Investigating Food Waste Diversion and Compost Use in Urban Agriculture for Soil Management in Mwanza, Tanzania

by

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A dissertation
presented to the University of Waterloo
in fulfillment of the
dissertation requirement for the degree of
Doctor of Philosophy
in
Environment

Waterloo, Ontario, Canada, 2021

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Author's Declaration

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

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

Abstract

African countries are urbanizing at a rapid rate. Studies on African agriculture have focused on rural food production, but research on *urban* agriculture may be key to ensuring urban food and soil security. In this dissertation, four studies were conducted to evaluate pathways for integrated soil fertility management, considering both social perspectives and nutrient management.

The aim of the first study was to understand the social component of urban agriculture in the rapidly developing city of Mwanza, Tanzania. Semi-structured interviews were conducted using judgement and snowball sampling with urban farmers (n=34). Questions included their reasons for engaging in urban farming, their cultivation practices, perspectives on soil management, and the constraints of urban farming. Qualitative analyses using coding software showed that urban farmers range in age and gender, as well as in experiences and cultivation practices. However, all participants reported farming manually using hand tools. Maize was the preferred crop among urban farmers during the rainy seasons, though a disease affecting maize crops has added uncertainty to continued maize cultivation. Where irrigation is possible through ponds, wells, springs, streams, or the lake, irrigated crops are primarily leafy greens and vegetables, including cabbage (*Brassica spp.*) and amaranth greens (*Amaranthus* var.). Reasons for cultivating ranged from family sustenance (44%), to selling for income (15%), and even tradition, enjoyment, or exercise (39%). A majority of respondents (82%) would like to improve their soils. Most use manure to improve their soils and many (32%) believe that animal manure is the way to improve soil. Additionally, most (62%) urban farmers have not tried any form of food

waste compost but responded positively to try it if they had access to and were taught how to use it. The study concludes that urban agriculture is an integral social and economic aspect of Mwanza City.

The objective in the second study was to investigate the current waste management practices in the hospitality sector of Mwanza, Tanzania and propose a composting method for urban organic (food) waste that would be suited to the city's current waste management strategy. Questionnaires were used to survey restaurants (n=30) and hotels (n=20) around Mwanza, Tanzania on current waste management practices and opinions on organic waste. Over 50% of the waste generated by the hospitality sector in Mwanza, Tanzania is organic, and for a majority of restaurants (60%) and hotels (65%), organic wastes are already separated from other wastes before collection. However, the wastes are mixed in preparation for collection. Direct observations of the city's waste management strategy gave insight into waste collection, waste transfer, and final waste disposal. Wastes were collected by waste workers primarily using trolleys and wheelbarrows. Mixed wastes were gathered at waste transfer points within the urban city centre in large, blue containers. The containers, once full, were transported by trucks to the land dump in a rural ward. A rapid composting experiment was then designed considering space, cost, and skilled labour constraints, and conducted over a one-month period. The proposed rapid composting method reduced the volume of organic waste by more than 80% within one month. The resulting products were a compost with a C:N ratio of 14:1 that can be used as a soil amendment, albeit with higher application rates to meet crop nutrient needs, and black soldier fly larvae, which can be used as feed for ducks, chickens, pigs, and other livestock.

In the third study, the effects of organic and inorganic amendments on soil and crop growth were evaluated and compared over a short-term growing period. A complete randomized design was used to assign, in triplicate, poultry manure, inorganic nitrogen fertilizer, two types of food waste compost, and control treatments. Soil samples were taken after amendment application (before planting) and after harvest, and analyzed for physical (bulk density and soil water holding capacity), chemical (organic carbon, nitrogen, phosphorus), and biological parameters (soil microbial biomass-carbon). Amaranth greens (*Amaranthus* var.) and cabbage (*Brassica oleracea* var. *capitata*) were planted for two short growing periods, and their growth heights were monitored and compared between the treatments. Organic amendments (poultry manure and food waste compost) improved the water holding capacity of the soil by 14 to 19% and enhanced microbial biomass 1.7 to 4 times the inorganic nitrogen fertilizer treatment. Additionally, crop growth under organic amendments was comparable to crop growth under inorganic nitrogen fertilizer. In fact, inorganic fertilizer, when applied incorrectly, has detrimental effects on plant germination, increasing risks for urban farmers who do not receive proper instructions for use.

The fourth study explores future trends in urban soil organic carbon, comparing the effects of organic and inorganic amendment use for the next 100 years. CENTURY soil organic model was used to simulate historical conditions and land management leading to the current conditions using geographical information, local weather data, and soil parameters to align the model with Mwanza, Tanzania. Characteristics of four amendments (food waste compost, poultry manure, ash, and inorganic nitrogen fertilizer) and their application rates and frequency were added as parameters to simulate future trends in soil organic carbon. The greatest changes in soil organic carbon in 29 years under annual application were in food waste compost (+4002 gC/m^2) and poultry manure (+3203 gC/m^2) compared to ash (+2381 gC/m^2), and lowest with inorganic fertilizer application (+518 gC/m^2). Without any amendment the change in soil organic carbon in 29 years was -1154 gC/m^2. Additionally, organic waste amendments enabled highest accumulation of resistant carbon fraction (slow C), which is lost over time after natural land conversion to agricultural land use. Therefore, organic waste amendments can increase soil organic carbon through urban agriculture and counter the impacts of land conversion.

The recommendations from the research are that land zoning policies in developing cities, such as Mwanza, in Tanzania, and more broadly in sub-Saharan Africa, should support urban farming practices and use of organic waste amendments to maximize the benefits for food security and reducing environmental impacts of cities. Additionally, the tested rapid composting method demonstrated that, as a decentralized, small-scale system, it has the potential to be implemented at waste transfer points located around the city. While it may not have the capacity for processing all of the organic waste produced in the city, it can contribute to training waste workers as a pilot-scale system, and the skills can transfer to a larger-scale, centralized organic waste diversion and processing strategy.

Acknowledgements

"haba na haba hujaza kibaba"

-Tanzanian Proverb

In Tanzania, proverbs are a powerful way of conveying advice and deep meaning for living. The one above means: *little by little, a little becomes a lot.* This dissertation would not have been possible without the the little acts of support and encouragement of the people around me, and I would like to take a moment to thank them all.

To my supervisor, Maren, there are no words that can do justice to the support that you've shown through this dissertation journey. Thank you for believing in me and in my work. Thank you for the wisdom, guidance, and motivation that were much needed throughout the ups and downs of the dissertation. This journey would not have been possible without your support!

To my committee members: Andrew, Dawn, and Christine, thank you for being open to talking about and reading through the dissertation chapters on multiple occasions. Thank you also to interim committee members Bruce Frayne and Dan McCarthy. As well as partners abroad: Ahad from Guavay who is pioneering the compost market in Dar es Salaam; Anthony Kimaro for providing critical logistical support; Michael Yhdego, the pioneering researcher in Tanzania on compost-to-soil input; Makarius Victor Mdemu from Ardhi University; Highness Msuya and Cevin Tibihenda from ARI; and other correspondents: Kata Tisza (ISWA), Elmens Kaboni (ARI), and Pasquale Borrelli (UNIPV). Without the presence of multiple perspectives, one risks the danger of tunnel vision. Thank you for providing the diverse perspectives and questions that encouraged a holistic shaping of the dissertation.

To my parents Fayaz and Shellina, and siblings Sharmin and Arish, you have been my greatest fans as I pursued higher education, even when my path was not clear. Your love, patience, and faith in me kept me going while I completed my dissertation work both in Canada and in Tanzania. I am thankful to have a supportive family!

To my family in Tanzania, thank you for making me feel like I was at home. A big thank you to my aunts and uncles, Rafik (ada), Shamimma, Shirin fui, Karim chachu, Shabnam chachi, Sadru mama and mamima, and my cousins, Teizeen, Shezu, Afroza, Shimona, and Ali.

An especially big thank you to my aunt, Shelina. Without her unconditional support and love my work in Tanzania would not have been possible. She is also the reason I was able to keep a balance between work and relaxation while in Tanzania! To her, I dedicate this dissertation.

To my friends in Canada, thank you for being my support network. From late night working sessions to chats about the overpowering emotions that come with dissertation undertakings and helping me take breaks from work (especially the ones that including climbing), without which burnout would have been inevitable. And for also supporting me through the inevitable burnout! Special shout-outs to the ones who went over and beyond: Sabrina (aka Babs), Rebecca Chin, Elli, Jenn Lau, Shahid, Eliza, Bogdan, Ale, Stephanie, Madu, Tay, Ashley, Emma, Alice, Shamika, and Tanya!

To my lab group, especially Emmanuel, Solveine, Ons, Marianne, Meaghan, and Will. With your support and guidance in the lab, the tedious tasks of lab work were less overwhelming and more enjoyable. Thank you for always being open to questions and discussions about the lab procedures and the intriguing results!

To my friends in Tanzania, thank you for taking the time to reconnect and for being my support – a home away from home. Thank you especially to Raheel Kanji for helping me with the Swahili translations and for proofreading the Swahili questionnaires and interview questions.

To the Ecology Lab (Anne and Bev), MAD, and SERS (especially Jennifer Nicholson), thank you for organizing events that helped me learn more about the work being done in the Faculty of Environment while also providing productive break times! The workshops and holiday crafts at the Ecology Lab and the presentations at the SERS Salon were highlights of my time on campus. And the use of technology from MAD made workshop presentations and statistical analyses all the more effortless.

And last, but not least, my partner, Nick Rollick, whom I met towards the end of the PhD journey, but who has been pivotal in supporting and ensuring its completion! Words cannot describe how lucky I am to have you as a partner.

Special mention also goes to people I have never met but have made such a difference in my life. Most importantly, Ramin Djawadi for the Game of Thrones and Westworld soundtracks and the YouTubers who know how to combine the best tracks into music for the zone! Epic soundtracks made dissertation writing an adventure rather than a chore.

"It always seems impossible until it's done."

-Nelson Mandela

Dedication

This dissertation is dedicated to my aunt - my *jawa*,
Shelina Rattansi,
for love and support without bounds

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List of Abbreviations

ASP aerated static piles

C carbon

C:N carbon-to-nitrogen

CA conservation agriculture

CEC cation exchange capacity

CRD complete randomized design

CTRL control

DAP days after planting

EC electrical conductivity

FWC-1 food waste compost

FWC-2 food waste compost

GHG greenhouse gas

GWP global warming potential

INF inorganic nitrogen fertilizer

ISFM integrated soil fertility management

MSW municipal solid waste

N nitrogen

OC organic carbon

P phosphorus

PM poultry manure

SDGs Sustainable Development Goals

SMB soil microbial biomass

SMB-C soil microbial biomass - carbon

SOC soil organic carbon

SSA sub-Saharan Africa

TN total nitrogen

WHC water holding capacity

Introduction

Problem Context and Research Rationale

Increasing population growth and rapid urbanization are placing increased demand and stress on food production systems (Ronald and Adamchak, 2010; FAO, 2016), which, in turn, adversely contribute to climate change (Vermeulen et al., 2012; FAO, 2016). Research on food production in Africa has mainly focused on rural agriculture (Sanchez, 2002; Sanchez and Swaminathan, 2005a; Fairhead and Scoones, 2005; Scoones, 2001, 2015; Lal and Singh, 1998; Lal, 2011). Agriculture in urban areas, on the other hand, has received less recognition despite its established prominence in many African cities (Drechsel et al., 2008). As a result, the fate of cultivated urban soils remains largely unknown, especially as human populations tend toward urban areas (Lorenz, 2015).

The pressures on food production systems are acute in SSA (sub-Saharan Africa) where per capita food production has stagnated (Sanchez, 2002), and soils are experiencing nutrient depletion (Drechsel et al., 2001b) and accelerated erosion (Lal and Singh, 1998). The rate of urbanization is faster in SSA than any other global region (Anderson et al., 2013), and urban population growth in SSA is expected to double between 2000 and 2030 (UNFPA, 2007). Additionally, urban waste production, particularly organic waste, is exceeding infrastructure capacity in developing cities in SSA (Okot-Okumu, 2012; Kaza et al., 2018). There is a need to address the consequences of rapid urbanization in SSA cities in a way that promotes sustainable development, defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987).

The main concerns for the sustainable development of SSA cities can be categorized under three themes: food production, soil fertility, and waste management. In 2015, the United Nations (UN) ratified the SDGs (Sustainable Development Goals) in an effort to provide a global blueprint for sustainable development (Sustainable and Goals, 2018). The SDGs comprise 17 goals that seek to ensure human beings can thrive in a healthy environment while protecting the planet and its resources from further degradation (Sustainable and Goals, 2018). To stimulate sustainable development in SSA cities, efforts would need to be focused on addressing SDG 2 (zero hunger) and SDG 11 (sustainable cities).

The SDGs, therefore, provide a platform of discourse for the present research (Figure 1). The aim for SDG 2 is to end hunger by achieving food security and improved nutrition and to promote sustainable agriculture (Sustainable and Goals, 2018). Aid to agriculture in SSA is declining, small-scale food producers work with limited capacities and resources, and food prices fluctuate with weather-induced shocks, civil insecurity, and declining food production (United Nations (UN) Economic and Social Council, 2019). Therefore, there is a need to research local alternatives to improve food production within the limited resources available to small-scale food producers. The aim for SDG 11 is to make cities and human settlements inclusive, safe, resilient, and sustainable (Sustainable and Goals, 2018). A key concern within SDG 11 is the inadequate urban infrastructure for waste handling and appropriate disposal (United Nations (UN) Economic and Social Council, 2019), especially in SSA where a majority of waste is disposed of in open dumpsites (Hoornweg and Bhada-Tata, 2012; Kaza et al., 2018). A target of SDG 11 is promoting resource-use efficiency within cities (Ayambire et al., 2019), which can be achieved through the recycling and alternate use of the waste streams. Consequently, the aim of this research is to explore the diversion of urban organic waste and its conversion to compost (SDG 11), and the integration of the compost into urban food production systems (SDG 2) in a SSA city.

Researchers assert to varying degrees that compost from organic wastes could replenish soils depleted of carbon and nutrients and increase the productivity of cultivated soils (Yhdego, 1994; Sikora and Enkiri, 2001; Martínez-Blanco et al., 2013; Franco-Otero et al., 2012; Agegnehu et al., 2016). Additionally, nutrient cycling using composts could facilitate increased carbon storage in soil and decreased atmospheric carbon (Ciais et al., 2013). Therefore, the conversion of organic waste into compost and its application on urban soils would contribute positively to SDG 13 (taking action to combat climate change and its impacts) (Sustainable and Goals, 2018). However, the use of composted urban food wastes on cultivated urban soils remains unexplored in SSA cities. The present research bridges the knowledge gap through four studies on differing aspects of urban agriculture in Mwanza, Tanzania. The city was selected for its rapid urbanization, population growth, the presence of urban agriculture as well as the social supports already in place for the researcher.

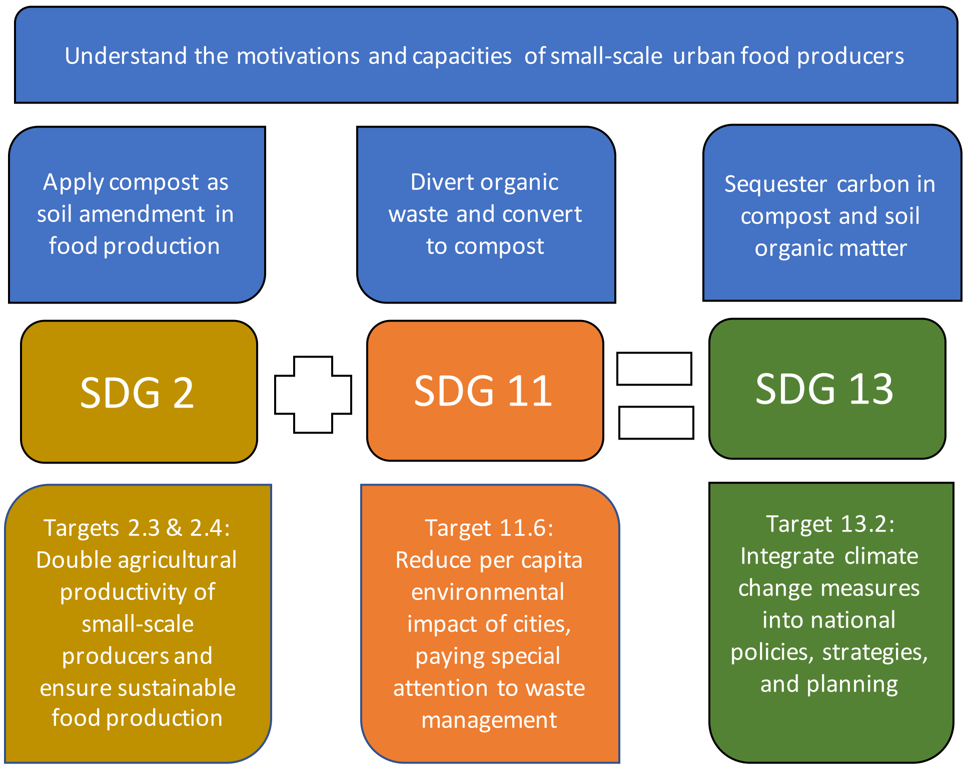


Figure 1: The SDGs (Sustainable Development Goals) 2, 11, and 13 are at the core of this dissertation. The top row shows the four components of this dissertation: 1) understanding the reasons for urban food production and the capacities of urban food producers; 2) Exploring the diversion of urban organic waste and conversion to compost to contribute to SDG 11; 3) Investigating the application of compost to urban soils as an input to develop capacity for small-scale urban farmers and for sustainable food production, both of which are aims of SDG 2; and 4) Probing the potential for carbon sequestration in compost and soil, which can help inform policies on urban planning that can reduce the impact of urban development and urban agriculture on climate change.

Dissertation Structure

The dissertation is presented in manuscript format. The dissertation begins at Chapter 1 with a review of literature on waste management, soil fertility, and food production, and draws links between the three themes within the overarching context of a changing global climate and the geographical context of SSA (sub-Saharan Africa). The chapter identifies the opportunities in literature that provide the motivation for the present research, followed by the objectives and questions underlying the research.

The main body of the dissertation consists of four chapters, each presenting the methodology and results of separate studies. The connections between the studies and SDGs 2, 11, and 13 are presented in each chapter. Chapter 2 explores the perspectives of the urban farmers who cultivate within Mwanza City. The objective of this study was to understand farmer motivations and capacities for practicing urban agriculture, their perceptions of urban soil fertility, and the barriers and opportunities for compost use. Urban farmers were engaged in conversations about urban agricultural practices through in-depth interviews. The findings presented in this chapter show that urban farmers are concerned for continued productivity of their soil without the use of amendments and recognize the need for soil improvement.

The dissertation transitions from urban agriculture in Chapter 3 to focus on the generation of urban waste, specifically organic wastes, and the current waste management system in place in Mwanza City. The aims of the study were to determine the waste management practices at the major sources of organic wastes – restaurants and hotels – and to investigate the potential for converting urban food wastes into compost for use as a soil amendment. The outcomes of this study show that there is a potential for organic waste diversion from restaurants and hotels in Mwanza City, where wastes are already separated at the time of waste generation. Additionally, compost can be produced from the urban food wastes within a thirty-day time period using a rapid composting method.

Compost use is tested in urban agriculture through a field trial study reported in Chapter 4, in which the application of organic and inorganic amendments is compared in urban agriculture. The effects of organic and inorganic amendments on urban soil fertility were evaluated using soil physical, chemical, and biological parameters. The effects on crop growth were assessed through height measurements of amaranth greens (*Amaranthus* var.) and cabbage (*Brassica oleracea* var. *capitata*) during two short growing seasons in an urban agriculture plot. The findings of this study demonstrate that organic amendments are comparable to inorganic amendments for crop growth. However organic amendments contribute to improved soil quality, which nitrogen fertilizer does not.

The dissertation then focuses on the future of cultivated urban soils in Chapter 5 to determine the capacity of organic and inorganic amendments to replenish the depleting soil organic carbon in urban soils. In the study five scenarios were compared to assess the long-term implications on soil carbon using Century Soil Organic Matter Model. The projections show increased soil organic carbon over at least the next 80 years in soils receiving annual organic amendment application, especially food waste compost.

The concluding chapter (Chapter 6) synthesizes the major findings from the four study chapters and presents key contributions within the context of the conceptual framework, followed by recommendations for further research.

Chapter 1

Literature Review

1.1 Climate Change: The Overarching Context

Climate change has been defined by the Framework Convention on Climate Change as "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods" (Field et al., 2014). Anthropogenic activities have increased GHG (greenhouse gas) emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which in turn influence the radiative properties of the atmosphere (Ciais et al., 2013), resulting in significantly increased global temperatures. Globally, the year 2017 was one of the three warmest on record at 1.1°C above the pre-industrial period (Coninck et al., 2018; Sustainable and Goals, 2018).

Factors that contribute to GHG emissions include food production, waste management, and land conversion/soil degradation. Food production systems contribute, directly and indirectly, 19% - 29% of global anthropogenic GHG emissions (Vermeulen et al., 2012). A portion of food-related GHG emissions are a result of food waste and loss through food processing, distribution, and consumption, which ends up in waste streams (Gustavsson et al., 2011). Waste management contributes to GHG emissions through the anaerobic decomposition of organic waste in landfills, resulting in the release of methane (CH_4), which is 21 to 25 times more potent as a greenhouse gas than carbon dioxide (Scheinberg et al., 2010; Kaza et al., 2018).

Food production historically required the conversion of natural landscapes to agricultural use, a change that results in the release of atmospheric carbon and depletion of SOC (soil organic carbon) (Lal, 2010). Land area for agriculture is decreasing due to erosion, contamination, and conversion to non-agricultural uses, which will require intensification of the current agricultural land (Lal, 2013a). Globally, 24% of the land area has been degrading over the last 25 years, directly affecting the livelihoods of 1.5 billion people (Bai et al., 2008). Soil degradation is a major development issue that is mutually reinforced by pressures on land, poverty, and migration on a global scale (Dewitte et al., 2013).

Increased intensity of land-use conversion and land-use, due to population pressure, is strongly linked to soil degradation, e.g., erosion and nutrient depletion (Drechsel et al., 2014). Soil degradation releases atmospheric carbon (GHG emissions) that contribute to climate change (Lal, 2007; Bai et al., 2008; Datta et al., 2013). Additionally, the degradation of terrestrial vegetation (e.g., the removal of vegetation cover) causes increasing climatic variability by affecting rainfall-producing convection circulation in the local area, which leads to decline in rainfall (Malley et al., 2008). The increasing variability of precipitation caused by climate change also leads to further soil degradation (e.g., wind erosion during phases of drought and water erosion during heavy rains), and, if left unchecked, can lead to desertification (European Commission, 2013a). Therefore, the systems that drive climate change are also impacted by climate change, which results in unsustainable development.

As the global human population is expected to increase from 6.7 billion in 2010 to 9.2 billion in 2050 (Ronald and Adamchak, 2010), the demand for food is expected to increase, as will GHG emissions resulting from agricultural activities (FAO, 2016). The relationships between food, waste, and soil (Figure 1.1 A) will come under extreme strain.

The global food demand in 2050, for example, is expected to be driven by population and income growth, as well as rapid urbanization (FAO, 2016). Half of the human population currently lives in urban areas, and it is expected that by 2030 almost 5 billion people will be living in urban areas (UNFPA, 2007). However, cities of all sizes are faced with challenges of infrastructure and service, the biggest of which is managing solid waste (UN-HABITAT, 2010). The effects of urbanization will be most prominent in the developing world, such as African and Asian countries where the urban population is expected to double between 2000 and 2030 (UNFPA, 2007) and over 50% of the generated municipal solid waste is organic in nature (Couth and Trois, 2012; Narayana, 2009; Sujauddin et al., 2008; Parizeau et al., 2008).

The additional challenge for food production is the need to increase food supply while concurrently adapting to the impacts of climate change (Thornton et al., 2011). Countries in SSA (sub-Saharan Africa) will be particularly susceptible to increased climate variability,

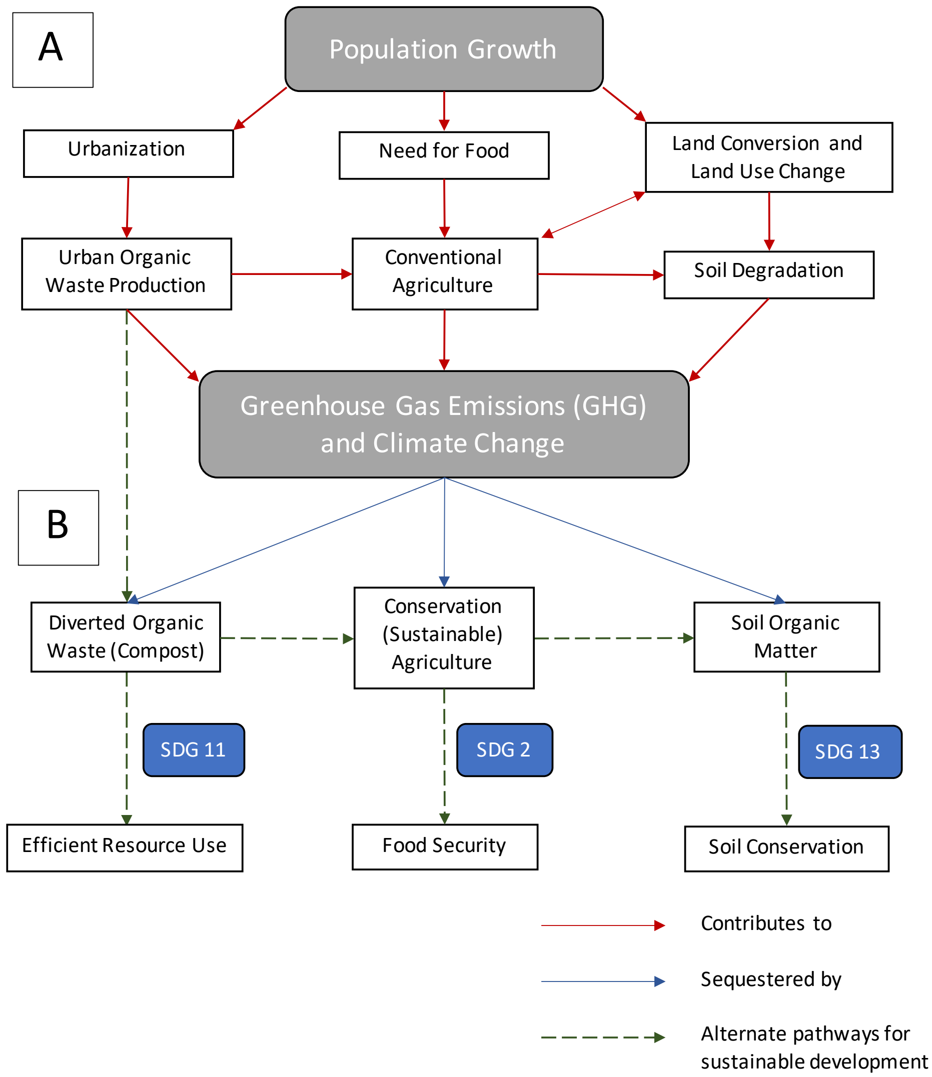


Figure 1.1: The conceptual framework is divided into two parts. In Part A, population growth and anthropogenic contributions to GHG (greenhouse gas) emissions are linked through urbanization, waste production, need for food that results in land use change and conventional agriculture, and consequently soil degradation. In Part B, GHG emissions can be curbed by diverting urban organic wastes toward conservation agriculture, increasing soil organic carbon, and contributing to the SDGs (Sustainable Development Goals). Resource-use efficiency within urban areas contributes directly to SDG 11 - sustainable cities. Sustainable agriculture is a target of SDG 2 - zero hunger. Combating climate change through carbon sequestration is an aim of SDG 13 - action against climate change.

facing impacts that include heat extremes, drastic changes in rainfall patterns, increases in evapotranspiration driven by higher global temperatures, and deterioration towards more arid conditions (Serdeczny et al., 2017). Furthermore, climate change is likely to modify future disease trends in humans, livestock, and crops, which will increase public health risks (Thornton et al., 2011).

Current strategies for coping with climate change can be divided into two general categories: reducing GHG emissions and increasing carbon sequestration (Johnson et al., 2007). Natural gas produced in landfill environments can be curbed by diverting organic waste and controlling the decomposition process. Food production, on the other hand, is dependent on land use. While food production systems impact soil fertility, inversely, changes to land management practices can also affect food production. The depletion of soil carbon stocks, for example, contributes significantly to atmospheric carbon (Datta et al., 2013), but soil carbon can also be a sink for atmospheric carbon. The increase of soil carbon is proportional to a decrease in atmospheric carbon (Lal, 2007).

Therefore, the potential exists to mitigate GHG emissions by diverting organic wastes and transferring the nutrients and carbon stored within organic food wastes into the soil for crop cultivation. With rapid urbanization, this is particularly relevant for urban food production where the need to assess nutrient cycles through urban waste recycling is a key factor to influencing the sustainable development of urban areas (Lorenz, 2015).

1.2 Organic Waste Management

Globally, the World Bank estimates that 3 billion urban residents generate 1.2 kg of MSW (municipal solid waste) per person per day, which is predicted to increase to 1.42 kg per person per day with an estimated 4.3 billion people residing in urban areas by 2025 (Hoornweg and Bhada-Tata, 2012). There is a divide in waste management between developed and developing countries. Even though developed countries produce more waste per capita than developing countries (Adhikari et al., 2008; Kaza et al., 2018), developed countries have implemented waste management plans that take into account waste capacity, maintenance of systems, educational and public awareness, and source separation (Ikhlayel and Nguyen, 2017). Whereas the focus of waste management for developing countries is primarily on waste collection and managing landfill sites (Ikhlayel and Nguyen, 2017; Kaza et al., 2018).

Uncollected solid wastes in developing countries pose a public health risk by clogging drains, which causes flooding and the spread of water-borne diseases (UN-HABITAT, 2010). Additionally, uncollected wastes are burned or dumped in open places, and in most cases, are located in environmentally sensitive areas in SSA, such as wetlands, at forest edges, or adjacent to water bodies (Okot-Okumu and Nyenje, 2011). The health data from UN-HABITAT (2010) show that rates of diarrhea and acute respiratory infections are significantly higher for children living in households where solid waste is dumped or burned in the yard, compared to households in the same cities that receive regular waste collection service. The wastes that are collected are commonly disposed of in landfills, which is the most preferred waste disposal method in developing countries (Ikhlayel and Nguyen, 2017), but also contributes to GHG emissions (Ciais et al., 2013). In a study assessing greenhouse gas emissions from waste management in Africa, Couth and Trois (2012) estimated that the greenhouse gases emitted from landfills in Africa is equivalent to 66 $MtCO_2$ per year.

The issue of landfill gas can be abated through separation of organic wastes from the waste stream and subsequent processing of the organic waste through controlled aerobic decomposition. Studies have been conducted on source separation to determine household perspectives on, and feasibility of, separation at the source in various developing countries (Parizeau et al., 2006; Sujauddin et al., 2008; Narayana, 2009; Guerrero et al., 2013). Parizeau et al. (2006) found that there was already a culture of separating organic waste and composting by some households in Siem Reap, Cambodia for improving soil quality, but those who did not partake in composting were more opposed to waste separation. en Wang et al. (2017) argues that consumer patterns of eating out often result in more food waste than food that is prepared or consumed within the household. Additionally, Pirani and Arafat (2014) reported that the fraction of organics in restaurant waste is almost double that of hotels. Studies on source separation in developing countries have focused on household and municipal wastes rather than the hospitality sector. Therefore, there is an opportunity to further research waste management practices and the potential for organic waste recycling in the hospitality sector.

According to Guerrero et al. (2013), the success of recycling not only depends on participation levels but also on the efficiency of the equipment and infrastructure. Waste management studies in Tanzanian urban areas are shifting focus, slowly, toward waste sorting, recycling, and the potential for processing organic wastes through composting (Mbuligwe et al., 2002; Kaseva and Mbuligwe, 2005; Vuai, 2010). According to Oberlin et al. (2011), technology-intensive processes are minimally viable in Tanzania because of the higher dependence on skilled personnel, installation and maintenance of mechanical parts, and high dependence on a stable waste infrastructure and market. Therefore, there is a need to generate a viable composting process that can be integrated seamlessly into the existing waste management plans within the country.

1.3 Soil Fertility and the Soils of Africa

Soil is a valuable and non-renewable resource at the human life timescale (Frossard, 2006). Purposes of soil use vary from food and fuel production to provision of ecosystem services, such as denaturing of pollutants (Lal, 2013b). Soils are an important aspect of cropping systems. The capacity of soils to supply nutrients, minerals, water, and air to the roots of plants in sufficient amounts is referred to as soil fertility (European Commission, 2013a). Due to their age and lack of volcanic rejuvenation, a majority of soils in Africa are inherently low in fertility (Bationo, 2009). According to a recently compiled atlas by the European Commission (2013a) for African soils, the prominent soil types are easily erodable and strongly weathered with low water- and nutrient-holding capacity.

Traditionally, African farmers practiced shifting cultivation, allowing soils to fallow for up to fifteen years and maintain fertility (European Commission, 2013a; Bationo et al., 1998). However, with increased population pressure and colonialism, African farmers were relegated to low potential agricultural lands (Bationo et al., 1998). This also caused a transition into continuous and annual cropping systems, and so the fallowing period gradually decreased from fifteen years to one or two years (Bationo et al., 1998). However, continued population pressures and political restrictions now force farmers to grow crop after crop in the same soil, which has resulted in soil nutrient depletion (European Commission, 2013a).

According to Scoones (2001), farmers recognize that nutrient depletion is occurring in fields and will correct it when it is affordable and remunerative to do so. Farmers often judge the fertility of their soil empirically, through local knowledge and experience (Fairhead and Scoones, 2005), crop growth, and yield trends (Bationo et al., 1998). For example, throughout much of Africa, farmers deliberately select land with many and large termite mounds, which indicates soil fertility (Fairhead and Scoones, 2005). In SSA, farmers use indicators such as the presence of plant species that only thrive under low soil fertility, the incidence of weeds such as *Striga hermonthica*, as well as differences and changes in soil colour, texture, and ease of cultivation to determine their soil's fertility (Bationo et al., 1998).

Farmers also apply creative and sophisticated methods by exploiting variation in terrain and microclimates, use crop and livestock synergies, and locally available inputs, and invest in soil fertility when economically favourable (Fairhead and Scoones, 2005). For example, smallholder farmers in Rwanda and Malawi traditionally deal with environmental constraints, such as dryland areas, through polyculture or diversified farming, i.e. cultivating a wide variety of crops with varied sowing dates and overlapping crop cycles (Brooks, 2014; Dawson et al., 2016). Additionally, farm families in Kenya, Uganda, Tanzania, Malawi, Zambia, Zimbabwe, and Mozambique use various combinations of fallows, phosphorus, and biomass transfers with good and consistent results (Sanchez, 2002).

1.3.1 Soil Degradation in sub-Saharan Africa

However, there is a shortage of fertile land in SSA (sub-Saharan Africa). One cause is nutrient depletion, which accounts for about 7% of the agricultural share in the average GDP in SSA, with country-specific values ranging up to 25%, indicating soil nutrient mining as a significant basis of current economic performance (Drechsel et al., 2001b). Nutrient depletion, which is causing soil degradation in SSA, is in turn related to population pressure and land-use intensity (Drechsel et al., 2001b).

Another reason for ongoing fertility depletion is the low soil moisture availability (Bationo, 2009) particularly due to drought periods (Malley et al., 2008). Only about 14% of Africa is relatively free from moisture stress (Bationo, 2009). Additionally, soils are under increasing threat from a wide range of human activities as well as climate change. Ciscar et al. (2011) argue that African agriculture is at risk of being negatively affected by climate change due to changes in rainfall patterns, which are the dominant climatic factor for agricultural production.

When many threats occur simultaneously but are not countered, soils lose their capacity to carry out important functions, which is known as soil degradation (European Commission, 2013a). For soils in SSA there is a need to address soil degradation through the promotion of soil management strategies that increase soil moisture and nutrient-holding capacity while fulfilling cultivation needs (Lal and Singh, 1998; Bationo, 2009).

The extent and rate of soil degradation in SSA is still under debate as there are no reliable data (Tully et al., 2015). Additionally, the increasing pressure on land is not matched by supportive agriculture policies, favourable product and input pricing, or corresponding marketing opportunities (Scoones, 2001). Therefore, the continued rate of soil degradation will depend on existing local soil fertility and farmers' capacities to invest in soil conservation measures and nutrient replenishment (Drechsel et al., 2001b).

One of the aims of this dissertation is to determine farmers' capacities and constraints with respect to soil conservation and nutrient replenishment measures. For the purposes of this dissertation, soil and land degradation will be used interchangeably and will be defined as a decline in soil capacity to maintain ecosystem functions and plant yields. The definition for soil quality and soil health, also interchangeable, will be "a measure of the condition of soil relative to the requirements of one or more biological species and/or to any human purpose" (Doran and Zeiss, 2000).

1.4 Food Production

According to UN statistics, SSA (excluding South Africa) is globally the poorest developing region (European Commission, 2013a). About 180 million Africans (100% more since 1970) do not have access to sufficient food to lead healthy and productive lives (Sanchez, 2002). Additionally, the Horn of Africa, which includes Ethiopia, Somalia, and Uganda, is one of the most food-insecure regions in the world with more than 40% of the population deemed to be undernourished (European Commission, 2013a). In fact, SSA is the only remaining region of the world where per capita food production has remained stagnant over the past 40 years, in spite of the fact that the economic sector of agriculture engages 70% of all Africans (Sanchez, 2002). There are a combination of reasons that resulted in stagnated food production, which include the breakdown of traditional agricultural practices (Sanchez, 2002), insufficient nutrient application and poor soil management (Sanchez, 2002; Bationo, 2009), the high cost of fertilizers and the low returns on fertilizer due to lack of information about fertilizers (Bationo, 2009; Gilbert, 2012), the volatility in policies supporting agriculture such as fertilizer subsidies (Sanchez, 2002; Gilbert, 2012), and harsh climatic conditions with inherently low soil fertility (Bationo, 2009).

