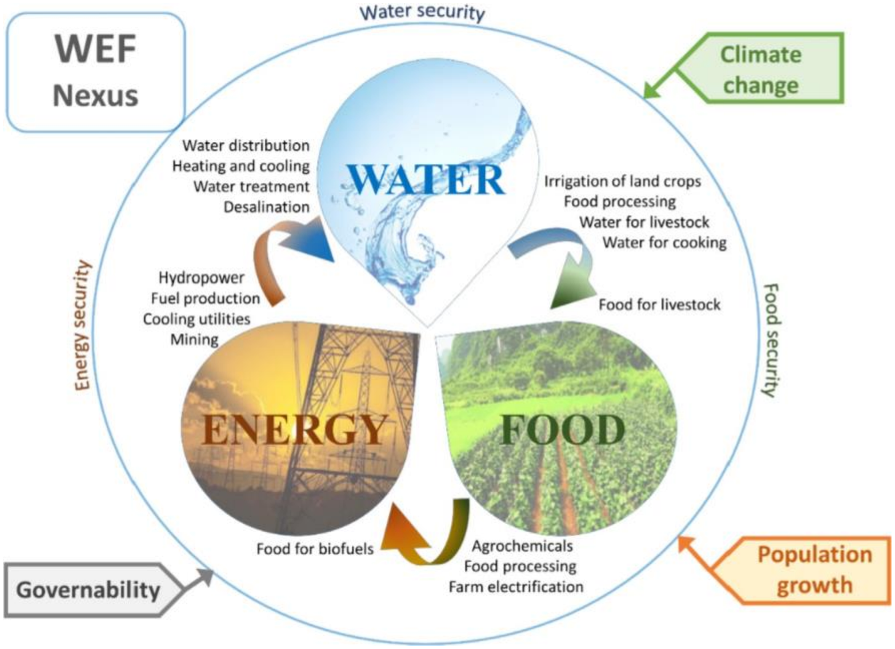


Figure 1. Summary of the water-energy-food (WEF) Nexus. The figure comes from (Mahlknecht et al., 2020)

2.2 Food security

It is crucial to highlight that attaining food security is not solely contingent upon an increase in food production; instead, it is a multifaceted and intricate process. The challenge at hand involves the modification of dietary patterns and the integration of novel technologies and tactics to ensure that the food production system is both sustainable and ecologically conscious. The right to sufficient nourishment and freedom from hunger is a fundamental human entitlement encompassing various dimensions of food security (Coronado-Apodaca et al., 2023).

Over time, the idea of the security of food has evolved to encompass additional dimensions beyond mere food availability. These dimensions include issues related to food availability and quality. The present food systems are causing the degradation of land, water, and ecosystems, the loss of biodiversity, the emission of excessive greenhouse gases, and ongoing malnutrition and hunger. The imperative for achieving food security necessitates a shift towards a sustainable trajectory, owing to the environmental impacts stemming from the widespread production of nutritional needs and climate change pressures. The transition towards sustainability can encompass various sectors, with the agricultural sector widely acknowledged as a critical opportunity for implementing improved practices toward achieving food security (Coronado-Apodaca et al., 2023).

The adoption of novel agricultural technologies that enhance soil properties, carbon accessibility, plant nutrient uptake, and crop productivity is imperative to uphold the interdependence of sustainability and food safety. In addition, adopting plants, mushrooms, insects, seaweed, and microalgae, some examples of substitute sources of sustenance has been advised as a potential approach to attaining sustainable food security (Coronado-Apodaca et al., 2023).

Moreover, the implementation of various techniques, including food production methods such as urban farming, aquaculture for fish, horticultural and vertical gardening, and sustainable agriculture, represent potential areas for investigation in the pursuit of sustainability (Ścieszka & Klewicka, 2019; Raposo et al., 2021).

The paradigms surrounding food security are subject to temporal and geopolitical fluctuations, as evidenced by the impact of global pandemics and armed conflicts. The advocacy for well-rounded and nourishing dietary practices has emerged as a pressing concern for various parties (Galanakis et al., 2021; Farsi Aliabadi et al., 2021), given that both obesity and undernourishment represent unhealthy nutritional states that are far removed from balance (Mariutti et al., 2021).

The imperative to revolutionize food systems is an indisputable fact beyond debate. The task involves establishing a viable and enduring approach toward accomplishing the requisite shift in food production that considers ecological, demographic, and cultural considerations and novel frameworks concerning the economic, political, and religious ramifications of relinquishing extant food production systems. This endeavor must also address diverse sustainability obstacles, including but not limited to climate change, resource depletion, biodiversity erosion, food security, and malnourishment, among other challenges (Pereira et al., 2020; Borsellino et al., 2020).

Notwithstanding its status as a ubiquitous transformational requisite, it is critical to be conscious that the demography and socioeconomic contexts of the locations where these problems are studied have a major impact on the agricultural systems in those areas. In the primary phases of the expansion of food security, the major emphasis was placed on satisfying the rising demand for food among the people. This was done without taking into consideration the possible pressure that this demand may have on natural resources or the negative effects it could have on the environment. The development of food security has been explored through various pathways. Instead of concentrating on expanding food production, attention has shifted to other measures, such as minimizing food waste via improved food management and modifying eating patterns to adjust the kinds of food necessary for a particular population, which is illustrated in Figure 2 (Coronado-Apodaca et al., 2023).

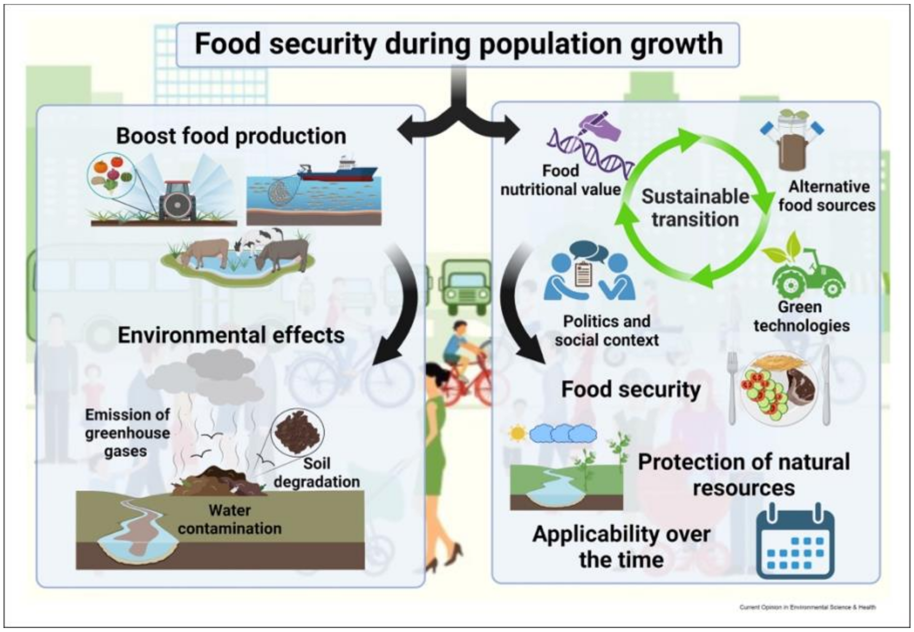


Figure 2. Food security strategic transitions and their potential effects. The figure comes from (Coronado-Apodaca et al., 2023).

The possible outcomes of various routes taken to achieve food security are depicted in Figure 2 which shows the drawbacks of a shift that views the rising population only through food needs. Soil deterioration from excessive farms, fertilizers, pesticides that pollute water supplies and other compounds, and greenhouse gas emissions from overgrazing are only a few of the possible adverse environmental consequences. Alternatively, it praises the benefits of an environmentally friendly change that considers elements such as the significance of the vitamin and mineral content and social, political, and economic context, both of which are foundations of food security adjustments and take into account various options for ensuring food security, counting the use of creative methods for cultivating food (like as combining technology advancements with organic farming) and other sources of food (Coronado-Apodaca et al., 2023).

With the emergence and evolution of many transition pathways, it is now abundantly obvious that the selections made about the specific transition chosen and the specific problems addressed will always be context specific. Discovering changes that are adaptable to the distinct nutritional, socioeconomic, ecological, political, or cultural variations in and between societies is one of the most pressing issues that currently confront the process of making decisions regarding food security because it calls for coordinated collective action instead of the adoption of several little initiatives if societies are to attain the desired goals. This is one of the most significant obstacles facing the decision-making process regarding food security (Coronado-Apodaca et al., 2023).

Even though it is obvious that moves in food security should be implemented under the supervision of work networks and allies, it is constantly necessary for them to be adapted in accordance with the preferences of stakeholders, particular food security problems, and the broader ecological and political settings of the local area. According to a study Coronado-Apodaca et al., 2023, it is also important for scientists and policymakers to collaborate in order to implement environmental protection measures and social and political demands (Dijkshoorn-Dekker et al., 2020).

Despite the significance of ensuring a steady food supply, high production levels must be adjusted to lessen the detrimental effects on the surroundings and natural resources caused by climate change. Recent reports have identified many key sustainability transitions, including farming 4.0, strategy-oriented systems for agriculture, complex viewpoints, and resident-consumer strategy. The goals of these approaches to sustainable development are to maximize the use of available resources, take into consideration a diverse set of factors, and put the spotlight on the role that everyday citizens play in bringing about this transformation (Klerkx

& Rose, 2020; Klerkx & Begemann, 2020; Mehrabi et al., 2022).

The relevance of the population's changing dietary habits is emphasized by Mehrabi et al., 2022. The researchers focus that community-wide eating patterns are the driving force behind food demand and should be a central consideration in policymaking. An increase in the number of people are switching to plant-based or "green" diets, decreasing the petition for meat and dairy harvests and boosting the supply of vegetables and fruits. The present market demand for organically grown food also encourages farmers to use sustainable agricultural methods.

The significance of food security is undeniable; nonetheless, it has been shown that food security must rest on several interrelated factors. These factors include food, the environment, water, society, and politics. Recent studies have documented the systemic destruction the food production industry has caused to the environment. When coupled with the effects of climate change, the direct method has led to scarce food and environmental quality (Coronado-Apodaca et al., 2023).

2.3 Water resources in the food system

Due to water ecosystems' significance in food production, their services are among the most crucial to address in the move toward justifiable food security (Yang et al., 2021). Therefore, the availability of water and the stability of food production are inextricably linked. Water shortages due to climate change have increased the probability of worldwide crop failure, especially in tropical areas where their impacts are more frequent due to climatic changes (such as high temperatures and droughts) (Pei et al., 2022).

Managing water in farming, adaptation to climate-smart farming, and the promotion of indigenous plant expertise are all examples of climate-resilient variables that may contribute to a loop between the availability of water and food production (Srivastav et al., 2021). If organic enrichers and pesticides are used judiciously in computationally severe or wide farming observes, water can be reused in environmentally friendly agricultural processes, lacking the costs associated with conserving water in the soil under present-day climate conditions (Zhang et al., 2022; Voutchkova et al., 2021; Parra-Arroyo et al., 2022). Recent investigations of a growing practice used in an urban area of California, US, reveal that it improves the management of water, soil utilization, and food supply for people and animals. However, more work is needed to develop policies that facilitate the administration of such practices, according to the findings of Lin & Egerer, 2020.

Agroforestry, which is defined as agriculture incorporating the cultivation and conservation of trees, has been offered as an alternative with increased attention over the last decade owing to the centrality of food security and the incorporation of natural services because it is applicable in regions of rural and urban agricultural production where there is a major lack of water, which has a significant influence on the soil. This process involves mixing forest trees with crops to increase the carbon and nitrogen cycle by trees and reduce water demand. The results indicate that besides, water spending can be optimized, fertilizer use can also be avoided, protecting natural resources from contamination (Pantera et al., 2021; van Noordwijk, 2021). Finally, plans for water reuse in agricultural zones near metropolitan areas depend on wastewater treatment that protects nutrients for food production while dramatically decreasing or removing toxic chemicals in consumer items (Drangert, 2021).

2.4 Challenges of food production

Despite its importance as a sponsor of the world's stream of food, agrarian activities are becoming more vulnerable to environmental change, recent studies from FAO showed (FAO, 2018; Li et al., 2020). This is because (a) The demand for food is rising, particularly for goods that require a lot of resources (caused by a growth in population, income, and urbanization); (b) The availability and quality of land and water for food production are decreasing; (c) while being one of the biggest producers of greenhouse gas emissions, the agriculture sector is becoming more and more endangered by climate change; and (d) Insufficient money is being spent on sustainable agriculture. Because of the predicted increase in urbanization (70% of the population will live in cities by 2050; (FAO, 2009)), agricultural land is expected to continue to decrease. The greater distance between rural farms and urban centers reduces the desirability of this practice since it lowers food quality, increases waste, and places an additional environmental strain on the system. Meanwhile, growing markets for animal products and bioenergy are diverting agricultural land from food production (Li et al., 2020), which could exacerbate already dire food shortages. The FAO mentioned that in order to make the transition from "business as usual" (BAU) to sustainable production, we need novel ideas and innovative technologies to enable environmentally friendly broadening, effective use of the environment and energy, and cutting down on the emission of greenhouse gases (FAO, 2018).

2.5 Environmental impacts of the food supply chain

The researchers (Porter et al., 2016) found out that the food distribution system, illustrated in Figure 3, is a complex system that encompasses numerous sectors (including agricultural, transportation, industrial operations, retail, waste, and land use) and involves a wide range of participants.

As shown in Figure 3, there are several stops along the way from the farm to the consumer for food intended for human consumption. "Upstream" refers to the first three steps, when the phrase "loss" is used; "downstream" refers to the last two steps, where the term "waste" is used. Each nation and food item follows a similar conceptual framework for the food supply chain (FSC) phases. The FSC is vulnerable to waste at any step. There are many different types of food waste: losses that occur during harvesting, such as those caused by damage and/or quality, following the harvest preservation and handling, including transportation distortions, interpreting loss, the failure to compensate for expenses due to manufacturing leakage and/or decline distribution wasting. Gustavsson highlights two types of food waste in the market system: supply chain waste and consumer waste. The former pertains to the loss of food occurring in the wholesale and retail sectors, while the latter refers to the wastage resulting from consumer behavior, which can transpire both inside and outside the household (Gustavsson et al., 2011).

In 2007, (*Food Wastage Footprint*, 2013; Gustavsson et al., 2011) conducted the first worldwide research to put a number happening the volume of food that is vanished or wasted by utilizing information derived from the FAO of the UN. The researchers calculated that around 1.3 Gt/year of food is lost or unexploited globally between farms and end users. The following technical article calculated a "cradle-to-grave" value of around 3.3 GtCO_2e by applying GHG emission coefficients to these losses; the great majority of these emissions (63%) arose during the agrarian making point (FSC 1; (*Food Wastage Footprint*, 2013)). In contrast (Hiç et al., 2016) estimated GHG emissions related to "surplus food" or the difference between what was produced and what was eaten, using a more top-down methodology. Emission estimates for 2005 using this technique are 27% lower than those using the *Food Wastage Footprint* (2013) (410 vs 560 MtCO_2ey^{-1}). However, they failed to factor in the GHG impact of leftovers at later points of the supply chain.

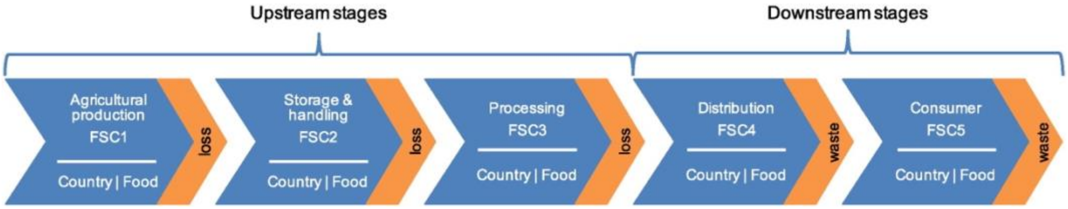


Figure 3. The food supply chain. The figure comes from (Porter et al., 2016)

2.5.1 Greenhouse gas emissions of the food system

Figure 4 depicts the weekly average home Greenhouse Gas Emissions (GHGEs) in $kg\ CO_2e$ per Standard Adult Equivalents (SAE) across the food system's various supply chain phases. Approximately 67.9% of weekly household GHGE spending on food is attributable to agricultural production and manufacturing. The largest contributor to GHGEs from consumer food expenditure was the hospitality industry at 25.4%, followed by trucking at 4.7% and wholesale commerce at 1.5%. Average weekly household GHGEs were 0.4% due to all other modes of transportation (i.e., water, rail, and air). According to Boehm et al., 2018, GHG emissions per SAE from food spending, on average each week, are divided down per manufacturing phase, and the 26 firms in the dietary supplement industry that supply American homes can be shown in Figure 5, GHGE contributions from various points in the food supply chain were not uniform across sectors.

The majority of GHGEs came from livestock production (86%), then liquid milk, dairy products, buttermilk (82%), and cheese (82%). Spirits, wine, and fruit and nut processing accounted for just a minor fraction of total GHGEs, whereas other sectors were responsible for the vast majority. On average, just 8% of each sector's GHGEs came through wholesale. Truck transport was responsible for 19% of GHGEs in the fruit and grain businesses and 13% in the vegetable and melon industries. The percentage of GHGEs from truck transportation was highest for these two sectors relative to all others. Only 1.4% of each sector's total GHG came from rail, water, and air transportation. The retail sectors responsible for the greatest amount of GHGEs were the fruit and nut, snack food, and breakfast cereal industries, respectively (27%, 27%, and 25%). Finally, the most significant contributors to GHGEs at eating establishments were the use of alcoholic beverages (39%), fish (30%), and beer (26%) (Boehm et al., 2018).

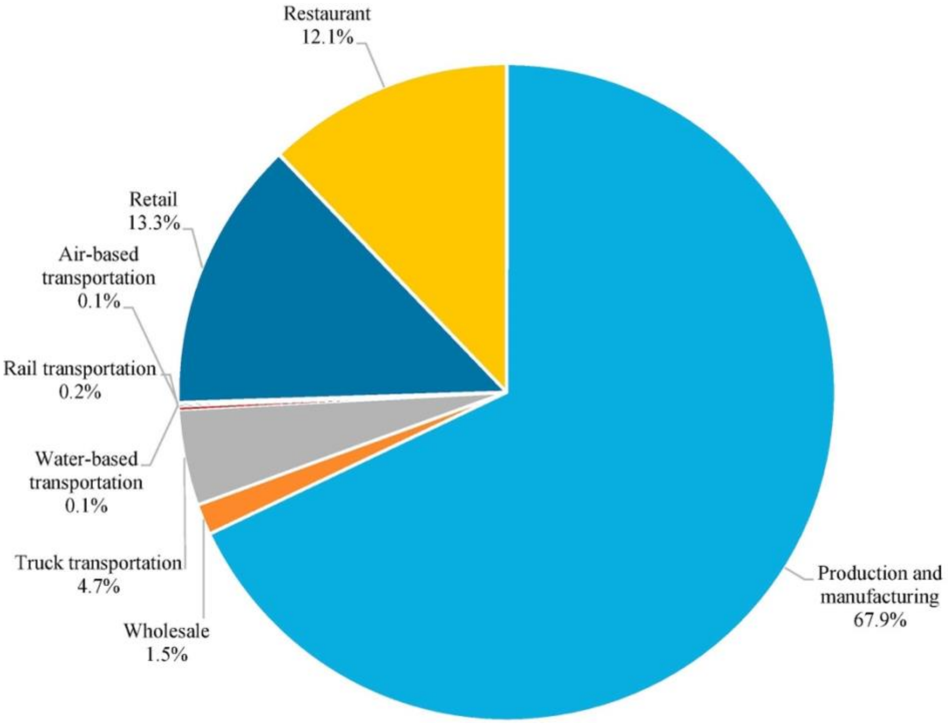


Figure 4. Average weekly household GHGEs per (Standard Adult Equivalents) SAE by supply chain stage (n = 4723 households). The figure comes from (Boehm et al., 2018)

In comparison to the extremely low GHGE category and the smallest GHGE quintile, families belonging to the highest quintile of GHGE have allocated a proportionately higher amount of their daily food expenditure, approximately 19%, towards the consumption of proteins. Compared to the lowest percentile, those in the top two GHGE categories spent much less of their food budget on grains (21% and 24% less, respectively). With a drop of 16% compared to those in the lowest GHGE percentile, those in the highest quintile of GHGE spending spent less on beverages as a proportion of their overall food budget. More than a third (32%) of the GHGE percentile's food budget was spent on fats, oils, and sugars as accoutrements and sweets. The quintile of greenhouse gas emissions has a substantially more considerable influence on the atmosphere (Boehm et al., 2018).

On average, families in the very high GHGE quintile produced 9.8 times as many GHGEs as those in the exceptionally low GHGE quintile. In comparison to families in the incredibly low GHGE quintile, households in the very high GHGE quintile spent an average of 8.8 times more each week on food. Households in the exceptionally high GHGE quintile had emissions intensities per dollar of food expenditure that were 7.3% and 6.1% greater than those in the very relatively low quintiles, correspondingly. The highest GHGE quintile households' secretions strength per dollar of revenue was 5.4% greater than the lowest GHGE quintile individuals (Boehm et al., 2018).

The weekly average of GHGEs produced by food expenditure at the household level is equal to driving an average US passenger car 174 miles (Boehm et al., 2018). The majority of the GHGEs associated with food consumption in the United States occurred during production. However, the percentage of GHGEs at each supply chain stage was not consistent across food sectors. The fresh vegetable and melon sectors have the biggest post-production GHGE contributions, including wholesale, transportation, retail, and food service. Boehm et al. (2018) found that consuming fruits and vegetables produced locally might be an effective technique for reducing the GHGEs caused by transportation in the food chain.