1.4.1 Conventional Agriculture

Historically, the assessment criteria for agricultural strategies have been within a narrow range, including metrics such as profitability or yield (Sachs, 2010). According to Gabriel et al. (2013), food production can be increased either through agricultural intensification, which is increasing output on the same land, or through extensification, which would require converting natural undisturbed land to agricultural production (Gabriel et al., 2013). Since the second half of the 20^{th} century, the development and use of improved seed stock and increased use of inorganic fertilizers, irrigation, and pesticides formed the technological basis for intensified food production (Zilverberg et al., 2010).

Some of the main aspects of intensive (conventional) agricultural practices include tilling, limited/no fallow, and removal of crop residues from the land. When soil is tilled, erosion is accelerated and SOC decomposes rapidly due to changes in soil moisture, temperature, and pore spaces, and affects levels of SOC as a result of its more rapid rate of decomposition (Datta et al., 2013). The practice of limited to no-fallow with removal of crop residues from cultivated lands hinders the soil's ability to replenish the nutrients and carbon that were lost during plant growth and harvesting (Lal, 2013a). In turn, the soil's productivity is reduced, making it necessary for the use of external inputs, such as inorganic fertilizers or manure, to provide nutrients for the next crop.

Globally, an increase in agricultural production through intensification not only led to higher nutrient inputs, but also higher nutrient outputs (McIntire, 2014). Improved crop varieties were introduced during the green revolution to promote agricultural productivity, which increased yields in Asia and Latin America by 70-90% but only by 28% in Africa (Sanchez and Swaminathan, 2005a). Instead, increases in African agriculture output have largely come from increased harvested areas rather than higher yields (McIntire, 2014).

Crop productivity in many parts of Africa is primarily limited by nutrients (Tittonell and Giller, 2013). Nutrients in African soils are being depleted annually through cultivation. Studies from 1989 have shown annual nitrogen (N) depletion at rates of 22 kg N/ha in SSA (Smaling et al., 1997), with an average depletion of 660 kg N/ha, 75 kg phosphorus (P)/ha, and 450 kg potassium (K)/ha over 30 years from cultivated land in 37 African countries according to one study (Sanchez et al., 1997). On an annual basis, the nutrient depletion is equivalent to US$ 4 billion worth of fertilizer (Gilbert, 2012). However, the average fertilizer use in SSA is only about 9 kg/ha, which has proved to be insufficient (Bationo, 2009). Inorganic fertilizers in Africa can cost two to six times as much as those in Europe, North America, or Asia (Sanchez, 2002), which may explain the greater amounts of fertilizer consumed by Asia, North America, and Europe compared to countries in SSA (Wanzala and Groot, 2013). Additionally, increase in inorganic nitrogen fertilization may not always improve the negative nutrient balance if nutrients are continually exported through leaching and crop uptake (Drechsel et al., 2001b).

The lack of nutrient application, poor soil management, and the expansion and intensification of agriculture are contributing soil degradation in SSA (Bationo, 2009; Tully et al., 2015). Therefore, nutrient management is one of the most important strategies to consider for the African continent, which cannot be achieved through conventional agriculture.

1.4.2 Conservation Agriculture

While crop productivity in many parts of Africa is primarily limited by nutrient availability, water availability also plays a role in rain-fed environments (Tittonell and Giller, 2013). Irrigation efficiencies can be supplemented with alternative agriculture activities, such as cultivating crops that require less water or CA (conservation agriculture) practices, which help to improve soil and water conservation (Coninck et al., 2018).

Sustainable intensification and CA can be an effective climate adaptation strategy (Coninck et al., 2018) and can curb or reverse the progress of soil degradation. The use of CA practices promote good land stewardship and minimize or reduce the global warming potential of agriculture (Johnson et al., 2007). Additionally, CA is one of the sustainable agricultural practices that has been grouped under the umbrella of ISFM (integrated soil fertility management), which is defined as "the development of adoptable and sustainable soil management practices that integrate the biological, chemical, physical, social, cultural, and economic processes that regulate soil fertility" (Vanlauwe and Giller, 2006). These practices include: reducing tillage; eliminating fallow but keeping soil covered with residue, use of cover crops or perennial vegetation; and avoiding over application of nutrient inputs to meet plant need (Johnson et al., 2007). The purpose of these strategies is to increase soil fertility and enhance soil health by increasing SOC. Organic amendments such as compost also contribute to SOC, which in turn drives soil microbial processes and replenishes the SOC pool (Vanlauwe and Giller, 2006). SOC plays an important role in enhancing crop production, improving soil structural stability, and mitigating climate change (Datta et al., 2013). About $34-40\%$ of the SOC that has been lost historically worldwide can be restored with the adoption of recommended management practices (Datta et al., 2013).

1.4.3 Urban Agriculture

Agriculture and subsistence farming is a significant source of income for a majority of the African population (Sotamenou and Parrot, 2013), and a substantial share of income for the urban poor (Zezza and Tasciotti, 2010). The majority of literature on African agriculture focuses on rural cultivated soils, and urban soils have generally not been included in studies on cultivated soils (Lorenz, 2015). Urban agriculture received little attention in the literature until 2008 (Graefe et al., 2019), despite its potential significance in developing countries (Hamilton et al., 2014). Urban agriculture is practiced by 800 million people worldwide, including 29 million households in Africa, and covers more than 5% of the total global cropland area (Lorenz, 2015). De Bon et al. (2010) demonstrated that urban agriculture in SSA serves the dual purpose of a risk-sharing strategy and an activity of cultural and traditional significance.

Urban agriculture can take different forms; it can be defined as cultivation only or can include animal husbandry, and can refer to crop production in large open spaces or backyard gardening (Zezza and Tasciotti, 2010; De Bon et al., 2010; Drechsel and Dongus, 2010). FAO (2007) defines urban agriculture as "the growing of plants and the raising of animals for food and other uses within and around cities and towns, and related activities such as the production and delivery of inputs, processing and marketing of products". In this dissertation, urban agriculture is defined as the growing of plants for food within and around cities and towns. The academic discussion on urban agriculture has mostly focused on connections to food security, human health, and economic benefits (De Bon et al., 2010; Zezza and Tasciotti, 2010; Hamilton et al., 2014). There is consensus among researchers for the integration of urban agriculture into urban planning (De Bon et al., 2010; Drechsel and Dongus, 2010; Game and Primus, 2015; Ayambire et al., 2019), especially as it can decrease the ecological impact of cities by reducing emissions of transport, packaging, and storage (Orsini et al., 2013). However, there are aspects of urban agriculture that require further investigation.

The increased academic interest in urban agriculture since 2008 showed repeated studies in five African countries: Ghana, Nigeria, and Burkina Faso in West Africa, and Kenya and Tanzania in East Africa (Graefe et al., 2019). However, the practice is less recognized by authorities in Africa than in the developed world, despite its long history (Drechsel and Dongus, 2010) and significant contribution to urban household income in African countries (Zezza and Tasciotti, 2010). In addition to livelihood, urban agriculture provides many benefits such as the production of vegetable and fruit crops, and the contribution to food security for the urban population (Zezza and Tasciotti, 2010; Lorenz, 2015).

Food security "exists when all people have physical and economic access to sufficient, safe, and nutritious food to meet their dietary needs for an active and healthy life" (FAO, 2016). A significant result of urban agriculture is the availability of fresh produce in the market without further processing (Orsini et al., 2013; Graefe et al., 2019; Ayambire et al., 2019). While urban agricultural practices provide the benefit of food security to urban dwellers, growing food in urban ecosystems, particularly on degraded urban soils, can be challenging (Lorenz, 2015). Soils in urban areas can range from undisturbed, altered only by environmental change, to disturbed soils degraded through urban activities such as construction, industry, and landfills (Lorenz, 2015). While there has been an increase in studies on urban soils, more research is needed on how to maintain or enhance urban soil fertility (Lorenz, 2015) because urban farmers may lack the knowledge and skills required to preserve urban soil resources (Orsini et al., 2013).

Moreover, the risks of chemical pollutants is currently unknown (Hamilton et al., 2014), which includes the risks posed by urban environments, such as soil contaminants, to the food produced from urban agriculture as well as the effects of urban agriculture practices, such as manure use, on the environment. The use of urban wastes has been explored in the literature, focusing mostly on the application of sewage sludge and wastewater (Orsini et al., 2013; Graefe et al., 2019). Some studies have also explored the use of organic wastes and composts in urban agriculture. Sotamenou and Parrot (2013) contend that compost adoption in SSA should be investigated further as part of a waste recycling commodity chain that involves farmers, municipal governments, waste sector, as well as non-governmental organizations and researchers. However, additional research is needed to investigate the effects of organic waste and composts on urban soil quality and carbon sequestration (Sotamenou and Parrot, 2013; Lorenz, 2015; Graefe et al., 2019).

1.4.4 Organic Amendments

One component of CA is the use of organic soil amendments to increase SOC, supply nutrients, and to potentially reduce GHG emissions (Ajwa and Tabatabai, 1994). In tropical soils, SOC helps maintain productivity by providing energy and substrates, and promoting biological diversity (Guimarães et al., 2013). A higher SOC content may also enhance crop growth and increase the efficiency of fertilizer use (Vanlauwe and Giller, 2006). According to Lal (2011), an increase in the SOC pool of 1 ton C/ha/yr in the root zone can increase annual food production in developing countries by 24 - 32 million tons of food grains and 6 - 10 million tons of roots and tubers.

There are various sources for organic amendments, including animal manure, municipal solid waste, sewage sludge, food waste, and green waste (e.g. leaves or crop residue), which can all be composted. Manure composting, for example, has been traditionally practiced by farmers for better handling, transport, and management (Bernal et al., 2009). Compost as a soil amendment improves soil moisture, soil structure, soil porosity, and water-air exchange in the root zone (Bekchanov and Mirzabaev, 2018). Soil is better aerated and has more space allowing crop roots to grow deeper and better access nutrients and water (Harris et al., 2001). Mylavarapu and Zinati (2009) reported that increased moisture retention from compost application proved to be particularly important in sandy soils during dry weather for sustaining plant growth. Annabi et al. (2011) found that composted urban wastes used as amendments in a 9-year study increased SOC stocks and soil aggregate stability, which helps build soil resistance to erosion. Martínez-Blanco et al. (2013), in their review of compost benefits for agriculture, identified nine potential benefits of compost application, including increased nutrient supply, carbon sequestration, crop yield, water-holding capacity, soil workability, and decreased soil erosion.

Carbon and nutrient content of composts vary depending on the source of organic material. The values reported in the literature of compost chemical characteristics from differing feedstock are provided in Table 1.1. As can be seen from the reported values, nitrogen and phosphorus content in composts is low, generally <3%. Odlare et al. (2008) reported that the mineral nitrogen concentration and microbial mineralization rate of composts was too slow to meet nitrogen requirements for crops. However, Bulluck et al. (2002) found that yields under organic production exceeded conventional production in the second year of amendment application, which was attributed to the long-term beneficial effect on soil properties. Additionally, in phosphorus-deficient soils, such as East African soils (Sanchez, 2002), the high application rate to meet crop nitrogen requirements is likely to increase the amount of phosphorus in the soil as well (Odlare et al., 2008). Moreover, organic amendments may provide micronutrients that farmers may not apply, such as manganese and zinc, and liming sources, such as calcium or magnesium (Bulluck et al., 2002).

The application of compost could result in environmental and agronomic drawbacks, such as gaseous and leachate emissions and increases in salt and heavy metal content (Ajwa and Tabatabai, 1994; Hargreaves et al., 2008; Martínez-Blanco et al., 2013). If used appropriately, and depending on the organic waste source, composts can improve the organic matter levels in marginal land and sustain long-term fertility and productivity of soils (Castaldi et al., 2008). While nutrient content may not be the most valuable gain from compost, the organic matter contributes to maintaining soil structure and provides an aerated and water-retentive environment for optimum root growth (Harris et al., 2001).

Even if composts may not replace mineral fertilizers in agricultural systems, they do provide an alternate substitute, which can reduce overall fertilizer production costs (Bekchanov and Mirzabaev, 2018). Therefore, the potential exists to increase carbon within food production systems while mitigating GHG emissions from diverted organic wastes (Yoshida et al., 2012) and sequestering atmospheric carbon in SOC stocks (Yu et al., 2012) (Figure 1.1 B). However, the use of urban food wastes to generate an effective compost amendment has not been fully investigated, especially in the context of urban soils.

Table 1.1: Reported literature values of compost chemical characteristics from varying sources as represented by the carbon (C), nitrogen (N), phosphorus (P) content of the compost as well as the alkalinity (pH) of the compost

Organic Compost Amendments	C %	N %	C:N Ratio	P %	pH	Reference
Manure Composts						
Cow manure	36.70	1.78	20.62	-	7.87	Bolan et al. (2012)
	36.68	1.72	21.3	1.68	8.7	Anwar et al. (2018)
Cow manure and maple tree litter	37.54	1.44	26.1	1.76	8.2	Anwar et al. (2018)
Pig slurry	8.09	0.72	11.20	0.31	6.9	Benítez et al. (2003)
Poultry manure	43.00	2.83	15.47	1.23	7.13	Fernandes et al. (1994)
	48.10	3.53	9.90	1.38	-	Evanylo et al. (2008)
	30.10	2.35	12.81	-	8.12	Bolan et al. (2012)
Solid Waste Composts						
Biosolids	22.6	2.23	10.13	0.71	6.8	Sikora and Enkiri (2001)
Municipal solid waste	17.38	1.15	15.11	-	7.10	Castaldi et al. (2008)
	32.73	1.41	23.21	1.04	7.83	Mylavarapu and Zinati (2009)
	13.10	1.41	9.30	0.56	6.34	Franco-Otero et al. (2012)
Sewage sludge	13.20	2.13	6.20	2.21	7.15	Franco-Otero et al. (2012)
Food and Green Waste Composts						
Food waste and chicken manure	-	0.97	-	0.96	7.89	Attiogbe et al. (2019)
Food waste and cow manure	24.85	2.02	12.35	-	8.05	Abdoli et al. (2019)
Green waste, bagasse, chicken manure	30.60	1.19	25.70	9.17	7.5	Agegnehu et al. (2016)
Market food waste	26.16	2.26	11.59	-	8.73	Yhdego (1994)

1.4.5 Focus on Agriculture in Tanzania

Tanzania is a tropical country in the horn of Africa, bordering the Indian Ocean to the East and eight countries in the other cardinal directions. The country has an approximate area of 945,000 km^2, of which 60,000 km^2 are inland water bodies including Lake Victoria, and 100,000 km^2 are committed to reserves and national parks (National Bureau of Statistics, 2012b). The country consists of Tanzania Mainland (the land mass inland of the ocean) and Zanzibar (the island mass off the coast of the mainland). The five major cities in Tanzania are Dar es Salaam, Mwanza, Mbeya, Tanga, and Arusha, the official language is Kiswhaili, though English is also used, and the country is home to 120 ethnic groups (National Bureau of Statistics, 2012b).

The mainland of Tanzania has prototypical tropical soils with generally low nutrient (nitrogen and phosphorus) content (National Bureau of Statistics, 2015b). While some areas of Tanzania are endowed with soils suitable for agriculture, for example in Arusha, Kilimanjaro, Morogoro, and Mbeya, most of the central and western plateau areas are composed of sandy loam soils with low water holding capacity and low nutrient content (National Bureau of Statistics, 2015b). A map from 1967 of the potential land uses within Tanzania in Figure 1.2 shows the suitability of soil for cropping purposes. A historic understanding of 1967 is important due to end of colonization in 1961 and the state of post-colonial soil fertility and land use. A more recent map (2003) of Mwanza region specifically (Figure 1.3) shows that the area around Mwanza City is classified as cambisols, which are soils only moderately developed due to limited age (European Commission, 2013b), under a wide variety of agricultural uses with maintenance of soil organic matter and nutrient levels (Figure 1.3).

However, the use of agricultural inputs, both organic and inorganic, is generally very low in proportion to the area under cultivation across Tanzania (National Bureau of Statistics, 2012b). In fact, while the agricultural sector comprises 23% of the National Gross Domestic Product in Tanzania (National Team, 2014), the nutrient depletion accounts for up to 25% of the Agriculture Gross Domestic Product (Drechsel et al., 2001a). Depletion of soil nutrients and organic matter in cultivated soils leads to decline in soil and crop productivity (Sanchez, 2002), which will further jeopardize food production in Tanzania (Drechsel et al., 2001a). Therefore, sustainable food production in Tanzania is in need of nutrient management to be able to sustain its growing population now and in the future (National Bureau of Statistics, 2015b).

The agricultural sector employs 70% of Tanzania's population and accounts for 27.6% of the country's GDP (COSTECH, 2016), an increase from 23% in 2014 (National Team, 2014). The 2012 census on agriculture in Tanzania reported a total of 5,838,523 households engaged in agriculture, with land utilization averaging at 2 ha per household (National Bureau of Statistics, 2012b). The dominant agricultural activity engaging households at the national level was crop production, of which maize (*Zea mays* L.) was the priority crop of choice nationwide (National Bureau of Statistics, 2012b).

While 68% of urban dwellers in Tanzanian cities practice urban agriculture (De Bon et al., 2010), the practice is underrepresented in national reports and data published pertaining to agriculture in Tanzania. In fact, when reporting agricultural household density for Zanzibar and Dar es Salaam (cities in Tanzania), the report disregarded urban agri-

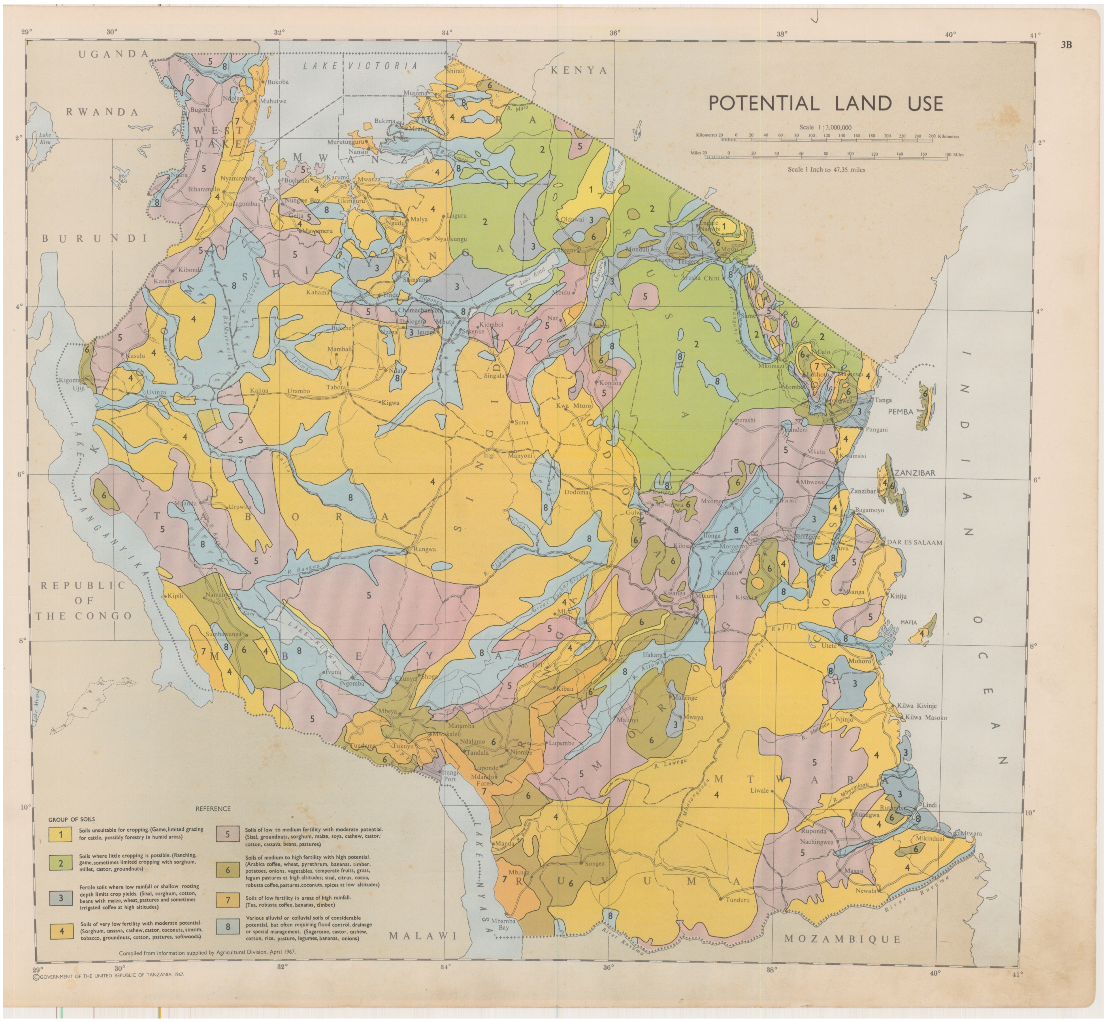
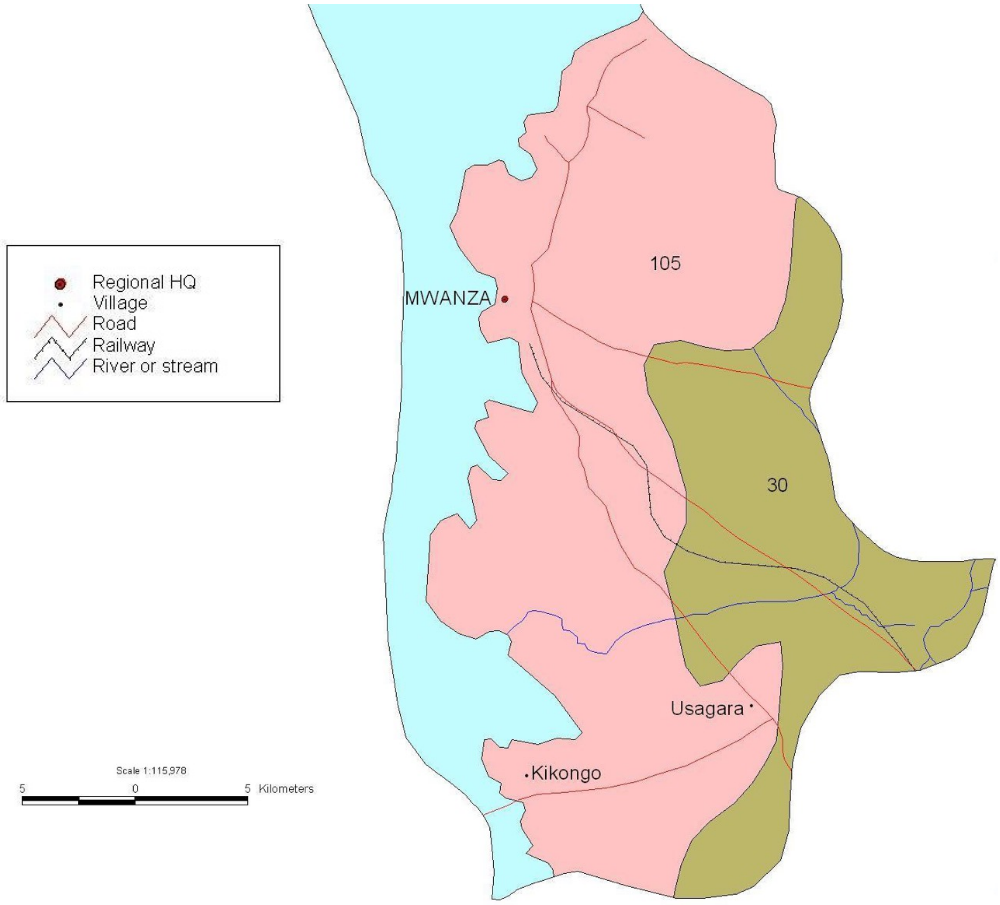


Figure 1.2: Map of soil fertility and the potential land use in Tanzania in 1967. Older maps provide historical context for soil types and land uses that preceded current land use and management. The land use marked as yellow (4), which includes the area around Mwanza City, indicates soils of very low fertility with moderate potential for cropping. Used with permission from The Geological Survey of Tanzania (personal communication, 2018).



Symbol	Limitations	Use and management
105	Vary with climate, topography, depth or stoniness	A wide variety of agricultural uses with maintenance of soil organic matter and nutrient levels
147		
30	Strong sodicity and salinity, very low fertility	Suitable for extensive grazing and in some places wetland rice

Figure 1.3: Map of Mwanza and surrounding areas showing soil classification and land use management from 2003. Around Mwanza City, the soil (labelled 105 and coloured pink) is classified as a cambisol under a wide wide variety of agricultural uses with maintenance of soil organic matter and nutrient levels. Used with permission from Elmens Kaboni (personal communication, 2017).

culture by stating: "However, most of these areas are urbanized and hence not typical examples of agricultural households" (National Bureau of Statistics, 2012b).

The Environment Statistics report published by National Bureau of Statistics (2015b) acknowledged farming as a livelihood occupation in both urban and rural areas of mainland Tanzania, reporting that 76.2% of the rural population and 26.7% of the urban population of the same age are farmers. However, this appears to be the only national communication where urban agriculture is recognized. Even though urban agriculture is a prominent activity in Tanzanian cities, existing by-laws actively oppose the practice (Crush et al., 2011).

At the national level, there is recognition that rapid urbanization has caused an increase in pollution, unplanned settlements, environmental degradation, and insecurity of land ownership (COSTECH, 2016). Additionally, waste management resulting from rapid urbanization and population growth is reported as a pressing environmental challenge (National Bureau of Statistics, 2015b). The national research priority recommended by COSTECH (2016) is to address issues resulting from urbanization. However, urban agriculture has not been considered in national reports, either as a contributor or as a solution, to pollution, environmental degradation, and increased waste production. The practice of urban agriculture can be a cause for sanitary and environmental challenges (De Bon et al., 2010; Crush et al., 2011), but can also add value to land use and provide employment (Howorth et al., 2001), as well as contribute to the urban food supply, especially of fresh vegetables (Lorenz, 2015; Ayambire et al., 2019). Therefore, there is a need to investigate and gather additional data for urban agricultural practices in Tanzanian cities.

1.5 Research Focus: Mwanza Region

Mwanza Region is located on the southern shore of Lake Victoria, which is in north-western Tanzania. The region consists eight districts: Ukerewe, Sengerema, Geita, Magu, Missungwi, Kwimba, Illemela, and Nyamagana (National Bureau of Statistics, 2012a). The city of Mwanza, which is the second largest city in Tanzania, was divided between Illemela and Nyamagana, however, with changes to the city's boundaries and council structure, the city now falls only within the Nyamagana district and within the purview of the Mwanza City Council (Mwanza City Council, 2008; Overseas Development Institute, 2016; Mwanza City Council, 2017).

Mwanza region, along with Kagera and Kigoma, is part of the western highland zone where the soils can be well-drained with good water holding properties, but there are also sandy to loamy soils with low fertility (National Bureau of Statistics, 2015b). Areas around Lake Victoria, such as Mwanza region, experience a bimodal rainfall pattern, with an average rainfall of 930 mm (National Bureau of Statistics, 2012a). The short rainy season (*kivuli*) between October and December, averaging 500 to 800 mm rainfall) (National Bureau of Statistics, 2012a; Council, 2016) and the long rainy season (*masika*) between March and May, averaging 1000 to 1400 mm rainfall (National Bureau of Statistics, 2012a, 2015b; Council, 2016). Light rains fall from June to August, averaging 100 mm of rainfall (Council, 2016). With the impacts of climate change, rainfall for the short rainy season is predicted to increase, whereas for the long rainy season, rainfall is projected to decline (Ogega et al., 2020). It is also postulated that as climate change progresses, the Lake Victoria basin may experience very wet conditions (Kajembe et al., 2016) as extreme climate events becoming more prevalent with increasing numbers of extreme wet days (Luhunga and Songoro, 2020).

The crops grown in the short versus the long rainy season do not differ distinctly, but during the short rainy season larger areas are planted and more households engage in cultivation as compared to the long rainy season (National Bureau of Statistics, 2012a). Maize (*Zea mays* L.) is the dominant crop grown in Mwanza region, followed by paddy rice (*Oryza glaberrima*), cotton (*Gossypium arboreum* L.), cassava (*Manihot esculenta*), sweet potato (*Ipomoea batatas*), beans (*Phaseolus vulgaris*), chickpeas (*Cicer arietinum*), and groundnut (*Arachis hypogaea*) (National Bureau of Statistics, 2012a). Fruits and vegetables are also grown in the region, including tomatoes (*Solanum lycopersicum*), okra (*Abelmoschus esculentus*), onions (*Allium cepa*), amaranth (*Amaranthus* var.), cabbage (*Brassica oleracea* var. *capitata*), spinach (*Spinacia oleracea*), and chillies (*Capsicum annuum*) (National Bureau of Statistics, 2012a). Two other concerns related to climate change and crop growth are the projected significant increase in temperature in the Lake Victoria region (Luhunga and Songoro, 2020) and the prevalence of plant diseases under changing climate conditions (Velásquez et al., 2018).

The presence of urban agriculture in Mwanza has been a long-standing precarious situation. For example, in 1966 Mwanza's town council prohibited crop cultivation and in 1982 urban authorities were authorized to destroy crops over 1 m high (Flynn, 2001). In spite of the lack of support from authorities, over 390,000 households are engaged in agriculture in Mwanza region, averaging at 16 agricultural households per square km, with over 55% of households only cultivating crops (National Bureau of Statistics, 2012b). However, Nyamagana district was excluded from the most recent agriculture census for

Mwanza Region published in 2012 (National Bureau of Statistics, 2012a), possibly due to the predominantly urban nature of the district.

Flynn (2001) reported that many people in Mwanza depend on food produced from urban agriculture, though there is concern among government officials by its prevalence. According to the most recent City Council profile, the council recognizes that urban farming within Mwanza city has been both extensive and intensive, and describes urban agriculture as the ‘persistence of peasant culture’ (Mwanza City Council, 2017). Crush et al. (2011) argue that in order for urban agriculture to be recognized as a legitimate land use and gain institutional and political support, comprehensive research is required into the links between urban agriculture and food security.

1.6 Research Direction

There is, therefore, a need for information about the motivations behind urban agriculture in African cities, the perspectives on current waste management strategies associated with urban wastes, the quality of compost that can be generated from urban food wastes, and the impacts of organic amendments on urban soil quality and crop growth compared to inorganic amendments. Drawing from the literature on waste management, soil fertility, and food production, the present research explores the diversion of urban organic (food) wastes and the application of the resulting compost in urban agriculture.

1.6.1 Hypotheses

This dissertation hypothesizes that if there is an inclination for urban farmers to improve their cultivated soil using organic amendments, specifically compost from food waste, and if soil quality can be improved with food waste compost, then food waste compost can be marketed for soil application to urban farmers. Additionally, if a method for processing urban food wastes can be developed within the logistical constraints of a current, local waste management strategy, then the integration of food waste diversion and processing can be visualized and, therefore, facilitated. Lastly, if an end-use for food waste compost can be established (e.g., soil application for urban agriculture and/or increasing soil organic carbon within urban settlements), then the policy incentives to divert urban organic (food) waste and apply organic waste amendments to urban soils can be established.

1.6.2 Research Objectives and Questions

The main objective is to determine a pathway toward integrated soil management using composted organic (food) wastes in urban agriculture, while considering the social and logistical perspectives of urban farmers and the local waste management system. The overall aim is to promote sustainable development within the geographical context of Mwanza City, and by extension, other developing cities in SSA. The main objective is divided into four components, each of which corresponds to one of the four study chapters.

Chapter 2: Urban Agriculture in Mwanza,Tanzania: Farmer Perspectives

Objective: Explore social perspectives of urban farmers regarding soil management and cultivation in urban agriculture.

Research Questions:

- What motivates urban farmers in Mwanza City?
- What knowledge and cultivation practices do urban farmers use?
- How do they manage the cultivated urban soils and crop nutrient requirements?
- What resources do urban farmers use and what constraints do they face?
- How do the urban farmers perceive cultivated soil fertility?
- What are the perceptions with respect to use of amendments, specifically compost from food waste, in urban farming?

Chapter 3: Opportunities in Hospitality Waste Management and Composting Food Wastes in Mwanza, Tanzania

Objective: Evaluate the hospitality sector contribution to urban organic (food) wastes and a potential solution for food waste processing that would work practically with the city's current waste management strategy.

Research Questions:

- How is waste managed in the Mwanza, Tanzania?

- How is waste managed in the hospitality sector, focusing on hotels and restaurants?
- What are the perceptions of waste generators (hospitality sector) with respect to current waste management practices in Mwanza, Tanzania?
- What are the current waste management practices and opinions regarding organic (food) waste in the hospitality sector?
- Can food waste be converted to compost using a rapid, low-cost approach that could also be integrated into the city's pre-existing waste management system?
- What is the quality of compost that could be produced with this method?

Chapter 4: Comparing Organic and Inorganic Amendments in Urban Agriculture in Mwanza, Tanzania

Objective: Evaluate the potential for nutrient management in urban agriculture using composts from urban organic (food) wastes and the effects on soil quality and crop growth.

Research Questions:

- What are the effects of urban food waste compost application on urban soil quality and crop growth?
- How effective is compost generated from urban organic (food) waste for improving urban soil quality and crop growth?
- How do the effects of organic amendments compare to inorganic amendments in urban agriculture?

Chapter 5: Simulations of Urban Soil Organic Carbon under Organic and Inorganic Amendment Scenarios in Mwanza,Tanzania using CENTURY

Objective: Assess the soil organic carbon trends for crop cultivation now and in the future with and without the use of soil amendments (organic or inorganic) using Century simulation software.

Research Questions:

- How does projected simulations of soil organic matter content compare under organic and inorganic land management over the next hundred years?
- In what carbon fraction pools do organic amendments provide the most SOC accumulation?
- How does food waste compost application compare to organic or inorganic amendment use in urban soil organic carbon projected over the next hundred years?

Chapter 2

Urban Agriculture in Mwanza, Tanzania: Farmer Perspectives

2.1 Introduction

Agriculture, as an economic sector, engages 70% of all Africans (Sanchez, 2002). However, the continent has the highest incidence of undernourishment that affects more than 256 million people (one fifth of the population) (United Nations (UN) Economic and Social Council, 2019).

The underlying causes of hunger vary among regions, though the main reason is likely low agricultural productivity in tropical Africa and remote parts of Asia and Latin America (Sanchez and Swaminathan, 2005b). Many of the chronically hungry in Africa live in rural farm households (Sanchez, 2009) where food expenses make up 50 – 70% of African household budgets, making households vulnerable to external factors such as poor weather that can negatively impact crop productivity and price hikes (McIntire, 2014). Additionally, small-scale food producers in African countries account for 40 - 85% of all food producers, compared to only 10% in Europe (United Nations (UN) Economic and Social Council, 2019).

Factors affecting rural agriculture also affect urban growth in African countries. Brückner (2012) showed that an increase in international prices of agricultural commodities combined with improved rainfall conditions decreased urbanization rate, whereas an increase in international prices, increased urbanization rate. Currently, Africa is urbanizing faster than any other continent with a 3.4% per year population growing rate from both natural population growth and rural-urban migration (Anderson et al., 2013). While agriculture in Africa is generally considered a rural activity, it also has a long-standing indigenous tradition in many urban areas (Drechsel and Dongus, 2010). Additionally, in the context of SDGs (Sustainable Development Goals), addressing the goal of Zero Hunger (SDG 2) will require "strengthening the resilience and adaptive capacity of small-scale and family farmers", which should also include urban agriculture (United Nations (UN) Economic and Social Council, 2019). Urban agriculture is defined as the growing of plants for food within and around cities and towns (FAO, 2007; De Bon et al., 2010; Drechsel and Dongus, 2010; Zezza and Tasciotti, 2010). However, there is a lack of critical information about urban areas and the urbanization process (Seto et al., 2013), and in particular urban agriculture (Graefe et al., 2019).

Studies on urban agriculture in developing cities have demonstrated the importance of urban agriculture for food insecurity. The study by Sawio (1994) in Dar es Salaam, Tanzania, showed that urban agriculture supplements daily food expenses and plays a key role in urban household survival in all social groups, not just the socially marginal. Zezza and Tasciotti (2010) reported, in a study involving fifteen developing countries around the world, that a positive correlation exists between active engagement in urban agricultural activities and greater dietary diversity for urban households.

There are drawbacks as well to urban agriculture. For the most part urban farming is conducted on land that has yet to be developed or cannot be developed because of environmental concerns, like flooding (White and Hamm, 2017). Often farmers do not have access to legal land, making agriculture a precarious and limited livelihood (Crush et al., 2011). However, McLees (2011) found that farmers employ diverse methods to acquire access to land in cities, even if temporarily, with benefits to both the farmer and the landowner.

Urban agricultural practices in SSA also face similar constraints as rural agricultural practices, such as high costs of inputs and lack of fertilizers (Sotamenou and Parrot, 2013). Additionally, urban agriculture can augment environmental problems. In the case of Mwanza, Tanzania, Flynn (2001) noted that policy makers recognized the contribution of urban agriculture to land degradation through clearing of indigenous vegetation and pollution of lake water as a result of fertilizer and animal waste runoff during heavy rains.

Increasing agricultural productivity while reducing environmental impact will require proactive and informed urban planning policies that allow for agricultural activities in urban areas. White and Hamm (2017) argue that urban agriculture needs to be understood as an integrated dimension of urban food system, considering the socio-ecological processes.

Cultivation decisions made by urban farmers ultimately affect the soil health of farmed urban areas, the fate of crops produced, and the impact on the surrounding natural and built environments.

Therefore, the forces driving urban agriculture in developing countries and the factors that play a role need to be evaluated from the point of view of urban farmers. Consequently, the aim of this study to investigate urban agriculture in Mwanza, Tanzania, a rapidly growing city in east Africa (Overseas Development Institute, 2016), through urban farmer perspectives. This study determines the current state of urban agriculture in the developing city by exploring motivations of and constraints faced by urban farmers. The study further evaluates the impact of urban agriculture in a developing African city with respect to cultivation practices and emerging risks. The study adds to the currently limited literature on urban agriculture in developing countries, enhancing our understanding of the challenges and opportunities of urban agriculture to contribute to food security and nutrient recycling from organic wastes. Further, in light of the global COVID-19 pandemic, the study also provides baseline information on urban agriculture in Mwanza, Tanzania before the impacts of COVID-19.

2.2 Materials and Methods

2.2.1 Study Site

Mwanza City is located on the southern shore of Lake Victoria in Northwest Tanzania covering 256 km^2 of which 185 km^2 is dry land area (Mwanza City Council, 2017). The city is located in the Nyamagana district of Mwanza Region. In 2008, the City Council reported three rural and seven urban wards within Nyamagana district, which increased to six rural wards and twelve urban wards in 2015 (Mwanza City Council, 2008, 2017). However, there does not appear to be a change in district's land area and the boundaries between the wards have not been clearly delineated in publicly available council reports. The city also receives bimodal rainfall; the short rains, known as kivuli, occur from October to November and the long rains, known as masika, occur from March to May (National Bureau of Statistics, 2015b).

The urban wards within Nyamagana district are: Mbugani, Butimba, Mkuyuni, Mabatini, Nyegezi, Nyamagana, Igoma (which was previously a rural ward), Pamba, Mkolani, Mirongo, Isamilo and Igogo (Mwanza City Council, 2017). The urban wards in which interviews were conducted are shown in Table 2.1 along with the land area, number of hamlets, and number of interviews conducted in each ward, which were sourced from Mwanza City Council (2017). The locations of the wards also determine the availability (or lack thereof) of nearby water sources. Mirongo, for example, is located at the shores of Lake Victoria, whereas Isamilo is in the hills of Mwanza city. The Mirongo River flows through the Nyamagana district, providing a source of fresh water to some urban locations.

2.2.2 Data Collection and Analysis

Data were collected through in-depth, semi-structured interviews with urban farmers in Mwanza's city centre from January to February 2018. The sampling method was a combination of judgement sampling and snowball sampling, which were methods used by Flynn

Table 2.1: Mwanza City ward locations with corresponding information on the percent (%) land area covered by each ward and the number of hamlets in each ward (Mwanza City Council, 2017, 2008), and the number of interviews conducted in each ward

Ward	Land Area (sq km)	No. of hamlets	% Land Area	Interviews
Buhongwa	45.0	18	17.6	2
Nyegezi/Butimba	20.9	8	8.2	6
Igogo	23.0	9	9.0	8
Pamba	2.0	10	0.8	2
Nyamagana	12.5	4	4.9	4
Mirongo	2.1	3	0.8	7
Isamilo	13.5	11	5.3	5

(2001) in a similar study in Mwanza, Tanzania. The reasons for using judgment sampling over probability sampling methods were two-fold: 1) a sampling framework (e.g., list of urban dwellers practicing urban agriculture) was not available, and 2) to deliberately select participants based on criteria best suited to answering the research question which pertained to urban farmers. The criteria for judgement sampling were the presence of urban agriculture indicators and the geographical locations of households to ensure inclusion of the various wards of Mwanza city in the study.

The study received guidance and approval from the University of Waterloo Office of Research Ethics. In accordance with ethics requirements, the prospective respondents were provided an information letter that provided a brief overview of the research, and a participation form to record their consent before the interviews were conducted. While the consent forms had a record of names and signatures of the study's participants, the recorded interviews did not bear any identifying information to ensure an anonymous interview process.

A total of 34 respondents were interviewed in-person. Out of the 34 respondents, 32 consented to the interviews being recorded. The recorded interviews were transcribed after the interviews had been conducted. The two non-recorded interviews were transcribed at the same time as the interviews. The duration of the interviews ranged from 20 to 50 minutes, depending on the length of the respondents' responses. The researcher conducted the interviews in Kiswahili, Tanzania's national language. The interview guide (Appendix A) consisted of short questions to gather quantitative census information (henceforth referred to as descriptors) as well as open-ended questions to prompt qualitative responses. The open-ended questions were concerning cultivation practices, soil fertility, and amendment use.

The descriptor information gathered from the interviews gives insight into the gender, age range, and education of the respondents as well as location, size, and ownership of the urban farms. Of the 34 respondents, 19 identified as female (56%) and 15 as male (44%). The ages ranged from 20 years old to 73 years old, with a relatively uniform distribution across age ranges. A visual representation of the respondents' gender and age distribution are shown in Figure 2.1.

With respect to education level, respondents' responses ranged from no formal education to completion of university, with the highest peaks at Standard 7 (41% respondents) and Form 4 (29% respondents), as is shown in Figure 2.2.

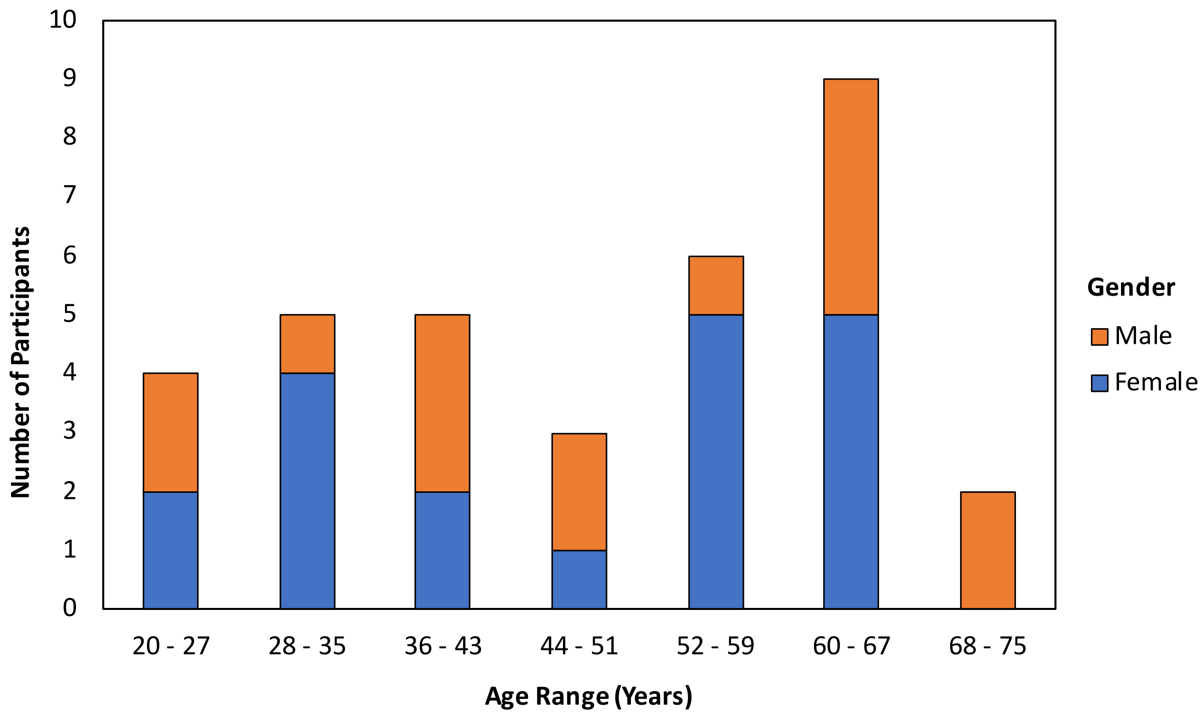


Figure 2.1: Distribution of age ranges corresponding to the gender of interviewed urban farmers. The youngest farmer interviewed was 20 years old and the oldest was 73 years old.

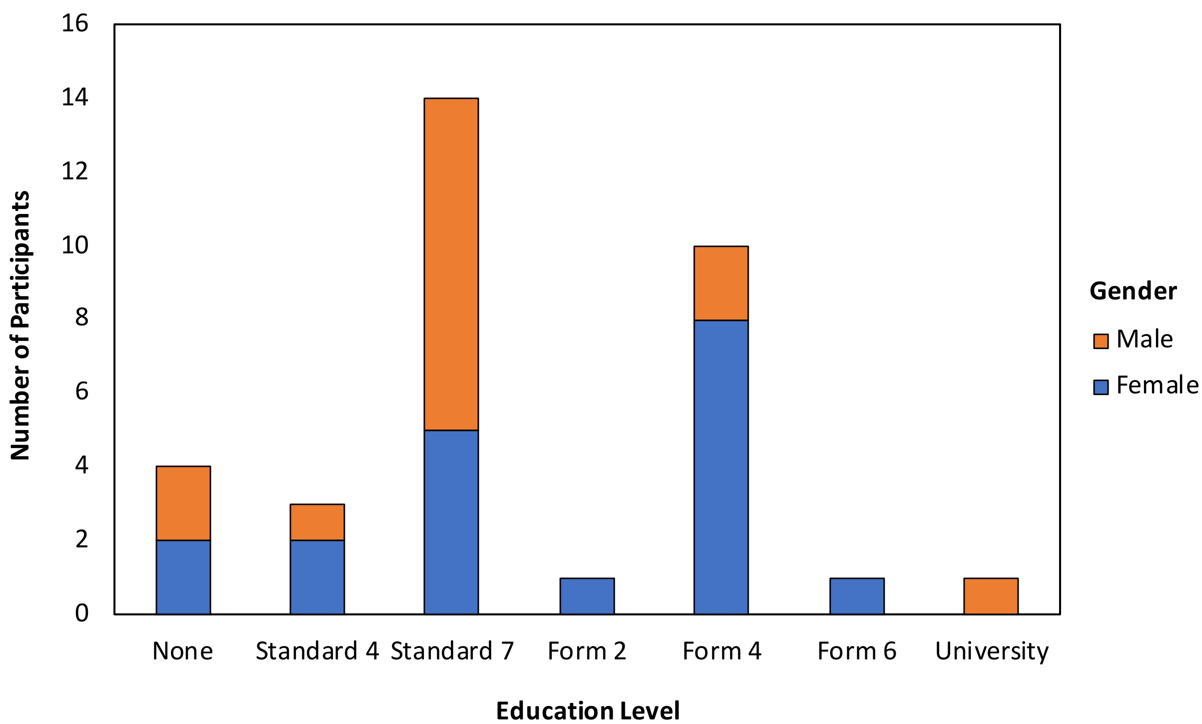


Figure 2.2: Distribution of urban farmers' education level corresponding to their gender. Standard 7 (primary school) completion was reported by more males than females, but Form 4 (lower secondary school) completion was reported by more females than males.

2.2.3 Statistical Analysis

The interview transcriptions were analysed using qualitative analytical software called Dedoose (Dedoose Version 7.0.23, 2019). The software enables quantitative analysis of interview descriptors and qualitative analysis of interview content through coding analysis. The emerging themes from the coding analysis of the interviews were divided into six categories: Personal, Cultivation, Amendments, Soil, Water, and Pests/Disease. The major themes within each category are discussed in the results and evidenced with statistical information (quantitative data) and excerpts from interviews (qualitative data) presented in Kiswahili and followed by an English translation.

2.3 Results

2.3.1 Getting to Know the Urban Farmers: Descriptors, Motivations, and Constraints

Of the interviewed respondents, more males than females reported completing Standard 7 (primary school), whereas more females reported having completed Form 4 versus males. In the Tanzanian education system, Standard 1 - 7 is primary school, with national exams set for passing Standard 4 and Standard 7. Forms 1 - 4 make up the first phase of secondary school, which, upon completion of the Form 4 examination, lead to Forms 5 - 6, the last phase of secondary school. The education level was also graphed with respect to the upbringing locations of the interviewed respondents, which was either reported as the village (rural area) or city (urban area). Of the 34 respondents, 8 reported growing up in the city whereas 26 reported having been brought up in village districts (rural areas). From the data, it appears that growing up in villages did not mean complete lack of education as 46% of these respondents reported completing primary education and 27% of them completed first phase of secondary school. Nonetheless, there are several respondents from both city and village upbringings that did report little to no schooling as well. The distribution is visually represented in Figure 2.3.

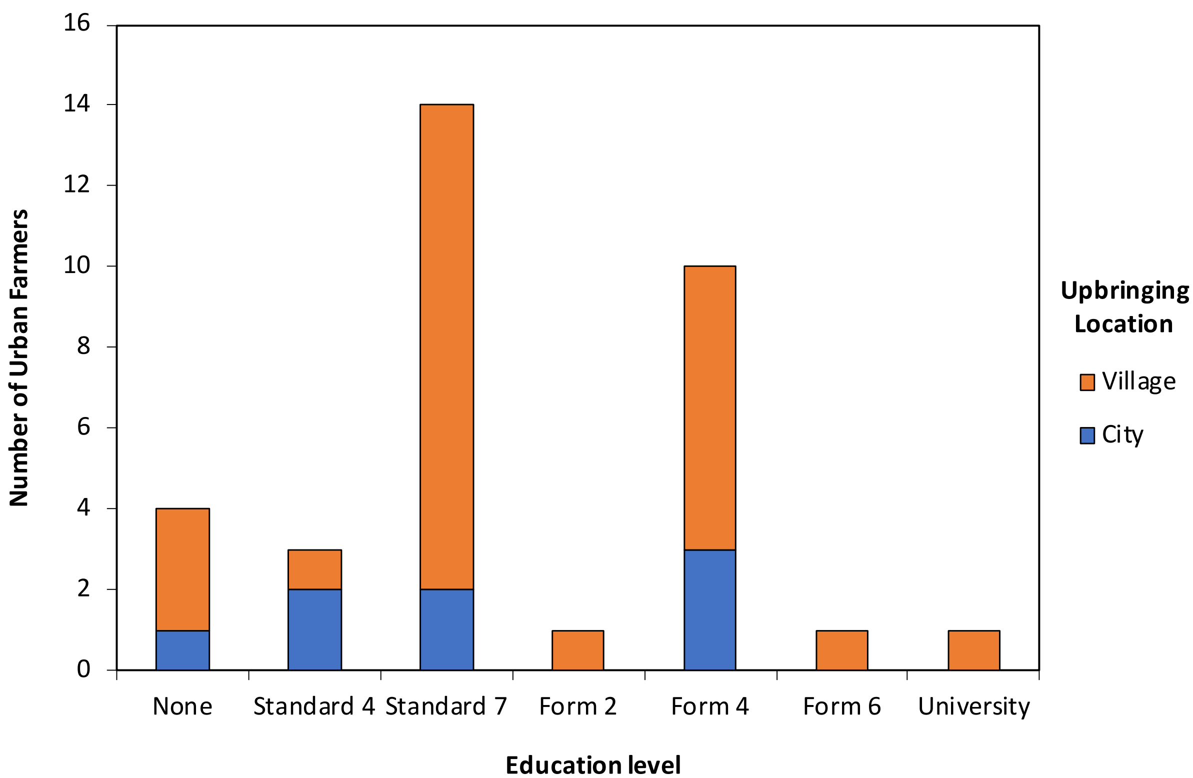


Figure 2.3: Distribution of urban farmers' education level in relation to the upbringing location of the interviewed urban farmers. There were more respondents that reported upbringing in the village districts over city upbringing and a majority reported completing some form of formal education.

The respondents were asked about their interest in agriculture and when they began cultivating. A majority of respondents (59%) said they began cultivating in the city over 10 years ago, 58% of who reported learning to cultivate as children with their families. The remaining 41% of respondents began cultivating in the city less than ten years ago, 64% of who began cultivating in the last five years from the time of this study (2018). Quantitative analysis of the gender descriptors shows that a majority of the respondents who reported starting in the last five years were female (8 out of 9).

The respondents were also asked about their knowledge of cultivation, for which 64% of respondents reported growing up in families of farmers and being taught by their parents or other members of their family. More males (13 out of 15 interviewed) than females (9 out of 19 interviewed) reported coming from families of farmers. Most of the females from families of farmers are over 45 years old. Whereas other respondents reported learning due to circumstances or by observation of other farms either in the city or in rural areas as is demonstrated by the following selected excerpts from the interviews.

"maisha, maisha tunayoishi ndavifundisha, kama inatakiwa nilima hili nipate kula" (Interview 18)

Translation: "livelihood, livelihood taught me to farm, if I want to eat I have to cultivate" (Interview 18)

"nimeji funza mwenyewe, nikua naangalia na nikaanza kufanya" (Interview 4)

Translation: "I taught myself, I saw others do it and I started to do it" (Interview 4)

"mimi kujifunza kulima, najifunza kwa bibi, ehh kwa bibi. bibi alikua akienda shamba na mimi namfata na jaribu jaribu" (Interview 20)

Translation: "me to learn farming, I learned it from my grandmother, yes, grandmother. She would go to the farm and I would follow and try it" (Interview 20)

Reasons for cultivating varied and some farmers expressed more than one reason. The reasons included food to eat (44%), food to eat and sell, especially that which is surplus (29%), to only sell (15%), for the children, especially to help with their schooling (24%), for tradition (21%), and for enjoyment/exercise (18%). Agriculture is ingrained into the culture and identity of the people in Mwanza, as is expressed in the following excerpts.

"kwa kweli hatuna sisi kilimo, hii ni kama lakshar ya mtu tu, yani unaona ardhi imekaa idle, alafu unakuwa na interesti labda niweke kama mboga" (Interview 11)

Translation: "truthfully, we don't have agriculture, this is just the tendency of a person, you see the land sitting idle, so you take an interest, maybe put in some vegetables" (Interview 11)

"kwasababu kilimo ni hutu wa mgongo, bila kilimo hakuna mtu yoyote anaweza kapumua" (Interview 29)

Translation: "because agriculture is the backbone, without agriculture not a person can breathe" (Interview 29)

"ehhh katika maisha mwana damu wanahitaji kula, sasa bila kula haujafanikiwa chochote kwa hiyo tunafanya hivo ilituweze kupata chakula kwasababu pesa tulio nayo ni ndogo hai toshi kunenda kununa chakula kila wakati" (Interview 30)

Translation: "for livelihood people need to eat, without food nothing can be achieved so we have to have access to food, because the money we have isn't enough to buy food all the time" (Interview 30)

One of the major constraints in urban areas is the availability of land for cultivation. While all interviewed participants had urban farms, 15 respondents reported having more than one farm of which 8 respondents said the other farm was in a rural vicinity. The sizes of the urban farms varied. The farmers reported the values in acres, which is the common measurement used for land area in Tanzania. The sizes in these results are converted to hectares (ha), a metric unit equivalency. The farm sizes varied from less than a quarter acre (0.10 ha) to six acres (2.43 ha). A majority of the farm sizes were reported at a 0.10 ha (41%), less than 0.1 ha (24%), and 0.2 ha (21%). A majority of respondents reported either cultivating alone or with one other person, though a majority of respondents reported having 4 to 6 members in each of their households. The number of members participating at the interviewed urban farms is shown alongside the reported farm sizes in Figure 2.4.

The tenure of the cultivated lands also varied; 47% respondents reported owning the land, 12% reported renting, while the other 41% reported borrowing the land, of which 43% reported that the borrowed land belonged to the government. Figure 2.5 visually displays the reported farm sizes with respect to farm tenure. While respondents do not regard land availability and land tenure as a difficulty of urban agriculture, they do consider it a restriction to increasing cultivation production.

Despite the limited size of urban farms, 22% of respondents reported practicing animal husbandry in addition to crop cultivation. Respondents predominantly possessed chickens and ducks, though one participant reported keeping goats and another reported owning pigs as well.

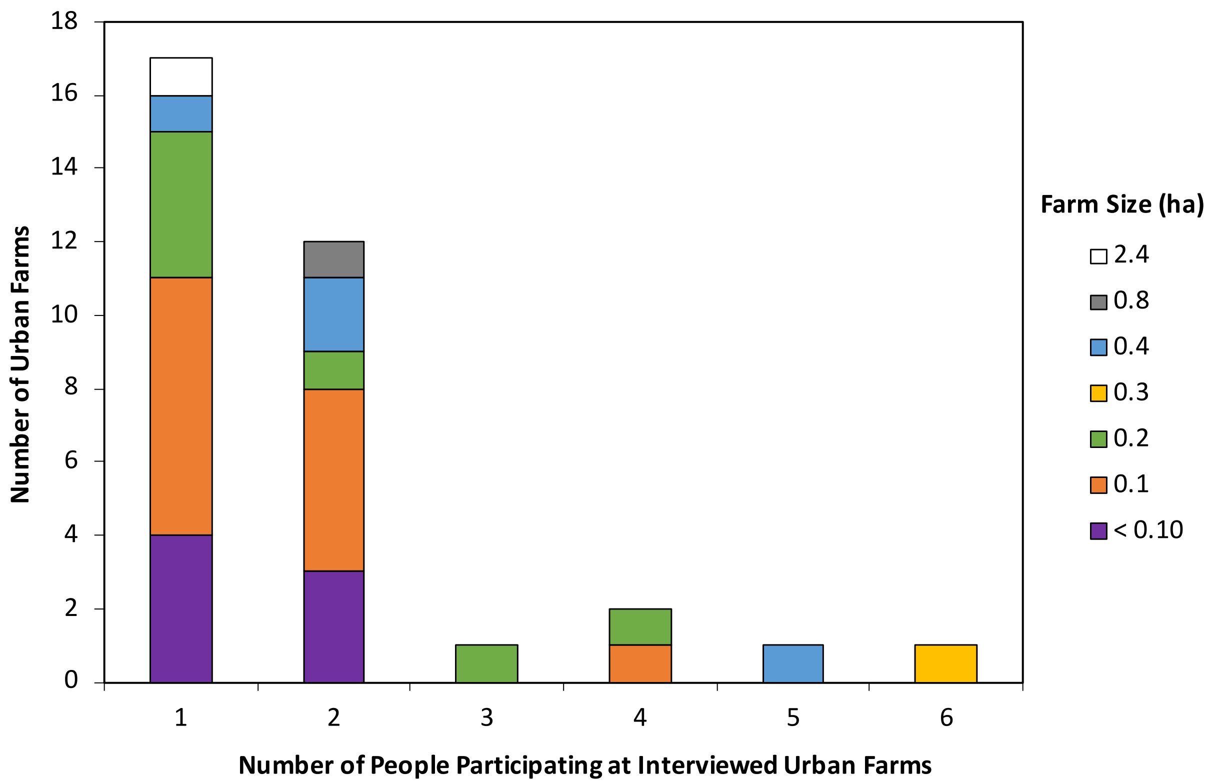


Figure 2.4: The number of participating members at each interviewed farm and the corresponding farm size. Regardless of farm size, a majority of urban farms are cultivated by only 1 or 2 people. At the same time, most urban farms are 0.2 ha or less.

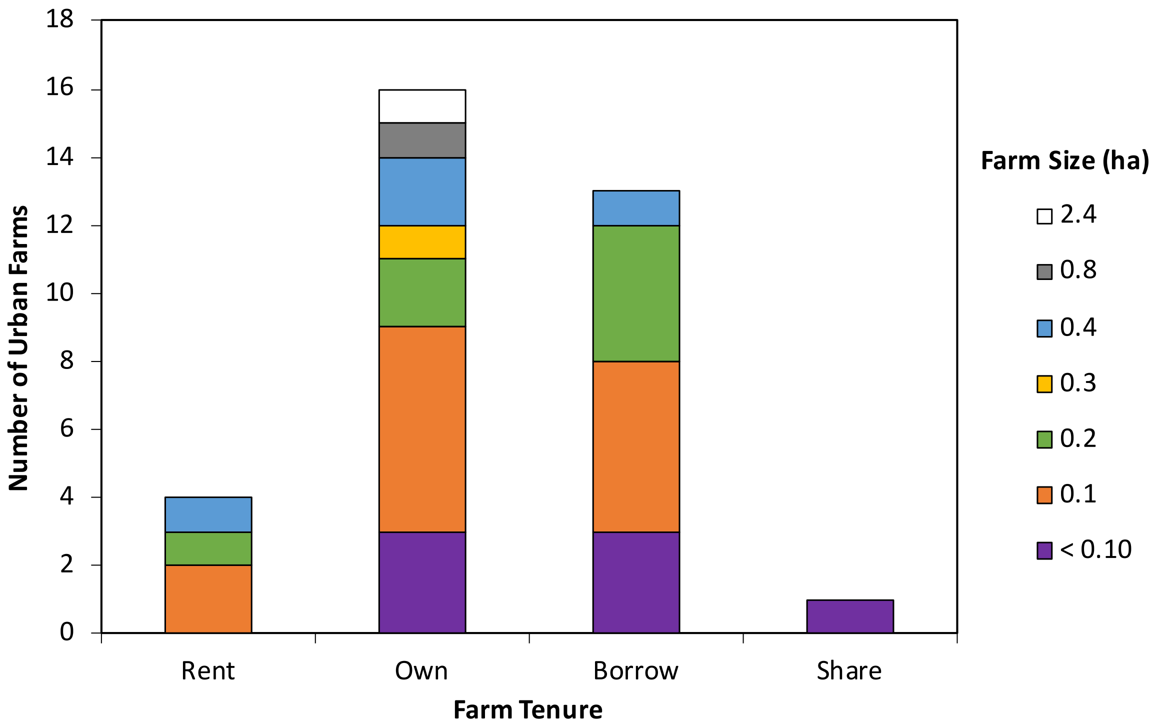


Figure 2.5: Distribution of urban farm tenure corresponding to the urban farm size. A majority of urban farms are owned, though many urban farms are also borrowed. There is more variation in farm size with ownership, though most farms are 0.2 ha or less for both owned and borrowed farms.

While responses regarding challenges related to urban agriculture varied across the respondents, the three major recurring themes were pests (31%), lack of materials, such as amendments or pesticides (22%), and water availability, including dependence on rain (31%). Other challenges common amongst some of the respondents were manual labour (13%), market price variability (9%), lack of money (6%), and lack of support (6%). Three respondents (9%) reported no challenges, stating that it was work to which they had become accustomed.

For 65% of respondents, farming is not their only source of income. Either they or their spouse have a primary occupation, with urban farming being a supplementary source of livelihood. However, for 35% of the respondents, farming is the only source of income/livelihood.

When asked what goals the respondents had with respect to their farm, responses varied. A majority of these were related to the cultivation area, such as wanting to own land (19%), wanting more land area (22%), and being able to grow more crops (28%). Other goals included making money (6%), continuing to provide food for the family (6%), owning farm animals (6%), improving the farm (3%), using store-bought fertilizer (3%), and leaving other work (3%). There were also respondents who reported having no goals (31%), 20% of who stated the space was not their own to have goals.

2.3.2 Cultivation Practices

With regards to cultivation practices, respondents were asked about the tools and techniques used for preparing the soil for seeding, crop seeding, and harvest. All (100%) of the respondents reported the use of hand tools, such as a *jembe* (hand-hoe), *panga* (machete knife), and rake, of which *jembe* is the primary tool for cultivation. All urban farmers prepare the farm manually using hand tools, such as the *jembe*, which is also part of the farmers' identity. One of the respondents implied in her interview that she would continue to be a farmer till the day she dies by using the *jembe* as a symbol.

> *"kwamfano hapo mimi nililima tu nilitifua na mkono, nikatoa majani nikatengeneza vizuri, nikachukua jembe nikakata mashimo, nikatupia mbegu yangu ya mahindi"* (Interview 15)
>
> Translation: "for example here I started, I tilled by hand, I removed the grass, I made it look good, I took the hand-hoe, I cut holes, and I put in my maize seeds" (Interview 15)

> *"ehh sasa niwaache kulima, sikusoma. wengine wanaambugia kusoma anaajiliwa kwa kazi. sasa mimi mama sikusoma, yani mimi natakufa na jembe langu hivi [puts jembe beside her into the ground]"* (Interview 34)
>
> Translation: "now to leave farming, I haven't studied. Others have gone to school, they can get work. I haven't gone to school, so me, I'll die with my hand-hoe like this [puts hand-hoe beside her into the ground]"

For cultivation practices, respondents were asked about the frequency of cultivation as well as farm and crop arrangement. The frequency of cultivation is dependent on the water source available to and accessible by each urban farmer. There was generally an even divide between respondents that reported cultivating continuously throughout the year (53%) and respondents that reported cultivating with the rainfall seasons (twice a year) (47%). A portion (14%) of respondents who reported continuous cultivation, also reported rotating crops after harvest.

"haina msimu kwasabau tuna maji sisi. wakati walikua kutoa maji namana tungesubiri wakati wa mvua, ndio kwa sasahivi tuna maji ya kumwagilizia naweza kulima tu wakati wote" (Interview 6)

Translation: "There is no season, because we have water. When they don't provide water then we wait for the rain, for now we have water to irrigate so we can cultivate at all times" (Interview 6)

"kwa mwaka, ukilima mazao ya muda mrefu, unalima kama mara mbili, sikua mazao ya muda mfupi unaweza ukalima mara nne, ukichanganya na niliaji katika siku za kyangazi, eh kwa hiyo maji iko karibu unakua na mwagilia" (Interview 13)

Translation: "per year, you could grow crops of long time, you would cultivate two times, but if the crops are short duration, you can cultivate four times; if you mix, you get food during kiyangazi (dry period), that's why if water is available nearby, we water the plants" (Interview 13)

"ehhh kwamfano msimu mwezi wa kumi napanda, navuna mwezi wa kwanza, naanda shamba kwamfano sasahivi namaisha aanda, ikinyesha mwezi wa pili napanda navuna mwezi wa tano" (Interview 26)

Translation: "ehhh for example I plant in October, I harvest in January. I prepare the farm, like for example at the moment I have already prepared the farm, once it starts raining in February, I will plant and harvest in April" (Interview 26).

"kila mwaka nalima, unalima, yani ikinyesha tu mvua unalima, ikiyangazi uanona tunachima hapo kisimo tunalima kuna kiyangazi tunamwagilizia" (Interview 34)

Translation: "I cultivate every year, I cultivate, once it rains, I start cultivating, in kiyanganzi you can see we dig here a well to draw water for irrigation during kiyangazi (Interview 34)

2.3.3 Cultivation Practices: Rainy Seasons and Urban Crop Production

Cultivation in Mwanza is categorized by respondents as *'kilimo cha kufata msimu'* (rain-dependent agriculture) and *'kilimo mwagiliaji'* (irrigated agriculture). Similarly, cultivated crops are also categorized either as *'mazao wa msimu'* (seasonal crops), which are primarily grown during the rain seasons, and *'mazao mwagiliaji'* (irrigated crops) or *'mazao bila msimu'* (crops with no seasons).

A majority of respondents (66%) reported relying on weather predictability for their cultivation activities. A majority of the respondents (68%) also reported reliance on rain-water as the primary source of water for growing seasonal crops. A small portion (26%) of these respondents also reported having another source of water to supplement the lack of rain or the growing of crops during the dry 'kiyangazi' seasons. These other water sources included spring water (9%) and municipal water supply (6%). Respondents that did not rely on rain seasons at all relied instead on nearby water sources such as municipal water (9%), rivers (9%), the lake (6%), and wells (6%).

"yani kilimo inatokea labda kama mvua imenyesha" (Interview 10)

Translation: "cultivation begins when the rain falls" (Interview 10)

Maize (*Zea mays* L.) is the primary crop grown during the rainfall seasons, and the main source of maize seeds is from agro-shopkeepers in the city. While some respondents reported growing solely maize, other respondents reported co-planting maize with other crops such as potatoes (*Solanum tuberosum*), beans (*Phaseolus vulgaris*), or peanuts (*Arachis hypogaea*) where the crops alternate in each cultivated rows. Rice (*Oryza glaberrima*) is also grown in rainy seasons.

"mi napanda mahindi tu" (Interview 23)

Translation: "I only plant maize" (Interview 23)

"mahindi, peke yake" (interview 26)

Translation: "maize, by itself" (Interview 26)

"uchanganiko - mahindi hili nyapandikize na mazao mengine kuna vyakula ambayo vinaendana na mahindi kama viyazi, karanga, maharage; sasahivi ndo nilivi pandikizana na mahindi nilipandikiza maharage" (Interview 13)

Translation: "[it's] mixed - maize is planted with other food crops that are compatible with maize like potatoes, peanuts, beans; right now I've planted maize with beans" (Interview 13).

"unaweza ukaaumua kuchanganya mahindi na maharage ndani lakini unaweza ukapata maharage mahindi unakosa, unaweza kupata wote, inategemea kama mvua zinanyesha" (Interview 17)

Translation: "you can decided to mix maize with beans in between, you can get beans and lose maize or you can get all of it, it depends on whether the rains fall" (Interview 17)

With respect to crop arrangement, 22% respondents reported practicing inter-cropping, though the practice was due to shortage of space rather than a purposeful benefit for the crops. One respondent talked about an agricultural set of co-planted crops (*"kilimo mset"*), which was explained as a practice of optimizing space through mixing of crops like cassava and maize, even beans. There was no indication that the respondents were aware of the potential soil nutrient benefits of inter-cropping methods. Rather, it seemed a result of crop diversification as a risk management strategy within a limited space.

"zaidi zaidi unaweza ukafanya kilimo mset, kwa hua sasahivi eneo ni ndogo lazima ulime tu kilimo mset, unakadilie tu vipimo vile, yani uchanganye, unaweza ukapanda mihogo kapanda na mahindi kapanda nyingine unaweka hapa ata maharage kwa ajili ya kufinua maeneo" (Interview 29)

Translation: "increasingly you can intercrop, here right now the space is small so it necessitates intercropping, you can test it out, you mix, you can plant cassava and maize and another you can put beans to optimize the space" (Interview 29)

Respondents also reported growing cassava (*Manihot esculenta*), taro (*Colocasia esculenta*), sugar cane (*Saccharum officinarum*), okra (*Abelmoschus esculentus*), and onions

(*Allium cepa*), which do not fall in either seasonal or irrigated category of crops, most likely because they are perennial tropical plants.

Short duration crops include greens, also called *'mboga mboga'*, such as spinach (*Spinacia oleracea*), amaranth greens (*Amaranthus gangeticus*), collard greens (*Brassica oleracea* var. *Viridis*), cabbage (*Brassica oleracea* var. *Capitata*), Chinese cabbage (*Brassica rapa*), and tomatoes (*Solanum lycopersicum*). These crops need to be watered regularly, which is why they are also referred to as *'mazao mwagiliaji'*. The watered crops are also called *'mazao wa muda mfupi'* (crops of short duration) because these consist mostly of greens that are ready for harvest within a short period of time. For example *mchicha* (amaranth greens) are ready for harvest in three weeks after planting.

"ahh sio msimu, kwamfano mchicha ukimwaga leo, badaa ya weeki mbili inakua, ya tatu unauza, hila si wa si" (Interview 32)

Translation: "ahh not with the seasons, for example mchicha you can plant today, after two weeks it's grown, the third [week] you sell, this is how it is" (Interview 32)

When asked about sources of seeds, agro-shopkeepers in town were reported to be the main source, which offer a variety of seeds, including hybrid maize seeds. The urban farmers were not as aware of the nature or cultivar of the seeds that they bought. Some urban farmers prefer to get their seeds from the rural farms, which they can then harvest from their own crops.

"naenda kununua [mbegu ya mahindi] kwa dukani, sijui nchi, hata siangaliyaga, mi naendega tu kununua mbegu za umeandikwa bada ya miezi mitatu maisha kua (Interview

24)

Translation: "I buy them [maize seeds] from the shop, I don't know from which country, I don't even look, I go get the seeds on which it's written harvest-ready in three months"

"nanunua [mbegu za mahindi, mboga mboga] kwene maduka ya pembejeo, kila kitu, ah viyazi, vile vinakuana malando, mbegu ya malando kule kijijini wana mashamba makubwa ata haca tano sita. kwa hiyo unanenda kwa mwanashamba unaomba, unaumpa mtu pesa kama uwezi, unavuna unakata yale malando yako, unakua sasa na malando yaloe ndo unapanda ni shina ndogo tu. unavuna unajaza ni majunia sasa unakuana unasimika kwenye malando yako" (Interview 25)

Translation: I buy them [seeds of maize and greens] from the agro-shops, everything, ah potatoes, those are from potato plants, seeds of potato plants from the village, they have large farms even 5 or 6 hectares. So you go to the village and ask, or you send money with someone if you can, you harvest and cut your own potato plant, and you now have your own potato plant, that which you plant is only a small stem. You harvest, you fill your bag, and now you see you have your own supply of potato plants. (Interview 25)

"mbegu? ah kwa sasa ninakuta watu wanaenda kijijini, namwambia "utakuta mbegu uko! niletea", baas ananiletea. kama bamiya mtu akikuletea kama kikombe hiyo", nyingi sana huwezi ukamaliza. kwa hiyo unaomba tu kiasi flani cha kutosha shamba lako baas. na hikatokea ukavuna na wewe unaweza ukabakiza mbegu vile vile, na mbegu nikitunza kama kikombe hicho inatosha kabisa" (Interview 20)

Translation: seeds? ah for now I find people who are going to the village, I say to them "if you find some, bring me some, enough to fill a cup like this" [cups hands together], more than that you can't finish. Like so, you ask for enough to suffice your farm. And when you harvest you can keep some seeds of those seeds, and so I keep a cup of it and it's plenty" (Interview 20)

With regards to the harvest, 35% respondents reported using the harvest for food only, 15% reported growing to sell only, and 50% of respondents reported using the harvest for food and to sell, of which 41% reported selling only a little or that which was in surplus (as is explained in the quote below). The respondents that grew maize and cassava also reported making flour out of the crops for better storage and continued access to food for the family. One respondent reported checking market prices first before making the decision of either selling the crops or using them for food as is shown in the second quote below. The third quote below shows the combination of the harvest use and the centrality of agriculture to the person's life.