Boehm et al., 2018 found that the retail and food service sectors might be prioritized in reductions in GHG emissions (from the agriculture supply) that are being made. Furthermore, they demonstrated that meat consumption and meat-related spending are significant drivers of GHGEs in the American food system and individual households. The primary contributor to weekly home GHGEs came from the livestock and fishing industries.

This finding is in alignment with prior lifespan tests, which have demonstrated that the production of meat and animal-based products is accompanied by the highest levels of GHGEs (Eshel & Martin, 2006; Garnett, 2009; Kari Hamerschlag, 2011; Steinfeld et al., 2006; Weber & Matthews, 2008). Some research suggests that a plant-based sustenance produces fewer GHGEs than a high-meat diet (Scarborough et al., 2014; Soret et al., 2014).

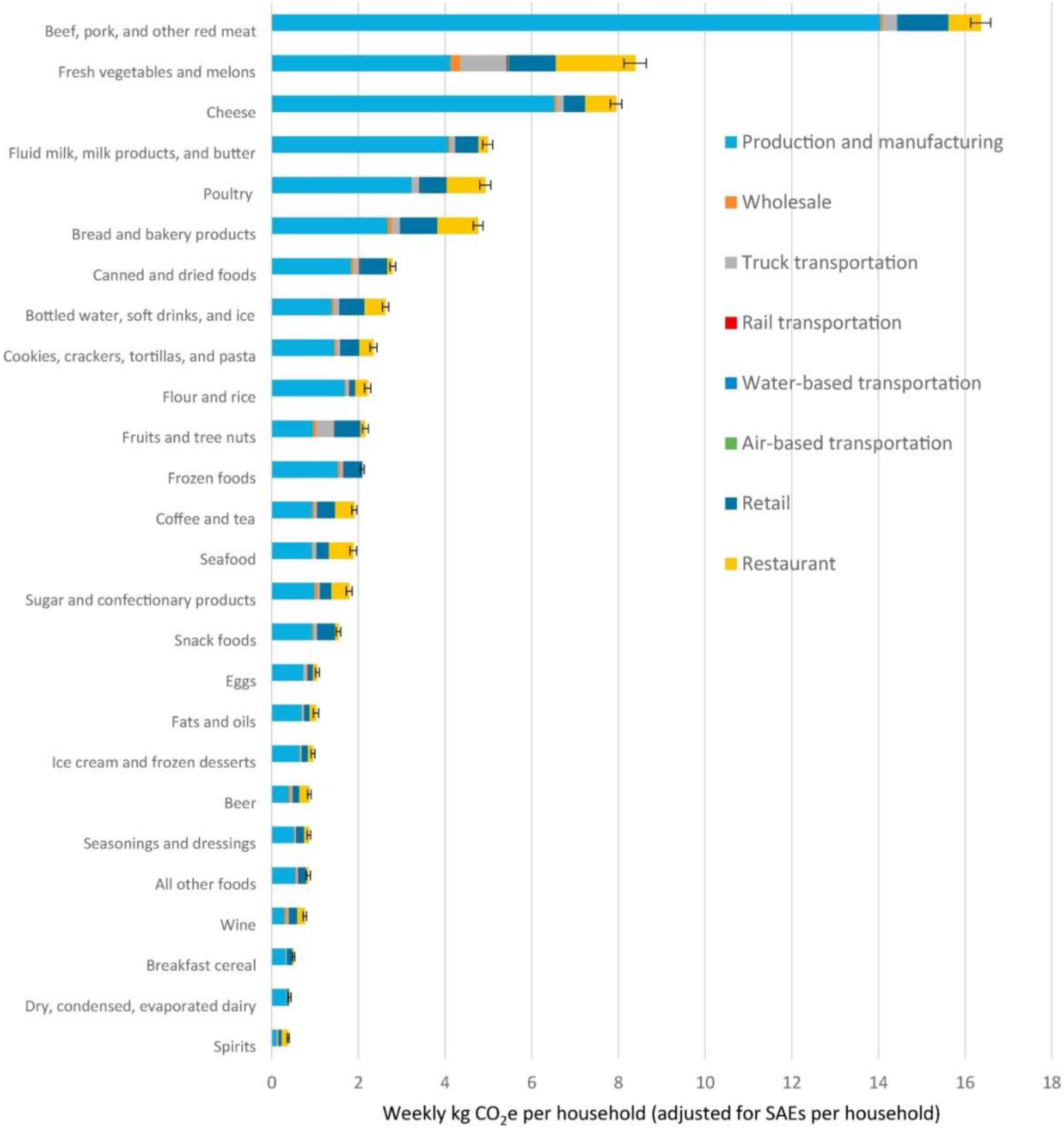


Figure 5. Average weekly home GHGEs per SAE, broken down by supply chain stages, for food service system businesses (n = 4723 households). The figure comes from (Boehm et al., 2018).

However, despite the trend towards eating less meat, Ontarians still consume a large amount of protein from sources other than meat, such as milk, cheese, and other dairy products, based on a study by Topcu, 2018. Increases in the utilization of no-red meat alternatives and decreases in the consumption of red meat goods, especially beef, suggest that Ontarians are moving towards healthier and less carbon-intensive animal products. This shows that individual dietary choices could shift over time and that these shifts can lead to better, less carbon-intensive diets. Consequently, as the end users, the public can play an important role by manufacturing sustainable decisions, such as picking food items in a period and consuming fewer foods based on animals. Topcu, 2018 notes that the carbon footprint of diets is particularly heavy in two areas: the production of animal products and greenhouse vegetables.

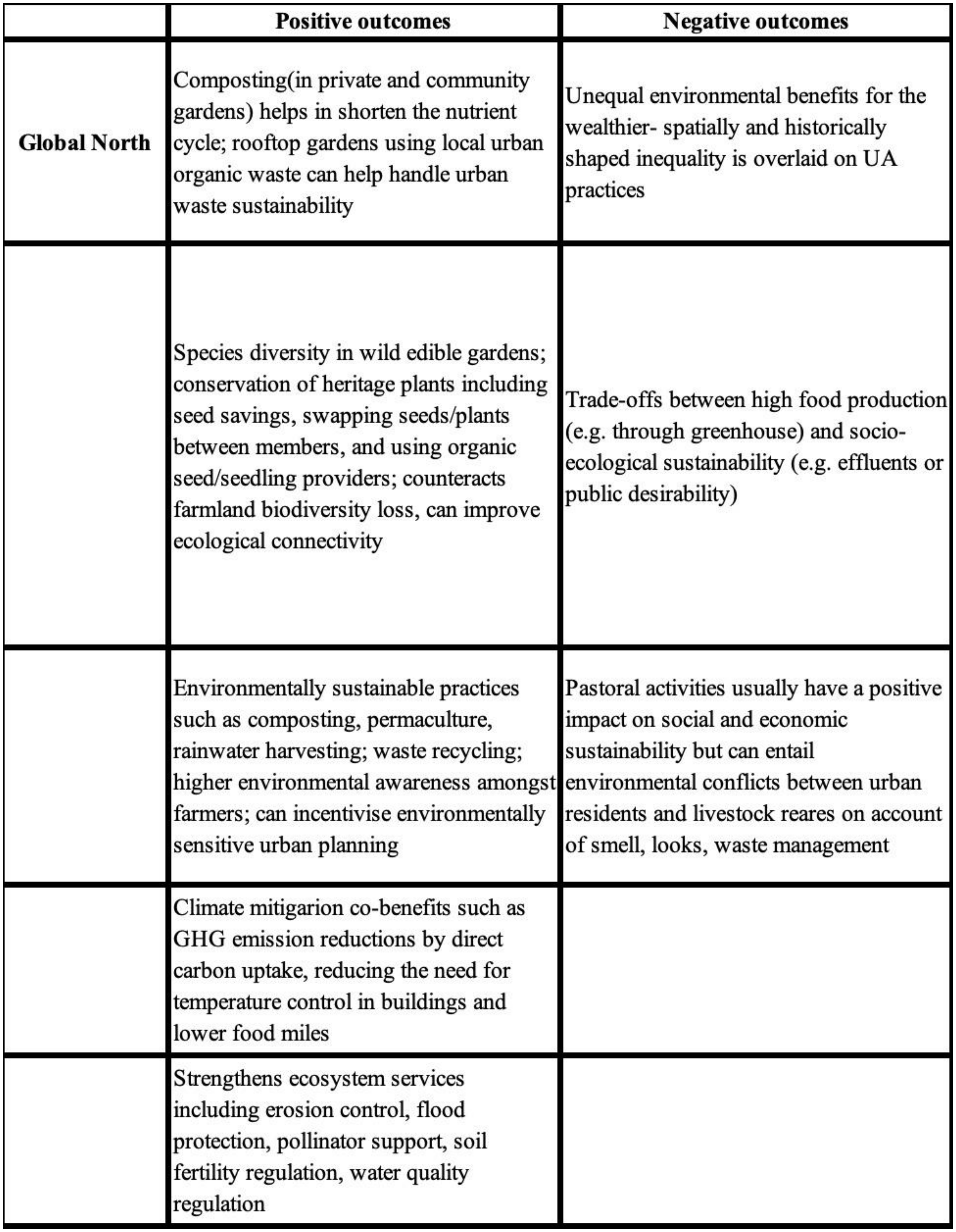
In addition, (Drewnowski et al., 2015) observed that refined-grain foods, which are high in energy density but low in GHGEs per gram and calorie, had a lower GHGE content overall.

2.6 Urban farming

Urban farming is an alternative to traditional farming in rural areas, which entails growing, preparing, and redistributing food in and around metropolitan centers. In addition to protecting the availability of fresh food for large customers, this strategy also helps cities adapt to climate change by recycling urban trash, creating greenbelts, and employing residents. Waste recycling in urban farms also promotes urban symbiosis by contributing to the progress of a citywide rotary economy and preserving nature reserves outside of metropolitan areas (Li et al., 2020).

2.6.1 Positive and negative environmental outcomes of urban and peri-urban agriculture

The literature presents various viewpoints on the results, with varying accounts of positive and negative outcomes across various parts of the world (Tables 2 and 3). The potential benefits of incorporating strategies for promoting biodiversity and species richness and implementing sustainable urban practices have been widely discussed in academic literature. Meanwhile, northern cities alone claim climate mitigation advantages. This highlights the need for further research on the effects of urban and peri-urban agriculture (UPA) on reducing greenhouse gas emissions in the Global South. Southern cities look to areas outside their borders to generate pollution and garbage to mitigate their negative environmental impacts (Rao et al., 2022). A study in Antananarivo, Madagascar (Aubry et al., 2012), provides a case study on how urban farming may reduce flood danger upstream but increase water pollution downstream. More articles focus on the negative social effects of UPA in northern cities, such as the exclusion of minorities and people with low incomes from sustainability narratives (Rao et al., 2022).



	Positive outcomes	Negative outcomes
Global North	Composting(in private and community gardens) helps in shorten the nutrient cycle; rooftop gardens using local urban organic waste can help handle urban waste sustainability	Unequal environmental benefits for the wealthier- spatially and historically shaped inequality is overlaid on UA practices
	Species diversity in wild edible gardens; conservation of heritage plants including seed savings, swapping seeds/plants between members, and using organic seed/seedling providers; counteracts farmland biodiversity loss, can improve ecological connectivity	Trade-offs between high food production (e.g. through greenhouse) and socio-ecological sustainability (e.g. effluents or public desirability)
	Environmentally sustainable practices such as composting, permaculture, rainwater harvesting; waste recycling; higher environmental awareness amongst farmers; can incentivise environmentally sensitive urban planning	Pastoral activities usually have a positive impact on social and economic sustainability but can entail environmental conflicts between urban residents and livestock reares on account of smell, looks, waste management
	Climate mitigarion co-benefits such as GHG emission reductions by direct carbon uptake, reducing the need for temperature control in buildings and lower food miles	
	Strengthens ecosystem services including erosion control, flood protection, pollinator support, soil fertility regulation, water quality regulation	

Table 2. The positive and negative environmental effects of urban and peri-urban agriculture on global north. The table comes from (Rao et al., 2022).

	Positive outcomes	Negative outcomes
Global South	integration of subsistence livestock rearing in UPA helps maintain soil fertility and enable nutrient cycling; increase soil fertility and nutrient cycling, protects biodiversity and reduces waste and pollution	Water contamination due to agricultural chemicals coupled with poor landfill and sewage management can enhance disease; negative downstream impacts (e.g. higher water pollution due to intense paddy cultivation)
	Shortens production-consumption chains, with benefits for SDG12; enhanced species diversity and protection of flora and fauna	Excessive inputs increase land productivity but with environmental tradeoffs, especially when industrial fertilizers are used. With frequent irrigation this leads to nutrient depletion (through harvest and leaching) and instant replenishment (through manure/fertilizer and partly wastewater irrigation) resulting in the accumulation of poorly leached phosphorous and temporary depletion of nitrogen and potassium
	Absorption of floodwater where urban farmlands act as buffer zones, preventing/limiting flood in slums	Unintended health impacts: uncontrolled and long-term irrigation by wastewater leads to human and environmental damages
	Ecosystem restoration with long-term farming transforming barren land and improving food production, water holding capacity, biodiversity	
	Environmentally sensitive urban planning through allowing flexibility for trade-offs between pollution control and economic development	

Table 3. Environmental effects of urban and peri-urban agriculture, both positive and negative, on the global south. The table comes from (Rao et al., 2022).

2.6.2 Types of urban farming

Various urban farming systems have been developed, such as rooftop farming, which involves cultivating crops on the roofs of buildings. Vertical farming is an additional method that entails growing crops in stacked layers, while a plant factory is an indoor vertical farming system designed to produce high-quality food efficiently. The term 'indoor farming' refers to the practice of cultivating plants in an enclosed space with carefully managed environmental conditions (including but not limited to factors such as climate (air conditioning/heating, CO_2 levels, lighting, water, food, and nutrition). The term 'controlled environment agriculture' (CEA) describes a similar idea. Careful adjustment of environmental factors, such as the intensity of the LED lights used to simulate sunshine, may significantly increase crop output. Recent developments in sensor technology have made it possible to keep tabs on the CEA's ecosystem. The Internet of Things (IoT) is a concept that may be implemented to enable the automation of the agricultural process with the future creation of a chain of wireless sensors (Li et al., 2020).

Figure 6 illustrates the variety of urban agricultural methods that are springing up in today's big cities within the built environment. Rooftop farming is the most common kind of envelope-integrated system since roofs are enormous, underutilized solar-exposed urban sites. Farming on rooftops often takes place in either hydroponic-equipped rooftop greenhouses (RG) or intensive green roofs (Benis & Ferrão, 2018).

Examples of cutting-edge creations in this last category comprise local green power manufacturing via solar PV, waste heat capture from the HVAC system, circulatory water sources, collecting rainwater, and cooling technologies that evaporate (Gould & Caplow, 2012). According to a few companies in North America and Europe, it is possible to produce a significant amount of locally sourced food year-round for urban residents on underutilized rooftops (Benis & Ferrão, 2018).

Vertically Integrated Greenhouses (VIG) are a patented idea for growing plants vertically on building facades (Adams & Caplow, 2012). Double-skin building facades integrated with hydroponic systems comprise VIG systems (Benis & Ferrão, 2018).

The concept of VIG has been settled and patented for facades (Adams & Caplow, 2012). According to (Benis & Ferrão, 2018), VIG systems are comprised of building facades that feature a double skin and are integrated with hydroponic systems.

Another approach to high-yield urban food production is VF, which involves cultivating plants in multi-story urban structures without the need for soil (Benis & Ferrão, 2018). Certain scholars advocate for the validity of vertical farming (VF) on ecological grounds, contending that indoor plant cultivation entails lower energy consumption and reduced pollution compared to certain agricultural methods employed on natural terrains. Moreover, they assert that peri-urban regions are frequently unsuitable for agricultural production due to their high toxicity levels (Dickson Despommier, 2010). The practice of utilizing skyscrapers for cultivating crops, commonly referred to as Sky Farms (Germer et al., 2011) or Plant Factories (PF) (Kozai, n.d.), involves employing demanding closed establishing mechanisms.

Commercial urban farming has also seen the creation of components that do not need a separate outside operating space, such as repurposed shipping containers' (SC) heating and cooling systems. SC farms may be erected in unused lots, storage areas, underground spaces, or even rooftops, and they can harvest year-round because of their cutting-edge temperature control technology and hydroponic growing apparatus. Compactness, adaptability, wide availability, cheap cost, and simple transport are just a few of the many benefits of shipping containers (Benis & Ferrão, 2018).

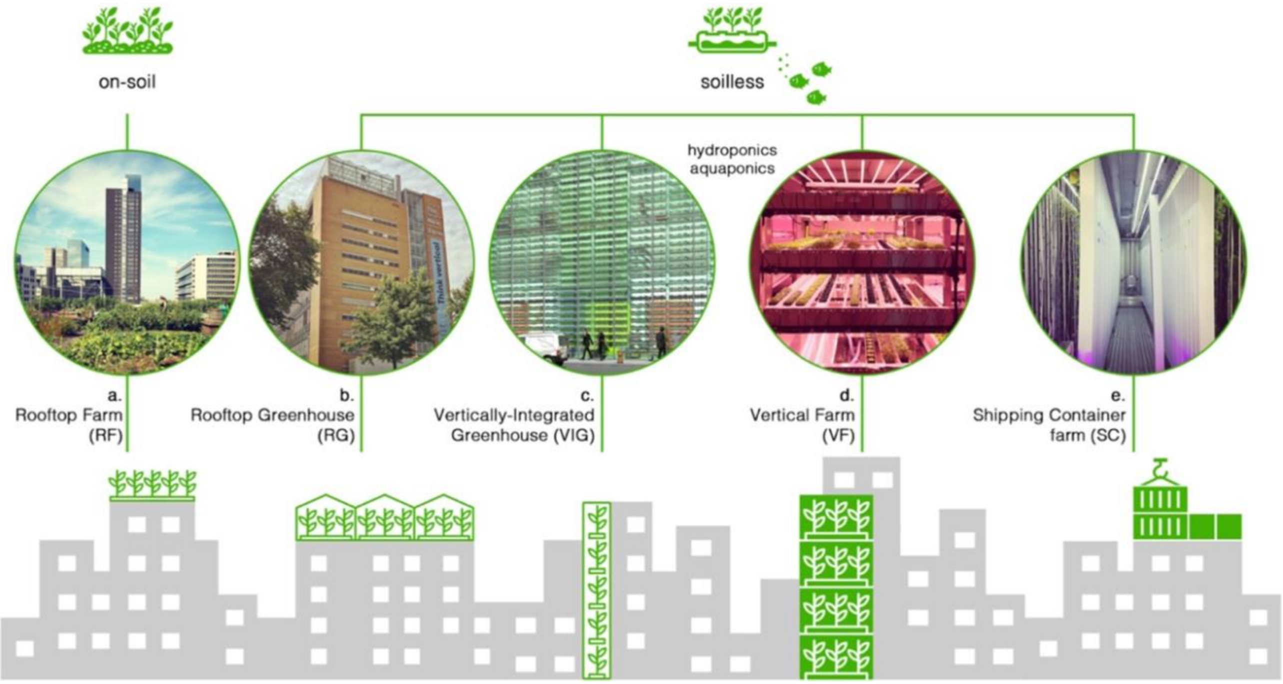


Figure 6. Typologies of commercial urban farming. The figure comes from (Benis & Ferrão, 2018)

The classification of soilless agriculture or controlled environment agriculture (CEA) is depicted in Figure 7. According to Ragaveena et al., 2021, the primary farming techniques comprise hydroponics, aeroponics, and aquaponics.

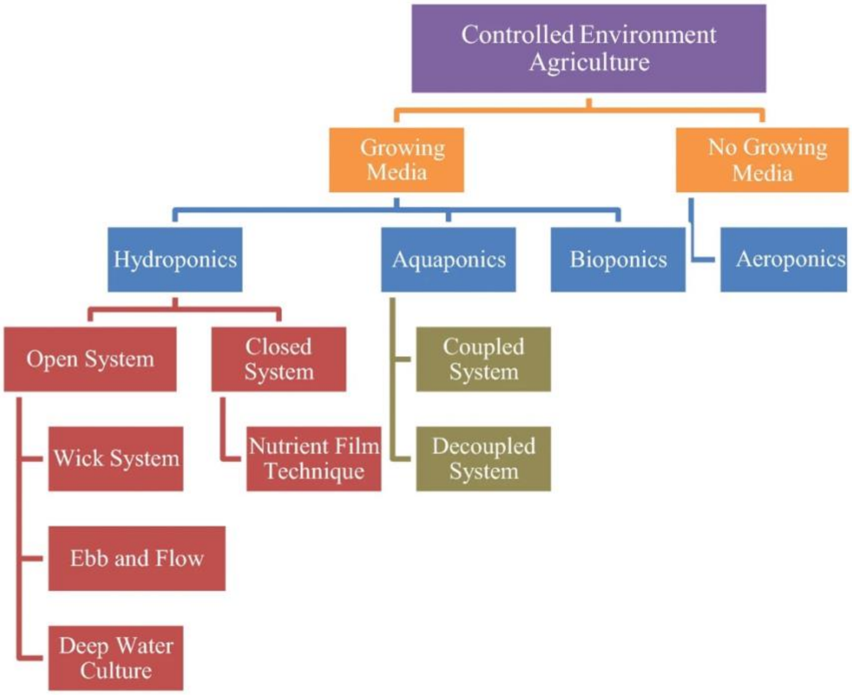


Figure 7. Classification of several controlled environment farming techniques. The figure comes from (Ragaveena et al., 2021)

2.6.2.1 hydroponics

Hydroponics is an emerging technology that involves cultivating plants in a water-based nutrient solution, utilizing various mechanical supports such as sand, gravel, perlite, rock wool, peat moss, coir, vermiculite, or sawdust. Hydroponics can be classified into two distinct categories: Open System and Closed System. According to (Ragaveena et al., 2021), in an open system, the plants are supplied with a nutrient solution once, and any excess solution is subsequently drained. Nutrient solutions are recycled and reused in closed systems (Mohapatra et al., 2019). Due to its environmental benefits (less soil pollution, less nutrient runoff into wells, lakes, groundwater, etc.) and increased crop yields, the closed system or recirculation system has gained widespread acceptance in recent years (Saito et al., 2017).