"kwamfano kama mboga mboga, unaota nyingi unaiuza, kwasababu kwamfano unakuta mboga imekua kwa wakati moja, uwezi kukula kwa wakati moja, kwa hiyo lazima utakula kidogo, nyingi utapeleka sokoni" (Interview 15)

Translation: "for example leafy greens, you grow a lot you sell, because if you find they all are harvest-ready at the same time you cannot eat them all at once, that's why you eat some and the rest you take to the market" (Interview 15)

"mimi kisha vuna cha kwanza ni naaangaliya kwanza bei imekaa vipi, naweza nikauza, au naweza nyingine nikabaki kwa ajili ya familia yangu wakatumia" (Interview 23)

Translation: "me, once I've harvested, I first check where the prices are at, I could sell or I could keep for the family to use" (Interview 23) *"kama nalima labda nimelima spinach mboga za majani, tunatumia tunatumizia nyumbani na kama ikizidi unaweza kuuza kidogo; sasa mimi na asili ya kulima, asili yangu mimi, nikiona udongo nasikia natakataka kulima"* (Interview 6)

Translation: "for example, I grow spinach, leafy greens, we use it at home and if there's leftover we can sell a little; now me, I am from the real farming, it's my nature, if I see soil I feel the want to farm" (Interview 6)

2.3.4 Perspectives on Soil Fertility and Use of Soil Amendments

While perceptions of cultivated soil varied, with some respondents saying it is good and some saying it is not doing so well, a majority of respondents (82%) would like to improve their soils. Respondents recognize soil depletion through anthropomorpic statements, such as "*imechoka udongo*", which means that the soil is tired or "*ache ipumzike*", which means to let it rest, or "*amechakachaka*", which means it has worn out.

Respondents use two different ways to gauge the fertility of their soil: their eyes (38%) (looking at either colour (6%) or texture (25%)) and plant growth (44%). One respondent reported having her soil tested and was awaiting results. Other respondents (16%) did not report any means of gauging soil fertility. Respondents are also noting changes in soil as is expressed in the following excerpt, which also shows how fertility is gauged.

"ehhh mabadiliko ya udongo nimeona, udongo naona inakua kama walaini kama wa powda powda, umekosa kama nguvu vile, ukipanda kitu kinakufa" (Interview 14)

Translation: "yes, I've seen changes with soil, the soil I'm seeing has become softer like powder, it lacks strength, when you grow plants on it, the plants die" (Interview 14)

Respondents varied in their choices regarding amendments; some use a variety of amendments, some stand firm with their preferred choice, and some even use none. Across all the urban farmers that were interviewed, the use of manure was a common thread, with cow manure the most popular choice used by 53% respondents, followed by poultry manure (38%), goat manure (9%), rabbit manure (3%), and pig manure (3%). Other inputs used by urban farmers included inorganic fertilizers bought from agro-shopkeepers (38%), crop residue (29%), and waste compost (9%). Respondents who used a variety of amendments demonstrated an understanding of the role that different amendments can play, such as some work to establish crops while others help them grow and fruit. Some respondents explained the manure equivalency to store-bought fertilizer.

"kuna aina mbili za mbolea, unaweza kuweka mbolea kupandia, alafu badai ukaweka mbolea ya kuuzia" (Interview 23)

Translation: "There are two types of fertilizer, you can put fertilizer for planting and then for growing" (Interview 23)

"mbolea kuna ulea, kuna kani, kunakuuzia na kunakubebeshea" (Interview 30)

Translation: "Fertilizers there's ulea and kani, one for growing and the other for helping bear fruit" (Interview 30)

"ehh vimina ikisha tumia samadi, samadi naweka ile ya kupandia, inamana inapokoa inamaliza ata weeki mbili najua kabisa wamaisha shika chini, kuenda kwa tatu naweka

mbolea ya kuuzia dukani" (Interview 21)

Translation: "I put the manure for planting, it means that in two weeks I know that the plant has taken hold in the soil, then the third week I put the store-bought fertilizer for growing" (Interview 21)

"hi na hi [referring to two compost samples] vinarutubisha, inafanya mimea inarutubika, hi na hi [referring to poultry manure and ulea samples] vinazalisha" (Interview 12)

Translation: "this and this [referring to two compost samples] they nourish, they make plants healthy, this and this [referring to poultry manure and ulea samples], they promote growth" (Interview 12)

When asked where they get the manure, some respondents reported using the manure from the animals that they kept, some reported asking neighbours or others in the city that keep animals, and others reported travelling far to get the manure. The excerpts related to the source of manure also provide insight into the farmers' perspectives on the presence of farming, as well as the importance of having amendments.

"watu hapo mjini wanao ngombe, unaweza ukaenda ukaomba tu, kule kijijini kinyesi kinaweza kikawa kinatumika shambani sana, lakini kwa mjini hapa unakuta watu wengi si hawana mashamba kwa hiyo kile kinyesi ya ngombe anakirunda tu hapa kwa hiyo wengine wananenda naomba nakuja navuruga napandiya mashima ya mboga" (Interview 25)

Translation: "people here in the city they have cows, you can go and ask them. There in the village, the manure is used on the farms a lot. But here in the city you'll see not a lot of people have farms, so the cow manure is gathered and people can go ask, get the manure, and bring it back to grow food" (Interview 25)

"napata kwa wenyeji wanaofuga, ni mbali kweli saa nyingine unakosa, kwasababu wakulima imekua wengi kama sasahivi sina mchicha wengi kwa kukosa mbolea" (Interview 31)

Translation: "I get it from people who keep animals, it's far truly, sometimes I don't get any because there are a lot of farmers, like now I don't have a lot of amaranth greens because I missed out on fertilizer" (Interview 31)

The frequency of amendment use, manures and inorganic fertilizers, varied among respondents. However, it appeared that manure was generally applied in anticipation of the rain season at the beginning of each growing season or once a year. The type of amendment and frequency of use also varied with the situation year to year for each respondent. One respondent explained their thought process regarding amendment use that captures the inconsistencies in determining frequency of use.

"ehh sana sana labda ni kama emergency kuweka mbolea inapobidi, mbolea kama kani, ulea, yani fertilizer, mani au nani mbolea ya ngombe ya kuku, kama ikibidi - situmi mara kwa mara, ukuchagua kutegemea na msimu ya mvua, kwamfano kama ulea inahitaji maji mengi ukiweka mvua ikiwa za chache inaungua unaona? lakini kama ni mvua za kawaida natumia sasa hi ya ngombe, ambayo haiwezi kaunguza hata kama mvua zita" (Interview 26)

Translation: "more often if there is an emergency to put fertilizer then it's necessary, fertilizer like kani, ulea, you know fertilizer, as well as fertilizer of cows and chickens, if it is needed - I don't use it often or frequently, you base it on the rain season, for example ulea requires a lot of water, if you put it when there is little rain it will burn the plants, you see? but if the rain is normal I use cow manure, which does not burn even if the rains stop" (Interview 26)

"naweka [samadi] kipindi cha mvua inanyesha, unaweka alafu baasi mvua ikinyesha inafanya hivi mbolea inakua nzuri kwa ajili ya kuoteshea mazao" (Interview 17)

Translation: I put it [manure] when it's time for the rain, I put it then the rain falls and it makes nice to grow plants in" (Interview 17)

The respondents who reported using leaves on their farm did not initially offer that information when asked about the amendments that they use on their farm. The practice of using crop residue, such as leaves of maize and cassava crops, appears to be a habitual aspect of farm preparation, and is considered to work as a fertilizer for the soil. It is also used as a strategy for intercropped plants where the residues of the harvested crops, such as maize, were returned to the soil for the crops still growing, such as cassava.

"hapana situmii [mbolea au samadi], hivo hivo tu. [later in the interview] mti ya mahindi kama hivo unapoenda kukata mahindi, si unakata tu mahindi kama ni maboa unaweka pembeni, unachukua mahindi yako, inamana yale inakua kama mbolea humo humo, naacha humo humo"

Translation: "no, I don't use it [fertilizer or manure], I grow just so [later in the interview] maize stalks when you go to cut the maize, you cut it like it's wood and leave it, you only take the corn, it means it becomes fertilizer in there, I leave it in there *"huaga tunapanda mahindi na mihogo, sasa mihogo inatakiwa ukishatoa mahindi, inamana yale si anakosa nguvu yanaanguka kwa hiyo unakuanapalilya humo humo unayapandishia kwa hiyo yanaozea humo yanakua mbolea, mabua manake"* (Interview 30)

Translation: "we plant maize and cassava, now cassava, once you've removed the maize, it's like it loses strength and starts to fall, so you put it back where you grew it so that it decomposes and becomes fertilizer, the stalks I mean" (Interveiw 30)

2.3.5 Improving the Soil: Need for Amendments and Knowledge

Respondents also recognize the need for soil amendments for their soils, and many (32%) stated animal manure as the way to improve soil. However, some respondents stated that the soil needed fertilizer (9%) or more water (9%).

"yani unaweza kwa badilisha kwa mbolea, unaweza ukatumia mbolea ya ngombe au ya kuku unaona. kwamfano ukitumia mbolea ya ngombe kidogo nanili unaweza ukaboresha udongo kwa mbolea ya ngombe, kama ukipata mbolea ilio eva kabisa kabisa, acha yale mavi ya ngombe mabichi mabichi hapana, imekua kama udongo kama udongo myeusi ukiweka ndio inakua safi" (Interview 31)

Translation: you can change with amendment, you can use cow manure or poultry manure you see. For example, cow manure can improve soil, if you can get the manure matured completely, not the wet kind no, it should be like soil, like black soil, if you put that it will be good" (Interview 31)

Respondents also noted a need for more knowledge transfer regarding agricultural practices, such as ways of improving the soil.

"kama mtalaama nanishauri, nafanya [boresha udongo]" (Interview 11)

Translation: "if I can get the right advise, I would [improve soil]" (Interview 11)

When asked about their opinion of using composted food waste as a soil amendment, 77% respondents responded positively even though 62.5% of these respondents had not yet tried any form of food waste based compost. There were some (23%) respondents who expressed skepticism regarding compost from food waste. Some respondents reported already making their own composts from kitchen/food wastes.

"mbolea ya chakula ni nzuri sana kwamfano hapa, hapa kipindi ambayo silimi, namwaga chakula ma uchafu uchafu ule, namwaga namwaga, namwaga uko shambani" (Interview 15)

Translation: "amendment from food is very good, for example, here in this area that I don't cultivate, I dump food waste and dust and dirt, and then I put it on my farm" (Interview 15)

"hiyo nafikiria ni nzuri lakini ndo sijaipata, ni nzuri kwasababu hi pia ni mbolea hi, kifukia chini ikioza naweka shambani" (Interview 22)

Translation: "I think it's good but I haven't gotten any, it's good because it's also a fertilizer, to put in the ground and when it's decomposed to put on the farm" (Interview 22)

2.3.6 The Occurrence of Pests and Disease

A majority of the respondents reported having to manage for pests and diseases, especially recently. In terms of crops affected, the most emergent theme was the recent infestation plaguing maize crops across Tanzania. The responses from the respondents suggest that the infestation began affecting Mwanza's urban maize crops in 2017, the harvest before the interviews were conducted. *Dudu* (singular) and *wadudu* (plural) are the general terms for pests or insects in Kiswahili and *ugonjwa* is the general term for disease. The respondents did not know the cause of the maize infestation, though some respondents speculated it could be *viwa* (caterpillar), or *funza* (insect), or bacteria. Respondents used both terms, *wadudu* (pests) and *ugonjwa* (disease), to describe the infestation of the maize crop.

The effect of the infestation, according to the farmers, is that the corn of the maize crop becomes powder, as is communicated by a respondent in the quote:

> *"mahindi sasahivi wameingia wadudu wanao kula mahindi sana, kama mwaka jana wamekula mahindi mpaka yanatoa unga, kwa hiyo sijapata bado majibu ya wadudu hawa lakini kwa mahindi kulingana changa moto sasahivi ambayo ameingina wadudu, wadudu wanaingia sasahivi wanaharibu sana mazao"* (Interview 25)

> Translation: *"Maize crops right now are infested with insects that eat the corn a lot, like last year they ate the corn until it came out like flour. I haven't yet gotten an answer about the insects but it is the current hardship; these insects, they come in and they spoil the crop a lot"* (Interview 25)

The consequences of the infestation was the loss of maize crops, which for many urban farmers is a source of livelihood and sustenance, and also resulted in hesitation to plant maize crops again. The respondents communicated their helplessness against the infestation.

"useme tu hali ni mbaya kwa sababu mahindi anaharibu lakini tulikuatumaisha lima tena lakini sasa ugonjwa amekuja ameharibu mimea ndo tumekatana tamaa" (Interview 16)

Translation: "Let's say the situation is bad because the maize has spoiled, but for livelihood we grow it again, but now the disease has come and spoiled the crop , which is disappointing" (Interview 16)

The interviewee is stating that crop loss was an acceptable risk in urban farming, but did not discourage replanting of the same crops. However, the presence of the infestation is discouraging because the risk of crop loss now becomes guaranteed crop loss, inferring that planting the same crops again would be ill advised.

For the farmers who were able to afford pesticides there was no information regarding the appropriate treatment and, therefore, were unaware as to which pesticide would work against the infestation. They also reported the infestation was not limited to Mwanza and was plaguing crops across Tanzania.

"kama hiki kipindi imeenda inakuana wadudu sana, hakuna dawa tulioweka, sikupata dawa nilinunua, tanzania nzima mahindi iko mbaya nani ilishambuliwa sana na wadudu" (Interview 18)

Translation: " For example, the period that just passed there were a lot of pests but there was no pesticide to put, I didn't get a pesticide to buy, the maize crop across Tanzania is affected a lot by pests" (Interview 18)

The other crops generally known to be afflicted by disease and pests are tomatoes, rice, and amaranth greens. However, the respondents who reported these explained that was the nature of growing these crops, and exhibited confidence in the effectiveness of the pesticides that they used. Others who did not use pesticides accepted crop loss as a part of cultivation practice.

"nyanya uwezi kulima bila dawa" (Interview 9)

Translation "You can't cultivate tomatoes without pesticides" (Interview 9)

"sasa kama pesa hakuna kununua dawa baasi wadudu wanakula nashambuliwa mimea wewe unakosa chakula" (Interview 17)

Translation: "Now, if you don't have the money to buy pesticides, the pests will eat, spoil the plants, and you lose food" (Interview 17)

2.3.7 Management of Pests and Disease

While respondents discussed the use of store-bought pesticides, some respondents also reported using home-based remedies, such as the use of ash. One respondent also reported using a tobacco-based remedy passed on in his family. However, the effectiveness of the use of ash is contested even among the respondents.

"mara nyingi mi situmiagi dawa, hmmm asilimi kubwa hasutumii dawa, na kama majivu haya, nikipika nakuta namwagiya majivu yale, baasi" (Interview 15)

Translation: "most of the time I don't use pesticides, I don't have a big farm so I don't use pesticides, I have ash, when I cook I can take the ashes and put them on the farm" (Interview 15)

"majivu ukiweka, majivu haiana msada makubwa sana kama dawa wa kiwandani" (Interview 13)

Translation: "ash if you put, ash doesn't help as much as pesticides from the store" (Interview 13)

"wamenifundisha lakini kwasababu zamani sisi huko kigoma labda ata sija, kama hawa jamaa tulikua tifuuna wadudu kama hawo tulichukua kama ugoro - tumbaccu, inatengeneza tuguro ule unachukuana majivu unachanganya alafu unamwagilia kwenye mimea" (Interview 16)

Translation: they taught us but because long time ago in Kigoma we used to kill pests with ugoro - tobacco, it is made by mixing tobacco and ashes and then putting the mixture on the plants" (Interview 16)

2.4 Discussion

2.4.1 Urban Farming Comparisons: Motivations and Constraints

Urban agriculture is a core activity in Mwanza, Tanzania and does not show signs of declining, which reflects the notion that urban agriculture has a long-standing indigenous tradition in Africa (Drechsel and Dongus, 2010). A majority of the interviewed participants have been engaged in urban agriculture for over ten years, which is similar to findings of other studies that agriculture is practiced by established urban residents and not limited to recent rural migrants (Sawio, 1994; Flynn, 2001; Schmidt, 2012).

Many who engage in urban agriculture received the knowledge and practice of farming from a young age, having been taught by their family members. Prain et al. (2010) found that farmers in Kampala include their children in the practice as young as 8 years old. The work of Sawio (1994) in Dar es Salaam also included information on where the respondents of the study were born, and found that most were born in regions bordering Dar es Salaam and those that are rich agriculturally. However, neither study delved deeper into how and when the knowledge of cultivation was passed on to the respondents who now practice urban agriculture. This study found that while urban farmers predominantly acquire cultivation knowledge from family members, others learn through observation and trial and error. This study did not find evidence of formal education received by urban farmers, directly or indirectly, for agricultural practices. However, transfer of knowledge from agro-shopkeepers, where seeds, fertilizers, and pesticides can be bought, was noted. Therefore, this study contributes to the literature the sources and approaches for urban farmers' cultivation knowledge and presents the groundwork for research to further explore drivers of knowledge mobilization.

Several interviewed residents had been brought up in the city, all of who began practicing urban agriculture within the last ten years. Most of the interviewees who began agriculture in the last five years were female. According to the study by Sawio (1994) in Dar es Salaam, women tend to practice urban agriculture more than men. Studies have also looked at women's relationship with urban agriculture in SSA (Hamilton et al., 2014). One of these studies, by Bryld (2003), suggests that women dominate urban agriculture because the closeness of the plots to the home allows for agricultural activities to fit easily into women's daily work routines, and that men generally regard agriculture as a marginal activity rather than a serious occupation. This study found that urban agriculture in Mwanza is not limited to a specific gender or age group, with a mix of male and female respondents and ages ranging from 20 to 73 years old. While it is true that the proximity of the plot to home enables women to engage in urban agriculture, not all women cultivate plots that are close to home. Several women in this study indicated having more than one farm plot, at least one of which was located in a rural vicinity. Additionally, the findings of this study do not concur with the argument that men regard urban agriculture as a marginal activity. Both men and women interviewed in this study regarded urban agriculture as a means for livelihood and a way to give life to idle land. This study does, however, concur that cultivation is not the only source of livelihood for most households and is used as a way to supplement household income (WinklerPrins, 2017). Therefore, it is posited that the gender variance in urban agriculture may be due to economic well-being of individual households, and the city overall, rather than the proximity of land or the attitude toward urban agriculture. Substantiating the correlation requires further research.

The reasons for engaging in urban agriculture varied with some urban farmers growing for self-consumption or for selling, which were the expected reasons, though some urban farmers also included reasons such as for tradition and for enjoyment or exercise. The findings of De Bon et al. (2010) asserted that urban agriculture is a source of food for urban dwellers, primarily for self-consumption, though with increasing land pressure, selling becomes the preferred alternative. In the present study, it was found that home consumption was favoured over selling, though a portion of respondents also reported cultivating solely to sell. As Howorth et al. (2001) concluded, the role of urban agriculture for food production is gaining importance, especially as urban agriculture is a means of employment for a significant proportion of urban population. As urban growth and pressures on land continue, the fate of urban harvest can be expected to tend strongly toward market recourse (De Bon et al., 2010).

The presence of agriculture in urban and rural areas, in combination with livelihood needs, appears to encourage more urban resident to take up farming. In much of Africa, urban agriculture has been shown to contribute a significant share of income for the urban poor and for households where it constitutes a livelihood (Zezza and Tasciotti, 2010). It is common in the Global South for people to pursue multiple livelihoods, and farming for food or income is compatible with other livelihoods (Owusu, 2007; White and Hamm, 2017). It was found in this study that farming is not the only source of income for a majority of residents who reported having additional occupation.

Even when farming is not the only source of income, it remains a source of livelihood and sustenance for all, which reflects the 1990's findings of Sawio (1994) in Dar es Salaam, the largest city in Tanzania, and of Flynn (2001) in Mwanza. Flynn (2001), who only interviewed women in Mwanza, found that urban agriculture was practiced by both the poor and the wealthy. Sawio (1994) found in Dar es Salaam that urban agriculture was not limited to the socially marginal populations. This is consistent with the review by Graefe et al. (2019), which confirms that urban agriculture forms a livelihood strategy across all socio-economic groups of a city, though the urban poor profit more from the dietary diversification than richer households (Tasciotti and Wagner, 2015).

One of the major constraints in urban areas is the availability of land for cultivation. There are different terms in the literature for the different agricultural land spaces in urban environments. Flynn (2001) described the urban cultivated plots as either a kitchen garden, garden, squatter garden, or farm. They are defined as follows: "a kitchen garden is a small garden adjacent to one's dwelling; a garden, including one owned outright or a squatter one, is a plot located at some distance from one's dwelling; a farm is a larger plot located in another part of the municipality or in another village" (Flynn, 2001). According to Orsini et al. (2013), urban horticulture systems are traditionally classified as: allotment and family gardens, simplified extensive systems, shifting cultivation, and intensive systems. McLees (2011) introduces the concept of open-space farming, defined as agriculture on undeveloped land in urban environments, in which several farmers work at one farm.

According to the definitions provided by Flynn (2001), urban cultivation is defined as gardening rather than farming. This is consistent with some of the comments by the respondents who insisted that what they had was not a *bustaan*, a garden, not a *shamba*, a farm. This is most likely due to the smaller size of agriculture operations in urban areas.

The urban farm sizes in Mwanza were predominantly 0.2 ha or less, with a majority equal to or less than 0.1 ha, which is consistent with the findings of Prain et al. (2010) in urban Bukesa, a district in Kampala, Uganda, where plots of more than 0.1 ha were scarce.

The land that was borrowed or shared for urban agriculture in Mwanza fits the description of open-space farming. The legality of borrowed and shared land occupation was not explored in this study, though some participants did acknowledge using government-owned land. Previous studies have shown that farmers take advantage of open-space farming, such as vacant neighbourhood plots, especially in cases where buying their own plot is restricted by high costs (Sawio, 1994; Flynn, 2001). McLees (2011) in their study concluded that while access to open-space farming can be seen as farmers as squatters gaining illegal access, an examination of relationships between rights-holders and farmers revealed a variety of benefits to the stakeholders. This is an area that requires further investigation.

WinklerPrins (2017) posits that urban agriculture provides ecosystem services through green spaces, plants, and habitats that can contribute to urban environmental resiliency. Howorth et al. (2001) argue that urban farms can protect land against a variety of hazards, such as pests, thieves, squatters, and garbage dumping. From the observations of this study, the farmed lands do indeed add green spaces to the urban environment. However, variables such as lack of ownership or secure tenure and poor cultivation practices can be a cause of concern with respect to improving soil ecosystems for continued cultivation.

While some urban farmers' goals were to own land or to increase land area for growing more crops, there were some urban farmers who did not have any goals for their farms. The main concern was that the land they cultivated was not their own space to have goals.

McLees (2011) found that farmers were concerned about the insecurity of land access, and a similar concern could be driving the lack of long-term goals from some respondents in this study. WinklerPrins (2017) presents that critical planning debates of urban space production suggest that cities need to be rethought to serve the goals and aspirations of all their inhabitants. However, the long-term goals of urban farmers are yet to be investigated in urban agriculture studies.

Studies have focused more on challenges related to urban agriculture. These include growing food in degraded urban soils (Lorenz, 2015), the possible to link to disease-carrying vectors (Afrane et al., 2004; Hamilton et al., 2014), access to main agricultural inputs, fertilizers, water, and the food safety risks due to various sources of pollution (De Bon et al., 2010). Some of these challenges were also expressed in this study, primarily the access to agricultural inputs, such as soil fertility enhancing amendments and pesticides, as well as the availability of water. While research has expressed concern on human health, such as the possible link between urban agriculture and malaria (Lorenz, 2015), the farmers in this study were more concerned with pests affecting crops.

2.4.2 Comparing Cultivation Practices in Urban Agriculture

According to the review by Graefe et al. (2019), the major problems with urban agriculture include environmental pollution due to irrigation with untreated wastewater and the need for nutrient management to meet crop requirements without contributing to runoff. In this study, more urban farmers reported relying on rainwater than irrigation water as the primary source of water. The sources of water used could be polluted, such as rivers, lakes, and wells, but could also be treated, such as municipal water supply. The concern of contaminated wastewater in urban agriculture is also presented by Orsini et al. (2013) and Hamilton et al. (2014). Lorenz (2015) suggests the use of recycled treated wastewater in urban agriculture should be promoted and decentralized low-cost water treatment technologies should be developed for this purpose.

Crops are irrigated manually in Mwanza, which is similar to the information provided by Orsini et al. (2013) for traditional mixed farming cultivation systems in tropical regions. The irrigated crops are primarily leafy greens and vegetables, such as cabbage (*Brassica spp.*) and tomatoes (*Solanum lycopersicum*), as well as perennial crops, such as onions (*Allium cepa*), okra (*Abelmoschus esculentus*), and sugar cane (*Saccharum officinarum*), which is consistent with the review by Graefe et al. (2019) for developing countries. The primary rain-fed crops were maize (*Zea mays* L.) and rice (*Oryza* spp. L.), which was also reported by Lorenz (2015) for SSA. Longer-term crops, such as cassava and taro, would require irrigation in addition to rain seasons due to their longer growing term.

Urban farmers, for the most part, grow multiple crops, though there is an emphasis on maize as the primary crop, which is a dominant staple in eastern Africa (De Groote et al., 2010; Mahuku et al., 2015). According to the review by Orsini et al. (2013), fruit and vegetable crops have a much higher yield in African countries as compared to other food crops, such as grains. However, the shift to fruit and vegetable production from the farmers that predominantly produce maize or rice would require access to water for irrigation based on the current approach of urban farmers in Mwanza.

Urban farming in Mwanza is practiced using manual labour and hand tools only, which is consistent with the findings by Prain et al. (2010) in their study of Kampala's urban farming. In Mwanza, all urban farmers rely on the hand hoe for their cultivation practices and see it as part of the farmer identity. Hand tools are also commonly used in rural agriculture (Doraiswamy et al., 2007; Makki et al., 2009). The hand hoe is a multipurpose tool as was demonstrated by Makki et al. (2009) in a study investigating the use of hand tools in Sudanese agriculture and by Naab et al. (2017) in Ghanaian agriculture. Makki et al. (2009) found that women often use ill-suited hand tools designed for men, but they would rather stop farming than spend resources on tools whose durability they doubt.

The frequency of cultivation practices demonstrates a mixture of mixed farming and extensive monocropping systems, as described by Orsini et al. (2013). There were three cultivation choices that dictated the frequency of cultivation. One was the reliance of rain for cultivation, which limited frequency of cultivation to twice a year in line with the bimodal rain seasons. This form of cultivation results in extensive monocropping of maize, though some farmers do intercrop maize with cassava, beans, or peanuts. The second is the use of rain seasons in combination with a means for irrigation, which allows for the three cultivation cycles: seasonal crops twice a year during the rains seasons and leafy greens in the dry season. The third is continuous cultivation regardless of the seasons because of access to water for irrigation. The latter two cultivation choices constitute mixed farming systems because of the variety of crops chosen and planted by the urban farmers. In addition to the frequency of cultivation, the practices used by farmers also inform the impact that urban farming has on the soil and the crops.

Intercropping, specifically for cereal-legume, was not as common a practice in Mwanza's urban agriculture as was reported by Orsini et al. (2013) for urban agriculture in developing countries. The urban farmers who do practice intercropping do so as a means for maximizing land use and reducing risk with crop diversification than for agronomic benefits. Risk reduction from crop diversification is a strategy that was also reported by Prain et al. (2010) in Kampala.

In Mwanza, cereal-legume intercropping is mainly used for crops grown during the rain seasons, such as maize and beans or peanuts. Though cassava is also intercropped with maize. The practice of intercropping maize with beans or peanuts is beneficial to add nutrients to soil for crop production as both beans and peanuts are able to fix nitrogen. However, the practice of intercropping maize and cassava may instead deplete nutrients further, as both maize and cassava are reliant on soil nitrogen, making it solely a risk-management strategy. With the already low soil fertility in Mwanza, sharing knowledge of the benefits of strategic intercropping could help improve soil fertility. Wang et al. (2014) demonstrated that maize-based intercropping can be an efficient cropping system for sustainable agriculture with well managed fertilizer inputs in China.

Some urban farmers also practice crop rotation, though the reasons were neither apparent nor discussed by respondents. Crop rotation can also result in nutrient depletion. According to Lal and Singh (1998), soil nutrients depleted from a maize/bean rotation removes about 58 kg ha^{-1} N, 13 kg ha^{-1} P, and 56 kg ha^{-1} K in Tanzania. However, in Mwanza's urban agriculture, farmers growing irrigated vegetables rotate crops more regularly than rain-fed crops. While Drechsel et al. (2008) argue that irrigated vegetable production provides protective soil cover throughout the year, intensive production does require soil protection and external inputs to maintain productivity. It is expected that continuous cultivation without nutrient replenishment will deplete soil fertility.

2.4.3 Urban Soil Fertility and Amendment Use

According to Lal (2007) the rate and magnitude of soil organic carbon depletion are high in soils with low available water and nutrient holding capacities, such as those of Mwanza's urban area. In Mwanza, urban farmers may not realize the impact that they have on soil fertility and crop productivity. Urban farmers do care about the quality and fertility of the soils they cultivate. They use properties such as the colour and texture of the soil, but primarily the ability of plants to grow on the soil. While urban farmers may believe their soil is satisfactory, all of them concur on the need to improve the soil's fertility. Farmer's perception of soil has been explored in some rural agricultural studies, such as that of Solomon et al. (2016) where smallholder farmers in Ghana and Liberia were interviewed and landscape features were discussed. Farmers identified regions of anthropogenically enriched dark soils that had been transformed from highly weathered, yellow-to-red tropical soils, that they considered to have made fertile (Solomon et al., 2016). Other studies have discussed farmers using the presence of termite mounds as a sign of soil fertility (Fairhead and Scoones, 2005). However, farmer's perceptions of the soil have not been explored in urban agriculture literature, and, therefore, the results in this study fill a gap in literature.

The best way to improve the soil, according to the urban farmers, is using manure. Harris et al. (2001) in West Africa found that smallholder farmers "consider manure to be a cornerstone of their soil fertility management strategy". However, the effectiveness of manure depends on how it is applied to the soil (Harris et al., 2001). Drechsel et al. (2008) discussed that manure application rates can be high on sandy soils, which can lead to leaching with frequent irrigation, which was found in Kumasi, Ghana where poultry manure and NPK fertilizers are used on cabbages.

In this study, it was also found that urban farmers relied on manure as a primary amendment, though inorganic fertilizers were also used to increase crop productivity. It is expected that since the frequency of manure use varied, farmers may be over applying at the time of application, which can be a problem during rain seasons. However, this claim is limited by lack of information about application rates.

Solomon et al. (2016) found that indigenous method of targeted waste deposition transforms nutrient-poor and carbon-poor soils to enriched dark soil in a study was conducted in Ghana and Liberia. The waste types described included ash and char residues from cooking, animal-based organic inputs such as bones, and harvest residues.

In this study, it was demonstrated that urban farmers in Mwanza also recognize the ability of organic wastes to increase soil fertility, from the use of crop residues to generating compost from kitchen/food wastes. This is in addition to the animal manure, which are also organic wastes.

2.4.4 Pests and Disease

A downside of urban agriculture found in this study was the spread of disease, such as the maize infestation. Respondents reported that the maize infestation is plaguing the whole country, which is consistent with the review of maize lethal necrosis (MLN) crop disease and its emergence in East Africa Mahuku et al. (2015). The outbreak began in 2011 in Kenya and has since been confirmed in other eastern African countries, including Rwanda, Uganda, Democratic Republic of Congo, South Sudan, Ethiopia, and Tanzania.

While it is not yet known what tipping point allowed for the emergence, the outbreak has been determined to be caused by the widespread use of highly susceptible hybrids, the presence of thrip vectors, the presence of MLN-causing virus, and continuous cropping of maize (Mahuku et al., 2015). The symptoms of the disease are yellow streaks on maize leaves parallel to leaf veins, chlorotic mottling, leaf deformation, local lesions, and necrosis (Fentahun et al., 2017; Kiruwa et al., 2020). The disease caused yield losses of up to 90% in 2012, which resulted in an estimated grain loss of 126,000 metric tons valued at in Kenya alone. The effects of this disease are dire for farmers in east Africa who rely heavily on maize as a staple crop. Additionally, it appears that maize seeds available from agro-shopkeepers may be of the same variety, which would make maize crops in urban areas more susceptible. However, studies on MLN have been limited to rural agriculture.

The study in Northern Tanzania by Kiruwa et al. (2020) found that the occurrence of the disease was higher in the long rain seasons than in the dry or short rain seasons, which would apply also to urban agriculture. The close proximity of urban farms and high foot traffic in many urban areas can increase the spread of pests and diseases. This study has shown that urban farmers also invest in growing maize crops and have experienced similar symptoms to the MLN disease, which currently has no countermeasure. The study by Kiruwa et al. (2020) concludes that regional scientists should utilize farmers' degree of awareness in identifying MLN hotspots, especially as this disease mainly affects small-scale farmers who cannot afford pesticides to control the vectors (eg. beetles and thrips). The present study demonstrates that the occurrence and spread of crop diseases in urban agriculture requires further attention from epidemiologists and should be included in agricultural studies. Additionally, further investigation is required on the existence or availability of differing varieties of maize in urban areas to increase resilience to diseases like MLN.

2.5 Conclusions

This study adds to the currently limited literature on urban agriculture in developing countries, enhancing understanding of the challenges and opportunities presented by urban agriculture. Urban agriculture in Mwanza engages urban farmers of all skill levels, from adept experts with inherited and tested knowledge of cultivation to the recent novices learning by trial and error. Constraints to cultivation include constricted space for crop growth, reliance on rainy seasons for crop irrigation, and declining soil fertility without adequate access to, and availability of, amendments to meet cultivation needs. Urban farmers recognize the need for improving soil fertility to increase crop productivity. Urban farmers tend toward use of organic amendments such as manure or crop residue to replenish cultivated soil. This presents an opportunity for rapidly urbanizing cities to create nutrient cycles between growing urban organic (food) wastes and urban agriculture.

A growing concern among urban farmers is a disease spreading across the maize (*Zea mays*) crops, which makes research on urban agriculture even more critical to urban food security in developing countries. While this study fills a gap in the literature, the constraints faced by urban farmers are expected to increase with climate change and urbanization. Therefore, there is still a strong need for additional studies on urban agriculture. Further, in light of the global COVID-19 pandemic, the study also provides baseline information on urban agriculture in a growing sub-Saharan city, which can be used to assess the impacts of COVID-19 on urban farmers in developing cities.

The outcomes of the study demonstrate that urban agriculture is a strong presence in Mwanza city, which is an indicator of urban agriculture in rapidly urbanizing cities in sub-Saharan Africa. The presence of urban agriculture is expected to continue as people who cultivate urban land do so not only for subsistence and income, but also for enjoyment and tradition. To further perceive the benefits from urban agriculture to food security and to prepare for mitigation of environmental impacts from cultivation practices, urban agriculture should be given legal consideration and be integrated in urban land use and zoning policies locally and nationally.

There are some limitations to wider applicability of this research. This research is based on one study location and the results may be dependent on the characteristics of the study area. More robust sampling from different regions to gather regional perspectives and a large sample size is needed to validate findings at a national level. Additionally, a more comprehensive understanding of urban agriculture is also needed from perspectives of other relevant stakeholders, such as the Ministry of Agriculture and city planners. Future research should also examine complex dynamics of urban agriculture, including the interface between urban/rural agriculture, market opportunities and networks for urban agricultural producers, as well as intrinsic and extrinsic factors of agricultural production within urban environments. Future research could also focus on collecting data on Strengths (S), Weaknesses (W), Opportunities (O) and Threats (T), collectively referred to as SWOT analysis, to urban agriculture.

Overall, there is a need for interdisciplinary research between social scientists, economists, and agroecologists to provide perspectives that enhance success, adoption, and sustainability of urban agriculture. Results of such studies could be used in making recommendations to policy makers/stakeholders for integrating urban agriculture into city/urban planning for sustainable development.

Chapter 3

Opportunities in Hospitality Waste Management and Composting Food Wastes in Mwanza, Tanzania

3.1 Introduction

3.1.1 Waste Management and Greenhouse Gases

Waste management is a growing global concern (UN-HABITAT, 2010), especially with the rapid rate of global urbanization (Seto et al., 2013). According to the United Nations (UN) Economic and Social Council (2019), waste generation worldwide will double from 2 billion tons in 2016 to 4 billion tons by 2050 with increasing urban population. However, waste generated in low-income countries, which are predominantly located in SSA (sub-Saharan

Africa), is expected to triple by 2050 (Kaza et al., 2018). In these countries, solid waste management dominates 30-50% of municipal annual budgets (UN-Habitat, 2016).

One of the major concerns with solid wastes is GHG (greenhouse gas) emissions (Hoornweg and Bhada-Tata, 2012). In landfill conditions, organic waste decomposes anaerobically resulting in the release of landfill gas, which is a mixture of mainly methane (around 50%) as well as carbon dioxide and other gases (Hoornweg and Bhada-Tata, 2012). Methane has a GWP (global warming potential) 25 times greater than carbon dioxide over a 100-year period, but over a shorter time period of 20 years, its GWP is 72 times that of carbon dioxide (Kaza et al., 2018). The organic fraction makes up more than 50% of the waste stream in developing countries (Parizeau et al., 2008; Sujauddin et al., 2008; Narayana, 2009; Couth and Trois, 2012). Countries in SSA, for example, generate more GHG emissions per person from urban waste management activities than other developing countries (Couth and Trois, 2012). In East Africa, the rapid rise of the urban population, particularly from rural to urban migration, is posing additional challenges of increased waste volumes (Okot-Okumu, 2012).

Reducing the adverse environmental impacts of cities through municipal waste management is one of the key targets under Sustainable Development Goal (SDG) 11: Sustainable Cities and Communities (UN-Habitat, 2016; United Nations Economic and Social Council, 2017). Efforts that can help reduce GHG emissions from solid wastes include reducing waste, improving waste collection, and implementing waste diversion through recycling and organic waste processing (Hoornweg and Bhada-Tata, 2012). Therefore, GHG emissions from landfills can be averted through diversion of the organic waste fraction.

3.1.2 Organic Waste Diversion and Composting

Benefits of managing the organic waste fraction separately from other wastes extend beyond mitigating greenhouse gas emissions. Diversion of organic waste from the main waste stream can also reduce the volume of wastes directed to landfills, extend the life of landfill sites, and reduce disposal costs (Okazaki et al., 2008). Moreover, the organic fraction can be repurposed through controlled anaerobic digestion for natural gas energy, or through aerobic digestion for use as a soil amendment (Polprasert, 2007).

Controlled aerobic digestion, commonly referred to as composting, is one of the best-known and well-established processes that allows for the stabilization and sanitation of organic waste (Martínez-Blanco et al., 2013). There are various methods and scales of composting, though they broadly fall within four categories: passive piles, ASP (aerated static piles), windrows, and in-vessel systems (Graves, 2000). The various methods and scales of composting influence the duration, equipment, and monitoring required for the composting process (Lashermes et al., 2012; Cerda et al., 2017; Abdoli et al., 2019).

To date, research on composting has focused on understanding the parameters that influence the process, as well as optimizing the process. Researchers have used a variety of pilot-scale methods and experimental setups (Dimambro et al., 2015; Abdoli et al., 2019) to evaluate the effects of design (Bari and Koenig, 2001; Raut et al., 2008; Sidelko et al., 2010) or input material (Goyal et al., 2005; Chang et al., 2006; Cheung et al., 2010; Gabhane et al., 2012) on the composting process, the compost product, and the monitoring parameters. Key monitoring parameters in the studies include temperature (Fernandes et al., 1994; Agunwamba and Nwoke, 2016), pH (Cheung et al., 2010; Wang et al., 2016), and microbial dynamics (Raut et al., 2008; Cheung et al., 2010). Other parameters include moisture content, C:N (carbon-to-nitrogen) ratio, ammonia toxicity, oxygen concentration, and free air space (Graves, 2000; David, 2013). The resulting compost, generally an organically rich, dark brown, soil-like substance, can vary in quality and stability depending on the type of feed stock (raw material) used in the composting process (Azim et al., 2018).

Composting activities are prevalent in countries with high-income economies (based on gross national income per capita), such as Canada, at small-scale and large-scale facilities (Hoornweg and Bhada-Tata, 2012). However, composting activities are rarely undertaken in low-income countries, like Tanzania, even though the organic materials represent a greater portion of the waste stream (Hoornweg and Bhada-Tata, 2012). One main reason for the shutdown of centralized composting facilities in developing countries is the incompatibility of plant design with the solid waste characteristics, which infers lack of local knowledge and appropriate structure (Guerrero et al., 2013). The advice provided by UN-Habitat (2011) to decision-makers in low-income countries is to disregard solid waste management recommendations from international consultants unless they demonstrate an understanding of, and account for, local conditions.

3.1.3 Waste Management in Tanzania

Waste management is of particular concern in Tanzania, a low-income country in East Africa (Kaza et al., 2018), that is urbanizing rapidly at an average rate of 4-5% per year (United Nations (UN) Economic and Social Council, 2019). The 2012 Tanzanian census of private households showed that only 8.3% of households had their wastes collected, whereas a majority of the wastes (69%) were buried, dumped in a pit, or disposed of in other ways (e.g. open dumping, bush dumping) and the rest (22.7%) were burned (National Bureau of Statistics, 2015b).

Waste collection systems in SSA are generally more developed in cities than rural areas (Kaza et al., 2018). Waste-related studies conducted in Dar es Salaam, Tanzania show that privatization of solid waste collection services improved collection of daily waste in the city from 10% in 1994 to 40% in 2001 (Kaseva and Mbuligwe, 2005). However, the city currently has no formal waste diversion strategy (Lyeme et al., 2017) even though a majority of the wastes are organic (58%) or recyclable (16% plastic, 19% glass, cardboard, and paper) (Senzige et al., 2014).

Studies on organic waste composting were also conducted in Dar es Salaam (Yhdego, 1992, 1994; Mbuligwe et al., 2002), and community-based composting efforts gained traction for a brief period in the city (Oberlin et al., 2011). However, in spite of the academic and community interest, composting has failed to be integrated into the solid waste management strategy in Dar es Salaam, and by extension, in Tanzania.

The main factors to consider when determining an appropriate composting process are choice of technology, size and capacity of facility, and costs and financing (David, 2013). The key challenges derived from the literature with respect to implementing composting strategies in a developing country like Tanzania are:

- Complexity: the scale of operation, and managing collection, transport, and disposal systems has a significant influence on the quality and viability of the composting process (Oberlin et al., 2011; Kaza et al., 2018);

- Expertise and equipment: technology-intensive processes are minimally viable in Tanzania because of the higher dependence on skilled personnel, installation and maintenance of mechanical parts, and high dependence on a stable waste infrastructure and market (Oberlin et al., 2011; Kaza et al., 2018);
- Lack of land: often, there is insufficient land available for basic city functions (Kaza et al., 2018);
- Financial resources: operation of waste management services are affected by lack of revenues from waste generators or lack of funding (Kaza et al., 2018); it is unlikely that composting projects in Africa will proceed without funding from developed countries (Couth and Trois, 2012).

The present study focuses on Mwanza, a city within Tanzania that has not received as much attention with respect to waste management. This study posits that to overcome the challenges of organic waste diversion in a developing country, like Tanzania, an appropriate composting strategy requires low capital costs, minimal technology, limited dependence on skilled personnel, and the capability for integration into existing waste management strategies. The objectives of the study were to: investigate waste generator perspectives in the hospitality sector; determine the local waste management strategy and associated constraints; evaluate the suitability of a rapid composting method within Mwanza City given the constraints of the local waste management strategy; and characterize the chemical profile of the compost product derived from the rapid composting method.

3.2 Materials and Methods

3.2.1 Study Site

Mwanza region has a population of close to 3 million (National Bureau of Statistics, 2015a) with an average annual population growth rate of 5.5% (Cummings et al., 2016). It is the second-most densely populated city in Tanzania, after Dar es Salaam (National Bureau of Statistics, 2015b). The region of Mwanza is divided into eight districts (National Bureau of Statistics, 2012a), and the city of Mwanza is located in the Nyamagana district, which has the highest population density reported at 944 people per square km (National Bureau of Statistics, 2015b). Mwanza city has both urban and rural land areas with land use varying from agriculture, marketplaces, railway infrastructure, as well as residential, commercial, and industrial buildings (United Republic of Tanzania, 2017; United Nations Economic and Social Council, 2017).

The region experiences bimodal rainfalls with a short rainy season between October and December and a long rainy season between February/March and May with dry seasons in between (National Bureau of Statistics, 2012a, 2015b; Mwanza City Council, 2017). The city, at an altitude of 1140 m, receives annual precipitation ranging from 700 and 1000 mm/year (Mwanza City Council, 2017), as well as mean minimum temperature of 19°C and maximum 28°C over a period of 1985-2015 (CustomWeather, 2020).

3.2.2 Participant Surveys for Waste Generators

In-person participant surveys were carried out in Mwanza within the commercial hospitality sector (restaurants and hotels). The objective was to explore the perspectives of waste generators with respect to waste management practices and services within the city.

The study received guidance and approval from the University of Waterloo Office of Research Ethics. In accordance with ethics requirements, the prospective respondents were provided an information letter with a brief overview of the research, and a participation form to record their consent before completing the survey. The survey data was de-identified to ensure an anonymous process. The survey (Appendix A) consisted of a combination of closed- and open-ended questions on the topics of waste storage, waste disposal, waste separation, and opinions of waste management. The surveys were translated into the local language (Kiswahili), pre-tested, and improved for clarity before implementation. Focusing on the hospitality sector in Mwanza city, surveys were conducted by the researcher from July to August 2016 with participation from a total of 20 hotel and 30 restaurant managers.

Direct observation of the city's waste management strategy was an integral and ongoing component of this study. Observations were conducted in public settings with notes taken on the equipment used by waste workers, the location and size of areas designated for waste management, and the equipment used to transfer waste from local designated areas to the larger landfill site. The objective of the direct observation data collection was to understand the local factors at play in the city's waste management strategy with respect to collection, transfer points, and final disposal site.

3.2.3 Composting Experiment

The composting experiment was conducted in December 2017 on a rented plot of land within Mwanza City, which is situated at 2°31'24.71"S 32°53'51.46"E. The plot size was chosen with consideration of the limited areas available at waste transfer points. The chosen area was cleared of debris and a blue tarpaulin was laid on the ground, covering a total area of 1.22 m by 3.05 m. The tarpaulin was secured with a border of flat stones. Each pile had square base dimensions of 0.91 m by 0.91 m, and a height of 38.1 cm to start. Additional flat stones were used to delineate partitions for the piles (Figure 3.1).

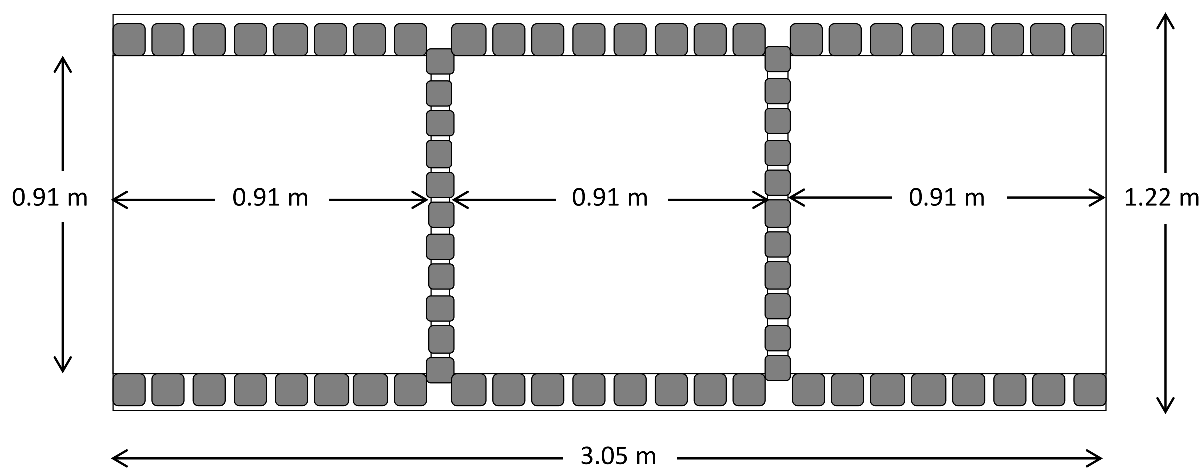


Figure 3.1: This schematic shows the dimensions of the total area of the layout (1.22 m x 3.05 m) and dimensions assigned for each pile (0.91 m x 0.91 m). Flat stones (grey) were used to secure the tarp on the ground and to separate the compost piles.

Food wastes were collected from marketplaces, street restaurants, and street fruit vendors within the urban centre over three days. The feedstock (raw materials) comprised of general fruit and vegetable wastes, such as pineapple peels (*Ananas comosus*), watermelon shells (*Citrullus lanatus*), potato peels (*Solanum tuberosum*), plantain skins (*Musa para-*

disiaca), tomatoes (*Solanum lycopersicum*), spinach (*Spinacia oleracea*), amaranth greens (*Amaranthus gangeticus*), and corn husks (*Zea mays* L.). The food wastes were coarsely chopped to 2 cm to 4 cm using a machete, which helps to expedite the composting process (Oberlin et al., 2011). Some components of the fibrous food wastes were difficult to chop manually, such as dried corn husks and sugar cane residue, and were left to be greater than 4 cm.

On the third day of collection a sufficient volume was collected for pile construction, and the food wastes were distributed evenly into three piles. The wet weight of the feedstock (food waste) in each pile was measured using a locally available body scale and recorded when the piles were constructed. The starting weights of the piles were: 44.3 kg in Pile 1 (C1); 43.8 kg in Pile 2 (C2); and 44.3 kg in Pile 3 (C3). While the collected wastes may have experienced preliminary decomposition on the first and second day of waste collection, the equal distribution between the three piles mitigated the influence of the effects. The day when the compost piles were constructed was labelled as Day 1.

The composting experiment was conducted during the rainy season in Mwanza city. To prevent the piles from getting wet, the piles were covered with a single, woven polyethylene tarp. The tarp exterior was blue and water resistant, and the interior was white. The tarp was propped on stakes set at the corners of the composting area and secured with stones on the front end to keep rainwater away from the piles and to prevent the tarp from flying away in heavy winds.

Ventilation, an important component of the composting process (Fernandes et al., 1994; Guo et al., 2012; Mussari et al., 2013; Abdoli et al., 2019), was provided by creating space for airflow between the tarp and the enclosing net on either side of the area and at the back of the piles, which was 15 cm away from the white concrete wall. The piles were always covered with the tarp except when measuring compost characteristics once per day for 31 days. The compost piles were exposed to additional ventilation during pile turning (Guo et al., 2012; Mussari et al., 2013).

The compost piles were monitored for three parameters on a daily basis: temperature (Fernandes et al., 1994; Agunwamba and Nwoke, 2016), pH (Cheung et al., 2010; Wang et al., 2016), and height. The compost thermometer and the pH meter were purchased in Canada and transported to the field site by the researcher as these two items were not available locally. Other monitoring parameters included observations of changes in colour, decomposition, and insect activity.

The temperature was measured at the centre of each pile, which has been shown to be a representative location for measuring compost temperature (Fernandes et al., 1994; Bari and Koenig, 2001), using a compost thermometer. A FreeGarden TEMP^{TM} compost thermometer was used for the experiment. It has a 48.3 cm (19 inch) stainless steel stem with a pointed tip that can read temperatures from 26.5°C to 82.3°C. It also has a 6.35 cm (2.5 inch) dial that displays the temperatures as well as the associated compost stages: slow, active, and hot. Compost stages can also be determined by the microbes that dominate the process, which can be characterised as mesophilic stage (20°C – 45°C) (Schiraldi and De Rosa, 2016) and thermophilic stage (>45°C) (Fernandes et al., 1994).

The pH of each pile was measured at three separate random points in each pile to the same depth as the length of the probe (15 cm). The pH meter, a Luster Leafs rapitest model, was obtained from Lee Valley Tools. It operates as a result of chemical reactions between the bi-metal probe and the alkalinity or acidity of the substrate. The meter can measure pH from 3.5 (strongly acidic) to 9 (strongly alkaline). Between each measurement, the probes were wiped with the cloth in the probe kit before being inserted into the next measurement location.

Pile height was measured at the centre of each pile from the bottom to the peak of the pile. Before the piles were constructed a small, flat stone, 1 cm in height, was placed at the centre of the square to pinpoint the location once the square was covered with food waste. At each measurement for pile height, a long stick was put through the peak of the pile until it met the stone. A marker was used to mark the depth, which was then measured using a measuring tape.

The temperature dictated the turning of the piles. When the temperature dropped to 43.3°C (which was the threshold on the compost thermometer) or below in the first two weeks, the piles were turned. The piles were turned manually using rubber gloves such that the content that was in the middle of the piles was moved to the outside and the material that was on the outside of the piles was shifted into the centre of the pile. The temperature, pH, moisture, and height of the piles were measured again after the piles were turned. The base dimensions were also measured after the piles were turned.

After the second week, the piles were turned when there was a decrease in temperature after already having increased until the temperatures dropped below 26.5°C. At this point the piles were turned one more time and left to mature for one week. The piles were monitored and turned again at the end of the week to ensure no changes had occurred and were left to continue to mature.

At the end of the process, the resulting compost (i.e. the end product) from each pile was weighed and sampled. The samples were sieved < 2 mm, air-dried, and sealed in plastic bags in accordance with importing procedures for transport to Canada (CFIA, 2014). The exporting procedure is further elaborated in Appendix B.

3.2.4 Chemical Analyses

The samples were imported to the University of Waterloo in Canada for chemical analyses. These analyses included determining the OC (organic carbon), TN (total nitrogen), inorganic N (nitrogen) in the forms of ammonium (NH_4^+) and nitrate (NO_3^-), and P (phosphorus)) content.

For OC and TN analyses, carbonates were first removed from the compost samples through acid washing (Dyer et al., 2012). Samples of 2.0 g were treated with 50.0 ml of 0.5 M HCl mixed on a reciprocating shaker (Heidolpj Unimax 1010 DT, Schwabach, Germany) at 240 rpm three times over 24 hours. After settling, the acid solution was removed with a pipette and the sample was washed with 50 ml distilled deionized water once and shaken at 240 rpm every four days to remove the acid from the compost samples. The samples were then oven-dried at 45°C for 2 days after which they were ground in ball mill (Retsch®ZM1, Haan, Germany) to 250 μm and analysed in an Elemental Analyzer (Costech 4010, Cernusco, Italy) for OC (%) and TN (%).

The extractable P content was determined using the Olsen P ascorbic acid method (Amacher et al., 2003), analyzed on a Shimadzu 1800 UV-Vis Spectrophotometer (Shimadzu Corp., Kyoto, Japan) at 880 nm wavelength.

For NH_4^+ and NO_3^- analyses, 5 g of compost samples were extracted with 25 ml 2.0 M KCl using a reciprocating shaker (Heidolpj Unimax 1010 DT, Schwabach, Germany) at 180 rpm for 15 minutes. The extract was filtered through Whatman 42 filter paper. For NH_4^+ analysis, 0.2 ml filtrate was reacted to 0.5 ml of Reagent A and Reagent B. Reagent A is comprised of 0.05 g sodium nitroprusside (also called sodium nitroferricyanide), 13 g sodium salicylate, 10 g sodium citrate, and 10 g sodium tartrate dissolved in 100 ml of water and then diluted in a 1:1 ratio with deionized distilled water. Reagent B is comprised of 6 g sodium hydroxide in 100 ml water, and 2 ml bleach (5% sodium hypochlorite). Absorbance was read 1 hour after colour development using a Shimadzu 1800 UV-Vis Spectrophotometer (Shimadzu Corp., Kyoto, Japan) at a wavelength of 650 nm. For NO_3^- analysis, 0.1 ml filtrate was reacted to 1.0 ml vanadium chloride reagent and absorbance was read 8 hours later when the colour had developed using a Shimadzu 1800 UV-Vis Spectrophotometer (Shimadzu Corp., Kyoto, Japan) at 540 nm wavelength.

3.2.5 Statistical Analyses

Quantitative data collected through closed-ended survey questions were analyzed statistically on Microsoft Excel (2016) software. For questions with two response choices t-tests ($p<0.05$) were used, and one-way ANOVA analyses were used for questions with more than two response choices. Qualitative data collected through open-ended questions were analyzed using manual coding and frequency distribution on Microsoft Excel (2016) software to determine common response themes. The results from the surveys were sectioned into five categories: waste storage, waste disposal, waste responsibility, organic waste, opinions of wastes and waste services.

With the composting experiment, the differences in temperature and pH were compared between the piles and over time using factorial ANOVA analyses (SPSS statistics software). Data were checked for normality (Shapiro-Wilk's Test) and homogeneity (Levene's Test). Where statistically significant differences were found with ANOVA, estimated marginal means were compared using post hoc Tukey HSD tests. The effect of turning the piles was also included in the ANOVA analyses. The change in height was only analyzed statistically for the first 13 days, before pile dimensions were changed. A significance level of $p<0.05$ was used as the threshold for all statistics tests.

3.2.6 Limitations of the study

The intention of the study was to apply the current existing knowledge of composting methods to work with the limitations of the city's municipal waste strategy, rather than providing a comprehensive investigation of the rapid composting method. The aim of this study was to reflect, as closely as possible, the constraints faced by the municipality in Mwanza, including space, equipment, and labour.

3.3 Results

3.3.1 Survey Responses from Waste Generators

The responses from the surveys were divided into five categories: waste storage, waste disposal, waste responsibility, organic waste, and opinions of wastes and waste services. A summary of the quantitative results from the first four categories are provided in Table 3.1.

Waste Storage

For waste storage, participants were asked about the location of waste storage (outdoor versus indoor), whether bins were used for waste storage, and satisfaction with the method for storing waste. Majority of restaurants and hotels in Mwanza stored their waste outdoors (>60%), used bins to store their waste (>80%), and were satisfied with their method of storing waste (>80%).

Waste Disposal

Regarding collection services, the method and frequency of disposal, as well as fees for waste services were investigated. All hotel participants reported waste collection as the primary method of waste disposal and all reported paying for waste collection services. While most restaurants (87%) also reported waste collection as the primary method of disposal, other restaurant wastes were reportedly dropped off at a communal point (7%), buried (3%), or burned (10%). Some restaurants employed more than one method for waste disposal. Wastes dropped off at a communal point would then be collected and transported to local waste transfer points or the land dump site for disposal.

A majority of restaurants and hotels in Mwanza received daily waste collection (≥88%), and all received collection at least once a week. Further details are provided in Table 3.1. One-third of restaurant and about one-half of hotel respondents in Mwanza were willing to share information regarding the payment fees for waste collection. Payments by restaurant participants ranged from 2,000 TZS to 70,000 TZS per month, and hotel participants reported paying between 15,000 TZS and 500,000 TZS per month for waste collection services. When asked about the responsibility for waste management, the majority of restaurant and hotel participants indicated that the municipality should be responsible for waste management services as opposed to individuals or the private sector.

Organic Waste

With respect to the organic waste fraction of the waste, the aim of the questionnaires was to determine whether the commercial sector currently separates waste at the source and whether the organic fraction is managed separately. The findings in this section were the most interesting. While a majority of the participants perceived that organic waste makes up more than 50% of the waste stream in both restaurants and hotels in Mwanza, the management of the wastes differs between each category of participants. A majority of hotels (65%) in Mwanza currently store organic waste separately from other wastes. The responses from restaurants were divided, with 60% of participants storing organic waste separately and 40% not. While the willingness to separate organic wastes from other

Table 3.1: Summary of survey responses from restaurant (n=30) and hotel (n=20) participants in Mwanza

Category	Sub-Category	Restaurants	Hotels
Waste Storage	Location	Outdoor (67%)*, indoor (33%)	Outdoor (80%)*, indoor (20%)
	Containment	Bin usage (87%)*	Bin usage (85%)*
	Satisfaction	Satisfied (87%)*	Satisfied (85%)*
Waste Disposal	Method	Collected (87%)* Burned (10%) Communal dropoff (7%) Buried (3%)	Collected (100%)*
	Collection Frequency	Everyday (88%)* 3 times/week (8%) 4 times/week (4%)	Everyday (90%)* 4 times/week (5%) Once a week (5%)
	Payment	Pay for collection (83%)*	Pay for collection (100%)*
	Fee	2,000 - 70,000 TZS monthly	15,000 - 500,000 TZS monthly
Responsibility	Opinion	Municipality (80%)*	Municipality (80%)*
Organic Waste	Opinion	$\geq$50% of waste is organic	$\geq$50% of waste is organic
	Storage	Organic waste separate (60%)	Organic waste separate (65%)*
	Separation	Willing to separate (87%)*	Willing to separate (100%)*
	Paying for Separate Collection	Willing (27%) Not willing (43%) Undecided (27%)	Willing (50%)* Not willing (30%) Undecided (10%), unsure (10%)

*Determined to be the dominant response through statistical analyses (t-test or one-way ANOVA) at $p<0.05$ threshold for significance wastes was the dominant response for both restaurants and hotels, the willingness to pay for separate waste collection varied. A greater percentage of hotels in Mwanza were willing to pay for separate waste collection (50%) as compared to the percentage of restaurants (27%).

The separation of organic waste is not a conscious choice but a practical one; there is very little food packaging used in Mwanza and so only organic (food) waste is disposed into the bins that are placed in the kitchen. The other bins placed outside the kitchen are for other wastes, which are typically dry wastes like papers and plastic bottles. Even though the wastes are stored separately at the time of waste generation, the wastes are mixed at the time of collection for a majority of the cases and are transported to the landfill for disposal. There are a few cases (11%) where a third party collects the food wastes to use as animal feed as is shown in Figure 3.3.

Opinions

Open-ended questions were included in the surveys to provide opportunities for respondents to elaborate on their responses and, in particular, to explore opinions regarding changes that participants would like to see regarding waste management and the organic waste fraction. While opinions varied, there were several frequently occurring opinions, which are shown in Figure 3.2. The most frequent response was that collectors should come more often to collect the waste.

With respect to opinions about the organic waste fraction, the responses varied and even presented some contradictions. For example, more than 60% of hotel respondents

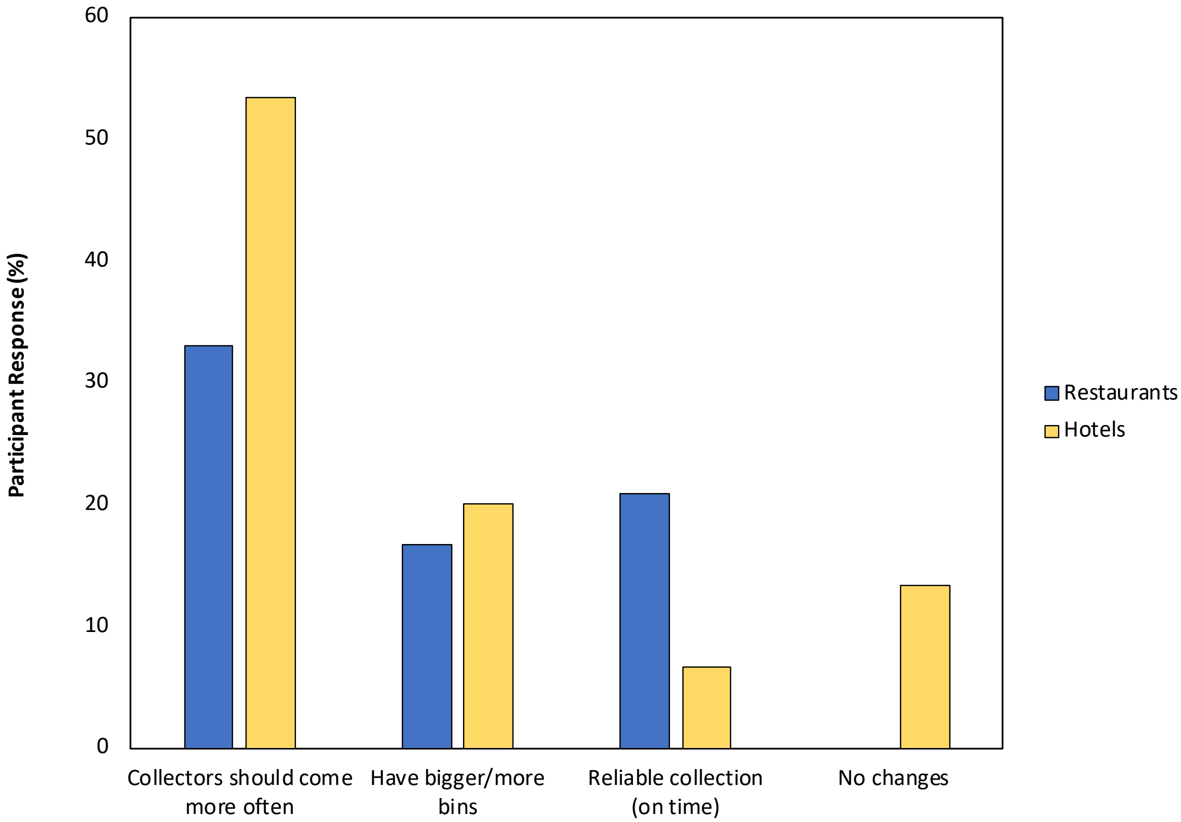


Figure 3.2: Most frequent opinions expressed by participants in response to changes they would like to see in Mwanza's waste management. The most common response was that collectors should come more often to collect the waste. The other two frequent responses were larger or more bins for storage and reliable (on time) collection. A low number of hotel participants (13%) expressed satisfaction with the current waste management services by stating no changes were required.

and 33% of restaurant respondents in Mwanza reported that there is no smell from the organic waste portion. This is attributed to the contained storage of organic waste as was pointed out by a respondent *"No smell because the bins are closed"*, and the daily collection of the waste as was pointed out by another respondent *"No smell. It is collected everyday."*. Though for other respondents, the smell is a major problem as was expressed by the following quote: *"Lots of smell and it spreads because the waste is collected every three days. The bins are not closed because it would smell more when opened."*

Another frequent response by 37% of hotel respondents in Mwanza shows that measures are taken to avoid the buildup of smell through regular cleaning of the bins, as was explained by one of the respondents *"They [the employees] clean the bins, have to clean the bins, it's a must to avoid the smell"*. Respondents demonstrate awareness of the organic waste decomposition process, as was stated by another respondent, *"If it [the organic waste] sits for a while, then there's a smell. But it's collected everyday, so no smell."*

Lastly, some restaurants have found alternate avenues to dispose of their food waste through third-party collectors. In one case a restaurant employee takes the food waste to a farm to feed pigs. However, one restaurant had regular organic waste collection for which they paid money. Respondent stated, *"We give food waste to a separate collector for animals (dogs) or the poor. We pay like 30,000 to 35,000 TZS per month"*.

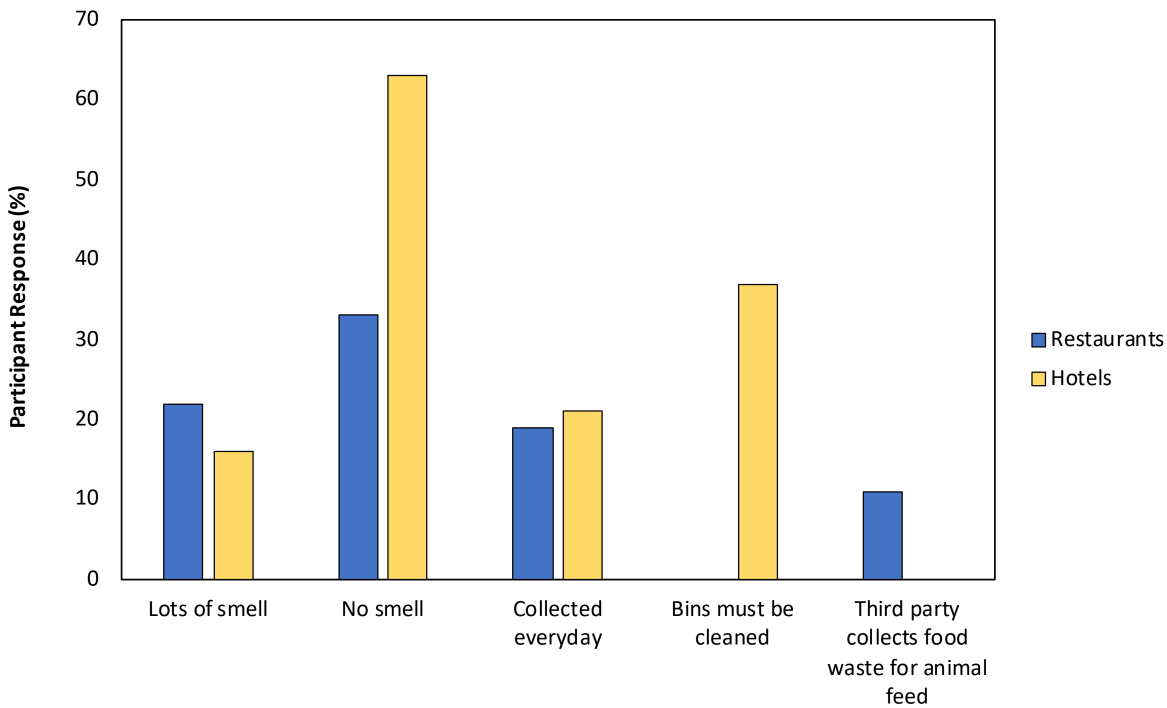


Figure 3.3: The graph shows the the most frequent opinions expressed by participants in response to how they feel about the organic fraction of their waste. The most common responses relate to whether or not the waste smelled, which a majority of hotel participants stated it did not. Consequently, the cleaning of the bins was necessary to dissipate any smell buildup. Other responses related feelings of organic waste to the collection of the waste, indicating that the feeling was neutral as long as the waste was collected.

3.3.2 Mwanza's Waste Management Strategy

Waste collection workers collect waste from different parts of the city, including waste from street sweeping. The wastes are deposited in large, blue containers at waste transfer points around the city. The blue containers are then picked up by trucks and transferred to the landfill site in the neighbouring ward of Buhongwa.

Observations conducted at one of the transfer points located on Uhuru Street at 2.516958 S, 32.899811 E, provided further insight into the land area and waste activities on a given day. The land area, determined through publicly available satellite images, was approximately 10 m by 10 m. There was a large blue container, which is generally always present at the transfer point, and a garbage truck that is parked at the site on Saturdays, which are the designated city cleaning days. Workers brought in garbage collected on wheelbarrows and handcarts. The garbage was then emptied into the truck that was parked in the area. The workers were clad in standard uniform – dark blue shirt and pants, rubber gloves, rubber boots, and face masks.

The wheelbarrows were mostly operated by women, and the handcarts, which were bigger than the wheelbarrows, were operated primarily by men. During the observation, one woman, who was not a waste worker, came by to empty her own dustbin into the container, but since the container was full, she was directed to the truck. The container was picked up by a truck to be transported to the landfill site in Buhongwa. Images of a wheelbarrow and waste-filled blue containers are shown in Figure 3.4.

Observations at the landfill site in Buhongwa (2.634806 S, 32.952367 E) also provided further insight into final waste disposal. Garbage trucks, designed to carry the large blue

Figure 3.4: Images of equipment and waste observed at waste transfer points: (a) a wheelbarrow for waste collection, (b) a large blue container where waste is deposited, and (c) a closer look at the interior of the blue waste container showing a mix of organic and other wastes.

containers from the waste transfer points, drive into the landfill area. The garbage is tipped from the truck, either adding to the heaps of waste already present or starting a new one; there appeared to be no organized manner in which the heaps were created or placed. Images of transportation of the waste containers on trucks, tipping at the landfill, and an example of a waste heap at the landfill are shown in Figure 3.5. Off to one side of the dumping site, a new, engineered sanitary landfill was in its early stages of construction.

Official waste workers could also be identified by a green collared shirt with white writing, *'Zingatia Usafi Wa Mazingira'*, that indicates their work in sanitation. Informal waste pickers, who were not wearing official attire, were observed at the site, recovering valuable wastes, such as recyclables from the waste heaps. The heaps were composed of mixed wastes, which included decomposing organic matter. The observations showed that the heaping of waste in piles is a common local method of organizing wastes in a given area.

Figure 3.5: Images of equipment for transport to the landfill site: (a) a waste worker (in official green t-shirt) guides the truck driver to connect with the blue waste container, (b) truck tipping blue waste container to add garbage to a heap of landfill waste (person in plain clothes is the researcher's guide); and images of waste at the landfill site: (c) a typical waste heap observed at the landfill site.

3.3.3 The Changes over the Composting Process

For the composting portion of the study, heaps (or piles) similar to the ones observed at the Buhongwa landfill site were created with only organic food waste to test the rapid composting method. The day of pile construction was labelled as Day 1. The piles were turned when the temperature went below 43.3°C, on Days 5, 7, 10, 13, 15, 18, 21, and 28. The compost piles experienced a weight reduction of 83 - 87% from the feedstock to final compost, as is shown in Table 3.2.

Table 3.2: Weight reduction of the initial wet waste to end compost weight (wet).

Pile ID	Wet Waste Weight (kg)	Compost Weight (kg)	Reduction (%)
Pile 1 (C1)	44.3	5.8	87
Pile 2 (C2)	43.8	7.6	83
Pile 3 (C3)	44.3	5.8	87

Statistical significance of monitored parameters (temperature, pH, and height) are summarized in Table 3.3. The threshold for statistical significance was $p<0.05$. There were no significant differences between the three piles, but there were significant differences over the compost duration in pH, temperature, and pile height. The effect of pile turning was also taken into consideration for the statistical analyses.

Table 3.3: The statistical significance of the effects of piles, time, and turning on temperature and pH of the composting process using factorial ANOVA.

	Temperature	**pH**	**Height**[1]
Pile	n.s.	n.s.	n.s.
Time	$F(30, 115) = 71.544$ $p < 0.001$	$F(30, 115) = 6.952$ $p < 0.001$	$F(12, 46) = 7.848$ $p < 0.001$
Turning	$F(1, 115) = 7.854$ $p = 0.006$	n.s.	$F(1, 46) = 11.854$ $p = 0.002$
Pile*Time	n.s.	n.s.	n.s.
Pile*Turning	n.s.	n.s.	n.s.
Time*Turning	$F(30, 115) = 71.544$ $p < 0.001$	n.s.	n.s.