In hydroponics, the application of water-soluble fertilizers and irrigation is combined in a procedure known as fertigation (Ragaveena et al., 2021). Irrigation water is injected with the concentrated solution (van Os et al., 2019). Soilless agriculture, where the hydroponic solution is used in enclosed environments like greenhouses and tunnels, accounts for around 3.5% of global vegetable output (Sambo et al., 2019). The three main issues with hydroponic plant cultivation are (i) the falling number of nitrates in edible plant tissue, (ii) ensuring the health as well as security of the vegetables, and (iii) ensuring that the plant's production has an appropriate nutritional composition (Ragaveena et al., 2021).

The key benefits of this hydroponic approach over traditional methods include (i) high water use efficiency, (ii) no use of pesticides, and (iii) the ability to eradicate soilborne pathogens like Ralstonia solanacearum, Fusarium oxysporum, and Verticillium dahlia, as well as nematodes and many other organisms that can survive in the deeper soil layers (Saito et al., 2017). The difficulties with traditional soil-based farming, such as a lack of or toxicity of a specific mineral in the soil, will directly affect the plants' growth (Ragaveena et al., 2021).

2.6.2.2 aquaponics

Aquaponics is the practice of combining the cultivation of crops and fish in a symbiotic system. Aquaponics has the potential to be implemented in non-conventional spaces, such as warehouses. The organic matter generated from the fish cultivation unit is utilized as fertilizer for agricultural produce. The cultivation system described by Love et al., 2015, does not involve the routine of organic pesticides, fertilizers, or antibiotics for the growth of plants and fish.

Aquaponics systems may be split into two categories: a coupled system and a decoupled system (Figure 8). There will be only a single loop between the fish-growing chamber and the plant-growing chamber in the coupled system. The decoupled system separates the fish and plant growth chambers so water from one does not flow into the other (Ragaveena et al., 2021). For this reason, a decoupled system is preferable to a connected one when it comes to pest control management (Stouvenakers et al., 2019). The most common and productive fish species for aquaponics are tilapia, carp, and African catfish. The high nitrate tolerance and poor oxygen tolerance of these fishes contribute to their success (Yep & Zheng, 2019).

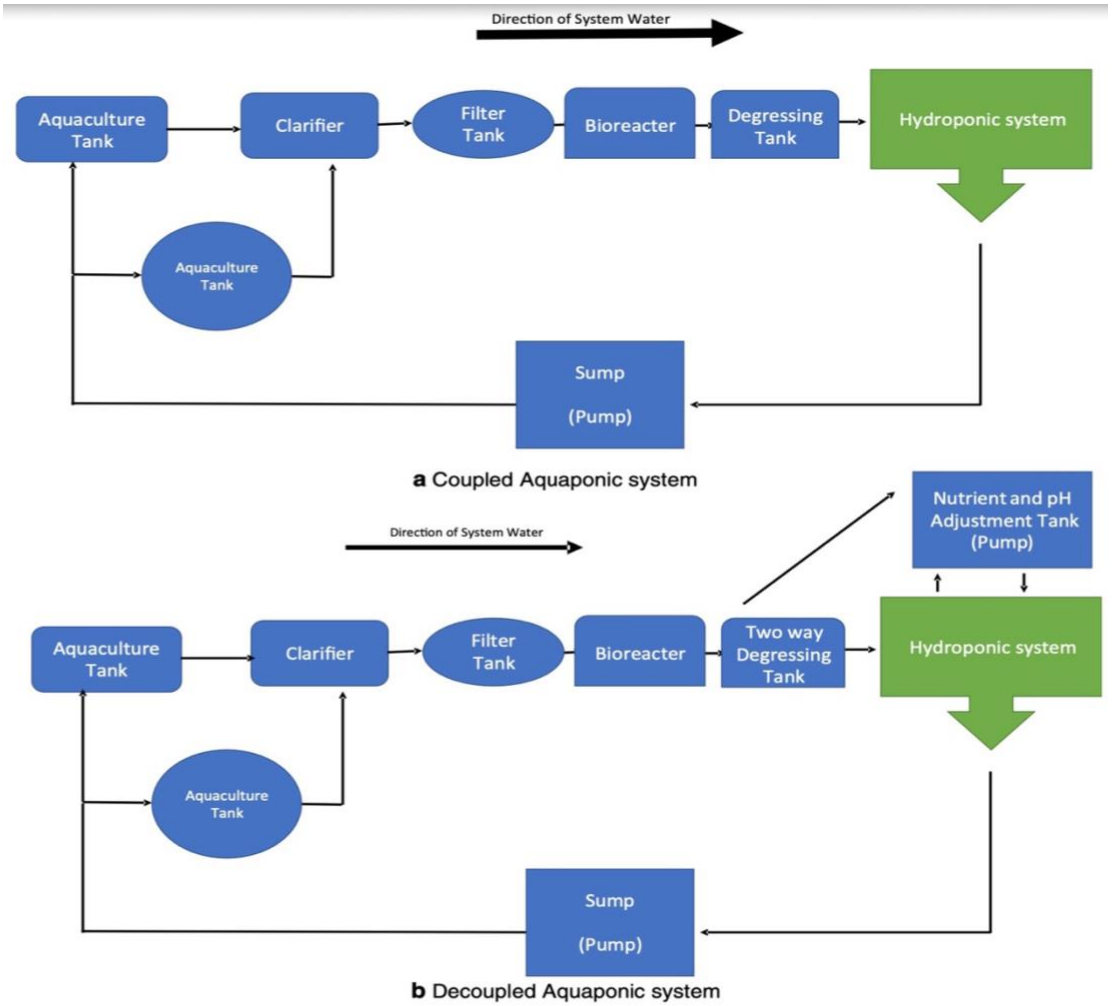


Figure 8. a. Coupled aquaponic system, b. Decoupled aquaponic system. The figure comes from (Ragaveena et al., 2021)

2.6.2.3 aeroponics

Aeroponics is a cultivation technique in which plants are suspended and exposed to a continuous spray of the nutrient solution via sprayers, foggers, or emitters, specifically targeting the roots. This technique is a subset of hydroponics. According to Kratsch et al., 2006, the roots of all plants are supplied with a liquid fertilizer from a standard container. An aeroponic system consists mostly of plumbing, a motor, spray nozzles, and a timer, from which nutritional solution is pumped into the growing medium. According to Ragaveena et al., 2021, the uniformity of plant harvests throughout the year is attributed to the easy accessibility of roots.

Some fundamental benefits of aeroponics are (i) soil-less farming, (ii) the nutritional solution kept in the shared tank may be utilized again, (iii) there will be reduced pest infestation, resulting in healthier plants, and (iv) simple collection, low-effort, high-efficiency, energy-saving (Pala et al., 2014). The aeroponic system's gas-dispersal mechanism is particularly noteworthy since it allows for very specific and nuanced regulation of nutrient content at the root zone of individual plants. Aeroponic systems provide nutrients to the plant's root zone in the form of a fine mist created by a sprayer (Figure 9). The timer aids in keeping the plant's fertilizer delivery on a regular schedule, which helps prevent the roots from drying up (Ragaveena et al., 2021).

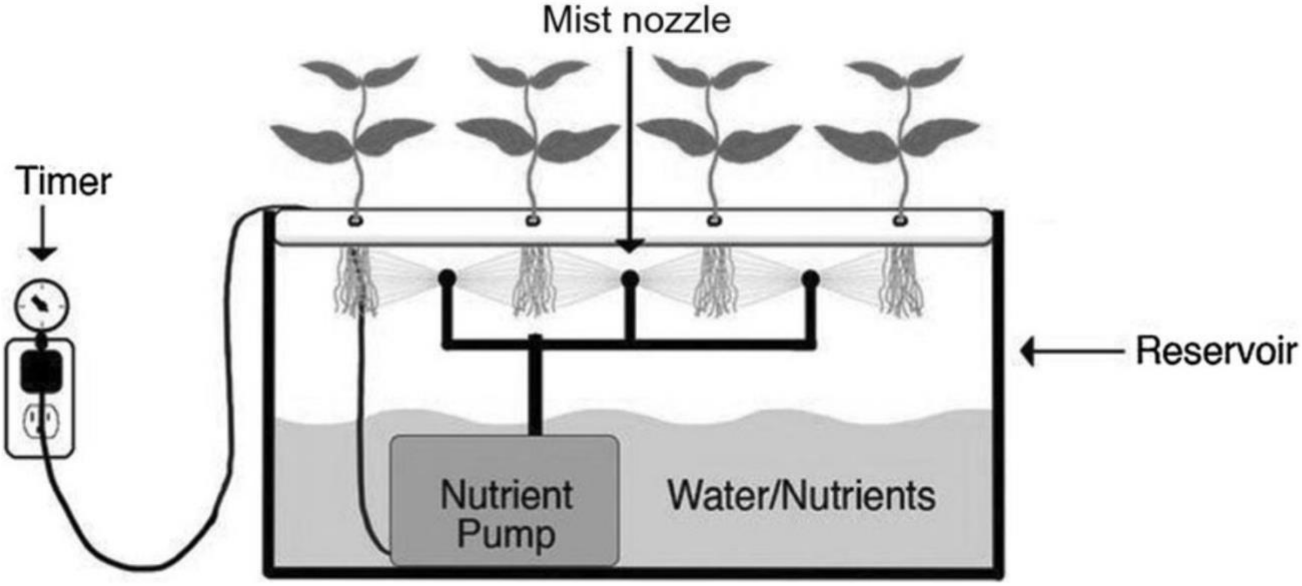


Figure 9. Aeroponic system. The figure comes from (Ragaveena et al., 2021)

2.6.2.4 Nutrient film technique (NFT)

In the NFT system, nutrients are recirculated to the plant roots for absorption, requiring ongoing monitoring of the nutrient solution to identify any deficiencies in ion content. As such, specific ingredients are added to optimize the nutrient solution. One of the primary limitations of this system pertains to the absence of a buffer in the nutrient solution, which may lead to the proliferation of plant diseases (Ragaveena et al., 2021). Troughs are designed with a slope of 0.3–2% (van Os et al., 2019) to facilitate nutrient optimization. Thin films of nutrient solutions are created and circulated close to the plant's roots. The drained solution is collected in a storage tank for later use. Proper optimization of the nutrient solution flow rate is necessary to ensure the growth of plants. A thin-film nutrition solution is applied to the root zone of NFT system plants, as shown in Figure 10, to provide them with nutrients. The timer is useful for keeping the plants' feeding schedule consistent (Ragaveena et al., 2021).

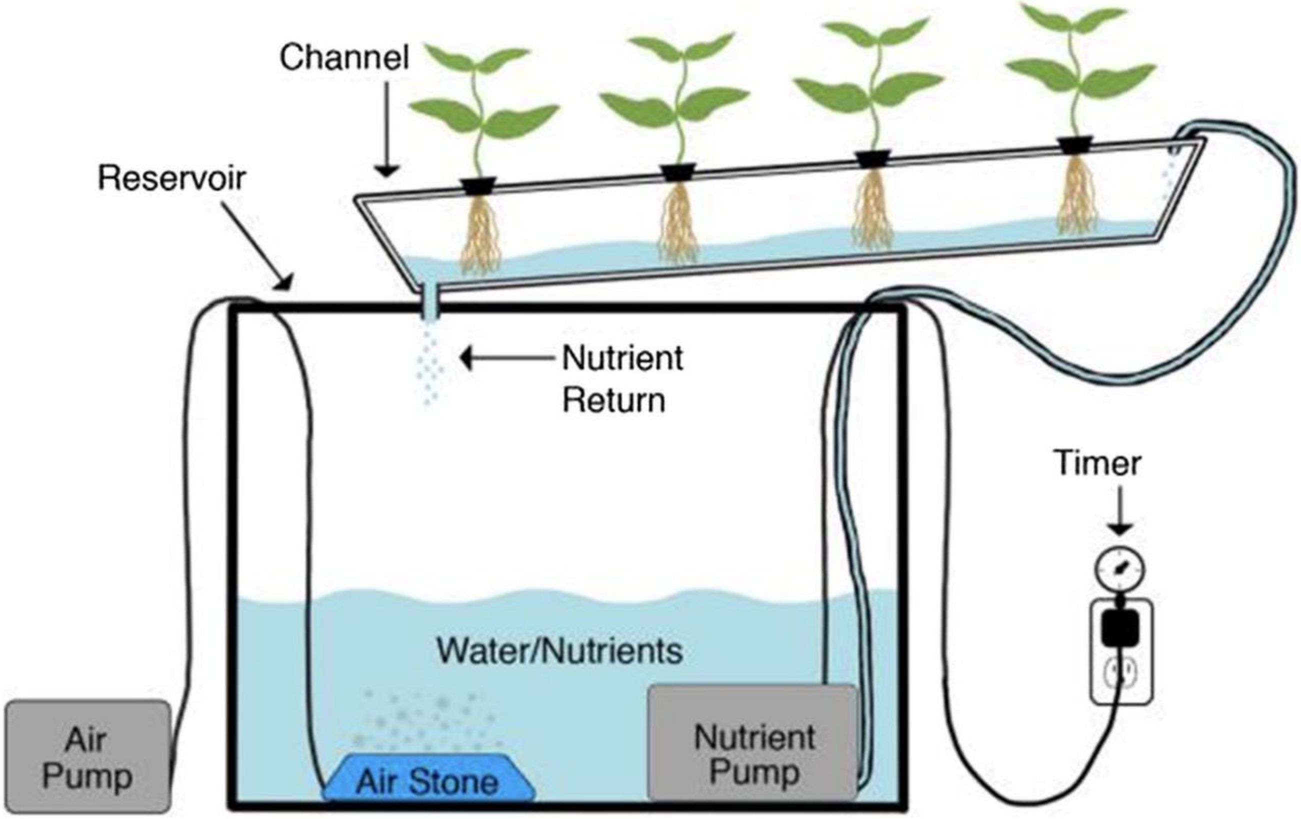


Figure 10. NFT system. The figure comes from (Ragaveena et al., 2021)

2.6.2.5 Bioponics

Biophonic is a farming technique that combines the principles of organic farming and hydroponics. It combines the benefits of hydroponics with those of aquaponics. There are several key differences between this method and hydroponics and aquaponics. Microorganisms' metabolic processes release plant-, animal-, and mineral-based natural compounds that provide the nutrients. Therefore, the term "bioponics" appropriately describes the integration of aquaponics and organic hydroponics. The concept of bioponics encompasses the cultivation of plants without soil, wherein microbial activity and biological processes are maximized, like organic farming, to facilitate plant growth. These chemical-free plants and crops are the result of cutting-edge research in hydroculture that has just emerged to ensure the well-being of future generations (Ragaveena et al., 2021).

2.6.2.6 Vertical farming on facades

The potential exists for building facades to integrate a wide range of Building Integrated Agriculture (BIA) and Vertical Farming (VF) systems. Various agricultural technologies are mapped out and placed in their respective categories in Figure 11. VF may be implemented on the outside of a building using a variety of different surfaces, including terraces, skylights, DSFs, windows, or even solid walls (Tablada & Kosorić, 2022). Longitudinal tubular growth modules may be employed, or downward containers can be anchored one on top of the other, as in the case of 'green' walls (Beacham et al., 2019). There is a wide range of technologies that may be used to meet the needs of different types and locations in terms of safety, accessibility, aesthetics, and productivity (Tablada & Kosorić, 2022). Farming behind facades is a time-honored tradition. Many apartments and condos in cities and suburbs around the world feature potted plants on their balconies or walls. If a family cannot access a garden, they may still engage in gardening and farming by using their balcony or window. Most of these operations are handled by families and rely on planting in soil and watering by hand (Tablada & Kosorić, 2022).

Hydroponics, aeroponics, and aquaponics are examples of more modern VF techniques that might be used in modern facade farming (Chatterjee et al., 2020; Despommier, 2009). The term 'hydroponics' refers to an arrangement of tubes or channels that uses the nutrient film technique (NFT) to bury plant stems in a flowing nutrient solution. For the purpose of maintaining the proper chemical composition, water is constantly sucked back into the nutrient reservoir (Tablada & Kosorić, 2022).

A different form of hydroponic growing, aeroponics, involves spraying the airborne plant roots with a cold nutrient mixture (Chatterjee et al., 2020; Despommier, 2009). Compared to traditional hydroponics, this method provides even tighter water control and utilization. However, unlike hydroponics, maintaining a cool environment for the nutrient assortment and the plant roots is difficult and calls for a higher level of expertise. Aquaponics systems create a symbiotic relationship between two reservoirs, one for fish farming and one for growing plants (decorative or edible). Plants are irrigated with nutrient-rich water derived from fish waste, and the decontaminated water is then returned to the fish tank (Tablada & Kosorić, 2022).

VF structures, which pose a danger of crops withering owing to the complexity of irrigation systems, may not be suitable for homeowners with novice operators and a knowledgeable person is required to administer nutrient solutions. However, automated irrigation drip systems are readily available for straightforward VF soil-based systems and can be programmed easily. There is no danger in installing a high-tech VF system on the facade of office, commercial, and industrial buildings, and the centralized digital administration will save money and energy (Tablada & Kosorić, 2022).

‘Digital urban farming’ refers to the use of technology and artificial intelligence, by the software usage and/or silicon-based hardware, to manage agricultural processes such as the timing of day and night, the temperature, the concentration of chemicals in growing media, and the cycle of crop growth (Carolan, 2020). In addition to using PV systems to generate power and provide shade, VF systems may also use these technologies. For example, a group of researchers (Tablada et al., 2018; Tablada & Zhao, 2016) designed and evaluated productive facade (PF) systems.

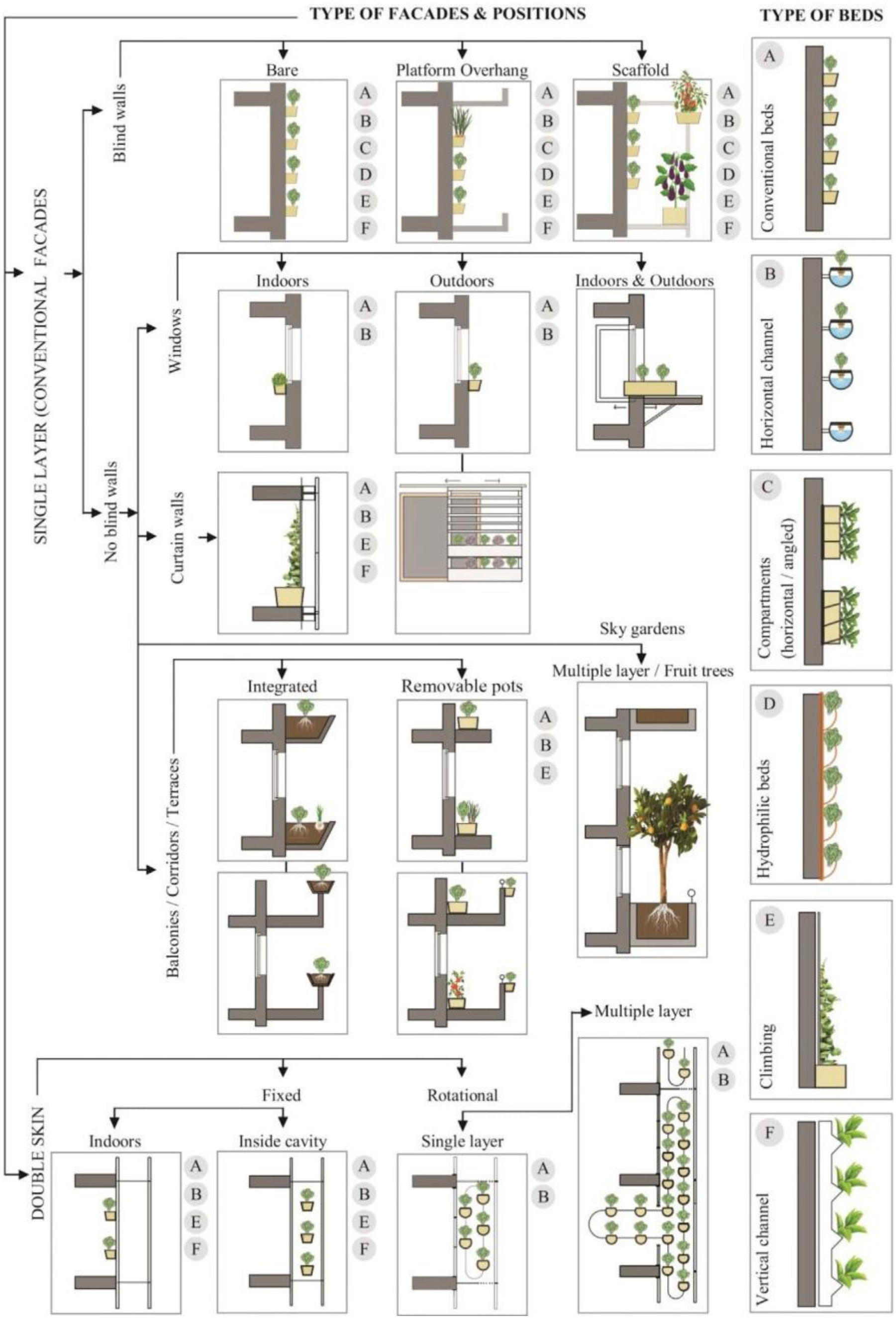


Figure 11. Classification of farming facades according to technological systems and position on the façade. The figure comes from (Tablada & Kosorić, 2022)

2.7 Crop selection and farm design

It is essential for decision-makers or farmers to develop site-specific strategies in order to improve agricultural production in terms of quantity, quality, and sustainability. Optimal economic and environmental performances can be achieved by selecting crops and adjusting system parameters (Li et al., 2020); however, just because those in charge are cognizant of the urban farmings' importance in determining the financial and ecological effects on architectural design.