Threshold for statistical significance is $p<0.05$ (n.s. = not significant).
[1]Changes in height were only evaluated for Days 1 - 13 while base dimensions were constant.

3.3.4 Compost Pile Dynamics

Temperature

The significant differences over time were determined by post hoc Tukey tests using $p<0.05$ as the threshold for statistical significance. The temperature within the piles was significantly greater on the second and third day than the first day, peaking at the highest average temperature of 58.13°C (±0.93°C) on Day 2. The temperature on Day 4 was an average of 50.2°C (±1.39°C), which was significantly lower than Days 2 and 3, but significantly higher than the days that followed. The temperatures were significantly lower before the piles were turned on Days 5, 7, 10 13, and 15 than the day prior.

The subsequent days the piles were turned were Days 18, 21, and 28. The temperatures on Days 17, 19 and 20 were significantly greater than the temperatures on Days 18 and 21, but there were no significant differences in temperature between Day 21 and Days 22 to 27, but there was a significant decrease in temperature on Day 28. Even after the piles were turned on Day 28, there was no significant difference in temperature between Day 28 until Day 31, implying that the composting process was complete. The temperatures on Days 30 and 31 were significantly lower than Days 1 to 27. The mean temperatures for the composting process are shown in Figure 3.6 along with minimum and maximum air temperatures.

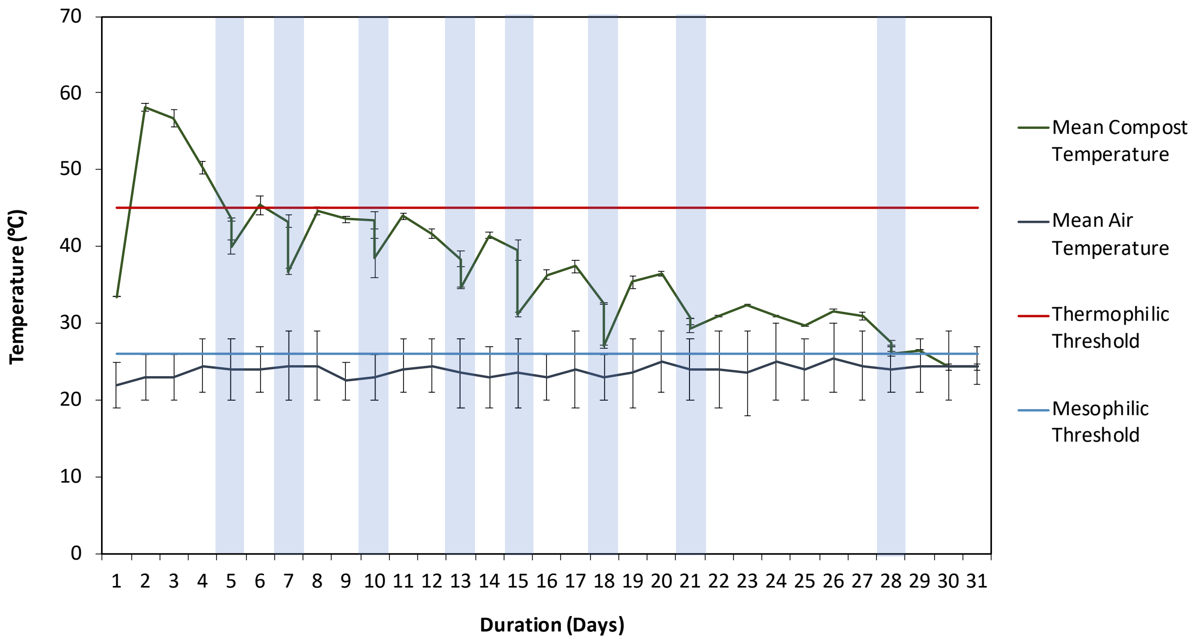


Figure 3.6: Changes in mean temperature of the composting process over time. The highlighted areas indicate that the piles were turned on that day. The graph also displays the thresholds for mesophilic temperatures (20°C – 45°C) (Schiraldi and De Rosa, 2016) and thermophilic temperatures (>45°C) (Fernandes et al., 1994). Mean air temperatures are included as a reference for the duration of the composting experiment with minimum and maximum air temperatures for each day represented by the error bars.

pH

The pH was only significantly different for certain days over the process duration. The first was a significant decrease in pH from Day 1 to Day 2 when decomposition in the piles had begun. The acidity can be attributed to the breakdown of food wastes at a rapid rate. The pH then increased significantly from Day 2 to Day 3, decreased significantly to Day 4, then increased again significantly to Day 5. There were no subsequent significant differences in daily pH from Day 5 to Day 31. The pH trend over the composting process for each pile is shown in Figure 3.7.

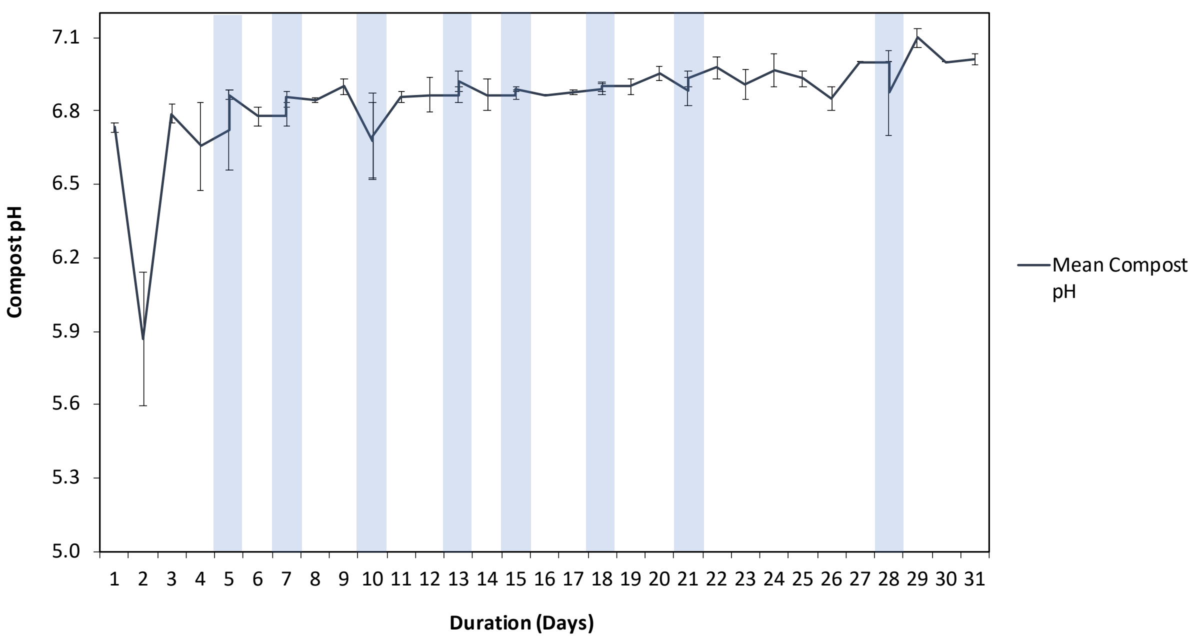


Figure 3.7: The mean changes in pH of the three composting piles over time. The highlighted areas indicate that the piles were turned on that day.

The general pattern observed is that piles created from chopped organic food wastes need to be turned every three days after the piles are created until three weeks have passed.

After which the composted organic waste can be left to mature, with one more pile turning a week later.

Pile Heights

The piles were at their maximum height on Day 1 when they were created and reduced significantly on Day 2. There was a significant difference in pile heights between Day 1 and all the other days. There were no significant differences between Day 2 and the following days until Day 13 before the piles were turned for the fourth time. When the piles were turned on Days 13, 21, and 28 the base dimensions of the piles were reduced to maintain a heap-like shape. The pile heights were maintained in the range of 17 cm to 22 cm over the period of Day 13 to Day 31. The subsequent reduction in base dimensions infers continued volume reduction.

3.3.5 Notes on Decomposition: Changes in Colour and Presence of Insects and Animal Activity

The compost piles were photographed daily to record observations of colour change. The freshly constructed piles were colourful for the first two days, with the green hues of amaranth green stalks and plantain peels, and the yellow of banana peels and cornhusks, and the orange and brown of carrot and potato peels. From Day 3 to 5, the colour of the piles changed to a uniformly light brown on the exterior; there were still some vibrant colours visible when the piles were turned for the first time on Day 5. On Day 6, the brown darkened and the piles appeared black by Day 8, which stayed consistent through to Day 13 when the piles were turned again. On Days 14 and 15, the exterior brownness of the piles had lightened but the turning on Day 15 showed that the piles were dark brown within. The resulting compost at the end of the process was a rich, dark brown. Select image of the progression demonstrate the colour changes in Figure 3.8 for the beginning of the process and Figure 3.9 for the middle to the end of the process.

While the scope of this study did not include identifying insects and animals observed as part of the composting process, there were select observations worth noting. On Day 5, during the turning process, it was noted that the center of the pile was very wet and smelled like sewer gas, indicating the occurrence of anaerobic processes. There were also numerous maggots occupying the center of the pile, which were identified as early instar stages of black solider fly. On Day 8 the presence of small flies was noted hovering over the compost piles. On Day 15, ants had moved into the third pile (C3). On Day 17, the hovering flies and ants were noted again for all piles. The maggots were observed whenever the piles were turned. The number of the early instar stage larvae seemed to have reduced by Day 27, replaced by later instar stage and prepupal stage soldier flies. Other infrequent animals noted were the occasional toad bug, dragonfly, lizard, salamander, and mouse.

3.3.6 Cost Breakdown

There were several costs associated with the composting experiment. A description of all the costs incurred by the researcher for the composting process are presented in Table 3.4. The costs have been categorized as either capital costs (one-time purchases at the beginning of the operation) or operating costs (on-going expenses incurred by the operation dependent

Figure 3.8: Images show colour changes during the composting decomposition process for Days 2, 3, 5b (the letter b denoting that the piles had been turned), and 6. The pile colour changes from visible oranges, greens, and yellows on Day 2 to a uniform light brown on Day 3, and a darker brown on Day 6.

Figure 3.9: Images show colour changes during later stages of the composting decomposition process for Days 8 and 11 when the pile colour is blackish brown; 15a and 15b (the letter a denoting before the piles were turned and the letter b denoting that the piles had been turned), the pile colour before turning is lighter brown than after turned; and 28a and 28b, which shows the same as colour change as Day 15a and 15b.

on the number of production units). The costs incurred in Tanzanian shillings (TZS) were converted to the equivalent US dollar (eUSD) because that is the predominant international currency. Exchange of TZS to the Canadian dollar or vice versa is not common in Tanzania.

The capital costs for the rapid composting process included the compost thermometer, the pH meter, and the cover for the compost piles. Waste pickup and chopping of waste were considered as operating costs of the composting operation. Costs for weighing the initial waste and final compost would only be necessary for monitoring waste reduction or the weight of final compost production. Therefore, select costs are denoted with a single asterisk to mark them as optional costs. There would also be human resource costs for manual labour. Tasks such as monitoring and turning the piles on a regular basis were conducted by the researcher, and, are, therefore, not included in the total cost. An estimated salary cost is also not provided as salaries can change over time. The costs provided are based on the one-time construction and maintenance of three compost piles. To extrapolate and calculate the annual costs would require additional information, including the amount of organic waste generated/collected per day, the number of waste transfer stations involved, and the number of personnel involved in the process, which were not collected in this study. Therefore, annual costs are not provided in this study.

3.3.7 Compost Quality Evaluated by Chemical Analysis

With respect to the chemical characteristics of the compost samples, the average OC was 8.22% and the average TN was 0.57%, which resulted in a 14.5:1 C:N ratio. The average P content was 423 mg P/kg. The values for NH_4^+ and NO_3^- had greater variability between

Table 3.4: Costs associated with construction of three composting piles in Tanzanian shillings (TZS) and equivalent US dollars (eUSD)

Item	**Cost (TZS)**	**Cost (eUSD)**	**Type of Cost**
Handcart Rent (3-day collections)	21,000	10.50	Operating
Waste Chopping[2]	15,000	7.50	Operating
Weighing the waste (scale for rent)	12,000	6.00	Operating[1]
Cover (tarps and mosquito nets)	60,000	30.00	Capital
Compost thermometer	50,000	25.00	Capital
pH meter	60,000	30.00	Capital*
Total	**218,000**	**109.00**	–

[1]Optional costs
[2]The researcher received help for waste chopping on one of the three waste collection days for which the cost was 5000 TZS. The 3-day waste chopping cost is calculated from that transaction.

piles, averaging at 134.51 mg N/kg (NH_4^+) and 38.73 mg N/kg (NO_3^-). The results for each pile are shown in Table 3.5.

Table 3.5: Chemical composition (organic carbon (OC), total nitrogen (TN), phosphorus (P), nitrate (NO_3^-), and ammonium (NH_4^+) of the compost samples

Pile ID	**OC (%)**	**TN (%)**	**C:N Ratio**	**P (mg P/kg)**	**NO_3^- (mg N/kg)**	**NH_4^+ (mg N/kg)**
C1	8.15	0.585	13.9	424.8	37.80	110.68
C2	8.35	0.547	15.3	433.4	30.49	80.07
C3	8.17	0.572	14.3	411.2	47.88	212.77
Mean	8.22	0.57	14.5	423.2	38.72	134.51
Standard Error	0.07	0.011	0.4	0.01	5.04	40.12

3.4 Discussion

The waste management strategy observed in Mwanza, Tanzania is a combination of the two waste management systems reported in SSA cities (Kaza et al., 2018). One is a dual system where waste is first collected using handcarts and trolleys, taken to a centralized location (transfer point), and later from the transfer point to the final disposal site using small vehicles and trucks (Kaza et al., 2018). The second system is where residents dispose of their waste in a designated area or dumpster in their neighbourhood (Kaza et al., 2018).

The results from the survey in Mwanza show that the hospitality sector, especially hotels, receive regular waste collection with a majority of wastes collected on a daily basis. Instances of burning and burying wastes were low in the surveyed sector. Collection costs represent 80 to 90% of the solid waste management budget in low-income countries (Hoornweg and Bhada-Tata, 2012). Frequent waste collection is especially necessary in hot climates because biodegradable wastes, such as food waste, decompose faster at a higher temperature resulting in unpleasant smells and the attraction of disease-causing vectors, such as flies (UN-Habitat, 2011; Matter et al., 2013). Therefore, the focus on collection is to provide sanitary environmental conditions for human health (Mwanza City Council, 2008; National Bureau of Statistics, 2015b; Mwanza City Council, 2017). The preferred changes that participants within the hospitality sector voiced were more frequent collection, bigger or more bins for waste storage, and reliable collection, all of which are also related to keeping a clean environment and avoiding adverse health effects due to uncollected wastes.

Addressing these concerns is hindered by lack of capacity and increasing population within urban centres (Marshall and Farahbakhsh, 2013). A growing concern is the large organic fraction of the waste stream (CCAC, 2015; Council, 2016), which is disposed of with other wastes in land dump sites, resulting in concerns regarding the global impact of greenhouse gas emissions (National Bureau of Statistics, 2015b). Interestingly, the problem of waste segregation that researchers found for household wastes in developing countries (Parizeau et al., 2008; Sujauddin et al., 2008; Okot-Okumu, 2012) was not a major problem for hospitality wastes in Mwanza. The survey results showed that several hotel and restaurants already separated organic wastes, which they believed to be more than 50% of their waste, from other wastes at the source. However, these wastes were mixed when collected. Additionally, there is a willingness from both hotels and restaurants to separate the wastes. This provides a unique opportunity for the municipality to take advantage of the already segregated waste streams and implement a waste diversion program for the city. The diverted organic waste can be processed using the process described in this study, which provides a starting point toward a more integrated and systematic organic waste diversion and processing strategy.

3.4.1 Comparing Compost Design and Dynamics

Researchers have used a variety of composting systems, which can be characterized as either passive piles, ASP (aerated static piles), windrows, and in-vessel systems (Graves, 2000). Researchers have also modified and combined composting systems. Oberlin et al. (2011) reported that the composting venture by KIWODET in Dar es Salaam used a modified system of passive aeration and regular turning, which is a combination of ASP and windrow composting. The design used in this study for rapid composting would be categorized as a modification of windrow composting, in which piles are kept aerobic through periodic turning to introduce oxygen into the pile (Mussari et al., 2013) as opposed to being aerated while the piles remain static (Fernandes et al., 1994; Mussari et al., 2013; Abdoli et al., 2019).

The frequency of periodic turning for aeration was reported in one study by Guo et al. (2012), where composting was conducted in stainless steel cylinders with additional holes for passive aeration. The composting wastes were turned on days 3, 7, 15, and 24 (Guo et al., 2012), whereas in this rapid composting study, the piles were turned more frequently (days 5, 7, 10, 13, 15, 18, 21, and 28), which is explained by the need for repeated aeration due to a lack of passive aeration.

According to Mussari et al. (2013) the ideal pile width for windrow composting is 4 m to 5 m and height is 1.5 m to 2.5 m. In KIWODET's composting venture, the pile height did not exceed 2 m, and the composting process for each batch took 42 days to complete (Oberlin et al., 2011). In this study, the piles, with an initial square base of 0.91 m by 0.91 m and a height of 38.1 cm, were smaller than those reported in other studies that also used some form of windrow composting. Even in studies using ASP, the pile dimensions had a base of 3.4 m X 2.3 m and 1.0 m height (Fernandes et al., 1994) and 1.5 m X 1 m x 0.9 m (Abdoli et al., 2019). However, the composting temperature and pH reported in this study conformed to the patterns observed in other studies, which demonstrates that there may not be one ideal size for composting, but rather ideal ratios of pile dimensions.

Composting typically has a temperature profile that is characterized by the rapid initial increase to thermophilic temperatures (>45°C) (Fernandes et al., 1994; Couth and Trois, 2012), sustained high-temperature period, and finally followed by a decline to near-ambient temperatures (Wichuk and McCartney, 2010; Azim et al., 2018). In the beginning of the process, mesophilic bacteria contribute to rise in temperature (Wichuk and McCartney, 2010). In studies by Fernandes et al. (1994) and Guo et al. (2012), thermophilic temperatures were achieved within the first two days. Consistent with other studies, there was a rapid increase to thermophilic temperatures in the first two days of this study as well. At this stage, thermophilic bacteria take over as the primary bacterial group (Wichuk and McCartney, 2010).

After the first four days, the temperatures in this study dropped below 50°C, entering a sustained high-temperature period between 40°C and 45°C for nine more days. Raut et al. (2008) indicated that compost temperatures can be maintained by aeration, which also helps with thermophilic decomposition of organic waste. In this study, the turning of the piles provided the aeration required to maintain high temperatures. As temperatures decrease, mesophilic bacteria become active again in the declining stage of composting (Chang et al., 2006). According to Cerda et al. (2017), the optimal temperature for biodegradation of the organic fraction of MSW is 37°C, which falls within the mesophilic range (Schiraldi and De Rosa, 2016; Azim et al., 2018). The temperature ranges in the rapid composting process of this study provided for active biodegradation at both thermophilic and mesophilic temperatures.

The pH decreases in the first stages of composting as the organic materials hydrolyze and organic acids release simple organic substrates and volatilize initial ammonia (Chang et al., 2006; Azim et al., 2018). The pH monitored in this study exhibited the same decline in the first two days followed by an increase on the third day. The experiment by Raut et al.

(2008) showed an overall increase in pH over time in the rapid ASP composting process compared to a decrease in pH over time in a non-aerated static composting process. In this study, the pH neither increased nor decreased overall. The average pH fluctuated between 6.66 and 6.90 from day 3 to day 10 after which it remained stable around 6.9, reaching neutral pH (7.01) toward the end of the process. According to Wichuk and McCartney (2010), pH trends and final values are dependent on the feedstock materials. The pH reported by Castaldi et al. (2008) on day 28 of frequently turned piles for MSW organic fraction composting was 7.56, which is higher than the pH for the compost in this study in a similar time frame. According to Attiogbe et al. (2019), the presence of black soldier fly larvae contributes to pH reduction to near neutral levels, which is consistent with the observations in this study.

3.4.2 Comparing Chemical Parameters of the Compost

Organic Carbon and Nitrogen

The average OC content in this study was 8.22%, the TN content was 0.57%, and the resulting C:N ratio was 14.5. According to Raut et al. (2008), a C:N ratio below 20 indicates an acceptable compost maturity. A C:N ratio between 1 and 15 enables rapid mineralization and release of N for plant uptake, whereas a C:N ratio between 20 to 30 allows for a balance between mineralization and microbial immobilization, which can contribute to nutrient storage (Brust, 2019). Comparing the results with values from literature, the OC and TN in this study are at least two-fold lower than that found in other studies. The average values from various studies are provided in Table 3.6 for comparison. Vuai (2010) reported an OC of 16.4% and a TN of 1.73% from Zanzibar's MSW (municipal solid waste) that was aerobically composted, and Castaldi et al. (2008) reported 17.38% OC and 1.35% TN of the final compost from the organic fraction of MSW.

The N content of the compost is dependent on the initial N content of the feedstock as well as the chemical processes during composting. Although the total N concentration generally increases during composting, N losses may occur by ammonia (NH_3) volatilization, leaching, and denitrification (Thangarajan et al., 2013). For example, Andersen et al. (2011) reported a total N loss of 51-68% in a small-scale composting process. Additionally, Yoshida et al. (2012) reported that 65% of nitrogen from composting yard waste is emitted to the atmosphere, mostly as NH_3 (96%) but also as nitrous oxide (N_2O) (2%) and nitrogen (N_2) (2%), which are by-products of the nitrification/denitrification process. High temperatures, such as those reached in thermophilic composting, favour NH_3 evaporation (Andersen et al., 2011). Therefore, the loss of N is a major concern of composting, which decreases the agricultural value of compost and also contributes to GHG emissions (Thangarajan et al., 2013).

Table 3.6: Comparison of OC (organic carbon), TN (total nitrogen), C:N (carbon-to-nitrogen) ratio, and P (phosphorus) in compost samples from various studies under differing composting processes

Composting Process	**OC %**	**TN %**	**C:N Ratio**	**P %**	**Reference**
ASP (aerated static piles)	43.0	2.83	15.5	1.23	Fernandes et al. (1994)
ASP	21.5	1.65	13.0	n.a.	Abdoli et al. (2019)
Windrow	26.2	2.26	11.6	n.a.	Yhdego (1994)
Windrow	30.6	1.19	25.7	9.17	Agegnehu et al. (2016)
Vermicompost	21.6	1.66	13.0	n.a.	Abdoli et al. (2019)
Soldier fly larvae	n.a.	0.97	n.a.	0.96	Attiogbe et al. (2019)
Rapid Composting	8.2	0.57	14.5	0.042	This Study

In the study by Attiogbe et al. (2019), where black soldier fly larvae were used to compost food wastes mixed with chicken fecal matter, the reported TN values ranged from 0.78 - 0.99%. These are the closest values reported in the literature to the value reported in this study (0.57% TN). The presence of black soldier flies could further explain nitrogen loss during the composting process because of the high conversion factor of nitrogen in food waste to protein by soldier fly larvae (Gold et al., 2018).

Carbon losses, dominantly released as carbon dioxide, have also been reported in other studies during composting (Chang et al., 2019). Lashermes et al. (2012) reported an average loss of 46% for composting sewage sludge mixed with branches, grass clippings, and leaves, and Chang et al. (2019) reported a loss of 59 – 69% total OC during composting of manure with straw. The loss of carbon as carbon dioxide from decomposition is better than loss as methane, which is the primary gas produced by anaerobic digestion (Hoornweg and Bhada-Tata, 2012), because methane has 25 times the global warming potential of carbon dioxide as a greenhouse gas (Kaza et al., 2018).

Guidoni et al. (2018) reported that there was a greater reduction in organic matter for systems with leftovers of raw fruits and vegetables as feedstock as opposed to systems with rice husks, which are higher in lignin content. An additional insight into carbon loss is provided by Tiquia et al. (2002) who stated that both mass reduction and OC loss are significantly greater in turned compost than in unturned compost. The presence of black soldier fly larvae has also been shown to contribute to an additional decrease in carbon content of the final compost (Sarpong et al., 2019). According to Sarpong et al. (2019), the avid eating habit and movement of the larvae through the organic waste results in increased surface area, which leads to a more rapid decline of organic carbon. Therefore, carbon losses from the composting process in this study are attributed to a combination of feedstock (fruit and vegetable waste), frequent turning of the waste, and presence of black soldier fly larvae.

Phosphorus

The P content is also useful to determine the potential uses of the compost. The average P content of the compost samples was 423 mg P/kg of dry compost (or 0.042%). The phosphorus content is lower than that reported in other studies, the values for which are provided in Table 3.6.

Many of the studies used for comparison included poultry manure in the feedstock. Fernandes et al. (1994) reported P values within 0.9 and 1.6% for compost produced from peat and poultry manure in aerated static piles (ASP). Agegnehu et al. (2016) reported an average phosphorus value of 917 mg P/kg (0.0917% P when converted) for compost primarily made from green waste and bagasse with a small portion of poultry manure. The study by Attiogbe et al. (2019) reported an average value of 0.76% P for compost produced by black soldier fly larvae from food waste mixed with chicken fecal matter. Poultry manure (or chicken fecal matter) as an organic amendment is known to have higher P content than other organic amendments, averaging at 2.7%, as compared to the 0.2% P average for cow manure (Thangarajan et al., 2013). Therefore, it is expected that compost generated from only urban food wastes, without the addition of poultry manure will not exhibit high levels of phosphorus content.

The study by Wei et al. (2015) reported the following values for different feedstocks:

MSW = 1170 mg P/kg (0.117% P), kitchen waste (KW) = 780 mg P/kg (0.078% P), green waste (GW) = 1860 mg P/kg (0.186%), food and vegetable waste (FVW) = 780 mg/kg (0.078% P). The compost from the current study has a lower P content than the values reported for KW, GW, and FVW. Sarpong et al. (2019) reported an increase in P content with the presence of black soldier fly larvae, but also noted that supply of phosphorus is dependent on the feedstock. Therefore, the lower P content for the compost in this study is attributed to the lack of P supply available in the feedstock.

Ammonium and Nitrate

The average concentration of NH_4^+ in the compost samples was 134.50 mg N/kg and NO_3^- averaged 38.72 mg N/kg. Nitrogen in organic waste is mineralized into ammonium (NH_4^+) and nitrate (NO_3^-) during nitrification, some of which is incorporated into the organic matter compost (Azim et al., 2018). NO_3^- is a form of plant-accessible nitrogen, and so the presence of nitrate compounds in the compost is an indicator of nutrients that will be available to plants when applied to soil. The concentration values of NH_4^+ and NO_3^- in the compost can also help inform the suitability for plant application and application rate for the desired plants, depending on the plant's nitrogen requirements.

The NH_4^+ levels reported by Castaldi et al. (2008) for the duration of MSW composting started at 120 mg N/kg, peaked at 190 mg N/kg peak on day 14, declined to 80 mg N/kg on day 28 and finally ended with 40 mg N/kg. The NH_4^+ content for the compost produced in Mwanza is greater than the end value reported by Castaldi et al. (2008), but is comparable to the NH_4^+ content reported within the first 28 days of composting. The

NO_3^- levels reported by Castaldi et al. (2008) increased over time, starting at 60 mg N/kg, to 90 mg N/kg on day 28, and 110 mg N/kg on the last day. The nitrate content in the present study's compost is less than that reported by Castaldi et al. (2008). The reason for the low levels of plant-available nitrogen in the form of NO_3^- is likely because of the nitrogen loss during the composting process as discussed earlier. Generally, a decrease in ammonium and increase in nitrate content indicates a mature compost, though results using NO_3^-/NH_4^+ ratio to evaluate compost maturity have been contradictory (Azim et al., 2018).

Two important parameters to assess compost quality are maturity, which is associated with plant growth and phytotoxicity of the compost, and stability, which is related to the degree of decomposition of the organic matter (Cerda et al., 2017). High ammonium concentrations indicate compost instability (Sánchez-Monedero et al., 2001), and can be considered phytotoxic because of the potential for ammonia volatilization (Azim et al., 2018). An implication of biological nitrification is acidification as a result of NH_4^+ oxidation (Castaldi et al., 2008), which could result in phytotoxicity, negatively impacting plant growth. According to Zucconi and De Bertoldi (1987) the maximum ammonium content in a mature compost should be <0.4 mg/g (Guo et al., 2012). In this study, the ammonium content was 0.1345 mg/g, which is less than the minimum recommendation, indicating that the final compost was stable.

3.4.3 Integrating Rapid Composting into the City

This study makes a case for integrating rapid composting into Mwanza city's waste management strategy. According to Rothenberger et al. (2006), decentralized composting systems are low cost and less dependent on technology, which would make them a suitable option for the municipality. The rapid composting presented in this study is a decentralized system as well as a fast, small-scale, and cost-effective method of converting organic (food) waste into compost in an urban environment.

The rapid composting method has several advantages. With >80% weight reduction, the amount of waste that needs to be disposed of after the process is significantly lower than that which was collected. Even if the final end product is land-filled, the processed waste will take up less landfill space and reduce disposal costs (Okazaki et al., 2008). However, the end product and by-products can also be used for alternate purposes, transforming the waste of one process into a resource for another. Having more than one end use can make composting a more attractive venture because composting is often a break-even or just marginally profitable business (Oberlin et al., 2011).

The compost can be useful as a soil amendment for agriculture, particularly urban agriculture, which is a prominent activity within and around Mwanza city (Mwanza City Council, 2008). According to Cooperband (2002), the recommended qualities for on-farm use of compost are C:N ratio between 10:1 and 15:1, neutral pH (6-8), and free of weed and pathogen by achieving temperature of 55°C for 72 hours during composting process. The compost produced in this study meets the C:N ratio, pH, and temperature criteria. Guidelines on compost quality vary between countries (William, 2000; CCME, 2005; David, 2013;

Dimambro et al., 2015). For example, the guidelines by CCME (2005) require compost to be cured for 21 days and exhibit less than 8°C rise in temperature above ambient to ensure maturity and stability of the compost. Even though the composts were not cured for 21 days, the rise in temperature in the compost was less than 8°, which could indicate a mature and stable compost. A report on compost guidelines in Zanzibar indicated Tanzania's standards on organic fertilizers, which are required to have a pH between 6.5 and 8.5, a minimum total OC of 12%, a minimum TN of 1% and a C:N ratio of <20:1 (Henam and Sambyal, 2019). Based on these guidelines, the compost produced through this rapid composting study would not meet the nutrient requirements of an organic fertilizer, and based on the nutrient analyses, high application rates of composts would be required to meet the nitrogen and phosphorus requirement for crops (Thangarajan et al., 2013). KIWODET, a community-based composting venture in Dar es Salaam, made use of additives like cow dung, chicken manure, ashes and charcoal dust to increase nutrients, and demonstrated a viable composting operation through compost sales to a core group of customers (Oberlin et al., 2011). Nonetheless, it is postulated that even if the resultant compost does not have high N and P content, it is better to compost than let organic waste decompose in landfill environments and it is beneficial to add the compost to the soil than not adding anything. Therefore, the potential of using compost from urban food waste for urban agriculture in Mwanza, Tanzania is further investigated and discussed in Chapter 4.

The composting process also attracts many insects that are related to the composting process, with distinct stages of degradation used by various arthropods to complete their life cycle within the compost (Kumar et al., 2018). One of these insects is the black soldier fly, which can be utilized as a protein source for livestock, such as ducks, chickens, or even fish fostered in aquaculture (Newton et al., 1977; Bondari and Sheppard, 1981; Attiogbe et al., 2019). Newton et al. (1977) and Bondari and Sheppard (1981) concluded over four decades ago that there needs to be further work to devise methods of efficiently producing soldier fly larvae on livestock manure or waste materials as the growth media. Using black soldier fly larvae to convert organic waste to compost is gaining more attention (Cheng et al., 2017), especially for removal of heavy metals and mercury contamination (Attiogbe et al., 2019; Sarpong et al., 2019). This study has demonstrated that rapid composting of urban food and vegetable waste can serve as a suitable growth media for black soldier fly larvae, which can also be harvested for other uses, such as feed for livestock.

According to the key conclusions outlined in the literature, the challenges to implementing composting in developing countries include complexity of the operation, dependence on technology or skilled personnel, lack of land, and acquiring the necessary funding (Oberlin et al., 2011; Couth and Trois, 2012; Kaza et al., 2018). With respect to complexity, the composting process in this study had a simple setup of chopping food wastes and gathering the wastes into piles. Composting is a generally forgiving process (Hoornweg and Bhada-Tata, 2012), therefore, a general guideline of turning of the piles every three days can be implemented for three weeks to standardize the process and then the compost can be left to mature for 10 days to complete the process. This predictable process provides opportunity for training personnel on the composting method without need for expensive equipment or complicated technology.

Based on the cost analysis, the process can be started at about $110 USD with additional operating costs of handcart rent and waste chopping to be added as the process continues. The municipality currently employs workers to collect waste using wheelbarrows and handcarts who then deposit collected wastes at transfer points located throughout the city centre, which is consistent with the waste management reported for developing countries (Kaza et al., 2018). As a starting point, organic wastes could be collected separately, especially from food markets (Yhdego, 1992) and fruit stalls where the wastes are predominantly organic. The wastes could still be deposited at transfer points, as is the normal process, and a portion of the land area at the waste transfer point could be dedicated to compost production.

The dimensions of the composting process in this study were 0.91 m by 0.91 m per pile, and the dimensions of the transfer point observed in Mwanza were approximately 10 m by 10 m. The small-scale aspect of the rapid composting provides benefit in this situation, one compost pile would take up a small fraction (1/100) of the total transfer point space. The city also employs waste workers to be stationed at the transfer points to monitor the waste that is collected. The compost piles constructed at the transfer points can be monitored by the staff stationed there, or additional staff can be employed for the organic waste project specifically. Therefore, the low-cost and small-scale aspects of the rapid composting process make it possible to integrate into the current waste management strategy of Mwanza city.

While there are benefits to the rapid composting process and its potential integration into the city's waste management strategy, there are also drawbacks. In this study a one-time weight of organic (food) waste was converted into compost over 31 days in triplicate. However, there are other factors that would need to be explored for integration in the waste management strategy, such as how the composting method may accommodate daily waste collections and the on-going addition of food wastes, as well as seasonal variation in sources of food waste (Adhikari et al., 2008).

The rapid composting process is also a manually intensive process for collecting wastes, chopping food wastes, turning the compost piles at the prescribed times, and frequently monitoring piles. Solid waste management already dominates 30-50% of municipal annual budgets (UN-Habitat, 2016), and these labour tasks may add to the costs associated with solid waste management. Additionally, the small-scale composting method does not have the capacity to process all the organic waste produced within the city center. For example, In Dar es Salaam, Tanzania's largest city, the current rate of solid waste generation is 0.4 kg/cap/day (Mbuligwe et al., 2002), and organic waste accounts for 78% of all household wastes in the city (Kaseva and Mbuligwe, 2005). At this rate, one composting pile with 44 kg of food waste would accommodate wastes from only 140 people per day, which would require a month of processing according to this rapid composting method.

However, this small-scale composting process is a starting point that can provide training for waste workers and operators to understand and get accustomed to the composting processes. Centralized composting systems, unlike decentralized systems, require technical machinery and a higher degree of specialized skills, which is what makes them more prone to failure (Rothenberger et al., 2006). Once the municipality and the waste workers have had the opportunity to learn from the small-scale rapid composting systems, they can then use the expertise to upgrade to larger scale organic waste processing projects for their waste management strategy.

3.5 Conclusions

Over 50% of the waste generated by the hospitality sector in Mwanza, Tanzania is organic. A clear opportunity exists for the municipality and associated private tenders to take advantage of the already separated organic wastes in Mwanza's hospitality sector before the wastes are mixed for collection. Recognizing the resource value of organic waste through composting can help reduce the volume of waste that needs to be managed in landfills.

This study has demonstrated that rapid composting is a low-cost and reliable method for processing diverted urban food and vegetable wastes. The rapid composting method is a decentralized, small-scale system that with the potential for integration into the city's current waste management strategy. The composting systems can be situated at existing waste transfer points, where collected wastes are deposited on a daily basis. The composting process is advantageous because it results in over 80% waste reduction and also yields more than one product: the compost, which can be used as a soil amendment, and the black soldier fly larvae, which can be used feed for ducks, chickens, pigs, and other livestock. The resulting compost may require higher application rates for use as a soil amendment for agricultural purposes to meet plant nitrogen and phosphorus demands.

Future studies should investigate other components of the food waste compost that were not within the scope of this study for comparison against Tanzanian standards for organic substrates and to evaluate the suitability for application on farmed soils. These additional chemical characteristics include electrical conductivity, total or available potassium, as well as the quantity of Arsenic (As_2O_3), Cadmium (Cd), Mercury (Hg), Chromium (Cr), Lead (Pb), Zinc (Zn), Copper (Cu), and Nickel (Ni) in organic waste. Health of compost can also be further validated by pathogenic test to screen the compost for pathogenic organisms, such as *E. coli* and *Salmonella spp.*

Further studies are also required to evaluate the variation in feedstock characteristics throughout the year, prioritizing food waste generated by the hospitality sector. While the composting method put forward in this study would not have sufficient capacity to process all the urban organic (food) wastes produced within the city, it can serve as a pilot-scale strategy to train waste workers. With skilled personnel, the rapid composting system can function as a stepping-stone to a larger-scale, centralized organic waste diversion and processing strategy.