For the purpose of simulating, assessing, and optimizing urban agriculture practices toward greater sustainability, Li et al., 2020 recommend an extensive and flexible guidance framework. Several various frameworks of urban farm systems will be evaluated in the complex measurement model concerning their net present value, cradle-to-gate CO_2 emissions, water consumption, and land use. The evaluation model will be included in an optimization framework to help find the optimal configuration and operation of the system. The farming modules were optimized to determine the best conditions for growing a certain crop (including, but not limited to, specific levels of heat, moisture, light, and carbon dioxide).

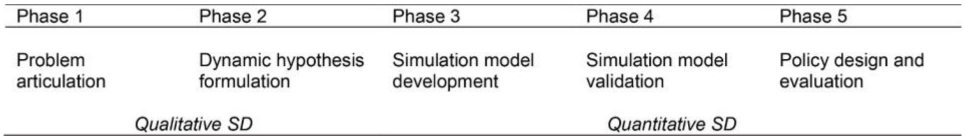
The environmental impact of a micro aquaponics system was evaluated using a life cycle assessment method (Maucieri et al., 2018). Life cycle cost analysis was used by (Liaros et al., 2016) to undertake a techno-economic assessment of urban plant factories. The potential impacts of urban farming on other industrial and ecological systems were also studied at the network level. In order to help a massive Swiss retailer make decisions about what products to buy and enhance supply chain management, (Stoessel et al., 2012) used an LCA tackle to thoroughly evaluate the life cycle value and the carbon and water footprint of 34 fruits and vegetables. Using the urban energy-food nexus to cultivate tomatoes in an atrium nursery was evaluated using an approach that combines LCA with the ecological network analysis (ENA) (Piezer et al., 2019).

Chapter 3
(Methodology)

3.1 System dynamics

In contemporary academia and practice, there has been a significant surge in recognizing and utilizing system dynamics (SD) as a prominent technique for modeling and simulating complex systems in conjunction with various other systems thinking methodologies from health care (Egan et al., 2018; Atkinson et al., 2018) to sustainability (WR Stahehel, 2016; Rebs et al., 2019; Golroudbary & Zahraee, 2015). There are major benefits to utilizing SD. Firstly, SD employs a comprehensible graphical symbol system and user-friendly modeling software, facilitating the comprehension of complex system dynamics. Secondly, it possesses the capability to involve stakeholders actively and continuously throughout the modeling process, enabling their meaningful participation and contribution. Lastly, SD facilitates the development of aggregate causal (simulation) models, which prove particularly advantageous in the context of policy analysis and design (Schoenenberger et al., 2021).

In terms of SD, the process of creating and evaluating models typically encompasses some or all of the phases depicted in Table 4. In the first phase, it is essential to define every aspect of the problem, focusing on fundamental aspects such as the selection of main concepts, identification of important variables, determination of the time horizon to be taken into account, as well as an in-depth analysis of the historical patterns exhibited by the key concepts and variables (Schoenenberger et al., 2021).



Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Problem articulation	Dynamic hypothesis formulation	Simulation model development	Simulation model validation	Policy design and evaluation
Qualitative SD		*Quantitative SD*		

Table 4. SD model building and analysis process. The table comes from (Schoenenberger et al., 2021).

During the second phase, “Dynamic hypothesis formulation” should be considered. In the scope of reference modes, a dynamic hypothesis is a theoretical framework clarifying the underlying structure responsible for their emergence. Such a hypothesis can be articulated through verbal explanations, represented by causal loop diagrams, or depicted using stock and flow diagrams. These dynamic hypotheses play a critical role in guiding the inclusion or exclusion of elements within models. However, it is imperative to acknowledge that dynamic hypotheses, like all hypotheses, are not faultless and may not always accurately reflect reality. Consequently, the refinement and revision of these hypotheses form an integral aspect of the process of constructing robust models (*The System Dynamics Process*, n.d.). A dynamic hypothesis is developed to encapsulate the modelers' comprehension of the fundamental causal mechanisms being observed. Generally, this dynamic hypothesis is conveyed by employing various mapping techniques, including but not limited to causal loop diagrams (CLDs), stock-and-flow diagrams (SFDs), and model boundary diagrams. These tools facilitate the visual representation and clarification of the interrelationships among the relevant factors and variables within the system (Schoenenberger et al., 2021).

In phases 3 and 4, the processes of problem expression and dynamic hypothesis formulation constitute integral components of the qualitative aspect within the scope of SD. Subsequently, a simulation model is created to evaluate the explanatory effect of the dynamic hypothesis in conjunction with the specific problem under investigation. In this regard, the simulation model must undergo several standard validation checks to be valid in its utility and reliability (Schoenenberger et al., 2021).

In the realm of system dynamics, the term "validity" pertains to the internal structure of the model rather than its output behavior, as commonly referred to as the principle of "right behavior for the right reasons". Fundamentally, a valid system dynamics model encapsulates a theoretical representation of the functioning of a system in a particular aspect. Consequently, complete objectivity, quantification, and formality cannot be achieved in the process of model validation. Given that validity entails appropriateness in relation to a specific purpose, model validation necessitates the inclusion of informal, subjective, and qualitative elements (Yaman Barlas, 1994). For the model of this study, the right behavior for the right reasons is confirmed by system dynamics experts.

Finally, the validated simulation model is employed for policy design and evaluation. It is noteworthy that the final three phases, encompassing the formulation, validation, and application of the simulation model for policy design, reside within the quantitative section of SD. The final phase, policy design, denotes the complex process of recognizing prominent parameters and model relationships while identifying potential structural modifications (such as the inclusion or exclusion of parameters, variables, or relationships) within SD models. Such adjustments, when proficiently manipulated or implemented, possess the capability to "guide the behavior of crucial outcome variables toward a direction" (Schoenenberger et al., 2021).

In the mid-1950s, Jay W. Forrester developed the SD framework at the Massachusetts Institute of Technology. At the core of his initial concept, for all the complex systems, only two fundamental types of variables exist: stocks and flows. Stocks symbolize accumulations of units, and from the graphical view, it is represented as a rectangle, while flows, encompassing inflows and outflows, denote the movement of units over time and are visually portrayed as arrows (Figure 15). Stocks can only be altered through their interdependent inflows and outflows, while flows themselves are regulated by decision functions, depicted as valves on the inflow and outflow. Simulations in SD operate within a continuous time framework. The corresponding integral equation is as follows: (Schoenenberger et al., 2021).

$$Stock(t) = \int_{t_0}^{t} [Inflow(s) - Outflow(s)]ds + Stock(t_0)$$

Equation 1. Stock integral equation

Figure 12.Minimal stock and flow diagram (SFD). The figure comes from (Schoenenberger et al., 2021).

Forrester’s research findings demonstrate that complex systems primarily consist of interconnected causal loops, showing time delays (Figure 16). The present behavior of these closed systems is significantly influenced by their past behaviors. Consequently, unlike other scientific disciplines, such as economics, the system dynamics (SD) approach adopts an understanding of endogenous causation, wherein causal factors originate within the system (Schoenenberger et al., 2021). This perspective acknowledges the intricate interplay between system components and their dynamic feedback mechanisms, which contribute to the complex behavior and emergent properties observed in such systems.

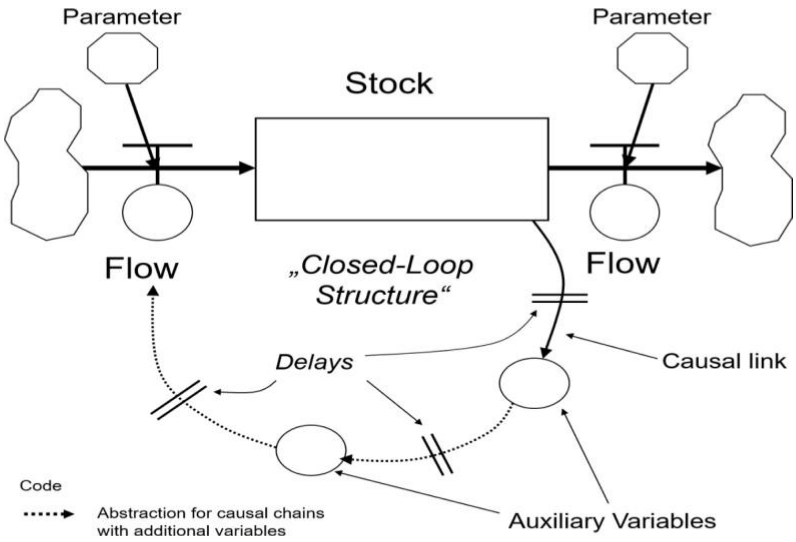


Figure 13. Closed-loop stock-and-flow diagram (SFD). The figure comes from (Schoenenberger et al., 2021).

3.2 Causal Loop Diagram

The primary objective of this study was to create a causal loop diagram (CLD) consisting of three loops, which are the foundation for the conceptual framework. Further discussion on the CLD will be provided in subsequent sections. The CLD demonstrates two types of feedback loops, namely reinforcing and balancing loops, as illustrated in Figure 17. A reinforcing feedback loop makes an amplified response, maintaining change with increasing magnitude. Consequently, this type of loop can result in exponential growth characterized by a progressively growing rate. It is noteworthy that although the growth may appear slow in its initial stages, it subsequently accelerates. On the other hand, a balancing feedback loop operates towards achieving a desired objective. If the present level of the variable under consideration surpasses the intended goal, the loop structure impels its value downward. Conversely, if the current level falls below the desired target, the loop structure makes an effort to elevate its value. In the following, all the created loops will be explained.

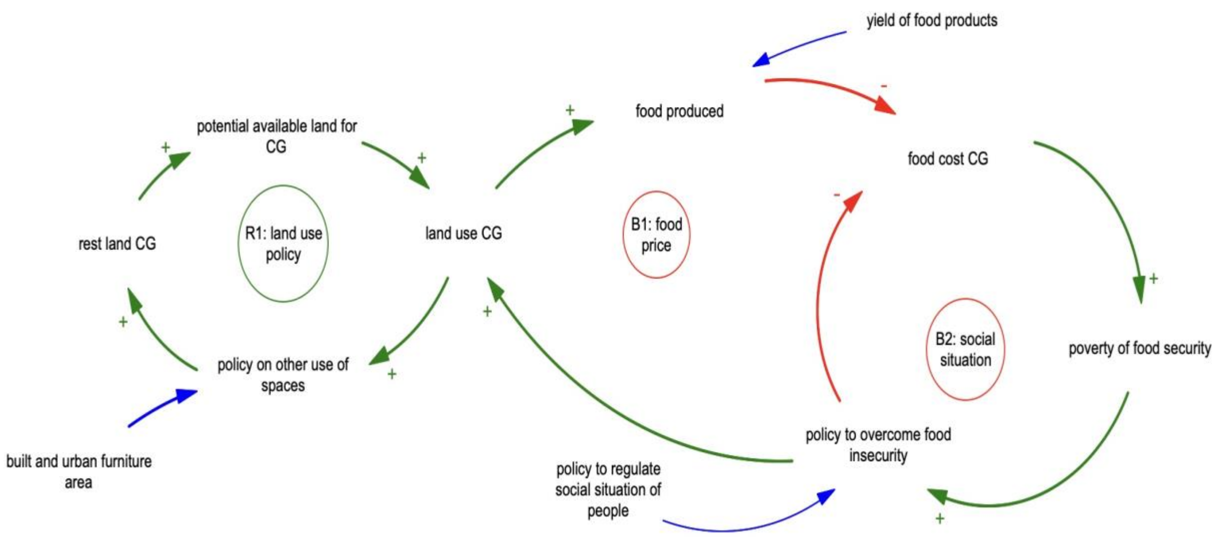


Figure 14. Causal Diagram Loop (CLD) of this study

3.2.1 Land use policy reinforcing loop

The Land Use Policy reinforcing loop is a dynamic system that explains the interaction between various factors influencing the allocation of land for community gardens. This loop highlights the interplay between the availability of potential land for community gardens, land use for community gardens, policy on other uses of spaces, and the presence of built and urban furniture areas.

The “potential available land for CG” represents the availability of land that has the potential to be converted into community gardens. It could include vacant lots, public spaces, or unused areas. The “land use CG” variable indicates the amount of land that is currently being used for community gardens. As this variable increases, it contributes positively to the reinforcing loop, strengthening the availability and development of community gardens. The “policy on other use of spaces” variable represents the strength of policies and regulations related to the use of land for purposes other than community gardens. A stronger policy restricts alternative uses of potential land, encouraging the allocation of land for community gardens.

The “built and urban furniture area” is representative of the presence of infrastructure and urban furniture in the area. This factor can act as an external influence, potentially weakening the policy on other uses of spaces if there is significant pressure for built and urban development. The “policy on other use of space” entity is influenced by the presence of built and urban furniture areas. When there is significant urban development, the policy on other uses of spaces may become weaker, allowing alternative uses of potential land and reducing the allocation of land for community gardens.

The “rest land CG” entity symbolizes the remaining land that has the potential to be converted into community gardens but has not yet been converted. It is influenced by the strength of the policy on other uses of spaces. A stronger policy restricts alternative uses, increasing the availability of rest land for community gardens.

The reinforcing loop behaves as when potential land for community gardens is available; it can be converted into land use for community gardens, increasing the amount of land dedicated to community gardens. As the land use for community gardens increases, it strengthens the case for implementing stronger policies on other uses of spaces, ensuring that potential land is allocated to community gardens rather than alternative purposes. However, the presence of built and urban furniture areas can exert pressure on the policy, potentially leading to a weaker policy on other uses of spaces and reducing the allocation of land for community gardens. With a weaker policy, more land becomes available for alternative uses, resulting in less rest land use for community gardens.

3.2.2 Food price balancing loop

The food price balancing loop is a dynamic system that illustrates the relationship between land use for community gardens, food production, food prices, poverty of food security, policy to overcome food insecurity, and the allocation of land for community gardens. This loop demonstrates the interdependence between these factors and their impact on food security and social well-being.

The “land use CG” entity represents the area allocated for community gardens. Increasing the land use for community gardens contributes to an increase in food production. The “food produced” entity represents the quantity of food produced from community gardens. As the land use for community gardens increases, more food is produced, resulting in a higher yield.

The “food cost CG” entity signifies the reduction in the cost of food produced from community gardens. When more food is available, the increased supply can lead to lower prices. The “poverty of food security” entity represents the level of food insecurity within a society or community. As food prices decrease, individuals facing food insecurity experience relief from the burden of high food costs, resulting in a reduction in poverty related to food security.

The stronger “policy to overcome food insecurity” entity reflects the implementation of policies aimed at addressing and reducing food insecurity. When poverty related to food security increases, policymakers are more motivated to enact and enforce policies that regulate the social situation of people, ensuring food security for all.

In this feedback loop, the “land use CG” entity represents the increase in land allocated for community gardens resulting from the implementation of stronger policies to overcome food insecurity. These policies may include incentives, subsidies, or support systems to encourage the expansion of community gardens.

The balancing loop behaves as increasing the land use for community gardens leads to a greater yield of food produced. The increased food production contributes to a decrease in the price of food produced by community gardens. Reduced food prices alleviate poverty related to food security, improving society’s food security. The reduction in poverty related to food security triggers policymakers to implement stronger policies to overcome food insecurity, aiming to regulate and improve the social situation of individuals. With the implementation of stronger policies, such as incentives and support systems, the land allocated for community gardens increases, creating a positive feedback loop that further increases food production and food security within the community. This balancing loop highlights the potential of community gardens and appropriate policies to address food insecurity, reduce poverty, and promote sustainable food systems.

3.2.3 Social situation balancing loop within the food price balancing loop

The Social Situation balancing loop is another balancing loop that operates within the larger Food Price balancing loop. It clarifies the connection between the price of food that has been produced in the community garden, poverty of food security, stronger policies to overcome food insecurity, and the availability of affordable food for food-insecure individuals. This loop emphasizes the interplay between these factors in shaping the social situation and addressing food insecurity.

The “food cost CG” entity represents the cost of food produced from community gardens. Higher food prices restrict access to nutritious food for individuals experiencing food insecurity. The “poverty of food security” entity reflects the level of economic hardship experienced by individuals who lack consistent access to enough and nutritious food. Higher food prices exacerbate poverty related to food security. The “policy to overcome food insecurity” entity represents the implementation of robust policies aimed at addressing food insecurity. As the poverty of food security increases, policymakers are motivated to develop and enact stronger policies to alleviate this issue. The “food cost CG” entity signifies the affordability of food produced in community gardens. When stronger policies are implemented to overcome food insecurity, they often involve measures to reduce the cost of food from community gardens, making it more accessible to food-insecure individuals.

The balancing loop behavior is described in the following. Initially, the food cost of community garden produce influences the poverty of food insecurity, as higher prices limit access to nutritious food, exacerbating economic hardship for food-insecure individuals. The increasing poverty of food security prompts policymakers to enact stronger policies to overcome food insecurity, aiming to address and mitigate the challenges faced by food-insecure individuals. These stronger policies often include measures to reduce the cost of food from community gardens, making it more affordable for those experiencing food insecurity. As the food cost of community garden produce decreases, the availability of affordable food increases, creating a positive feedback loop that improves the social situation of food-insecure individuals.

The improved social situation, characterized by greater access to affordable and nutritious food, reinforces the need for and effectiveness of stronger policies to overcome food insecurity, completing the balancing loop. This nested balancing loop within the Food Price balancing loop underscores the significance of affordable food options and policy interventions in reducing food insecurity and improving the social well-being of vulnerable residents.

3.3 Geospatial analysis

This study analyzed available park areas and community gardens in Montreal using ArcGIS Pro, a robust geographic information system (GIS) software. The primary dataset utilized was the shapefile of Montreal, acquired from Statistics Canada (Service des grands parcs, du Mont Royal et des sports & Secretariat, 2013; Service des grands parcs, du Mont-Royal et des sports & Secretariat, 2020). The shapefile was imported into ArcGIS Pro and through spatial analysis techniques, park areas (Figure 18) within the shapefile were identified by applying spatial filters based on designated land use and specific attributes. Among various urban locations, parks have emerged as highly suitable sites for community gardens due to their large space, green surroundings, accessibility, and established role as community gathering places. By transforming parks into community gardens, the natural landscape is preserved while simultaneously encouraging active community involvement, social interactions, and access to fresh produce. Furthermore, such initiatives contribute to urban greening, biodiversity, and environmental awareness, thereby enhancing the overall aesthetic appeal and well-being of urban residents. The successful implementation of community gardens in parks depends on careful planning, community engagement, and sustainable management to ensure their seamless integration into urban landscapes and alignment with broader urban development objectives. These park areas were then extracted and quantitatively measured using ArcGIS Pro’s geoprocessing tools to determine their total area.

Figure 15. Parks in Montreal

Additionally, community gardens (Figure 19) were identified within the Montreal shapefile using spatial querying capabilities, considering attributes associated with these gardens. The resulting community garden features were extracted, and their respective areas were then measured using geoprocessing tools. The total area covered by community gardens within the study area was calculated by adding all respective garden areas together. This methodology enabled a comprehensive assessment of the available park areas and community gardens, providing valuable insights into their spatial distribution and potential implications for urban planning and community development. The acquired data is provided in Table 5. It should be mentioned that the total land area of Montreal is 498.29 km^2 (Government Montrealof Canada, 2022b).

Figure 16. Community Gardens in Montreal 2014

	Number	**Surface area (m^2)**	**Percentage of the allocated area in Montreal**
Community Gardens	178	311185	0.06%
Parks	2218	66679700	13.38%

Table 5. Acquired data of community gardens and parks in Montreal using ArcGIS Pro

3.4 Case study, mind.heart.mouth garden

Andrea Tremblay initiated the establishment of the mind.heart.mouth garden (Figures 12, 13 and 14) at Concordia University's Loyola campus in Montreal, Canada, in 2019. The garden serves as a living laboratory, promoting regenerative agriculture practices for ecological and societal resilience. By embracing nature-based solutions and fostering accessibility, the garden enhances food security and offers experiential learning opportunities, serving as a model for sustainable urban farming on university campuses. The COVID-19 pandemic has highlighted the importance of utilizing community gardens to support marginalized populations during crises, and mind.heart.mouth has fostered valuable community connections and partnerships. Faculty collaboration plays a crucial role in achieving the initiative's short-, mid-, and long-term goals. The garden's intergenerational aspect fosters social connections, addressing food insecurity while promoting community resilience.

Overall, mind.heart.mouth has evolved over the past four years, offering diverse opportunities that align with Concordia University's Sustainability Action Plan (Andrea Tremblay, n.d.).

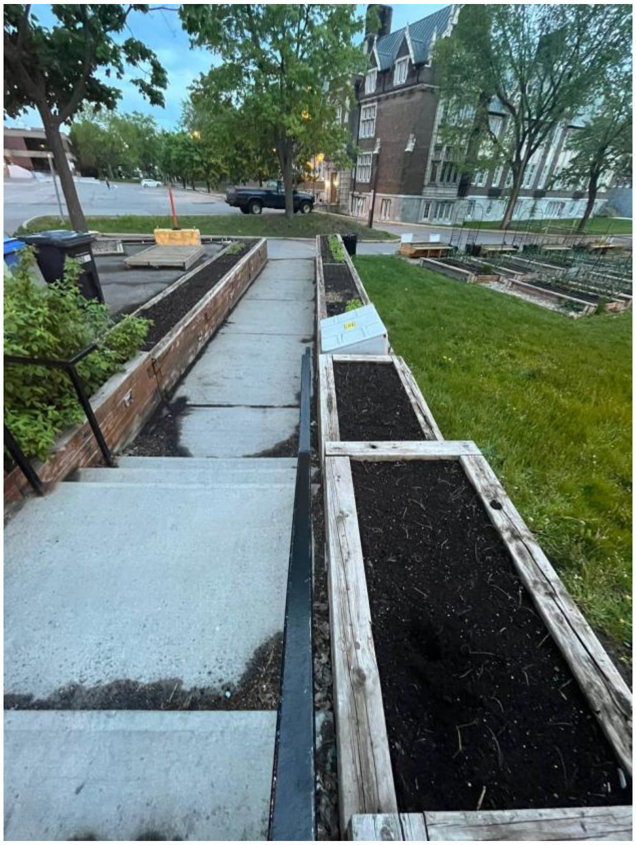


Figure 17. The entrance of mind.heart.mouth garden (May 2023)

Figure 18. Mind.heart.mouth garden (May 2023)

Figure 19.Mind.heart.mouth garden (July 2023)

There are 40 planting beds in this garden, and the data, including the planting bed's length, width and area, is provided in Table 6. So, the harvesting area is 115.60 m^2.

Planting bed number/ dimensions	**Length(cm)**	**Width(cm)**	**Area (m^2)**
1	177.8	63.5	1.13
2	152.4	63.5	0.97
3	182.88	63.5	1.16
4	1046.48	63.5	6.65
5	373.38	66.04	2.47
6	1041.4	66.04	6.88
7	317.5	63.5	2.02
8	153.67	63.5	0.98
9	182.88	63.5	1.16
10	1,183.64	63.5	7.52
11	213.36	60.96	1.30
12	213.36	60.96	1.30
13	213.36	60.96	1.30
14	213.36	60.96	1.30
15	254	129.54	3.29
16	254	129.54	3.29
17	254	129.54	3.29
18	254	129.54	3.29
19	254	129.54	3.29
20	254	129.54	3.29
21	254	129.54	3.29
22	254	129.54	3.29
23	304.8	91.44	2.79
24	304.8	91.44	2.79
25	304.8	91.44	2.79
26	304.8	91.44	2.79
27	304.8	91.44	2.79
28	304.8	91.44	2.79
29	304.8	91.44	2.79
30	304.8	91.44	2.79
31	304.8	91.44	2.79
32	304.8	91.44	2.79
33	304.8	91.44	2.79
34	304.8	91.44	2.79
35	304.8	101.6	3.10
36	304.8	99.06	3.02
37	304.8	101.6	3.10
38	304.8	104.14	3.17
39	304.8	101.6	3.10
40	462.28	91.44	4.23

Table 6. Planting beds and their dimensions in mind.heart.mouth

Also, according to the appendix, the total harvest of the year 2022 is 718,744.935 grams.

3.5 Modeling using the SD tool Vensim

The initial inspiration for this study took the importance of food security into consideration and built a system dynamic model motivated by providing local food for residents suffering from inadequate nutrition.

The Canadian government highlights income as the primary indicator for measuring poverty. However, poverty extends beyond income and encompasses various dimensions of daily life, including housing, food insecurity, health, and crime (Government of Canada, 2016). In the context of this study, the specific focus is on examining food insecurity within the broader poverty framework. By addressing the issue of food insecurity, this research aims to contribute to understanding and mitigating one of the critical aspects of poverty, thereby working towards improving societal well-being. The created model is depicted in Figure 20.

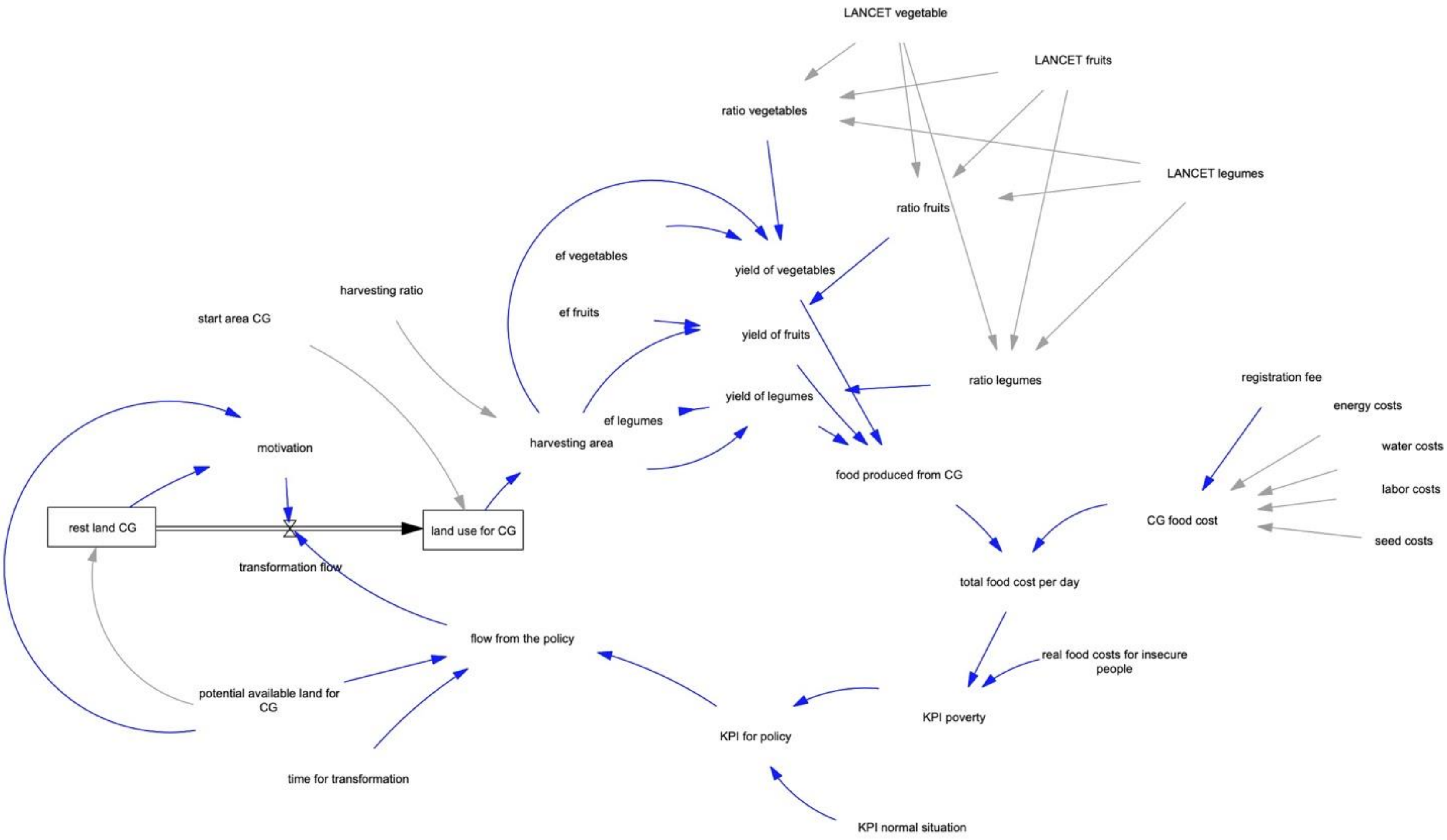


Figure 20. Vensim model

The simulation software Vensim was selected for this study to model and analyze the dynamics behavior of land use for a community garden. Two stocks were defined within the model: “land use for community garden” and “rest land community garden”. The initial value of “land use for community garden” (referred as CG) was set to the “start area CG”, representing the initial area designated for community gardening that was calculated by ArcGIS Pro that is equal to 311,185 m^2. Similarly, the initial value of “rest land CG” was set as the “potential available land for CG”, representing the remaining land available for future community gardening. In this phase, an assumption was made regarding implementing a robust and influential policy, wherein a plan was devised to allocate a fraction of 20% of the existing park area to establish community gardens. Considering the relevant information in Table 6, it was determined that the total surface area of parks within the Montreal region amounts to 66,679,700 m^2. Therefore, 20% of the area as mentioned earlier, would be 13,335,940 m^2.

A “transformation flow” was established between “rest land CG” and “land use for CG”, whereby land from the rest category is gradually transformed and allocated for community garden usage. The transformation flow is influenced by a motivation factor, which means that the motivation to convert more land to community gardens decreases when less land is available.

The “land use for CG” stock is expected to reach a maximum value known as the “harvesting area”. This harvesting area is affected by the “harvesting ratio”, which represents the percentage of the total harvesting area allocated to the community garden. Consequently, the size of the harvesting area available for community gardening activities fluctuates based on the specified ratio. Furthermore, the harvesting area is interconnected with three additional variables: “yield of vegetables”, “yield of fruits”, and “yield of legumes”. These variables represent the expected yields or productivity levels of vegetables, fruits, and legumes obtained from the community garden. Changes in these yield variables directly influence the overall productivity and output of the community garden. The following is the equation representing the “yield of vegetables” as an example:

$$\text{Yield of vegetables} = \text{ef vegetables} * \text{harvesting area} * \text{ratio vegetables}$$

Equation 2. Yield of vegetables equation

The productivity of the community garden in terms of "Yield of vegetables", "Yield of fruits", and "Yield of legumes" is influenced by the respective efficiencies associated with each food category: "ef vegetables", "ef fruits", and "ef legumes". In the model, "ef" stands for "efficiency". These efficiency factors represent the effectiveness or productivity levels of cultivating and harvesting vegetables, fruits, and legumes within the community garden.

In the other part of the model, the variables "Lancet vegetable", "Lancet fruits", and "Lancet legumes" are referenced from EAT-Lancet, a well-known dietary guideline (Willett et al., 2019) that offers recommendations on healthy diet habits. The Lancet values provide guidance on the ideal daily consumption of whole grains, tubers or starchy vegetables, vegetables, fruits, dairy foods, protein sources, added fat and added sugars. In this study, the macronutrient intake values for vegetables, fruits and legumes are considered to maintain healthy. Based on these Lancet recommendations and intake values, the "ratio vegetables", "ratio fruits", and "ratio legumes" can be defined. These ratios indicate the proportion of the overall yield that should be allocated to each specific food category to align with the principles of a healthy diet. The cumulative sum of the yields, namely "yield of vegetables", "yield of fruits", and "yield of legumes", represents the total food produced within the community garden and is denoted as "food produced from CG".

Additionally, the model incorporates various costs associated with operating a community garden. These costs include the "registration fee", "energy cost", "water cost", "labor costs", and "seed costs". The cost of food produced in the community garden (CG) is the sum of these costs. Consequently, the "total food cost per day" is determined by multiplying the "food produced from CG" by the "CG food cost", representing the overall cost incurred for producing the total food produced within the community garden on a daily basis.

Based on the information provided by the city of Montreal (Montréal, 2023), the cost associated with renting a plot or half-plot exclusively reserved for residents is written to be free. Additionally, there is a participation fee referred to as the "right of participation", which ranges between \$15 to \$30 per year. A registration fee of \$25 has been set to enhance realism within the model. This value has been chosen to reflect a practical and reasonable estimate of the registration cost based on the available information and to align with the intended level of realism and accuracy in the model's representation of community garden operations in the context of Montreal.

By integrating these components within the model, the productivity, costs, and economic implications of the community garden can be assessed. This approach allows for examining factors such as efficiency, food production, and associated costs, enabling a comprehensive understanding of the community garden's potential benefits and challenges.

In another section of the model, an indicator termed "real food costs for insecure people" is established, drawing on statistical data from Statistics Canada (Government of Canada, 2012). According to these statistics, it is recommended that each household allocate a minimum of $27 per day for their food expenses, and it is worth mentioning that this amount is for Quebec province in 2019 (Government of Canada, 2012). By considering the "total food cost per day" generated by the model and comparing it to the "real food costs for insecure people", an indicator referred to as "KPI poverty" is derived.

$$KPI\ poverty = \frac{real\ food\ cost\ for\ insecure\ people}{total\ food\ cost\ per\ day}$$

Equation 3. KPI poverty equation

It is noteworthy that KPI stands for "key performance indicator". This indicator is selected to assess and compare the situation of individuals classified within the poverty category to those in a normal situation, as defined by the "KPI normal situation".

By quantifying the gap between the actual food costs and the recommended costs, the "KPI poverty" provides insights into the relative food insecurity levels experienced by different population groups, aiding in evaluating the community garden's potential impact on reducing food insecurity and supporting vulnerable individuals. The minimum median income among Quebec residents is approximately $32,000 annually (Government of Canada, 2022a), with an allocation of about $9,800 towards food expenses (Government of Canada, 2019). A ratio of 0.31 is derived by dividing the food expenditure by income. Specifically, this Key Performance Indicator (KPI) represents the normative benchmark, indicating that 31% of residents' income is allocated toward food expenditure. If the KPI poverty reaches or surpasses the threshold of the KPI for a normal situation, less supportive policies are required. This is because low-income residents would fall within the individuals experiencing food security category.

The optimal condition within the model occurs when the value of “KPI for poverty” is equivalent to the “KPI for normal situation”. This signifies a state where the level of food insecurity among impoverished individuals aligns with individuals in more economically stable circumstances. Conversely, the most vulnerable situation is when the “KPI for poverty” reaches zero. In this context, a score of zero implies a complete lack of food security among impoverished individuals. Consequently, such circumstances necessitate the implementation of robust policies to address the issue. These policies should focus on transferring “rest land CG” to “land use for CG” and establishing additional community gardens. Expanding the number of community gardens will increase food production, providing livelihood to individuals experiencing food insecurity. Addressing this critical issue requires a comprehensive approach combining vital policy interventions with expanding community gardens to alleviate food insecurity and enhance the well-being of vulnerable populations.

By utilizing Vensim as the simulation software and incorporating the defined stocks and their interconnections, this modelling approach assesses and evaluates various scenarios related to land use for community gardens. It investigates factors such as motivation, harvesting area allocation, and yield levels and provides insights into the dynamic behaviour of community gardens and potential outcomes.

3.6 Scenarios

This study investigates three distinct scenarios while observing the baseline that is created based on real data gathered from the mind.heart.mouth Garden on Loyola Campus, Concordia University, Montreal, Canada and literature review. Some entities like “potential available land for CG”, “start area CG”, and “registration fee” are always constants. The data pertaining to “potential available land for CG” and “start area CG” is derived from Geospatial analysis conducted using ArcGIS Pro, while “potential available land for CG” is assumed to be 20% of the total park area in Montreal (13,335,950 m^2). It is imperative to highlight that the simulation runs for a period of 10 years.

3.6.1 Baseline

The used values on the baseline are defined based on mind.heart.mouth garden. According to the area calculation from Google Earth, total area of mind.heart.mouth garden is approximately $517.62\ m^2$, and the total planting beds or harvesting area (based on Table 4) is $115.60\ m^2$. It means that the harvesting ratio of this garden is about 22%.

For the categories "ef vegetables", "ef fruits", and "ef legumes", values are calculated based on the daily yield of food per m^2. In 2022, the total amount of harvested vegetables, legumes and fruits was 625.03, 93.5, and 0.2 kg, respectively. It means that the harvesting yield of vegetables per day per square meter, which is called "ef vegetables" is 0.0033. Similarly, "ef fruits" and "ef legumes" are 0.00000105 and 0.00049 $(kg/(m^2 * Day))$, respectively.

It is noteworthy that the definition of fruit, vegetable, and legumes is important. Based on one reference, one crop can be categorized as a vegetable, while the other references categorize it as a fruit. This study followed (*FoodData Central*, n.d.) as the reference to classify different crops. The lists of vegetables, fruits and legumes are provided in Tables 7 and 8.

Vegetables					
Basil	Beet	Bok choy	Broccoli	Cabbage	Carrot
Celery	Chicory	Chives	Coriander	Cucumber	Dill
Eggplant	Garlic/scapes	Kale	Leeks	Lettuce	Mint
Mustard	Parsley	Pepper	Onion	Oregano	Radish
Rainbow and Swiss chard	Sage	Spinach	Squash	Tomatoes and cherry tomatoes	Zucchini

Table 7. List of vegetables in mind.heart.mouth garden

Legumes	Fruit
Amaranth	Rhubarb
Beans	
Peas	

Table 8. List of legumes and fruits in mind.heart.mouth garden

The "registration fee" remains constant at "25 CAN" per year, encompassing the entire yield of the CG. Therefore, the registration fee's value is set to 0.000095 (CAN/kg) (25/(365* 718.74)). "Water cost" are set to zero, as water is provided free of charge in Montreal.

Considering the following calculations, the seed cost for this yield is negligible and has been set to zero. In mind.heart.mouth garden, the weighted harvest of the most popular vegetables, tomatoes, lettuce and kale, are "85,695", "32,575", and "76,235" kg, respectively. Suppose it is assumed that all the harvesting area is allocated for tomato, lettuce and kale cultivation. In that case, it means 14.6 grams of lettuce seed and 2.3 grams of tomato seed and 3.44 grams of kale are required (*Semences, graines et plants bio - La Ferme de Sainte Marthe | FERME DE SAINTE MARTHE*, n.d.; Wikifarmer, 2019, 2020). Based on the Lufa marketplace (*Urban Farming & Flowers - Lufa Farms Marketplace*, 2023), the real price of one gram of organic seeds is 4.19 CAN. Therefore, the seed costs for 20.34 grams of seeds (14.6 + 2.3 + 3.44) would be 85.22 CAN annually, equal to 0.0003 CAN per kg of food production daily. Therefore, seed cost has been set to zero due to the very low cost.

However, "Energy costs" are also set at zero, given the absence of devices that require energy in mind.heart.mouth Garden's operations. Likewise, "labor costs" are nil, as all personnel engaged in the garden are volunteers. According to Statistics Canada, the average annual household food expenditure amounted to $9,847 in 2019, converting to a daily average of approximately $26.97 (approximately $27). The "real food cost for insecure people" is established at $27, which represents the food expenditures incurred by these individuals for their food demand. This description has been set as the baseline model.

Entity	Value	Unit
Total amount of harvested vegetables in 2022	625.03	kg
Total amount of harvested fruits in 2022	93.5	kg
Total amount of harvested fruits in 2022	0.2	kg
Ef vegetables	0.0033	$(kg/(m^2 * Day))$
Ef fruits	0.00000105	$(kg/(m^2 * Day))$
Ef legumes	0.00049	$(kg/(m^2 * Day))$
Registration fee	0.000095	CAN/kg
Water cost	0	CAN/kg
Energy cost	0	CAN/kg
Seed cost	0	CAN/kg
Labor cost	0	CAN/kg
Real food cost for insecure people	27	CAN/day

Table 9. Entities and their values used in the model for the baseline

3.6.2 Scenario-1. Harvesting ratio

The first scenario investigates the influence of the harvesting ratio on community garden operations. It is important to recognize that not all available land can be fully converted into community gardens due to certain constraints, such as zoning regulations and topographical limitations. The concept of harvesting ratio comes in when determining the portion of land that can be allocated for community garden purposes and is suitable for cultivation and harvesting. The harvesting ratio in the baseline has been set to 0.22. In this scenario, it has been changed to 1, which means all the converted land has the potential to be used for cultivation, and the other values remain fixed following the “Baseline”. Although the harvesting ratio of 1 is not highly realistic due to the need to allocate a portion of the land for walkways, garden sheds, etc., this ratio is taken into account to demonstrate the impact of the community garden land use in an optimal situation.

In this context, the development of appropriate policies becomes crucial. City stakeholders and policymakers play a vital role in defining specific numerical values that indicate how much land should be dedicated to food production, aligning with their strategic objectives and considerations. These policies provide guidance on the allocation of land for community gardens and ensure the optimal utilization of available resources while addressing the limitations and considerations.

3.6.3 Scenario-2. Efficiency

The second scenario explores the impact of farming knowledge on yield, costs, poverty, and land within the community garden context. The primary objective is to investigate how the enhancement of farming knowledge can influence the overall yield of the community garden. In this scenario, the efficiency has been multiplied by a factor of 5, following the same increase rate of the first scenario (change harvesting ratio from 0.22 to 1). While all other values remain fixed as the baseline.

To achieve this objective, supportive actions are considered, such as the implementation of training courses by city managers aimed to improve the knowledge and skills of community garden participants. Additionally, another supportive action involves the provision of educational resources, such as lecture materials or instructional videos on online platforms, to facilitate access to experienced farmers' expertise. These actions are intended to promote knowledge acquisition and skill development among community garden participants, ultimately contributing to improved productivity and outcomes within the community garden setting.

3.6.4 Scenario-3. Cost

The third scenario of this study focuses on the analysis of total food costs within the system. Specifically, this scenario explores the behavior of the system with respect to real food costs in 2023, as well as the costs associated with community garden (CG) operations. The scenario considers factors such as an increase in labor and energy costs, which can impact the overall cost structure. However, water cost is disregarded since water usage in Montreal is currently provided free of charge.

This scenario considers the potential impact of introducing additional equipment, such as pumps and an irrigation timer, in mind.heart.mouth garden. According to relevant references (Dorr et al., 2023; Goldstein et al., 2016; *Rate D*, 2023), it is assumed that the energy cost per kilogram of yield in mind.heart.mouth garden would amount to approximately $0.0011 if such equipment were utilized. Furthermore, it is assumed that the labor cost for producing one kilogram of yield would be approximately $28.84 in the absence of volunteers. Table 10 shows the calculation for the energy costs.