Chapter 4

Comparing Organic and Inorganic Amendments in Urban Agriculture in Mwanza, Tanzania

4.1 Introduction

Increased demand on food production is placing soil fertility at risk (Frossard, 2006). Cultivated soils are being depleted of nutrients and organic matter, which exacerbates land degradation, contributes to climate change, and reduces crop yield and overall food production (European Commission, 2013a). It is estimated that agricultural soils have been depleted of their SOC (soil organic carbon) pool by 25% to 75% depending on climate, soil type, and history of land management (Lal, 2011). Increases in African agricultural output have primarily come from increased harvested areas rather than higher yield (McIntire, 2014), but conversion of natural to agricultural ecosystems is one of the main causes of SOC depletion and soil degradation (Lal, 2007). Reversing the effects of land degradation through sustainable land management is one of the key objectives under Goal 15 of the SDGs (Sustainable Development Goals) (United Nations Economic and Social Council, 2017).

African soils have fewer nutrients than those of other continents (McIntire, 2014) because African soils are old and lack volcanic rejuvenation, and are therefore, inherently poor in fertility (Bationo, 2009). Cultivation of African soils has resulted in further nutrient depletion (Gilbert, 2012). In African soils, crop harvest and soil erosion have constituted about 70% of all nitrogen losses, nearly 90% of all potassium losses, and 100% of phosphorus losses (Drechsel et al., 2014). Therefore, nutrient management is one of the most important strategies to consider for cultivating and maintaining fertility of African soils.

The highest soil nutrient losses occur in the densely populated countries in East Africa (European Commission, 2013a). As urbanization and population density continue to increase, agricultural productivity will be further affected by reduced arable land area (De Bon et al., 2010). Of particular concern is cultivation in African cities where urban agriculture engages 29 million households (Lorenz, 2015), but is limited by land availability and insecurity of land access (McLees, 2011).

Many African governments argue that the most practical solution to replenishing nutrients is increasing the use of inorganic fertilizers (Gilbert, 2012). The advantage of mineral fertilizers is the high solubility which helps plants take up the nutrients (Thangarajan et al., 2013). However, the average fertilizer use in SSA (sub-Saharan Africa) is only 8 kg/ha compared to the soil nutrient depletion rate of 60 kg/ha and the global average fertilizer use of 107 kg/ha (Wanzala and Groot, 2013). Additionally, due to runoff and leaching, only a portion of applied fertilizer is available for plant uptake (Vanlauwe and Giller, 2006; Doan et al., 2015; Tully et al., 2016). Barriers to fertilizer use in SSA include cost, lack of economic incentives to use fertilizer, and lack of information on how to use fertilizers appropriately (Wichelns, 2003; Gilbert, 2012; McIntire, 2014). The use of inorganic fertilizers may increase the risk of soil nutrient depletion and soil degradation (Drechsel et al., 2001b; Sotamenou and Parrot, 2013), and land degradation may further undermine the sustainability of agricultural production in most of the SSA (Obalum et al., 2012).

Historically, agricultural success has been assessed within narrow criteria, such as profitability or yield (Sachs, 2010), and so, the use of fertilizers to promote crop growth and yield can be advantageous. However, the use of fertilizers in agricultural systems effectively bypasses the biological processes that sustain productivity in natural ecosystems (Anderson and Ingram, 1990). Long-term or repeated fertilizer use can also increase soil acidification (Vanlauwe and Giller, 2006; Tully et al., 2015) and decrease abundance and biodiversity of soil organisms (Tully et al., 2015). The criteria of profitability or yield do not consider the health and quality of cultivated soil. Therefore, organic soil amendments have been proposed as economically viable alternatives for sustaining crop production in African soils (Doan et al., 2015). Organic matter from soil amendments such as manure or compost, which is incorporated into the SOC pool, plays an important role in improving soil structural stability, enhancing soil fertility, and as a co-benefit, it can help mitigate climate change by stabilizing atmospheric carbon concentration (Vanlauwe and Giller, 2006;

Datta et al., 2013).

Growing food in urban ecosystems is challenging, particularly when working with degraded soils (Lorenz, 2015). Due to rapid urbanization and population growth, urban areas are also producing increased waste volumes (Okot-Okumu, 2012), of which more than 50% is organic. Organic wastes, as a soil amendment, can be a source of carbon and nutrients in the soil (Yhdego, 1994; Castaldi et al., 2008). Therefore, the use of urban solid wastes should be explored as organic amendment for urban agriculture.

In Accra, Ghana, for example, urban solid wastes were composted successfully by urban farmers for use in urban agriculture (Orsini et al., 2013), though the effect of the compost on soil and crop productivity was not investigated. In Cameroon, it was found that 36% of farmers used compost exclusively or in combination with inorganic fertilizers, while 23% of urban farmers did not use any fertilizers and 41% only used inorganic fertilizers (Sotamenou and Parrot, 2013). Again, the effect of either fertilizer or compost use on soil quality and crop productivity was not explored. Additional research is required on how soil fertility can be maintained and enhanced in urban agriculture (Lorenz, 2015), by investigating the effects of inorganic fertilizers and organic amendments, such as compost, on soil quality and crop growth. Therefore, the objective of this study is to determine the effects of amendment application on soil chemical, physical, and biological characteristics, and crop productivity in an urban context, with a specific focus on comparing the benefits and disadvantages of organic versus inorganic amendment use in Mwanza, Tanzania.

4.2 Materials and Methods

4.2.1 Study Site

The field site was located in Mwanza City (2°31'24.71"S 32°53'51.46"E). Mwanza region experiences two rainy seasons through the year (National Bureau of Statistics, 2012a, 2015b), and the city experiences annual average precipitation between 700 and 1000 mm (Mwanza City Council, 2008). The short rainy season ranges from October to December and the long rainy season between March and May, with dry spells in between (National Bureau of Statistics, 2012a, 2015b). The intensity and duration of the short rainy season is less predictable than that of the long rainy season (Sugihara et al., 2010).

Mwanza region falls within agro-ecological Zone III and IV, which contain well-drained, volcanic soils of high ash content, well-drained soils with good water holding properties, as well as sandy to loamy soils with low fertility (National Bureau of Statistics, 2015b). The region is comprised of eight districts, of which Mwanza City occupies two districts: Nyamagana and Ilemela (National Bureau of Statistics, 2012a). This study was conducted within the Nyamagana district, which is under the jurisdiction of Mwanza City Council, whereas Ilemela district has its own municipal council (Overseas Development Institute, 2016).

According to Mwanza City Council (2017), the city of Mwanza is characterized by well-drained sandy loamy soil generated from coarse grained cretaceous. Fruits and vegetables grown in the region include tomatoes (*Solanum lycopersicum*), okra (*Abelmoschus esculentus*), onions (*Allium cepa*), amaranths (*Amaranthus* var.), cabbage (*Brassica oleracea* var. *capitata*), spinach (*Spinacia oleracea*), and chillies (*Capsicum annuum*) (National Bureau of Statistics, 2012a). While there is no distinct difference in the crops grown in the short versus the long rainy season, in general larger areas are planted and more households engage in cultivation during the short rainy season than the long rainy season (National Bureau of Statistics, 2012a).

The area around the study site had been used for urban agriculture for at least five years prior to this study and had a 5 m by 5 m plot area available for rent. Prior to this study, the site was used for tomato cultivation, and, most recently, was used to smolder wood into lump charcoal. Wood ash covered the entire 25 m^2 area. Of this area, 4 m by 4 m were used for the field trial.

A majority of agriculture in Mwanza occurs manually, using hand-hoes as the main tool for preparing the cultivation area (Mwanza City Council, 2008). To prepare for the field trial, the plot of land was tilled manually, using a hand-hoe to a depth of 15 cm. Large stones and chunks of charcoal were removed from the area, along with pieces of plastic that were also found as the soil was turned.

4.2.2 Experimental Design

The main 4 m by 4 m plot of land was divided into 16 subplots of 1 m x 1 m. The subplots were designated treatments following a CRD (complete randomized design). A lottery system was used to randomize triplicates of four treatments - PM (poultry manure), INF (inorganic nitrogen fertilizer), and two types of food waste composts (FWC-1 and FWC-2) - and a CTRL (control). The treatment assignments were randomly generated. The CRD arrangement is shown in Figure 4.1.

One of the food waste composts (FWC-1) was sourced from a company (Guavay) in Dar es Salaam that produces commercially available compost from marketplace organic waste using windrow composting. The company retails this compost commercially. The other type of compost (FWC-2) was made from urban organic (food) waste in Mwanza City using a rapid composting method (method described in Chapter 3). The composts were analyzed at the University of Waterloo to determine the OC (organic carbon), TN (total nitrogen), and P (phosphorus)content using the methods described in Chapter 3. The chemical composition of the two composts is provided in Table 4.1. The PM was acquired locally from a horticulturalist in the city, and the INF was bought from an agro-shop in Mwanza.

Table 4.1: Comparison of the chemical characteristics (OC (organic carbon), TN (total nitrogen), C:N (carbon-to-nitrogen) ratio, and P (phosphorus)) of the two types of food waste compost used in this study: compost sourced from Dar es Salaam (FWC-1) and compost generated in Mwanza (FWC-2)

Compost Type	**OC (%)**	**TN (%)**	**C:N Ratio**	**P (mg P/kg)**	**pH**	**NO_3^- (mg N/kg)**	**NH_4^+ (mg N/kg)**
FWC-1	6.6	0.5	14.5	168.8	9.3	44.24	35.95
FWC-2	4.1	0.3	13.2	148.3	8.3	52.47	243.99

The organic amendments were applied one week before the first soil sampling, which in turn was one week before the first planting. Soil amendments FWC-1 and PM were applied at a rate of 2.5 kg/m^2, whereas FWC-2 was applied at a rate of 1.5 kg/m^2. The organic amendments were spread out evenly on their designated replicates and mixed into the top 10 cm (4 inches) of the soil with a hand-hoe. The application rate for FWC-2 was limited by the amount of compost that was generated, whereas the application rate

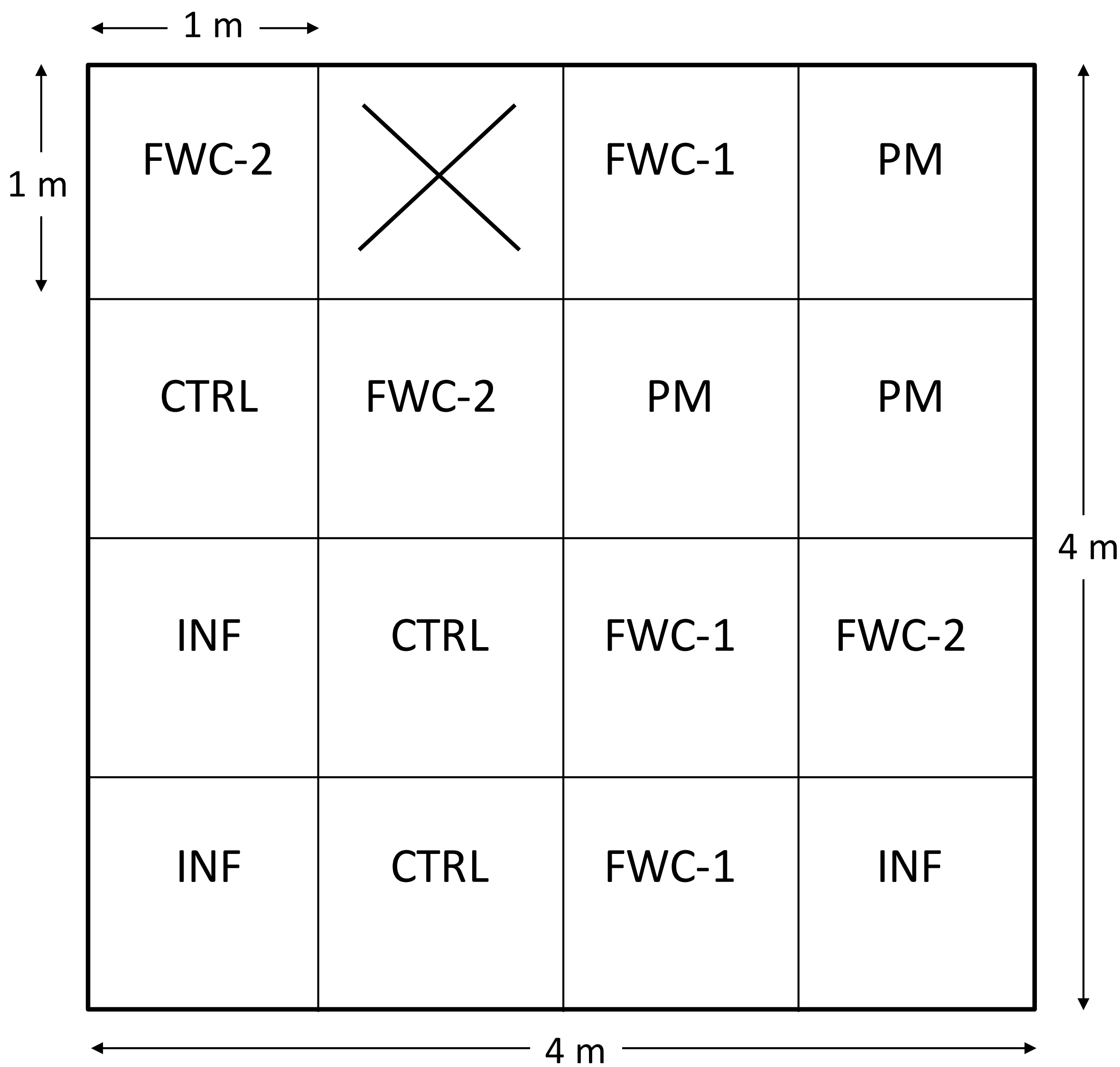


Figure 4.1: Complete randomized design arrangement of four treatments (PM = Poultry Manure, FWC-1 = Commercial marketplace compost from Dar es Salaam, FWC-2 = Food waste compost generated in Mwanza, INF = Inorganic Nitrogen Fertilizer, and CTRL = Control. The treatment assignments were randomly generated. The X on the schematic represents a subplot that was not part of the experiment (i.e., no treatment).

for FWC-1 and PM was limited by the amount that was acquired from local sources. Fertilizer treatments were applied in one of two ways: at the time of planting or after the seedling had germinated and gained prominence. Because the fertilizer bag lacked any written instructions, the decision to have two application methods resulted from the advice provided by the agro-shopkeeper from whom the fertilizer was purchased as well as an agriculture expert at the Ukiriguru Agriculture Research Institute (ARI-Ukiriguru) in Mwanza. Local knowledge from the agro-keeper recommended one water bottle cap (5 ml) filled with urea fertilizer to be applied around the seedling after germination. The agriculture expert, on the other hand, recommended a pinch of urea fertilizer to be applied at the same time as planting the seed.

4.2.3 Crop Planting and Growth Analysis

The two crops selected for the field trial were cabbage (*Brassica oleracea* var. *Capitata*) and amaranth greens (*Amaranthus gangeticus*), which are both commonly cultivated leafy green vegetables in Mwanza. Amaranth greens (also called *mchicha* in Swahili) are especially cultivated for their three-week maturation period, whereas cabbages can take anywhere from two to five months before harvest. The seeds for both crops were bought from an agro-shop in Mwanza. The cabbage seeds were sold in a labelled package. The amaranth green seeds, on the other hand, were sold in bulk by weight and packaged in a transparent, unmarked plastic bag.

To align with the urban agriculture strategies discussed in Chapter 2 and due to shortage of space, the two types of crops were co-planted for the field trial for two short-duration planting periods. The first growing period was from mid-December to early January and the second growing period ranged from early January to mid-February. According to the National Bureau of Statistics (2012a), the short rainy season in Mwanza ranges from October to December and January is a dry period. However, the city did not experience a strong rainy period in December 2017, instead the city experienced brief, heavy rains in January 2018. The organic amendments, applied only once in late November before the planting rotations, were not re-applied between the two growing periods. Fertilizer, on the other hand, was applied in both growing periods because fertilizer application was dependent on planting and plant growth.

In the first growing period, 6 cabbage and 18 amaranth seeds were planted per replicate. For fertilizer treatments, fertilizer was placed in the hole with the amaranth seeds but, for the cabbage seeds, the fertilizer was applied around the seedling after germination. In the second growing period, due to space constraints, 4 cabbage and 8 amaranth seeds were planted per replicate. In this growing period, fertilizer was placed in the hole with cabbage seeds but for the amaranth seeds fertilizer was applied around the seedling after germination. The difference is indicated by INF*, which indicates that fertilizer was applied at the same time as the seed during planting. The reason for the difference in fertilizer application were differing sets of instructions. Edge effects were minimized with a 10 cm border within the edge of each plot designated to be no-plant zones.

During the field trial, recorded observations included the number of plants that germinated per replicate, the heights (cm) of each plant measured from base at the soil level to the tallest leaf using a measuring tape, and the number of leaves produced, both folded and unfolded. The measurements were taken every day for one week after germination after which measurements were taken every other day until harvest on all plants that grew within each plot.

Publicly available weather information from CustomWeather (2020) was used to compile the daily maximum and minimum temperatures and daily maximum wind speeds experienced during the growing periods. While the amount of rainfall was not recorded or readily available, the days when it rained during the field trial were recorded by the researcher for the duration of the study. The growth trends were visually compared with the daily maximum and minimum temperatures, as well as maximum wind speeds and sequence of rain days to check for corresponding patterns with crop growth.

4.2.4 Soil Sampling and Soil Analysis

Composite soil samples were collected using a soil auger (5 cm diameter) from three individual points randomly selected in a 'V' shaped design for each replicate. The soil samples were taken from two depths: 0 - 10 cm (D1) and 10 - 20 cm (D2). The samples from the three randomly selected points were mixed together for each soil depth to create composite soil samples for each replicate. Soil samples were collected at two points in time. The first was before planting in early December 2017 (T1); at this time, the soils under organic treatments had already been amended their respective treatment (PM, FWC-1, and FWC-2). The second sampling time was after harvest in late January 2018 (T2). The samples were placed in plastic bags, sealed, and labelled.

The soil samples were transported to the soil laboratory at ARI-Ukiriguru where they underwent analyses for pH, SOC (soil organic carbon), TN (total nitrogen), available P (phosphorus), EC (electrical conductivity), and CEC (cation exchange capacity). Soil texture was analysed only for the soil samples taken at T1 because it is a soil parameter that does not change easily over a short period. The C:N (carbon-to-nitrogen) ratio was derived from the SOC and TN values.

A mechanical analysis was used to determine soil texture along with the USDA soil texture classification (Anderson and Ingram, 1990). Soil pH was measured at 1:2.5 soil to water ratio, and at 1:2.5 soil to 0.01 M KCl solution. According to Carter and Gregorich (2008), soil pH measured in water is representative of soil pH in the field whereas soil pH measured in a salt solution like $CaCl_2$ or KCl are less dependent on recent fertilizer history. After pH measurement in water, the supernatant liquid from settled samples was used to measure EC (Anderson and Ingram, 1990). The CEC was analysed using the pH 7 ammonium acetate method (Anderson and Ingram, 1990; Carter et al., 2004).

The SOC in the soil samples was determined using a dichromate redox method where consumption of oxidant was measured calorimetrically without external heating (also known as the Walkley and Black method) (Anderson and Ingram, 1990; Carter and Gregorich, 2008). The TN was determined using a Kjeldahl oxidation (Anderson and Ingram, 1990). The available P content was determined using the Olsen et al. (1954) bicarbonate extractant method followed by the Murphy and Riley (1962) procedure for calorimetric determination (Anderson and Ingram, 1990; Carter and Gregorich, 2008).

Bulk density core sampling was conducted by a soil technician from ARI-Ukiriguru at only one point in time, halfway between T1 soil sampling and T2 soil sampling. The bulk density analysis was subsequently conducted at ARI-Ukiriguru. A 5 cm diameter thin-sheet metal tube of known weight and volume was used to collect soil samples for bulk density. The soil was dried at 105°C for two days and weighed. The bulk density was determined by subtracting the weight after drying from the known weight of the tube and then divided by the known volume of the tube.

Due to the limited testing capabilities of the soil laboratory at ARI-Ukiriguru, a portion of soil samples had to be transported to Canada in September 2018 for further analyses. A portion (250 g) of the soil samples taken at T1 and T2 were air dried and sieved to < 2 mm in accordance with soil exporting procedures in Tanzania (Appendix B) and soil importing procedures for Canada (CFIA, 2014). The additional analyses for WHC (water holding capacity), ammonium (NH_4^+), nitrate (NO_3^-), and SMB-C (soil microbial biomass - carbon) were conducted between April 2019 and June 2019 at a soil laboratory at the University of Waterloo in Waterloo, Ontario.

For WHC, 30 g of soil samples were wetted using free-flowing water in pre-weighed containers with perforations on the bottom to allow for the water to drain. At field capacity (i.e. when excess water had drained), the container plus wet soil were weighed. The WHC (%) was determined by first subtracting the weight of the container from the final weight to obtain soil wet weight, then the dry soil weight was subtracted from wet soil weight, divided by the dry soil weight, and multiplied by 100.

For NH_4^+ and NO_3^- analyses, 5 g of soil samples were extracted with 25 ml 2.0 M KCl using a reciprocating shaker (Heidolpj Unimax 1010 DT, Schwabach, Germany) at 180 rpm for 15 minutes. The extract was filtered through Whatman 42 filter paper. For NH_4^+ analysis, 0.2 ml filtrate was reacted to 0.5 ml of Reagent A and Reagent B. Reagent A is comprised of 0.05 g sodium nitroprusside (also called sodium nitroferricyanide), 13 g sodium salicylate, 10 g sodium citrate, and 10 g sodium tartrate dissolved in 100 ml of water and then diluted in a 1:1 ratio with deionized distilled water. Reagent B is comprised of 6 g sodium hydroxide in 100 ml water, and 2 ml bleach (5% sodium hypochlorite). Absorbance was read 1 hour after colour development using a Shimadzu 1800 UV-Vis Spectrophotometer (Shimadzu Corp., Kyoto, Japan) at a wavelength of 650 nm. For NO_3^- analysis, 0.1 ml filtrate was reacted to 1.0 ml vanadium chloride reagent and absorbance was read 8 hours later when the colour had developed using a Shimadzu 1800 UV-Vis Spectrophotometer (Shimadzu Corp., Kyoto, Japan) at a wavelength of 540 nm.

Soil microbial biomass analyses for carbon (SMB-C) content provide a measure of the quantity of living microbial biomass present in the soil (Voroney et al., 2008). For the analyses, the soils were first incubated for ten days with deionized distilled water at 50% WHC to revive microbial activity within the soils. The laboratory processes of extraction and fumigation were performed as per the method described by Voroney et al. (2008). Incubated soil samples were divided into 30 g for fumigation with ethanol-free CHCl and 30 g remained unfumigated. Both fumigated and unfumigated samples were extracted with 0.05 M K_2SO_4 solution. The extracted samples were filtered, freeze-dried for 72 hours, and then analysed for SMB-C using an elemental analyser.

4.2.5 Statistical Analyses

For crop growth, the height measurements of the plants were compiled and analyzed for statistical significance with respect to time and treatment using repeated measures ANOVA in SPSS software (Page et al., 2003). The main assumption for repeated measures ANOVA is sphericity (homogeneity-of-variance-of-differences), which is determined using Mauchly's test. If sphericity assumption using Mauchly's test is violated, SPSS provides alternate tests that can be used with adjusted degrees of freedom. For this study, the Lower-bound test and associated adjusted degrees of freedom were used in cases where sphericity could not be assumed. Homogeneity of data sets were confirmed using Levene's Test and post hoc Tukey HSD tests were used to compare estimated marginal means.

For the soil characteristics, there were three factors in the study design: time, treatment, and depth. The results of the soil physical, chemical, and biological parameters were analysed for statistical significance using factorial (three-way) analysis of variance (ANOVA) in SPSS software (Page et al., 2003). The statistical differences with respect to each of the three factors as well as any interaction effects between the three factors were examined in the analyses.

Soil texture soil samples were taken at one point in time (T1) at the two depths, and so, were analyzed using a two-way ANOVA. Cores for bulk density were only sampled at one point in time and one depth, and so, the comparison for bulk density was analyzed using a one-way ANOVA. Before executing ANOVA in SPSS, the data were checked for normality using Shapiro-Wilk test and homogeneity using Levene's statistic. The ANOVA model has been found to be robust against normality assumption violations (Schmider et al., 2010). However, in cases where the homogeneity assumption was violated, the data were transformed using either a natural logarithm, square root, or inverse square root function to satisfy the homogeneity requirement. In cases where the ANOVA results reported statistical significance with respect to treatment, post hoc tests (Tukey HSD and LSD) were used in SPSS to further investigate the statistical difference and compare estimated marginal means between treatment groups.

The results from the factorial ANOVA for soil parameters are summarized in Table 4.2. A threshold of $p<0.05$ was used for statistically significant effects for time, treatment, and depth. There were no combined interaction effects between any of the factors (time*treatment, time*depth, treatment*depth, or time*treatment*depth) for any of the parameters.

4.3 Results

4.3.1 Soil Physical Characteristics

The soil texture of all samples, regardless of depth, was sandy loam, averaging at 72% sand, 14% silt, and 13% clay. For bulk density, there were no significant differences between the treatments. The average bulk density was 1.48 g/cm^3.

There were statistically significant differences in WHC (water holding capacity) with respect to depth ($p=0.028$) and treatment ($p=0.001$). The overall WHC was greater in the upper depth (0-10 cm) than at lower depth (10-20 cm). The post hoc analysis for treatment showed a significant difference between INF treatments and the FWC-1, FWC-2, and PM treatments (INF – FWC-1, $p=0.002$; INF – FWC-2, $p=0.026$; INF – PM, $p=0.001$) in favour of the organic amendments. The soil physical characteristics (soil texture, texture class, bulk density, and WHC) for all treatments are presented in Table 4.3.

Table 4.2: Summary of statistical significance of soil physical, chemical, and biological parameters using factorial ANOVA for time, treatment, and depth factors.

Parameter	Time	Treatment	Depth
Physical			
Bulk Density (g/cm^3)	n.a.	n.s.	n.a.
WHC (%)	n.s.	$F(4,40) = 5.970$ $\boldsymbol{p = 0.001}$	$F(1,40) = 5.181$ $\boldsymbol{p = 0.028}$
Chemical			
pH	$F(1,40) = 110.506$ $\boldsymbol{p < 0.001}$	$F(4,40) = 8.565$ $\boldsymbol{p < 0.001}$	n.s.
[1]SOC (%)	$F(1,40) = 11.702$ $\boldsymbol{p = 0.001}$	$F(4,40) = 3.059$ $\boldsymbol{p = 0.027}$	$F(1,40) = 6.652$ $\boldsymbol{p = 0.014}$
TN (%)	n.s.	n.s.	$F(1,40) = 13.446$ $\boldsymbol{p = 0.001}$
C:N Ratio	$F(1,40) = 7.425$ $\boldsymbol{p = 0.009}$	n.s.	n.s.
Available P (mg P/kg)	n.s.	$F(4,40) = 4.277$ $\boldsymbol{p = 0.006}$	$F(1,40) = 14.506$ $\boldsymbol{p < 0.001}$
[1]CEC (cmol/kg)	$F(1,36) = 5.581$ $\boldsymbol{p = 0.024}$	n.s.	n.s.
[2]EC (dS/m)	n.s.	n.s.	n.s.
[1]Nitrate (NO_3^-) (mg N/kg)	n.s.	$F(4,40) = 4.639$ $\boldsymbol{p = 0.004}$	n.s.
Ammonium (NH_4^+) (mg N/kg)	n.s.	n.s.	$F(1,40) = 773.713$ $\boldsymbol{p < 0.001}$
Biological			
[1]SMB-C ($\mu g/g$)	n.s.	$F(4,36) = 8.545$ $\boldsymbol{p < 0.001}$	$F(1,36) = 6.717$ $\boldsymbol{p = 0.014}$

Threshold for statistical significance is $p<0.05$ (n.s. = not significant, n.a. = not available). There were no significant interaction effects. Data transformed to satisfy homogeneity assumption are denoted by [1]natural logarithm, [2]inverse square root.

Table 4.3: Physical properties of the soils – soil texture (sand-silt-clay), mean bulk density, and WHC (water holding capacity) – with respect to amendment treatment (food waste composts FWC-1 and FWC-2, PM (poultry manure), INF (inorganic nitrogen fertilizer), and CTRL (control).

Treatment	**Sand-Silt-Clay (%)**	**Bulk Density (g/cm^3)**	**WHC[1] (%)**
FWC-1	72-14-14	1.42 (0.08)	33 (0.91) ^{a}
FWC-2	72-15-13	1.38 (0.26)	33 (1.07) ^{a}
PM	75-14-11	1.49 (0.04)	32 (0.85) ^{a}
INF	73-13-14	1.69 (0.07)	28 (0.94) ^{b}
CTRL	72-14-14	1.38 (0.04)	31 (0.67) ^{ab}

[1] Values with different letters (*a*,*b*,*c*) in the same column indicate a significant ($p<0.05$) difference between treatments. Values with the same letters indicate no significant ($p>0.05$) difference between treatments. Standard error for mean values is presented in parentheses.

4.3.2 Soil Chemical Characteristics

pH

The pH determined with water (H_2O) was consistently 1.2 points greater than the pH measured using KCl. For both H_2O and KCl analyses there was a significant difference in pH values between time T1 and time T2 ($p<0.001$), inferring that the soil became less alkaline over time. There was also significant difference ($p<0.001$) between PM and the other treatments. Soils with the PM treatment were significantly less alkaline (i.e., more acidic) than the rest of the treatments and the control by at least 0.3 points. Values for each treatment are presented in Table 4.4.

Soil Organic Carbon

Soil organic carbon (SOC) increased significantly (p=0.001) from time T1 (Dec 2017) to time T2 (Jan 2018) for all treatments and was significantly greater (p=0.014) in the upper (0-10 cm) depths than the lower (10-20 cm) depths. There were also significant differences in SOC with respect to treatment (p=0.027). The Tukey HSD test comparison of the means showed no significant differences between the treatments, though the LSD comparison of the means showed that SOC in FWC-1 and PM treatments was significantly greater than in both INF treatment and control [FWC-1 – INF, p=0.021; FWC-1 – CTRL, p=0.008; PM – INF, p=0.041; PM – CTRL, p=0.017]. There are no significant differences between FWC-1, PM, and FWC-2 treatments. The mean SOC content is highest for FWC-1 treatment, followed by PM, FWC-2, and finally INF and CTRL treatments. The %SOC values for each treatment at the two times and depths are shown in Table 4.4.

Total Nitrogen and C:N Ratio

The only significant difference with respect to TN (total nitrogen) was between the two soil depths. There was significantly more TN (p=0.001) in the upper depths than in the lower depths for all treatments. The values are presented in Table 4.4. There were no significant differences in TN between the treatments or over time. The overall C:N ratio increased significantly (p=0.009) from time T1 to time T2 but did not differ significantly with respect to treatment or depth. The values are presented in Table 4.4.

Ammonium and Nitrate

There were no statistically significant differences in ammonium (NH_4^+) with respect to time or treatment, though NH_4^+ content was significantly higher ($p<0.001$) in the upper 0-10 cm) depth versus the lower (10-20 cm) depth. On the other hand, the nitrate (NO_3^-) content was significantly ($p=0.002$) higher in the lower (10-20 cm) depth compared to the upper (0-10 cm) depth. Additionally, NO_3^- content was significantly lower in the INF-treated soils than in FWC-2 ($p=0.004$) and PM ($p=0.032$) treatments (Table 4.5). There were no statistically significant differences in NO_3^- over time.

Available Phosphorus

The available P (phosphorus) in the soil differed significantly with respect to depth ($p<0.001$) and treatment ($p=0.006$). For all treatments, the available P content was higher in the upper (0-10 cm) depth than in the lower (10-20 cm) depth. The values for available P at each depth for all treatments are shown in Table 4.4. The post hoc Tukey HSD test showed a statistically significant difference between PM and INF treatments ($p=0.002$). The PM treatments had a significantly higher amount of available P than the INF-treated soils. However, there were no significant differences among the organic amendment treatments and between the control. The values and significance of differences are also presented in Table 4.4.

EC and CEC

There were no significant differences for EC (electrical conductivity) with respect to time, treatment, or depth. The statistical analysis for CEC (cation exchange capacity) indicated significance with respect to treatment, however, upon further investigation of the data set, there was an anomalous value for CEC in one of the INF-treated replicates. The value was greater than 60 cmol/kg in the upper depth and greater than 40 cmol/kg in the lower depth even before fertilizer was applied to the replicate. After removing the outlier values for one INF replicate, there were no statistical differences with respect to treatment or depth, though there was an overall significant increase ($p=0.024$) in CEC from time T1 (9.32 ± 0.10 cmol/kg) to time T2 (11.40 ± 0.15 cmol/kg).

4.3.3 Soil Biological Characteristics

Soil Microbial Biomass - Carbon

The statistical analyses of the results show a significant difference with respect to treatment ($p<0.001$) and depth ($p=0.014$) for SMB-C. The SMB-C was greater at upper (0-10 cm) than at lower (10-20 cm) depths. Between treatments, the post hoc Tukey HSD test showed that there was significantly greater SMB-C content in PM treatments than FWC-2 ($p=0.041$), INF ($p=0.002$), and c ($p=0.002$) treatments (Table 4.5). The SMB-C was also significantly higher in the FWC-1-treated than the INF-treated ($p=0.005$) and C ($p=0.004$) soils. There was no significant difference between PM and FWC-1 treatments or between FWC-1 and FWC-2 treatments.

Table 4.4: Mean values for select soil chemical parameters: SOC (soil organic carbon), TN (total nitrogen), C:N (carbon-to-nitrogen) ratio, available P (phosphorus) , and pH at time T1 (Dec 2017) and time T2 (Jan 2018) in the upper (0-10 cm) and lower (10-20 cm) depths for all treatments (food waste composts (FWC-1 and FWC-2), PM (poultry manure), INF (inorganic nitrogen fertilizer), CTRL (control).

		SOC (%)	TN (%)	C:N Ratio	P (av) (mg P/kg)	pH (KCl)
T1		†		†		†
	0-10 cm	▽	▽		▽	
	PM	1.05 (0.1)^{ab}	0.22 (0.01)	4.91 (0.65)	103.53 (4.60)^{a}	7.38 (0.05)^{a}
	FWC-1	1.28 (0.22)^{ab}	0.23 (0.03)	5.59 (0.89)	74.61 (27.34)^{ab}	7.79 (0.01)^{b}
	FWC-2	0.86 (0.12)^{b}	0.23 (0.04)	3.19 (0.49)	82.21 (15.14)^{ab}	7.88 (0.10)^{b}
	INF	0.97 (0.32)^{c}	0.18 (0.04)	6.51 (2.76)	33.73 (12.55)^{b}	7.75 (0.01^{b})
	CTRL	0.62 (0.21)^{c}	0.18 (0.05)	3.83 (0.94)	74.41 (29.13)^{ab}	7.78 (0.10)^{b}
	10-20 cm	▽	▽		▽	
	PM	0.88 (0.29)^{ab}	0.16 (0.05)	5.85 (1.96)	57.73 (29.91)^{a}	7.49 (0.09)^{a}
	FWC-1	0.93 (0.17)^{ab}	0.16 (0.03)	6.12 (1.06)	61.22 (16.33)^{ab}	7.71 (0.02)^{b}
	FWC-2	0.86 (0.37)^{b}	0.16 (0.04)	5.23 (1.32)	34.72 (1.16)^{ab}	7.74 (0.05)^{b}
	INF	0.5 (0.11)^{c}	0.14 (0.04)	3.60 (0.26)	24.05 (12.58)^{b}	7.71 (0.02)^{b}
	CTRL	0.60 (0.16)^{c}	0.09 (0.03)	6.86 (1.93)	44.33 (5.19)^{ab}	7.72 (0.07)^{b}
T2		†		†		†
	0-10 cm	▽	▽		▽	
	PM	2.21 (0.27)^{ab}	0.23 (0.03)	9.47 (0.53)	99.38 (15.72)^{a}	7.01 (0.11)^{a}
	FWC-1	2.35 (0.31)^{ab}	0.26 (0.04)	9.05 (0.1)	69.45 (8.07)^{ab}	7.59 (0.20)^{b}
	FWC-2	2.1 (0.26)^{b}	0.24 (0.06)	9.68 (1.52)	81.66 (28.53)^{ab}	7.73 (0.15)^{b}
	INF	1.51 (0.67)^{c}	0.24 (0.07)	6.06 (1.12)	51.73 (9.94)^{b}	7.59 (0.06)^{b}
	CTRL	1.81 (0.78)^{c}	0.22 (0.03)	7.47 (2.35)	68.49 (15.3)^{ab}	7.77 (0.02)^{b}
	10-20 cm	▽	▽		▽	
	PM	1.91 (0.56)^{ab}	0.16 (0.04)	15.20 (7.45)	79.04 (12.05)^{a}	7.38 (0.04)^{a}
	FWC-1	1.90 (0.77)^{ab}	0.20 (0.03)	10.82 (5.63)	43.03 (20.83)^{ab}	7.53 (0.06)^{b}
	FWC-2	1.24 (0.5)^{b}	0.15 (0.05)	7.63 (0.7)	42.41 (19.17)^{ab}	7.52 (0.04)^{b}
	INF	1.11 (0.71)^{c}	0.18 (0.04)	4.95 (2.43)	32.20 (8.61)^{b}	7.55 (0.02)^{b}
	CTRL	0.59 (0.22)^{c}	0.13 (0.05)	6.69 (4.34)	27.31 (9.63)^{ab}	7.60 (0.03)^{b}

Values with different letters (a,b,c) in the same column indicate a significant ($p < 0.05$) difference between treatments. The symbol † represents significant difference over time and the symbol ▽ indicate significant difference with respect to depth in the soil parameter. Standard error for mean values presented in parentheses.