Energy Cost in Montreal (CAN/kWh)	Energy usage of case study (kWh/year)	Total annual yield of the case study (kg/year)	Energy Cost of the case study (CAN/kg)
0.06	12.26	718.84	0.001

Table 10. Energy costs in Scenario 3

So, the energy cost for mind.heart.mouth garden is approximately 0.001 Canadian dollars per kilogram.

In the mind.heart.mouth garden, people work as volunteers, so the labor cost is equivalent to 0. But in Scenario 3. Cost, it is assumed that nobody wants to work there as a volunteer to observe the system's behaviour. Table 11 shows the calculation for labor costs considering the relevant references (*Concordia University, Office of Sustainability - Mind.Heart.Mouth Volunteer Gardening Sessions*, n.d.; *Minimum Wage in Québec*, n.d.). It should be considered that the growing period starts from June 1st to September 15th, which is 106 days (about 15 weeks). Also, the working hours per day are 3 hours, and three days are working days each week.

Quebec's minimum wage (CAN/hour)	Number of workers (person)	Growing period in a year (day/year)	Total number of working hours annually	Total wage cost (CAN/year)	Total annual yield (kg/year)	Total wage cost (CAN/kg)
15.25	10	106	1,362	20,783	718.74	28.91

Table 11.Calculation of total labor cost in scenario 3

Regarding the registration fee, which is 25 CAN annually (on average) based on the Montreal Municipality (Montréal, 2023), the registration fee for mind.heart.mouth garden based on its weighted harvest would be 0.000,095 (CAN/kg).

By carefully examining the behavior of the system under these cost-related considerations, a comprehensive understanding can be gained regarding the financial implications and sustainability of the community garden project, providing valuable insights for decision-making and resource allocation. In Table 12, the data used in this model can be seen.

Entity/Scenarios	**Baseline**	**Scenario 1**	**Scenario 2**	**Scenario 3**
Potential available land (m^2)	13,335,950	13,335,950	13,335,950	13,335,950
Start area CG (m^2)	311,185	311,185	311,185	311,185
Harvesting ratio (-)	0.22	1.0	0.22	0.22
Efficiency of vegetables ($kg/(m^2 * Day)$)	0.0033	0.0033	0.0165	0.0033
Efficiency of fruits ($kg/(m^2 * Day)$)	0.00000105	0.00000105	0.00000525	0.00000105
Efficiency of legumes ($kg/(m^2 * Day)$)	0.00049	0.00049	0.00245	0.00049
Registration fee (CAN/kg)	0.000095	0.000095	0.000095	0.000095
Energy cost (CAN/kg)	0	0	0	0.0011
Labor cost (CAN/kg)	0	0	0	28.91

Table 12. Important model data

Chapter 4

(Results and Discussion)

The Results chapter of this study serves as a pivotal section where the outcomes of the defined scenario, as outlined in the methodology section, are comprehensively discussed. In this chapter, a precise analysis of the system dynamics behaviour is undertaken, allowing for a profound understanding of the complexities and interdependencies within the investigated system. A thorough exploration of the empirical evidence and its implications emerges by delving into the observed results. The outcomes substantiate the hypotheses through a comprehensive systematic review and address the extant gap in the literature review.

Within this section, the acquired data is presented and interpreted, thus providing an in-depth exploration of the observed system dynamics. The results are systematically organized, ensuring clarity and coherence in their presentation. The analysis begins by establishing a contextual framework that sets the stage for subsequent discussions. The observed system dynamics behaviour is examined from various perspectives, including qualitative and quantitative analyses. This multifaceted approach ensures a comprehensive and holistic assessment of the system dynamics under investigation.

Furthermore, the implications of the findings are carefully evaluated, proving their significance within the broader research context. Additionally, the identified insights may inform practitioners, policymakers, and stakeholders, facilitating informed decision-making processes within the domain of study.

4.1 Outputs of scenarios

By establishing scenarios and conducting the simulation, careful observation of the critical entities has been undertaken, and the outcomes are subsequently interpreted. The fundamental entities that assume a crucial role in this investigation encompass the “harvesting area”, “land use for CG”, “rest land CG”, “yield of vegetables”, “yield of fruits”, “yield of legumes”, “food produced from CG” and “total food cost per day”. The gathered data has been translated into Python, and the obtained graphs are depicted in the following:

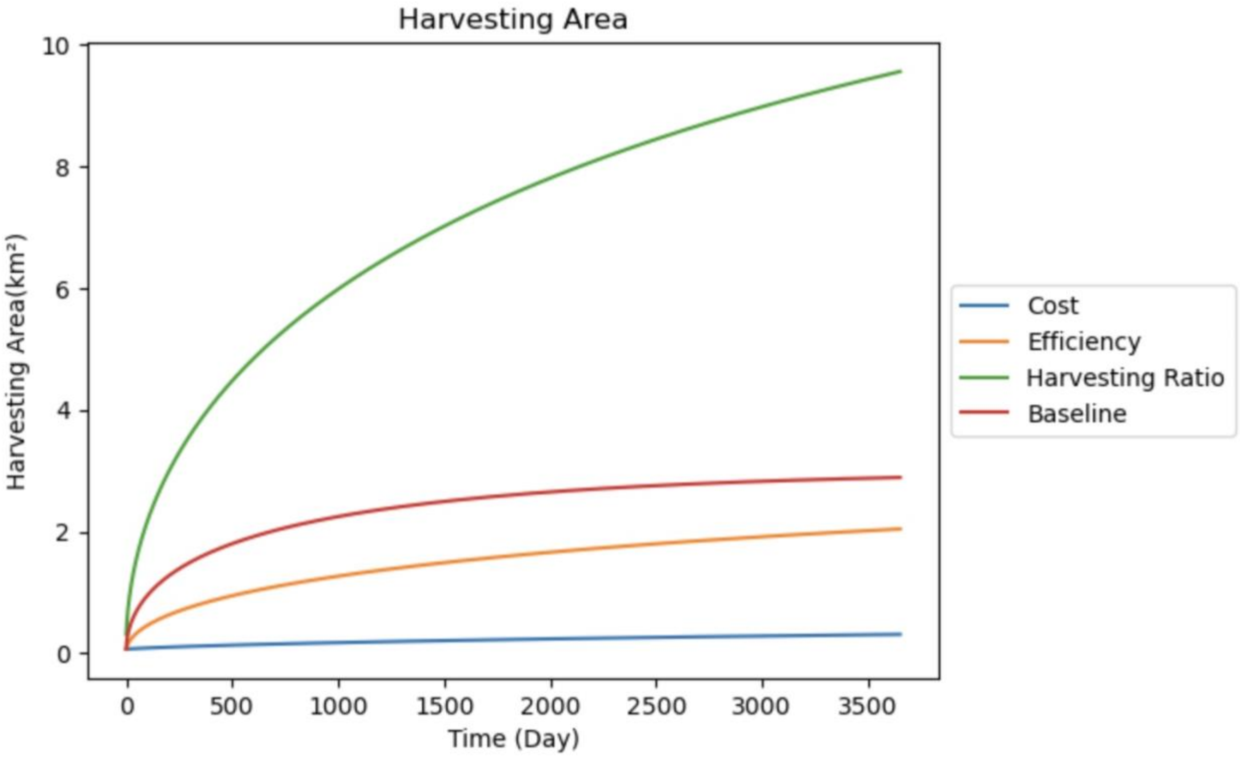


Figure 21. Harvesting area graph

The graphical representation of the harvesting area is illustrated in Figure 21. This visual representation delineates the allocation of land for harvesting across various scenarios, covering the time from t = 0 days to t = 3650 days (10 years). It is evident from the graph that the harvesting ratio scenario attains its peak value as a result of utilizing 100% of the allocated land for harvesting purposes. On the other hand, the cost scenario reaches its minimum value owing to financial constraints that hinder the development of the community garden.

Figures 22 and 23 depict a mutually complementary relationship between the "rest land" and "land use" in each scenario. As the extent of "rest land" decreases, the "land use" in the same scenario increases, and vice versa. Specifically, the baseline exhibits a peak value denoting the maximum "land use for CG." This observation underscores the urgent need for decision-making and appropriate policies and actions implementation to mitigate the high demand for land resources.

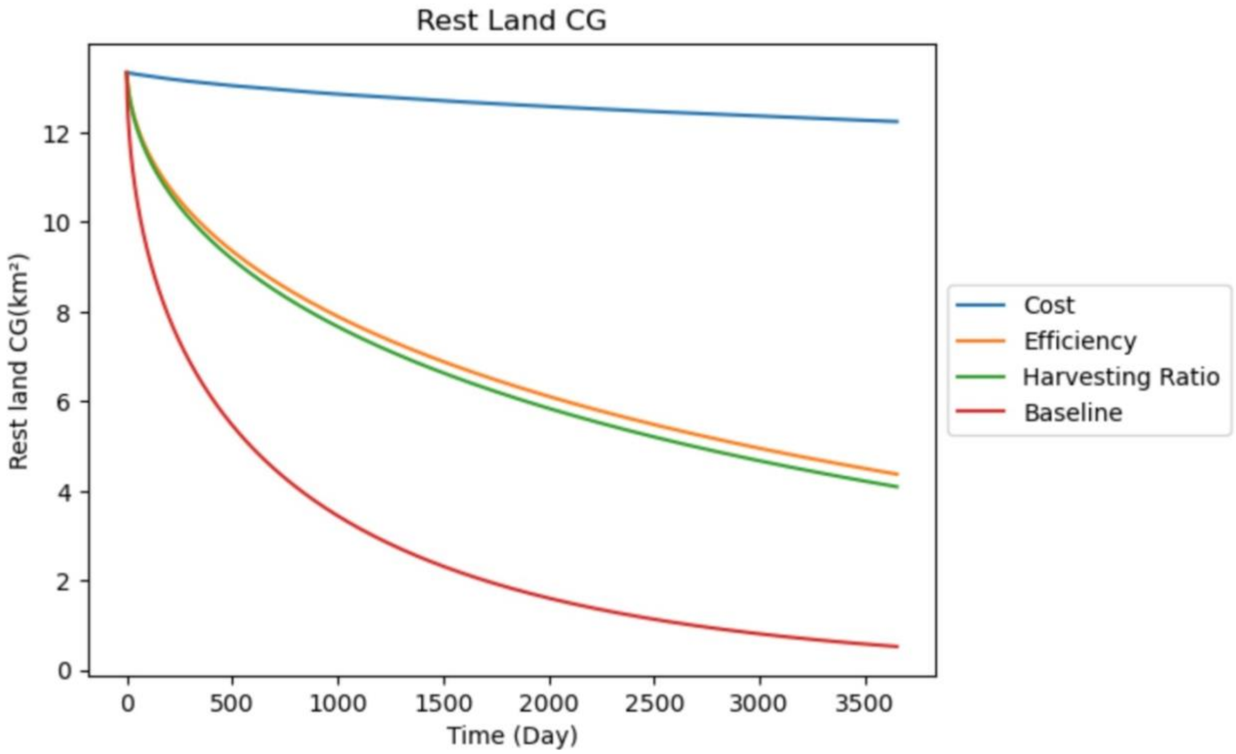


Figure 22. Rest land CG graph

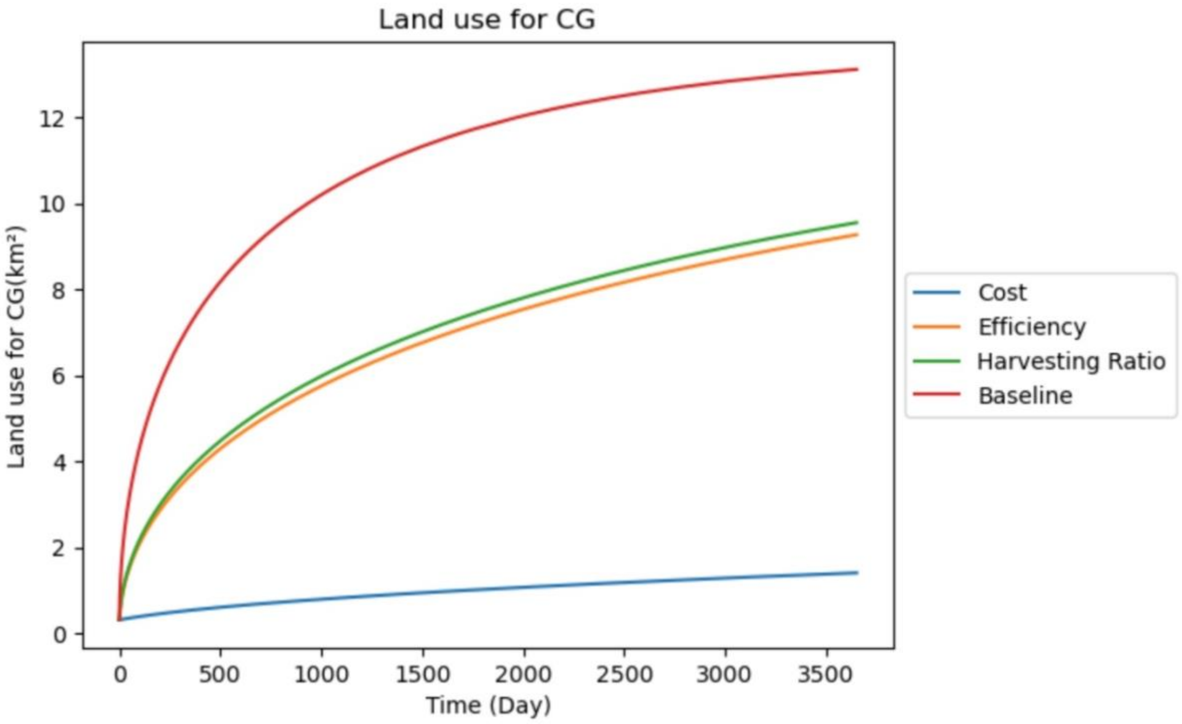


Figure 23. Land use for CG graph

Figure 24 presents the yield of vegetable graph across various scenarios. At the starting point (t=0), the yield stands at 123.6 kg in both the baseline and cost scenarios. However, for the harvest ratio scenario, the yield increases significantly to 561.83 kg; for the efficiency scenario, it further rises to 618.01 kg.

Upon progressing ten years, the yield for each scenario undergoes substantial changes. In the baseline scenario, the yield reaches 5,211.04 kg, while in the harvest ratio scenario, it experiences a remarkable surge, reaching 17,249.3 kg. Similarly, the efficiency scenario demonstrates an even more substantial increase, with the yield reaching 18,416.1 kg. The cost scenario exhibits a minor yield of 557.75 kg over the same period.

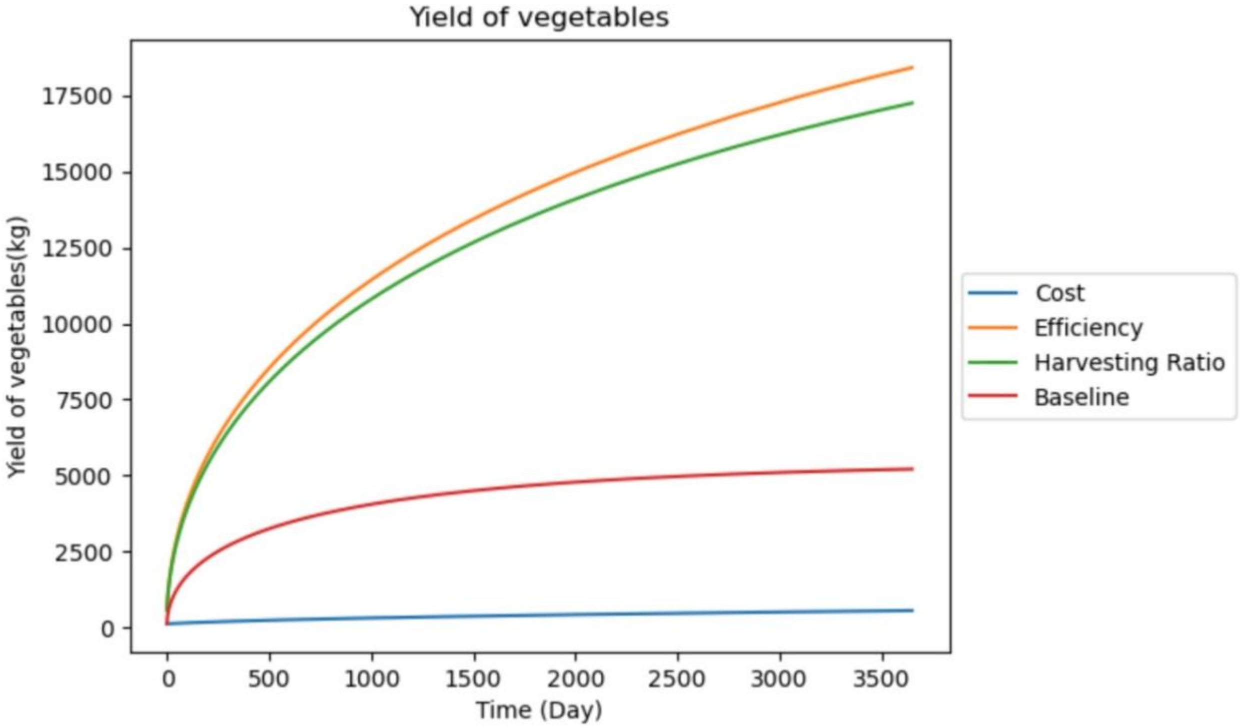


Figure 24. Yield of vegetables graph

Figure 25 shows the graph of the yield of fruit across distinct scenarios. Commencing at time t=0, the yield amounts to 0.026 kg for both the baseline and cost scenarios. In contrast, the harvest ratio scenario shows a considerable increase, elevating the yield to 0.11 kg, and the efficiency scenario demonstrates a further augmentation, resulting in a yield of 0.13 kg.

After ten years, noteworthy transformations in yield occur within each scenario. In the baseline scenario, the yield escalates to 1.1 kg, while the harvest ratio scenario experiences a remarkable surge with a yield of 3.64 kg. Similarly, the efficiency scenario reaches 3.89 kg for its yield. In contrast, the cost scenario demonstrates a relatively modest yield of 0.11 kg during the same period.

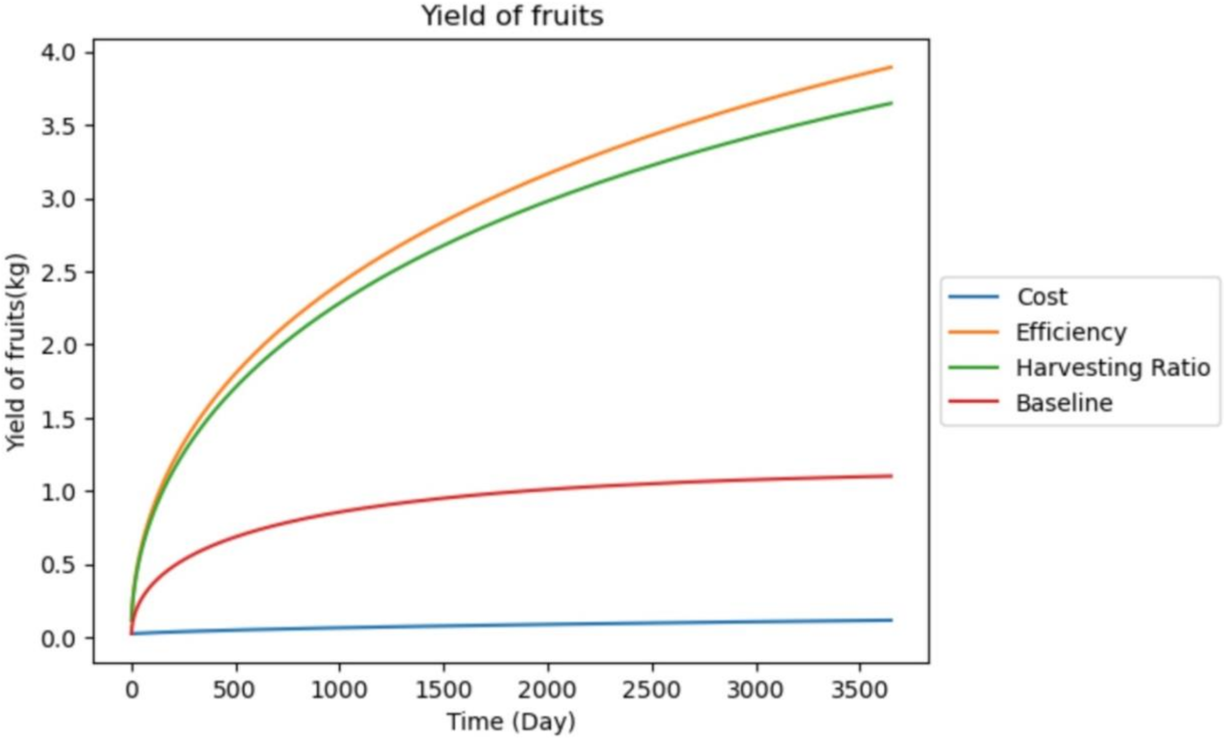


Figure 25. Yield of fruits graph

Regarding the yield of legumes, which is demonstrated in Figure 26, the same performance as the yield of vegetables and the yield of fruits can be observed. At t=0, the yield of legumes for both the baseline and the cost scenario equals 3.05 kg, while the yield of legumes for the harvesting ratio scenario and efficiency scenario are 13.86 and 15.25, respectively.

After a decade (t = 3650), the "yield of legumes" in the scenarios of "baseline," "harvesting ratio scenario," "efficiency scenario," and "cost scenario" attain values of 128.57, 425.59, 454.37, and 13.76, respectively. The increments observed in the "harvesting ratio scenario" and "efficiency scenario" highlight the effectiveness of implementing proper policies and measures when compared to the "baseline" and even the "cost scenario," which faces constraints from limited budgetary resources and consequently struggles to compete with the other scenarios.

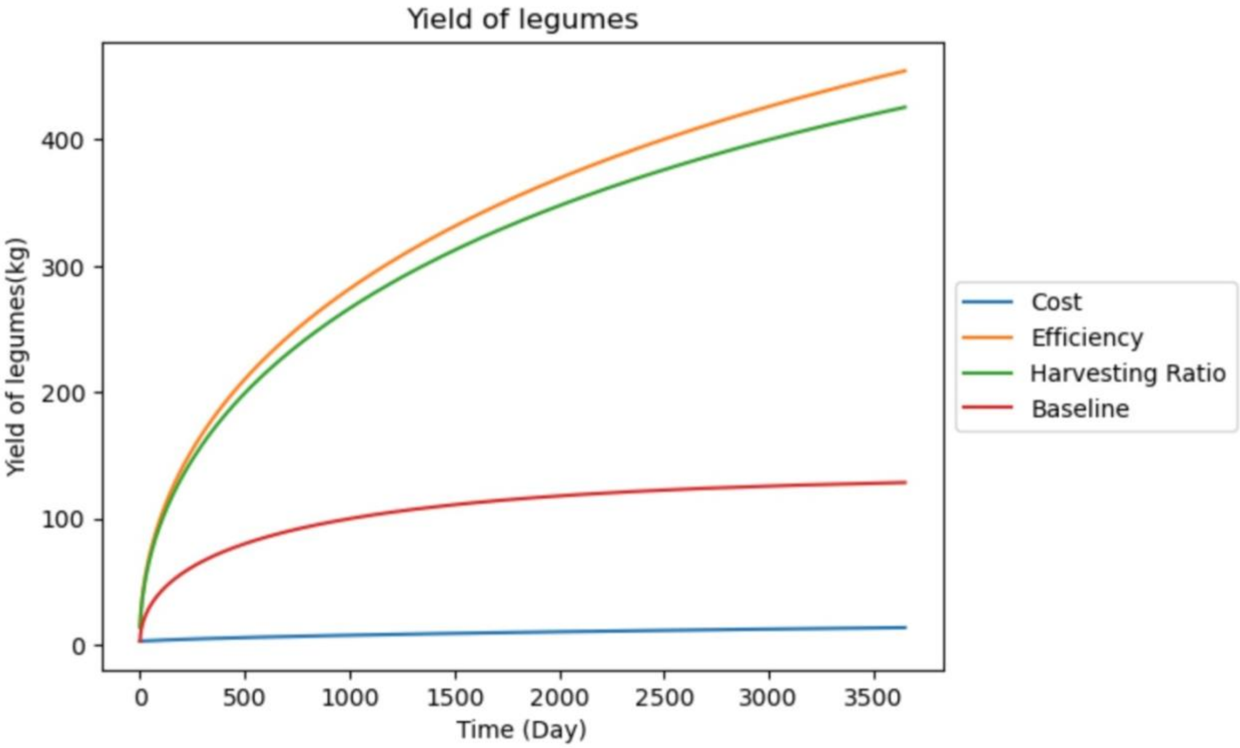


Figure 26. Yield of legumes graph

The total amount of yield of vegetables, fruits and legumes is considered as the "food produced from CG" and its graph is depicted in Figure 27.

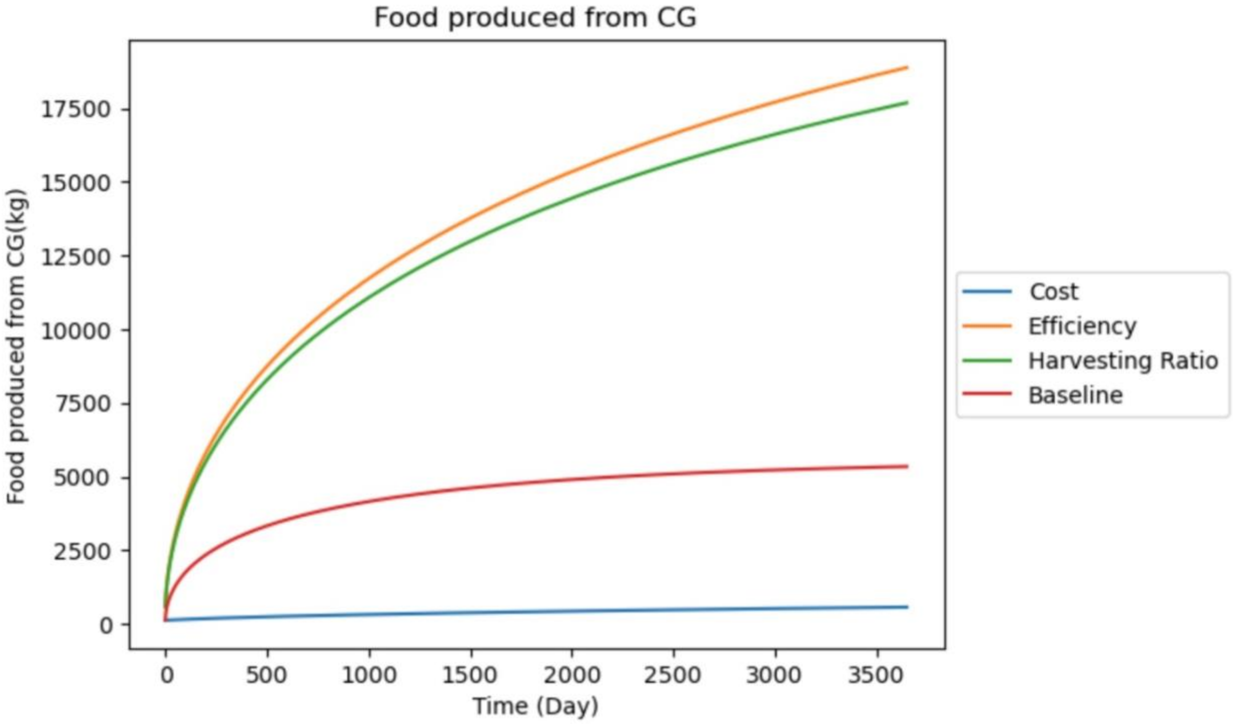


Figure 27. Food produced from CG graph

The graph of the total food cost per day is illustrated in Figure 28, which has a different performance in comparison to other entities. The total food cost per day at the starting point for baseline, harvesting ratio scenario and efficiency scenario are 0.01, 0.05 and 0.06 Canadian dollars per day, respectively, while the cost scenario incurs a substantially higher value of 3,662.43 Canadian dollars per day. After ten years, the amount will reach 0.5, 2.4, and 2.64 Canadian dollars per day for baseline, harvesting ratio scenario and efficiency scenario, respectively. For the cost scenario, at t = 3650 days, the total food cost per day is considerably increased and reaches 16,527.3 Canadian dollars per day.

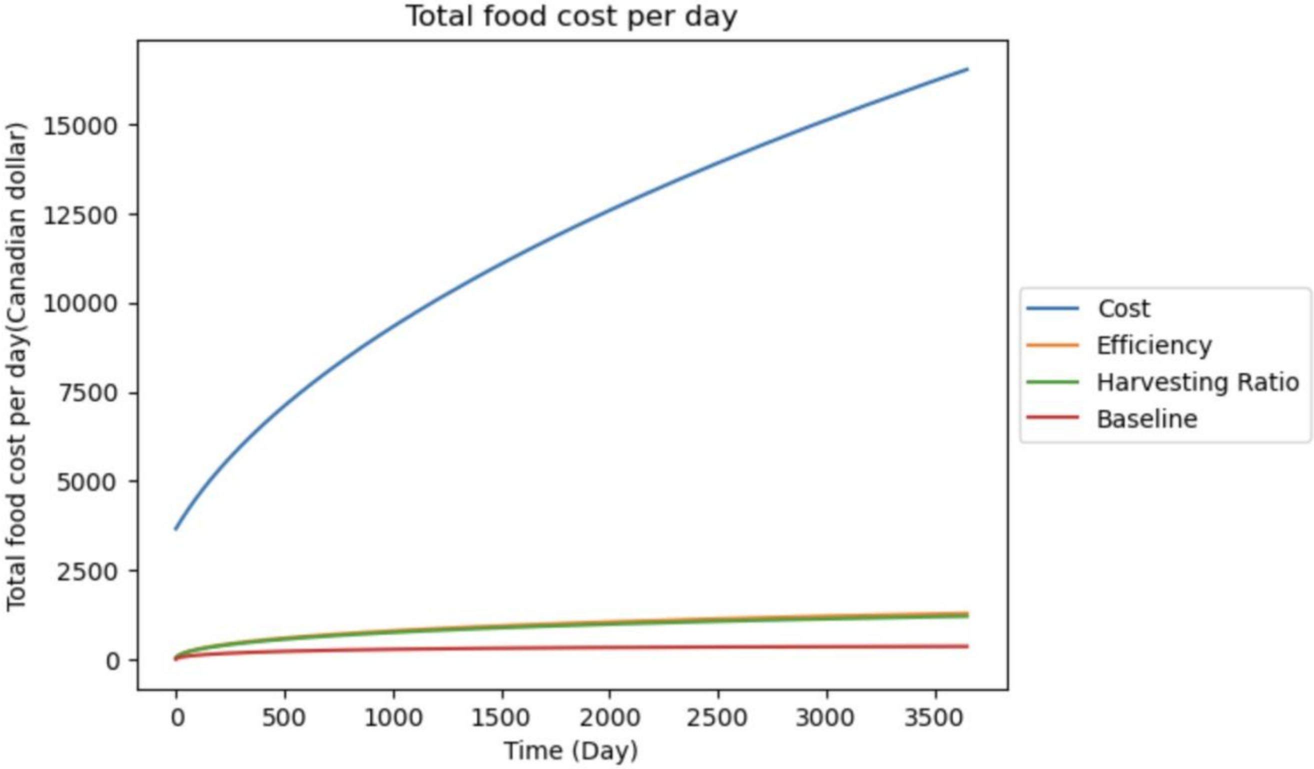


Figure 28. Total food cost per day graph

Table 13 shows the land usage for community gardens and harvesting areas at the starting point (t=0) and ending point (t = 3650d). The start point for all the scenarios has the same value (311,185 m^2), but after ten years, land usage for baseline reaches maximum value due to the absence of any approaches and policies. The land usage for "Harvesting ratio", "Efficiency", and "Cost" scenarios reaches "9,550,000 m^2", "9,270,000 m^2", and "1,400,000 m^2", respectively. This result can be interpreted as the land usage for the "harvesting ratio" scenario is less than the baseline due to the usage of 100% of converted land for the harvesting area, and the need for assigning more land is decreasing. For the "efficiency" scenario, almost the same result as the "Harvesting ratio" scenario is achieved, and the reason is that by increasing the garden's efficiency, more food can be grown and harvested in less land. However, for the "Cost" scenario, the result is different, and the land usage is less than in other scenarios because there is a limit in budget and by increasing the food production costs, there is not much potential to assign lands for community gardens.

Regarding "Harvesting area", it should be mentioned that after ten years, each scenario reaches its defined "harvesting ratio". It means that the "harvesting ratio" for baseline, efficiency, and cost scenarios was defined as 0.22, and for the harvesting scenario, its value was set to 1.

Scenario/Results	Land use (m^2) (t=0d)	Land use (m^2) (t=3650 d)	Harvesting area (m^2) (t=0)	Harvesting area (m^2) (t=3650)
Baseline	311,185	13,100,000	68,461	2,886,280
Harvesting ratio	311,185	9,550,000	311,185	9,553,990
Efficiency	311,185	9,270,000	68,461	2,040,050
Cost	311,185	1,400,000	68,461	308,926

Table 13. Land use for CG and Harvesting area's Results from the model's simulation

Table 14 provides the data regarding the yield of vegetables, fruits and legumes at the simulation's start and end points, and the result will be discussed in the next section.

Scenario/Results	Yield of vegetables (t=0)	Yield of vegetables (t=3650)	Yield of fruits (t=0)	Yield of fruits (t=3650)	Yield of legumes (t=0)	Yield of legumes (t=3650)
Baseline	123.6	5,211.04	0.026	1.1	3.05	128.57
Harvesting ratio	561.83	17,249.3	0.11	3.64	13.86	425.59
Efficiency	618.01	18,416.1	0.13	3.89	15.25	454.37
Cost	123.6	557.75	0.026	0.11	3.05	13.76

Table 14.Yield of vegetables, fruits and legumes

Table 15 shows the amount of food produced, and the food cost for each scenario on a daily basis at the start and final point of the simulation, and more details will be explained in the discussion section.

Scenario/Results	Daily amount of food produced (kg) (t=0d)	Daily amount of food produced (kg/day) (t=3650d)	The food cost (CAN/day) (t=0)	The food cost (CAN/day) (t=3650)
Baseline	126.67	5,340.72	8.67	365.8
Harvesting ratio	575.81	17,678.5	39.43	1,210.86
Efficiency	633.39	18,874.4	43.38	1,292.76
Cost	126.67	571.63	3,662.78	1,6528.1

Table 15. The amount of food produced and the food costs results from the model's simulation

Table 16 depicts the "food cost per kilogram", "harvesting area per kilogram of food produced" and "Number of people that can be fed" in different scenarios. For the "food cost per kilogram", the same result can be seen for all the scenarios except "Cost scenario" and for "Harvesting area per kilogram of food produced", again, the same results can be seen for all the scenarios except "Efficiency scenario" and it is obvious because these are constant values.

Regarding the "Number of people that can be fed", it should be mentioned that these values have been calculated merely by focusing on vegetable demand due to its considerable yield in comparison to fruits and legumes in community gardens. It can be concluded that the "efficiency scenario" after ten years can provide food for 61,387 people, which gains the best result among other scenarios because it has the potential to supply vegetables for a larger vulnerable residents. However, this value for "Baseline", "Harvesting ratio" and "cost" is "17,370", "57,497", and "1,859" respectively. Obviously, the "cost" scenario has the worst outcome due to a limited budget and existing financial constraints.

Scenario/Results	Food cost per kilogram (CAN/kg)	Harvesting area per kg of food produced (m^2/(kg/day))	Number of people that can be fed* (t=3650)
Baseline	0.068	540.42	17,370
Harvesting ratio	0.068	540.42	57,497
Efficiency	0.068	108.08	61,387
Cost	28.91	540.42	1,859

*Table 16. Food cost, Harvesting area and the number of people that can be fed. *Here, food means only vegetables.*

4.2 Discussion

This section discusses the acquired graphs of simulated scenarios from the result section in two main categories. The first is the analysis of the scenarios' results, and after that, the interdependencies between the result and sustainable development goals will be considered.

4.2.1 Fundamental outcomes

The result of three different scenarios, including baseline, has been analyzed in this section. "Harvesting Ratio scenario", "Efficiency scenario", and "Cost scenario" will be discussed, respectively. In the next step, the output of this study will be observed through real-world issues like the available food rate, that can be produced through community gardens considering food security and the required land area allocated to the community garden to have a food-secure society in Montreal.

4.2.1.1 Scenario 1. Harvesting ratio

The findings from Scenario 1, implemented with a harvesting ratio approach, indicate a substantial utilization of the land designated for the community garden, and a smaller amount of the allocated land observed in comparison to the baseline scenario. This outcome suggests that in instances where land has already been converted into a community garden, it is advisable to capitalize on its full potential by maximizing the cultivation area. This approach aligns with the optimal utilization of resources and reinforces the community garden's capacity to meet its objectives effectively. Additionally, this trend extends to the harvesting area, wherein the yield reaches its maximum value and exhibits an exponential growth pattern, distinguishing it significantly from the outcomes of alternative scenarios. The exponential increase observed in the harvesting area demonstrates the potential for achieving higher productivity in comparison to the other considered scenarios. The substantial difference in outcomes emphasizes the efficacy of the harvesting ratio to reinforce the community garden’s productivity and overall efficiency.

In terms of fruit, vegetable, and legume yields, Scenario 1 ranks second for attaining the maximum values, whereas the efficiency scenario claims the top position. The prominence of an experienced and knowledgeable farmer becomes evident in achieving such favourable outcomes. Nevertheless, the impact of the harvesting ratio on the community garden's production, specifically vegetables, fruits, and legumes, is significantly noticeable, resulting in a considerable disparity in output. Regarding cost, the harvesting ratio scenario costs more than the baseline, as it generates higher yields. Consequently, the registration fee, defined as the monetary amount payable per kilogram of yield, is expected to increase accordingly. This cost adjustment reflects the increased productivity and potential profitability associated with the implementation of the ratio harvesting approach.

4.2.1.2 Scenario 2. Efficiency

The outcomes of scenario 2, focused on maximizing the yield of food encompassing vegetables, fruits, and legumes, demonstrate a noteworthy increase in productivity. This positive outcome can be attributed to investments in knowledge acquisition and the employment of skilled farmers who can optimize community garden output through efficient management practices. With a focus on land utilization for the community garden (CG), it is observed that the area dedicated to CG exhibits exponential growth, surpassing the cost scenario while remaining below both the baseline and harvesting ratio scenarios. This finding suggests that by enhancing efficiency and productivity levels, there is a reduced demand for additional land, as experienced farmers can effectively maximize yield, control pests, and manage plant diseases. The trend observed in the harvesting area follows a similar pattern as land usage, further reinforcing the notion of increased efficiency and productivity, leading to heightened output within the community garden area.

Significantly, the yield obtained in the context of this study has reached its maximum level. This outcome effectively highlights the pivotal role played by knowledgeable and experienced farmers within this framework. Moreover, the efficiency scenario obtained the highest values for the food produced from the community garden (CG). Notably, when considering the overall cost associated with food production, regardless of the cost scenario, the efficiency scenario exhibits a higher cost than the ratio harvesting scenario and the baseline scenario. This cost disparity can be attributed to the significantly increased yield achieved in the efficiency scenario, which in turn corresponds to an elevated registration fee aligned with the yield. As such, the findings underscore the direct relationship between yield levels, registration fees, and overall food costs within the community garden area.

4.2.1.3 Scenario 3. Cost

The pattern exhibited by the cost scenario within the model distinguishes it from other scenarios due to its distinct characteristics. Unlike the exponential trends observed in other scenarios, the cost scenario demonstrates a linear increase and decrease across all graphs. Specifically, when considering land use allocation for a community garden, the least amount of land is dedicated to this scenario. The limited allocation of land can be attributed to the reluctance of stakeholders and politicians to endorse policies related to community gardens when costs are rising. Their motivation is diminished by budgetary constraints, resulting in increased resistance to support such initiatives.

In the context of land use, the cost scenario assigns only 1,400,000 m^2 the community garden after ten years. This value represents only 10.68% of the land allocation in the baseline scenario, which reaches 13,100,000 m^2. Furthermore, compared to the harvesting ratio scenario with a land allocation of 9,550,000 m^2 (72.9% of the baseline), and the efficiency scenario with a land allocation of 9,270,000 m^2 (70.7% of the baseline), the cost scenario consistently exhibits the lowest dedication of land to community gardens.

Regarding the yield graph, it becomes evident that the cost scenario yields the lowest increase in crop productivity. The agricultural output in this scenario experiences unfavourable growth rates, ultimately placing it in an inferior position compared to other scenarios.

Moreover, the cost scenario stands out in terms of total food cost per day, surpassing all other scenarios by a considerable margin. It is noteworthy that the cost scenario only accounts for energy and labour costs, along with registration fees, while disregarding water-related expenses. This approach fails to capture the comprehensive costs associated with running a farm, highlighting the need for government support to ensure the economic viability of community gardens.

The findings from the system dynamic model have significant implications for real-world issues such as feeding rate and the allocation of land area to community gardens in specific districts. The model demonstrates that the cost scenario yields the lowest value over ten years. This indicates that focusing solely on reducing costs may not be the most effective approach for achieving food security and poverty alleviation goals. On the other hand, the efficiency scenario, characterized by knowledgeable and experienced farmers, exhibits exponential growth and reaches a much higher value in ten years. This suggests that investing in training programs and empowering farmers can substantially increase food production and associated benefits. The harvesting ratio scenario, utilizing 100% of converted land, shows slightly higher values than the other scenarios, indicating its potential to contribute to improved food security outcomes. Lastly, the baseline scenario, which represents the absence of targeted programs, obtains the maximum value in land usage, highlighting the importance of implementing policies and programs to address community needs. Following these results, decision-makers must consider the trade-offs between land use costs, efficiency, and ratio harvesting when designing policies to enhance feeding rates, create employment opportunities, and determine the optimal land area allocation for community gardens in each neighbourhood and district.

4.2.1.4 Available food rate

According to the Government of Canada, 2022, the borough of Montreal, encompassing an area measuring 431.5 km^2, stands as the second largest city among the other cities of Canada with a population totalling 1,762,949 individuals. The primary purpose of community gardening is to provide fresh food to marginalized people characterized by limited access to fresh food (typically encompassing individuals residing in impoverished conditions or with generally low economic means). Notably, community gardens are well-known for their capacity to offer sustenance within areas known as "food deserts", where access to nutritious food is severely restricted. (McClintock, 2014).

By this explanation, the target population for this study would be people whose income is approximately below $30,000 per year. According to Census Profile 2021(Government of Canada, 2022a), "559,045" individuals have an income under $30,000 per year. This means that 31.71% of the population lacks sufficient funds to pay their food expenses, and they need to be supported by the government's policies to reach optimal food security.

Based on EAT-LANCET (Willett et al., 2019), every individual generally needs approximately 300 grams of vegetables, 50 grams of dry beans, lentils, and peas, and 200 grams of fruit daily.

Considering this data, if community gardens aim to cover the residents' vegetable, fruit, and legume demands, 167,713.5 kg of vegetables, 27,952.25 kg of legumes, and 111,809 kilograms of fruit per day should be produced. However, in the efficiency scenario, which has the highest yield, after ten years, the community gardens have the potential to produce 18,416.1 kg of vegetables, 454.37 kg of legumes per day, and 3.89 kg of fruits. This amount responds to 10.98% of the vegetable demand, 1.62% of the legume demand and 0.003% of the fruit demand for the vulnerable Montreal population. Table 17 shows the percentage of food demand coverage for vegetables, legumes and fruits in each scenario for vulnerable people.

	Vulnerable population demand (kg/day)	**% of food demand coverage by Scenario 1-Harvesting ratio**	**% of food demand coverage by Scenario 2-Efficiency**	**% of food demand coverage by Scenario 3-Cost**
Vegetable	167,713.5	10.28	10.98	0.33
Legume	27,952.25	1.52	1.62	0.05
Fruit	111,809	0.003	0.003	0.00009

Table 17.The percentages of food demand coverage

Based on the result of the efficiency scenario, which has the highest yield, it is not feasible to satisfy the vegetable, fruit and legume demand by allocating the food produced from the community gardens to individuals belonging to the poverty and food insecurity demographic. Also, the supply of fruits and legumes is much less than that of vegetables and is unsatisfactory.

4.2.1.5 Required land area to allocate to the community gardens

In the efficiency scenario, a production of 18,416 kg of vegetables is estimated after ten years, utilizing a harvesting area of 2.04 km^2. This outcome indicates that an allocation of 18.57 km^2 from Montreal's total park areas, which encompass approximately 66.67 km^2across the city, to community gardens managed by skilled farmers, would be sufficient to fulfill the vegetable demand of individuals experiencing food insecurity in Montreal.

	Vulnerable population demand (kg/day)	**Required land following the Scenario 1- Harvesting ratio (km^2)**	**Required land following the Scenario 2- Efficiency (km^2)**	**Required land following Scenario 3- cost (km^2)**
Vegetable	167,713.5	92.89	18.57	92.89
Legumes	27,952.25	627.49	125.5	627.55
Fruits	111,809	293,467.6	58,636.49	314,006.42

Table 18. Required land to supply food for vulnerable people

Based on the findings presented in Table 18, it is evident that the provision of fruit and legumes through community gardens to cater to the needs of vulnerable residents poses considerable challenges and appears unfeasible. Conversely, in the context of vegetable demand, the outcomes derived from the second scenario offer a more promising outlook, indicating that the vegetable requirements of individuals falling under the category of insecure food access in Montreal can be effectively addressed by allocating an area of 18.57 km^2 of parks. Regarding the "harvesting ratio" scenario, the required land to supply vegetable demand for vulnerable residents is 92.89 km^2 which is much more than the similar value for the efficiency scenario, and it proves that to supply the demand, the efficiency of the garden should be increased to have less land usage and more products. This can be achieved by experienced farmers and also by using state-of-the-art technologies and novel approaches. Like other results of the Cost scenario, it is away from reality and absolutely supportive policies and incentives should be assigned to develop and improve sustainability actions.

4.2.2 Sustainable Development Goals aligned with the result of this study

The Sustainable development goals that are covered in this study are SDG 2 (zero hunger), SDG 3 (good health and well-being), SDG 11 (sustainable cities and communities), and SDG 12 (responsible consumption and production) (United Nations, 2022). Community gardens fight against zero hunger by producing fresh food in the middle of urban areas and delivering it to impoverished people. As mentioned before, the primary purpose of community gardens is to provide food for impoverished people who need nutrition and fresh food.

The fundamental rules of community gardens are based on sustainable consumption and production. Some of these rules are producing organic food growing without pesticides and herbicides, reducing waste by using them as compost and reducing commuting by shortening the distance between suppliers and consumers.

Engaged volunteers and individuals can increase their health by doing physical activities such as gardening. Improve their mental health by spending their time in the greenery area. The community gardens are a perfect platform for training children and adults to get gardening knowledge and, at the same time, connect with others to increase their social interactions in their neighbourhood.

Regarding sustainable cities and communities, community gardens are such an excellent example of this sustainable goal due to their engagement in increasing the greenery area in cities, even in metropolitans, attempting to decrease greenhouse gas emissions by making the food supply chain shorter and help the cities to be resistance in terms of self-sufficient if some crisis like Covid-19 happens.

4.3 Limitations

As a type of urban agriculture, several parameters affect community gardens, which can lead to changes in inputs, processes, and output. In this study, the main and significant parameters have been taken into account. The parameters that have not been considered are as follows:

1. Time delay: Like any other project, from specifying the recourses, staff, and initial decisions to implementation, there is a time delay which is not considered in this study.
2. Zoning restrictions: It was assumed that all the areas of Montreal's parks are flat and can be converted into community gardens. However, by considering Montreal's topography, not only are all the parks' areas not flat, but there are also zone restrictions like huge rocks

and steep slopes.

3. Land allocation: In this model, only the park areas are considered as the potential land to be converted into community gardens. However, too many other lands in a city have this potential, like vacant lots and school grounds.
4. Costs: Due to a lack of data, cost analysis has been limited to available data. However, several factors can be considered as costs, like the effect of inflation.

4.4 Future studies

For future studies, the model can be improved regarding:

- Time delay, by implementing the actual delay time in the real community gardens.
- The feasibility of lands that can be converted to community gardens can be investigated.
- Cost analysis could be expanded and include inflation, implementation, labor, seeds, fertilizers, pesticides, herbicides, energy and water costs and several other parameters.

The other future study could evaluate food security using a system dynamics approach. One approach could be observing the behavior of the efficiency scenario by introducing novel agricultural methods and technologies. Also, this model can be expanded with much more detail to enhance its realism and reliable predictions.

4.5 Conclusion

The findings of the system dynamics model have essential implications for residents' feeding rate, and the required land for community gardens in the city. The efficiency scenario, which incorporates knowledge and experience from skilled farmers, exhibits exponential growth and significantly higher values over ten years. This suggests that implementing training programs and leveraging the expertise of experienced farmers can significantly enhance the productivity of community gardens. Consequently, a higher yield of food production can contribute to improving the feeding rate of residents in each neighbourhood.

Additionally, the harvesting ratio scenario, which maximizes the utilization of converted land to community gardens, performs slightly better than the other scenarios. This implies that allocating sufficient land area for community gardens can help meet the demand for food production. By effectively utilizing available land resources, communities can potentially increase the amount of food produced and thus improve the feeding rate of residents. Considering the required land for community gardens, the model emphasizes the importance of optimizing land allocation. The harvesting ratio scenario, which utilizes 100% of converted land, demonstrates slightly better performance. This suggests that allocating adequate land area for community gardens can maximize food production and potentially meet the demand for local food consumption.

The efficiency scenario, characterized by the most substantial yield, adequately satisfies 10.98% of the vegetable demand, 1.62% of the legume demand, and 0.003% of the fruit demand for the vulnerable population residing in Montreal. This outcome implies that the efficiency scenario's heightened yield can effectively cater to the vegetable demand of 61,383 individuals, the legume demand of 9,056 individuals, and the fruit demand of only 16 individuals. The yield of legumes and specifically fruit, is significantly negligible.

The findings of this investigation have been predicated on the supposition of allocating 20% of park areas in Montreal, corresponding to an area of 13.33 km^2. However, this allocation is deemed insufficient to satisfy the vegetable demand of the vulnerable population. Consequently, it has been deduced that an area of "18.57", "125.5", and "58,636.49" $km^2$is requisite to meet the vegetable, legume, and fruit demands of the vulnerable population, respectively.

It is noticeable that the yield of community gardens is much lower than establishing greenhouses in urban areas like rooftop farming or vertical farming. However, by considering the unique attributes of community gardens, like social interactions, increasing greenery area in the neighbourhoods, engaging residents with sustainable actions and training them with new skills like gardening, community gardens, in comparison to other types of urban farming, significantly can compensate for its low yield.

In summary, the model's results indicate that implementing training programs, leveraging experienced farmers, optimizing land allocation, and utilizing available land resources effectively can positively impact residents’ feeding rate and the required land for community gardens. These findings can guide policymakers and communities in designing and implementing strategies that enhance food security, alleviate poverty, and promote sustainable local food systems.

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Appendix

Thanks to Andrea Tremblay, the weighted harvest's data of mind.heart.mouth garden in 2022 has been provided in tables A.1 to A.6.

DATE/ weight in grams	AMARANTH	BASIL	BEANS	BEETS	BOK CHOY	BROCCOLI	CABBAGE
Monday, June 6							
Wednesday, June 8							
Friday, June 10							
Monday, June 13					2000		
Thursday, June 16					2110		
Monday, June 20					9740		
Monday, June 20					3155		
Wednesday, June 22							
Monday, June 27					18,800		
Wednesday, June 29							
Monday, July 4							
Wednesday, July 6							
Friday, July 8							
Monday, July 11	20		450	160		240	
Wednesday, July 13			100				
Friday, July 15			200				
Wednesday, July 20			1200	1220		565	
Monday, July 25			5000	3300		1000	
Wednesday, July 27		10	200			840	
			4200			2700	4200
Wednesday, Aug 3		10	4580			680	
Monday, August 8			300	950		1140	6110
Wednesday, Aug 10		5	7160			2100	
Friday, August 12			400			280	
Monday, Aug 15			2800			1300	
Wednesday, Aug 17			300	2200			
Wednesday, Aug 17			6000				
Monday, Aug 22			580			3300	
Wednesday, Aug 31			9400			300	
Friday, Sep 2			500				
Tuesday, Sep 6			9800			1500	
Wednesday, Sep 7						2100	4350
Monday, Sep 12			100				
Wednesday, Sep 14			14400	400		2500	
Friday, Sep 16							
Wednesday, Sep 21			12190			1000	
Wednesday, Sep 28			455	70		1460	
Wednesday, Oct 5			9000			2000	
Wednesday, Oct 12							
Wednesday, Oct 19		220	500	1060	800	610	2400
TOTALS (g)	20	245	89815	9360	36605	25615	17060

Table A.1. Weighted harvest data in 2022

DATE / weight in grams	CARROTS	CELERY	CHICHORY	CHIVES	CORIANDER	CUCUMBER	DILL
Monday, June 6							
Wednesday, June 8							
Friday, June 10							
Monday, June 13							
Thursday, June 16							
Monday, June 20							
Monday, June 20							
Wednesday, June 22							
Monday, June 27							
Wednesday, June 29							
Monday, July 4					100		100
Wednesday, July 6		350					
Friday, July 8							
Monday, July 11		1200					
Wednesday, July 13		450				100	90
Friday, July 15	2000			10		700	40
Wednesday, July 20							
Monday, July 25							
Wednesday, July 27	2000			20		710	40
						1800	80
Wednesday, Aug 3	1140	710		180		780	
Monday, August 8	3620	1150			50	2600	
Wednesday, Aug 10	190	17550		40	90	100	
Friday, August 12						955	
Monday, Aug 15						1600	
Wednesday, Aug 17	2700	8670				950	100
Wednesday, Aug 17	100						
Monday, Aug 22		5930				2000	
Wednesday, Aug 31	2800	1800				1100	
Friday, Sep 2	130			30		310	
Tuesday, Sep 6		7000				1500	
Wednesday, Sep 7				25		250	
Monday, Sep 12						600	
Wednesday, Sep 14	2000					500	750
Friday, Sep 16						200	
Wednesday, Sep 21	1600	11650					20
Wednesday, Sep 28	40			100		160	
Wednesday, Oct 5	15						10
Wednesday, Oct 12	400	12000					
Wednesday, Oct 19	10900	400	700	3000			
TOTALS (g)	29635	68860	700	3405	240	16915	1230

Table A.2. Weighted harvest data in 2022

DATE / weight in grams	EGGPLANT	GARLIC/ SCAPES	KALE	LEEKS	LETTUCE (all kinds)	MINT
Monday, June 6			300		1000	
Wednesday, June 8					150	
Friday, June 10					435	
Monday, June 13					750	
Thursday, June 16					1540	
Monday, June 20					7410	
Monday, June 20		295			995	300
Wednesday, June 22						
Monday, June 27		1200	1200		9800	
Wednesday, June 29		505	150		710	
Monday, July 4			7500		5100	100
Wednesday, July 6			3090			
Friday, July 8		240				690
Monday, July 11		80	3900		4280	
Wednesday, July 13			4.935		405	
Friday, July 15			1300			20
Wednesday, July 20						
Monday, July 25						
Wednesday, July 27			19200			20
				1000		50
Wednesday, Aug 3	1050	50		8400		90
Monday, August 8	950		950			240
Wednesday, Aug 10	300	90	300			820
Friday, August 12						
Monday, Aug 15	200					
Wednesday, Aug 17	1700		2330	5470		
Wednesday, Aug 17	300					
Monday, Aug 22	750		8220			80
Wednesday, Aug 31	680		8000	3400		
Friday, Sep 2						
Tuesday, Sep 6	4000		100			
Wednesday, Sep 7						
Monday, Sep 12	1400					
Wednesday, Sep 14	1800		1000	3700		
Friday, Sep 16			50			
Wednesday, Sep 21				700		110
Wednesday, Sep 28	480		120			
Wednesday, Oct 5			1300			
Wednesday, Oct 12				3000		
Wednesday, Oct 19			17220			850
TOTALS (g)	13610	2460	76235	25670	32575	3370

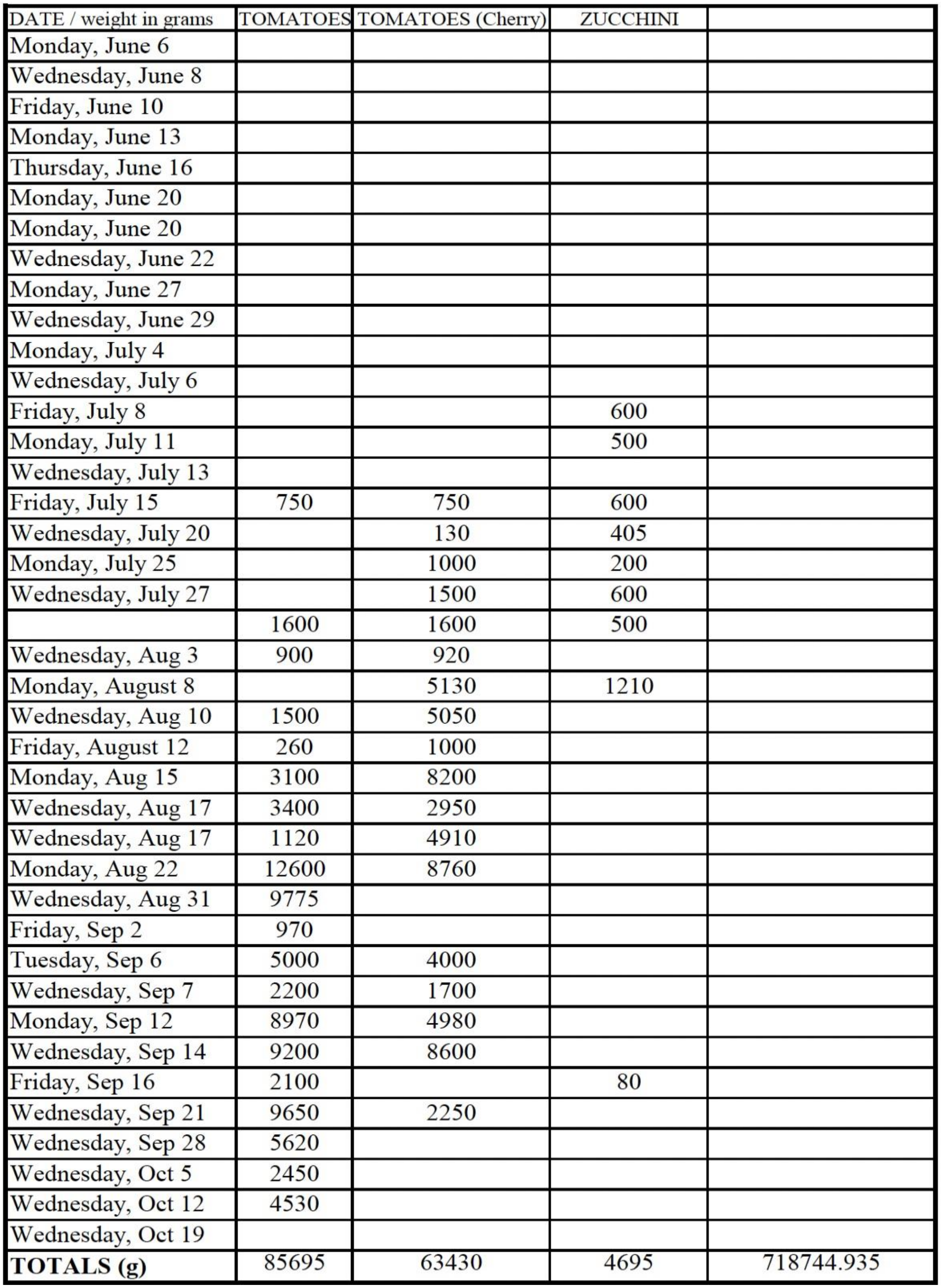
Table A.3. Weighted harvest data in 2022

DATE / weight in grams	MUSTARD	PARSLEY	PEAS	PEPPERS	ONIONS	OREGANO	RADISHES
Monday, June 6							
Wednesday, June 8							
Friday, June 10							
Monday, June 13							
Thursday, June 16							
Monday, June 20							
Monday, June 20							
Wednesday, June 22							
Monday, June 27							200
Wednesday, June 29							
Monday, July 4		100	700				
Wednesday, July 6			1940				
Friday, July 8			600				
Monday, July 11			250			10	250
Wednesday, July 13							540
Friday, July 15		400			1500		
Wednesday, July 20	120		180	65		25	55
Monday, July 25							300
Wednesday, July 27		520			1600		
Wednesday, Aug 3		665					210
Monday, August 8				50			300
Wednesday, Aug 10		610			2250	50	
Friday, August 12				60	105		10
Monday, Aug 15				4400	800		
Wednesday, Aug 17		660		495	1760		550
Wednesday, Aug 17					160		
Monday, Aug 22		80		750			310
Wednesday, Aug 31		10		280			200
Friday, Sep 2						20	80
Tuesday, Sep 6				5000			
Wednesday, Sep 7				1500		25	250
Monday, Sep 12				50			200
Wednesday, Sep 14				850	1400		1450
Friday, Sep 16				3080			
Wednesday, Sep 21				100			
Wednesday, Sep 28				60			
Wednesday, Oct 5				50			50
Wednesday, Oct 12							
Wednesday, Oct 19						200	
TOTALS (g)	120	3045	3670	16790	9575	330	4955

Table A.4. Weighted harvest data in 2022

DATE / weight in grams	RAINBOW and swiss CHARD	RHUBARB	SAGE	SPINACH	SQUASH
Monday, June 6				1200	
Wednesday, June 8					
Friday, June 10					
Monday, June 13				1000	
Thursday, June 16				1290	
Monday, June 20					
Monday, June 20	395			2350	
Wednesday, June 22					
Monday, June 27	2000				
Wednesday, June 29	190				
Monday, July 4	7800				
Wednesday, July 6					
Friday, July 8					
Monday, July 11			10		
Wednesday, July 13					
Friday, July 15					
Wednesday, July 20			30	600	2180
Monday, July 25	14900				2000
Wednesday, July 27				30	
					1700
Wednesday, Aug 3	630			10	1320
Monday, August 8	9490				
Wednesday, Aug 10	1645		195	1580	2000
Friday, August 12					910
Monday, Aug 15					
Wednesday, Aug 17	4520				
Wednesday, Aug 17					
Monday, Aug 22					860
Wednesday, Aug 31			30	600	
Friday, Sep 2			30	140	
Tuesday, Sep 6					
Wednesday, Sep 7	900		100	850	
Monday, Sep 12				2300	2100
Wednesday, Sep 14					
Friday, Sep 16				480	
Wednesday, Sep 21	1000		100		
Wednesday, Sep 28					
Wednesday, Oct 5					
Wednesday, Oct 12					
Wednesday, Oct 19	2250	200	500	400	
TOTALS (g)	45720	200	995	12830	13070

Table A.5. Weighted harvest data in 2022



DATE / weight in grams	TOMATOES	TOMATOES (Cherry)	ZUCCHINI	
Monday, June 6				
Wednesday, June 8				
Friday, June 10				
Monday, June 13				
Thursday, June 16				
Monday, June 20				
Monday, June 20				
Wednesday, June 22				
Monday, June 27				
Wednesday, June 29				
Monday, July 4				
Wednesday, July 6				
Friday, July 8			600	
Monday, July 11			500	
Wednesday, July 13				
Friday, July 15	750	750	600	
Wednesday, July 20		130	405	
Monday, July 25		1000	200	
Wednesday, July 27		1500	600	
	1600	1600	500	
Wednesday, Aug 3	900	920		
Monday, August 8		5130	1210	
Wednesday, Aug 10	1500	5050		
Friday, August 12	260	1000		
Monday, Aug 15	3100	8200		
Wednesday, Aug 17	3400	2950		
Wednesday, Aug 17	1120	4910		
Monday, Aug 22	12600	8760		
Wednesday, Aug 31	9775			
Friday, Sep 2	970			
Tuesday, Sep 6	5000	4000		
Wednesday, Sep 7	2200	1700		
Monday, Sep 12	8970	4980		
Wednesday, Sep 14	9200	8600		
Friday, Sep 16	2100		80	
Wednesday, Sep 21	9650	2250		
Wednesday, Sep 28	5620			
Wednesday, Oct 5	2450			
Wednesday, Oct 12	4530			
Wednesday, Oct 19				
TOTALS (g)	85695	63430	4695	718744.935

Table A.6. Weighted harvest data in 2022