Table 4.5: Mean values for soil parameters (soil nitrate and SMB-C (soil microbial biomass - carbon)) at 0 - 20 cm depth for all treatments (food waste composts (FWC-1 and FWC-2), PM (poultry manure), INF (inorganic nitrogen fertilizer), CTRL (control).

Treatment	NO_3^- (μg/g)	SMB-C (mg N/kg)
FWC-1	4.98 (1.03) ^{ab}	915.74 (154.7) ^{ab}
FWC-2	8.25 (1.89) ^{a}	464.24 (141.2) ^{bc}
PM	5.32 (0.97) ^{ab}	1099.44 (178.0) ^{a}
INF	2.40 (0.54) ^{b}	266.44 (52.6) ^{c}
CTRL	4.14 (1.34) ^{ab}	353.33 (125.9) ^{c}

Values with different letters (a,b,c) in the same column indicate a significant ($p < 0.05$) difference between treatments. Standard error for mean values presented in parentheses.

4.3.4 Crop Growth

Amaranth Growth

For the first growing period, amaranth seeds had germinated two DAP (days after planting) for all treatments, except INF* treatments. INF* denotes that the fertilizer was applied with the seeds at time of planting. There was a delay in germination for amaranth seeds under this treatment, germinating 6 - 8 DAP.

Amaranth plants in all treatments began losing their leaves 5 to 8 DAP, which is attributed to the high wind speeds ($\geq$20 km/h) that were prevalent 3 DAP and 6 - 7 DAP. The plants regained their growth and continued to grow steadily from 8 to 14 DAP, after which amaranth growth stagnated, and declined in some cases, in all treatments, except in Control treatments where growth resumed from 18 DAP. With the growth stagnated in the remaining treatments, the amaranth from the first growing period were harvested 22

DAP to allow space for the second growing period. The growth of amaranth from 8 - 14 DAP is shown in Figure 4.2.

Statistical analyses of amaranth growth showed a significant difference over time [$F(1, 22) = 11.965$, $p=0.002$], with respect to treatment [$F(4,22) = 26.756$, $p<0.001$], and an interaction between time*treatment [$F(4, 2) = 2.863$, $p=0.047$]. The amaranth growth was significantly rapid from 8 to 16 DAP, after which there was no further significant growth. The heights at 22 DAP were not significantly different than at 8 DAP. With respect to treatment, amaranth growth under Control, PM, and FWC-2 treatments exceeded that in FWC-1 treatment and INF* treatments. The average heights at harvest were 3.8±0.5 cm (CTRL), 2.4±0.6 cm (PM), 2.1±0.3 cm (FWC-2), 1.6±0.3 cm (FWC-1), 1.2±0.1 cm (INF*).

The growth of amaranth from 8 - 22 DAP is shown in Figure 4.3 along with the weather conditions for the growing period. There was a total of nine days of rain over a 22-day growing period. It had rained the day before planting, the day of planting, and the day after planting. There was no rain between 2 DAP and 9 DAP. It rained again 10 DAP, then no more rain until 16 DAP and 18 – 22 DAP. There were some instances of high winds at 18, 21, and 22 DAP, but it is unlikely that the winds alone are cause enough for the growth stagnation after 16 DAP. There was also a decline in daily air temperatures from 15 DAP. While maximum temperatures remained around 25°C, minimum temperatures declined to 18°C. Between 16 and 22 DAP the amaranth growth in the CTRL exceeded the growth in all other treatments.

For the second growing period, amaranth seeds germinated 3 DAP for all treatments.

Fertilizer was applied at 21 DAP around the seedlings that germinated in INF-treatment replicates. The amaranth crops grew steadily without any adverse effects, unlike the first round of growth, and were harvested at 33 DAP. The growth of amaranth planted in the second growing period is shown in Figure 4.4 for all treatments.

Statistical analyses of the second round of amaranth growth also showed a significant difference over time [$F(1, 66) = 363.620$, $p<0.001$], with respect to treatment [$F(4,66) = 7.501$, $p<0.001$], and an interaction between time*treatment [$F(3, 66) = 12.267$, $p<0.001$]. Amaranth growth under PM treatment significantly exceeded that of other treatments. There were no significant differences in growth between CTRL, FWC-1, INF, and FWC-2 treatments. The amaranth growth was significantly rapid ($p<0.001$) between each day that heights were recorded from 4 DAP to 32 DAP at which point the amaranth greens were harvested. The average heights at harvest were 34.7±2.3 cm (PM), 21.9±1.9 cm (CTRL), 19.4±2.8 cm (FWC-1), 17.0±2.0 cm (INF), and 11.9±3.0 cm (FWC-2).

The corresponding daily weather conditions (wind, temperature, and rain) for the second round of amaranth growth from 3 DAP to 32 DAP are shown in Figure 4.5. In total, there were fourteen days of rain over the 32-day growing period. It had rained the day before planting and it rained the day after planting. It continued to rain from 2 DAP to 5 DAP, after which it rained regularly at different intervals: 8 DAP, 10 DAP, 14 – 15 DAP, 17 DAP, 19 – 20 DAP, 22 – 23 DAP. From 24 DAP to harvest, there was no more rain. Strong winds (≥20 km/h) were prevalent on several days throughout the growing period. Minimum air temperatures fluctuated between 18°C and 19°C for the first five days after planting but remained mainly between 19°C and 20°C beyond 5 DAP. Maximum air temperatures fluctuated between 25°C and 26°C, dropping to 21°C 15 DAP, but then increasing to 31°C closer to harvest time. The most rapid growth of the amaranth was seen from 18 DAP when temperatures had reached 27°C. The weather conditions (rain days and daily temperature ranges) as well as the effects of treatment on amaranth growth are summarized in Table 4.6.

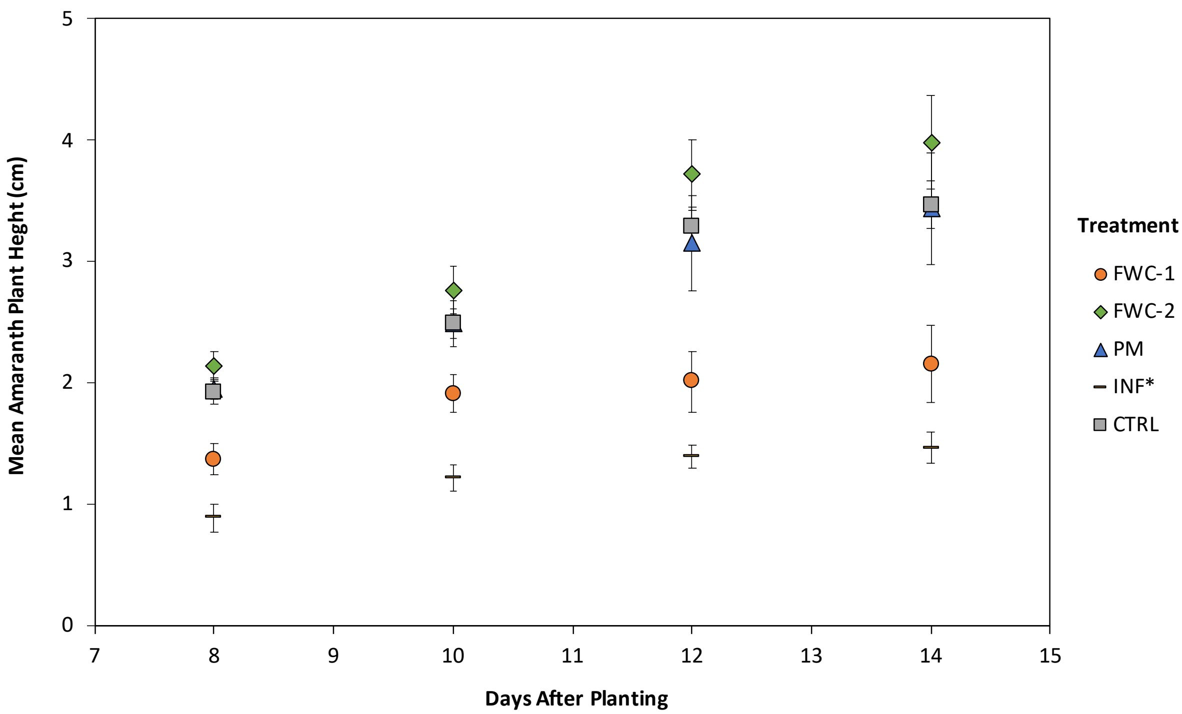


Figure 4.2: The growth of amaranth greens for the first planting is shown from 8 to 14 days after planting. The growth in FWC-2 treatments exceeds that of growth in PM and control treatments, which in turn exceed the growth in FWC-1 and INF* treatments.

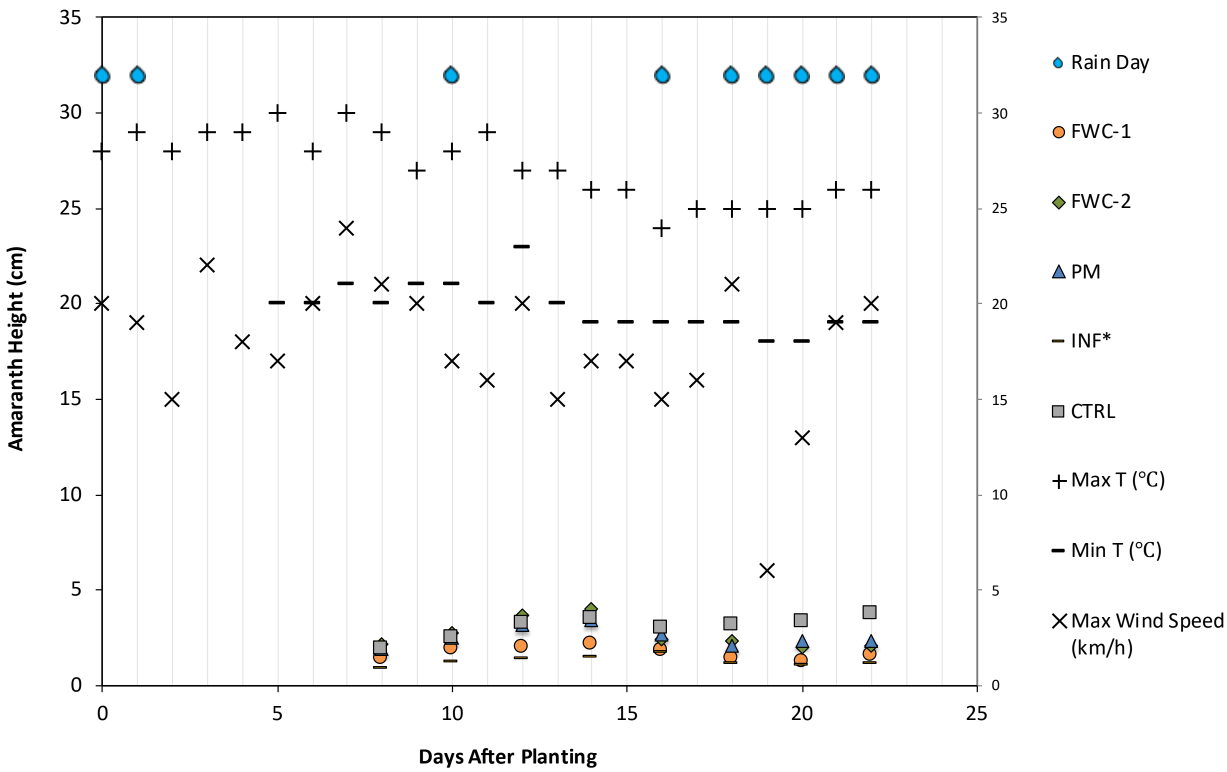


Figure 4.3: The growth of amaranth greens for the first planting is shown from 8 to 22 DAP (days after planting) along with minimum and maximum daily temperatures, daily maximum wind speeds, and whether or not it rained on any given day between the day of planting to when the amaranth were harvested at 22 DAP.

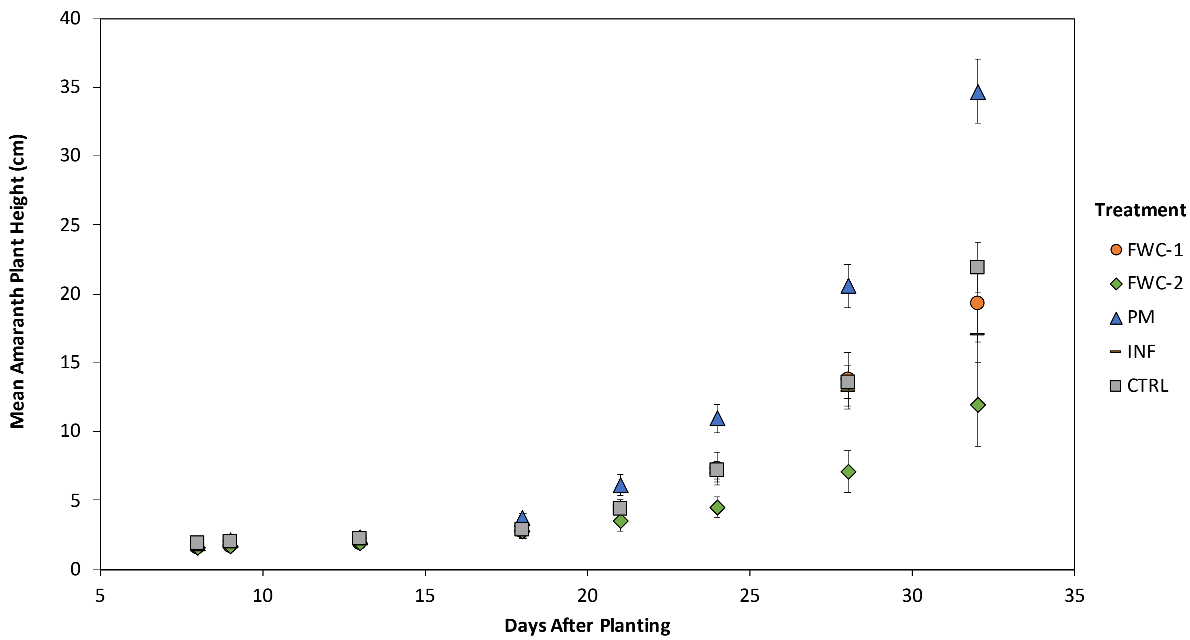


Figure 4.4: The growth of amaranth greens for the second planting is shown from 8 to 32 days after planting.

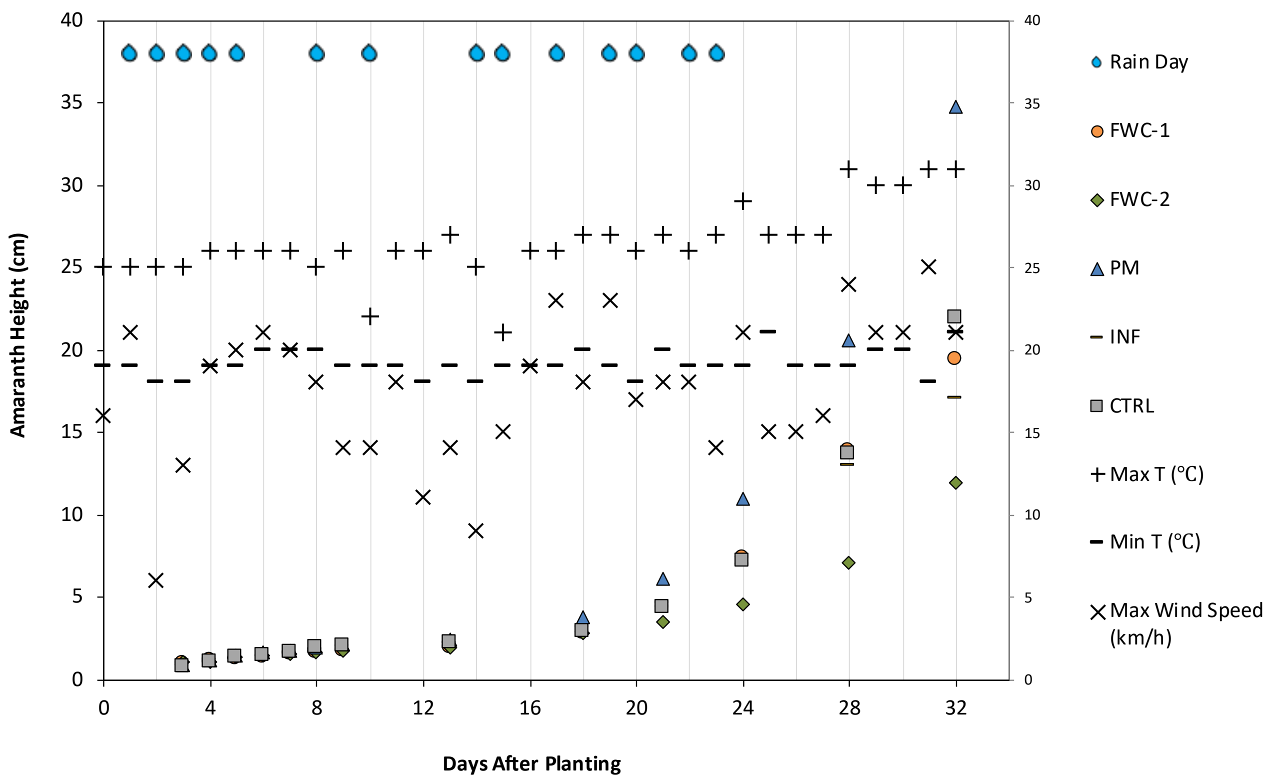


Figure 4.5: The growth of amaranth greens for the second planting is shown from 3 to 32 DAP (days after planting) along with minimum and maximum daily temperatures (T), daily maximum wind speeds, and whether or not it rained on any given day between the day of planting to the day before the amaranth were harvested at 32 DAP.

Cabbage Growth

Cabbage seeds had germinated in all treatments 7 DAP, and fertilizer was applied around the cabbage seedlings in the INF treatment replicates 14 DAP. Cabbages were harvested 55 DAP. Growth recorded from 15 DAP to harvest are shown in Figure 4.6 for all treatments.

Statistical analysis of the growth showed a significant difference over time [$F(1, 8) = 23.178$, $p=0.001$] but no significant differences with respect to treatment or interaction effects with time and treatment. With respect to time, cabbage growth showed no statistically significant difference between 15 DAP and 37 DAP. However, the heights of the cabbages at 55 DAP were significantly greater than the heights from 15 to 46 DAP. The average heights at harvest were 6.8±0.7 cm (INF), 5.2±0.4 cm (FWC-1), 4±0.0 cm (PM) 3.9±1.2 cm (FWC-2), 3.3±0.3 cm (CTRL).

Similar to amaranth growth, the cabbage growth was compared to the weather conditions that prevailed during the first growing period. Figure 4.7 shows the growth of cabbage along with the weather conditions (daily temperatures, wind speed, and days of rain) from planting (0 DAP) to harvest (55 DAP). The cabbages received 21 days of rain out of the 55-day growing period, with infrequent rain at the beginning of the growing period. It rained on the day of planting and the day after planting, and then again 10 DAP. Rain frequency increased in the middle of the growing period. From 18 to 42 DAP, the plants received regular rain with six rain days between 18 and 24 DAP, at which time the maximum daily temperatures ranged from 24°C to 26°C, and seven days of rain between 33 and 42 DAP, at which time the maximum daily temperatures ranged from 25°C to 27°C. There were no more rain days beyond 42 DAP and the maximum temperature range increased to 27°C to 31°C. There were several instances of high wind speeds (≥20 km/h), especially towards the end of the growing period, but they did not appear to adversely affect cabbage growth.

Statistical analysis of the second round of cabbage growth also showed a statistically significant difference over time [$F(1, 19) = 74.379$, $p<0.001$], but no significant differences with respect to treatment or interaction effect between time and treatment. Cabbage growth in INF* treatment was excluded from the statistical analyses because only one plant germinated and the growth lagged behind due to its delayed germination. With respect to time, cabbages showed no statistically significant growth between 8 and 21 DAP and between 32 and 36 DAP. The cabbage heights differed significantly from 21 to 32 DAP. The average heights at harvest were 2.7±0.4 cm (PM), 2.4±0.3 cm (FWC-1), 2.4±0.5 cm (FWC-2), 2.4±0.2 cm (CTRL), and 1.1±0.0 cm (INF*).

For the second round of cabbage planting, cabbage seeds had germinated in all treatments (except INF* treatments) at 5 DAP. In the INF* treatment only one cabbage seed germinated, out of all three replicates, at 13 DAP. Cabbages were harvested at 36 DAP due to the end of the field trial. The growth heights of the cabbages from the second growing period are shown in Figure 4.8 for all treatments. There was frequent rain at the beginning of the growing period from 1 - 5 DAP, 8 - 10 DAP, 13 - 15 DAP, 17 - 20 DAP, and 22 - 23 DAP. However, there was no rain in the period between 24 and 36 DAP. There were a total of 17 rain days over the 36-day growing period. Maximum daily temperatures mainly fluctuated between 25°C and 27°C at the beginning of the growing period until 23 DAP, after which the daily maximum temperatures increased to 27°C to 31°C. There were a few instances of high wind speeds (≥20 km/h) throughout the growing period, especially from 28 to 32 DAP. The weather conditions (rain days and daily temperature ranges) as well as the effects of treatment on cabbage growth are summarized in Table 4.6.

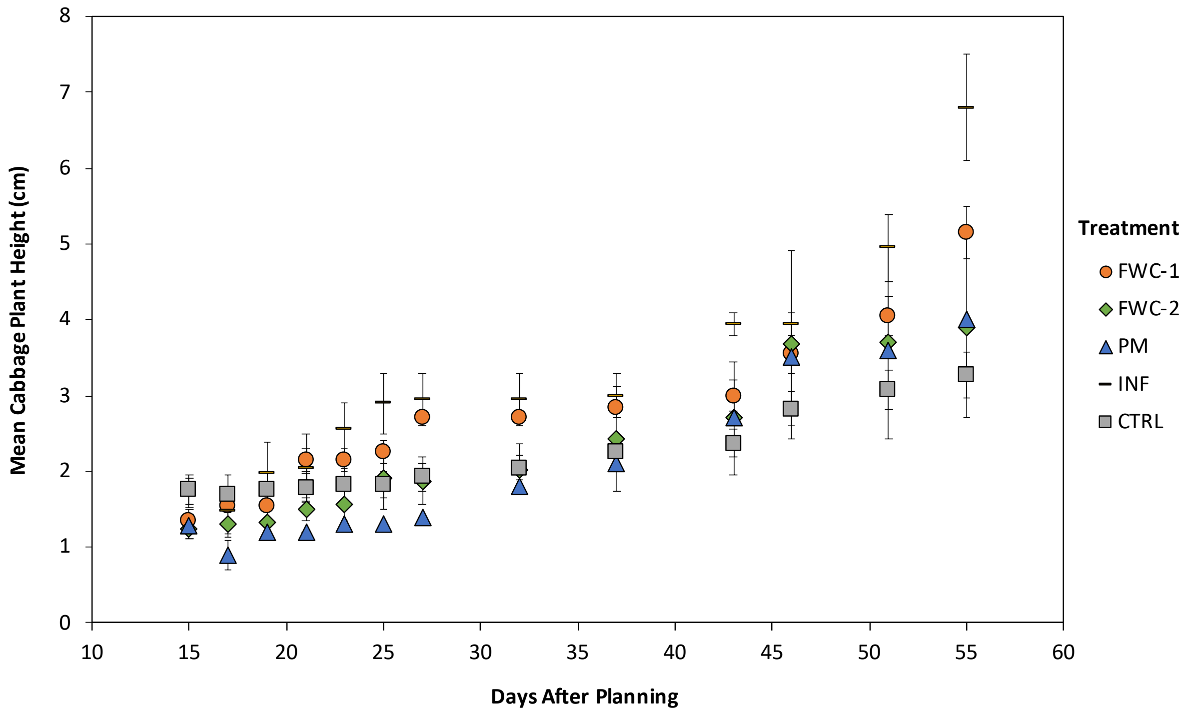


Figure 4.6: The growth of cabbage for the first growing period is shown from 15 to 55 DAP (days after planting). The growth in INF treatments is followed closely by growth in FWC-1 treatments, until 43 DAP at which point growth in F treatments exceeds that of other treatments. Cabbage growth in FWC-2 and PM treatments follows similar trends, and exceed growth in CTRL treatments.

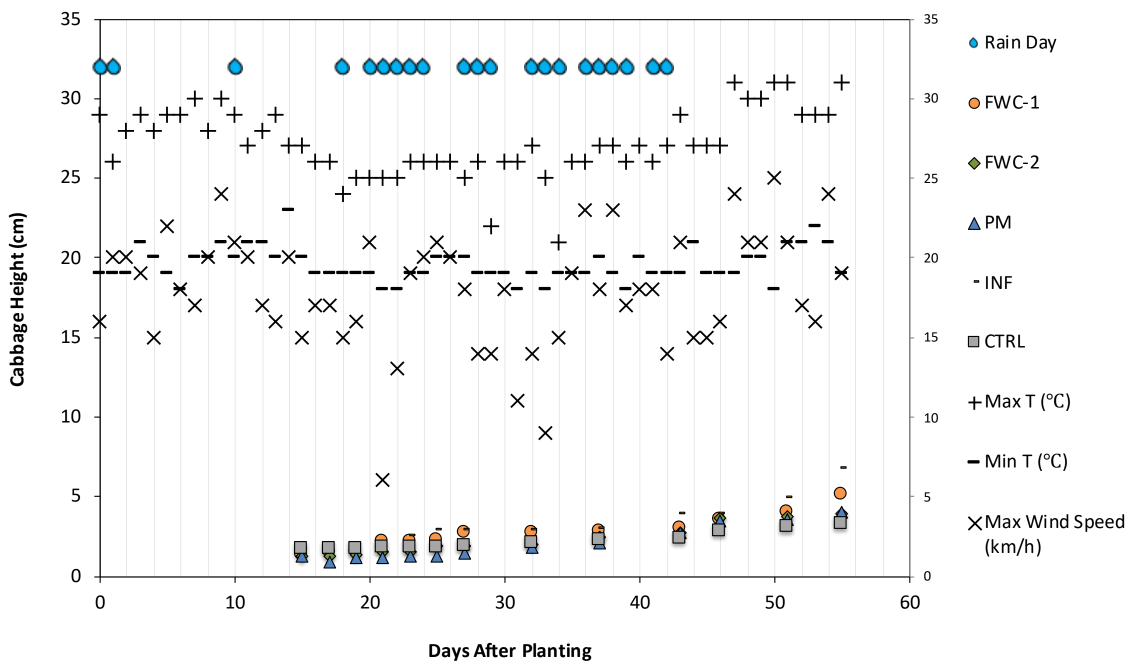


Figure 4.7: The growth of cabbage for the first planting is shown from 15 to 55 DAP (days after planting) along with minimum and maximum daily temperatures, daily maximum wind speeds, and whether or not it rained on any given day between the day of planting to when the cabbage were harvested at 55 DAP.

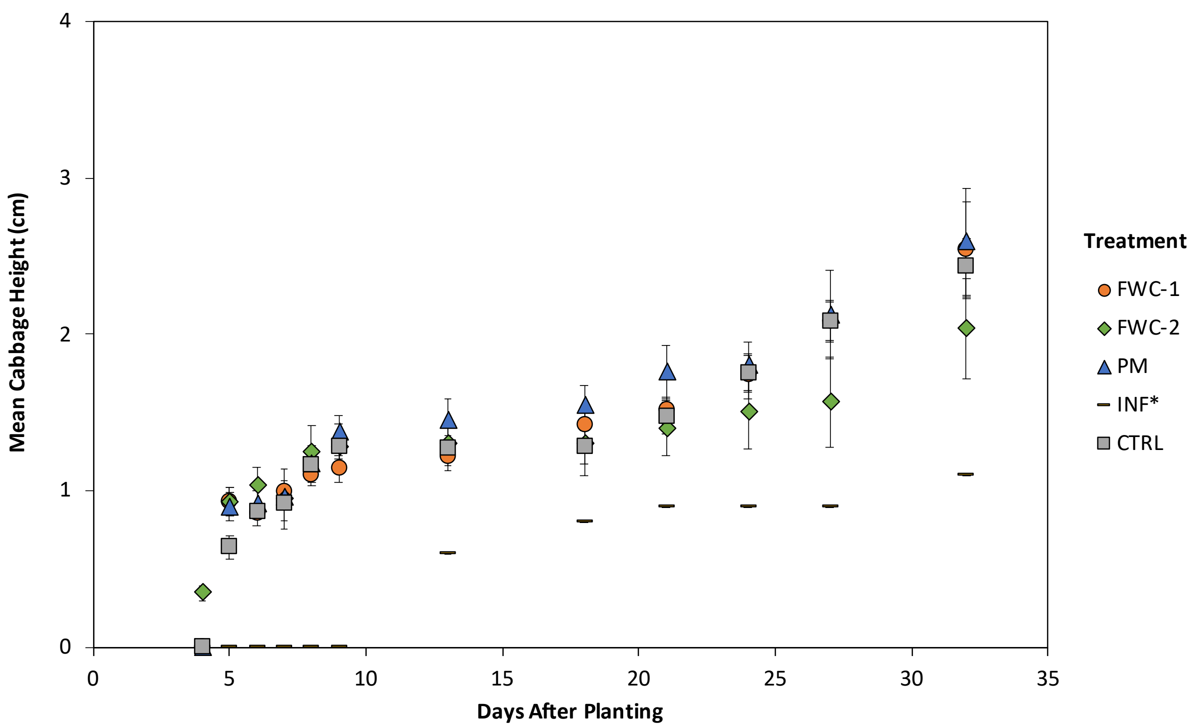


Figure 4.8: The growth of cabbage for the second planting is shown from 7 to 27 DAP (days after planting). The growth in all treatments follows closely with one another until 21 DAP at which point growth in PM, FWC-1, and CTRL treatments exceeds that of FWC-2 treatments. Cabbage growth INF* treatments is shown without standard error bars because only one seed germinated.

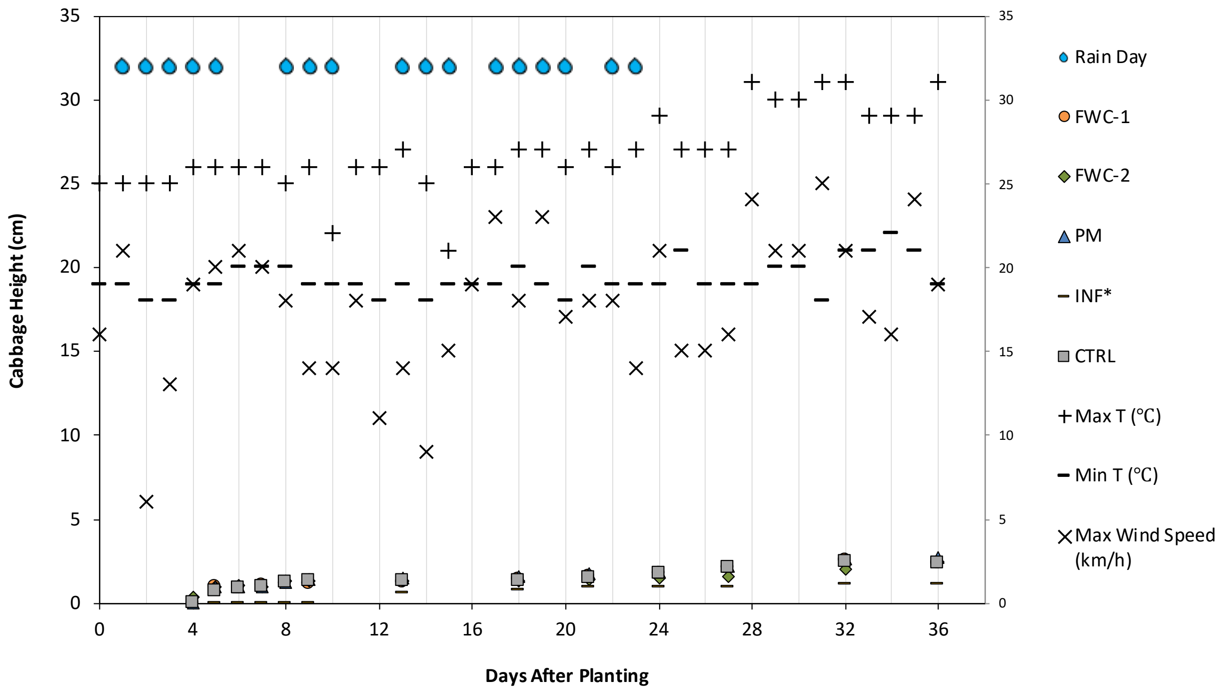


Figure 4.9: The growth of cabbage for the first planting is shown from 4 to 32 days DAP (days after planting) along with minimum and maximum daily temperatures, daily maximum wind speeds, and whether or not it rained on any given day between the day of planting to before the cabbage were harvested at 36 DAP.

Table 4.6: Summary of the weather conditions and treatment effects within the two growing periods for amaranth and cabbage plants in terms of rain frequency and minimum and maximum temperatures over the number of DAP (days after planting). Rain frequency is defined as infrequent (≤1/3 of the days), moderate (between 1/3 and 2/3 of the days), and frequent (≥2/3 of the days)

	First Planting	**Second Planting**
Amaranth		
Growing Period (days)	22	32
Rain Days	9	14
Rain Frequency 0 - 15 DAP	Infrequent	Moderate
Rain Frequency 16 - 23 DAP	Frequent	Frequent
Rain Frequency 24 - 32 DAP	n.a.	Infrequent
Temperature (min - max)		
0 - 15 DAP	19 - 30°C	18 - 27°C
16 - 23 DAP	18 - 26°C	18 - 27°C
24 - 32 DAP	n.a.	18 - 31°C
Treatment Effect on Growth[1]	CTRL, FWC-2 ^{a}	PM ^{a}
	PM ^{b}	CTRL, INF, FWC-1 ^{b}
	FWC-1 ^{c}	FWC-2 ^{c}
	INF* ^{d}	
Cabbage		
Growing Period (days)	55	32
Rain Days	21	17
Rain Frequency 0 - 15 DAP	Infrequent	Frequent
Rain Frequency 16 - 23 DAP	Frequent	Frequent
Rain Frequency 24 - 36 DAP	Frequent	Infrequent
Rain Frequency 37 - 55 DAP	Infrequent	n.a.
Temperature (min - max)		
0 - 15 DAP	18 - 30°C	18 - 27°C
16 - 23 DAP	18 - 26°C	18 - 27°C
24 - 36 DAP	18 - 27°C	18 - 31°C
37 - 55 DAP	18 - 31°C	n.a.
Treatment Effect on Growth	FWC-1, INF ^{a}	PM ^{a}
	FWC-2, CTRL ^{b}	CTRL, FWC-1 ^{ab}
	PM ^{c}	FWC-2 ^{b}
		INF* ^{c}

[1] Different letters in the same column indicate a significant difference ($p < 0.05$) between treatments (food waste composts (FWC-1 and FWC-2), PM (poultry manure), INF (inorganic nitrogen fertilizer), CTRL (control)).

4.4 Discussion

4.4.1 The Effect of Amendments on Urban Soil

According to Kimaro (2019), investments in organic amendments take a long time before paying back, and so, may be impractical for farmers who lack clear land tenure systems. However, this study demonstrated in a short-term field trial that organic amendments are comparable to, and in some cases outperform, nitrogen fertilizer use in urban agriculture.

Water Holding Capacity

The findings of this study confirm that the addition of organic amendments can improve water retention, increase SOC, and enhance microbial abundance in the sandy loam urban soils used for urban cultivation in Mwanza City. The average bulk density, 1.48 g/cm^3 for this site was in accordance with the typical value for sandy loam, which is 1.51 g/cm^3 (Gardiner and Miller, 2008). The sandy loam soils, characteristic of Mwanza Region in the Western Highlands Zone of Tanzania, are known have low WHC (National Bureau of Statistics, 2015b). In this study, WHC was found to increase with the addition of organic amendments, attributed to the presence of soil organic matter content, which is known to improve soil WHC (Evanylo et al., 2008; Kimaro, 2019). In this study, WHC was higher by 14 - 19% in soils treated with organic amendments than with nitrogen fertilizer. In other studies, the addition of organic amendments such as compost has reportedly increased soil water capacity by as little as 14% and as much as 35% (Agegnehu et al., 2015; Gay-des Combes et al., 2017).

pH

The pH in this field trial was also significantly lower for soils treated with poultry manure than all other treatments, whereas pH did not differ significantly across remaining treatments and the control. In the study by Agegnehu et al. (2015) the application of organic amendments did not significantly affect soil pH, whereas the study by Doan et al. (2015) showed that organic amendments increased soil pH. The soils in both cases were initially acidic and the pH resulting from organic amendment application remained below 7. Both Agegnehu et al. (2015) and Doan et al. (2015) investigated compost and biochar as the organic amendments. The pH of the control and amended soils in this field trial were also greater than that reported for Tanzanian soils (Ndakidemi and Semoka, 2006). The high pH levels at the site can be explained by the presence of wood ash prior to the field trial from the previous use of wood smouldering on the land. Ashes are strongly alkaline (Gay-des Combes et al., 2017) and composts produced with wood ash have a higher liming potential (Bougnom et al., 2010), similar to the liming potential of biochar, which has been shown to increase the pH of highly weathered tropical soils (Jien et al., 2021). The addition of biochar and compost to highly weathered tropical soils has also been shown to increase inorganic nitrogen and available phosphorus (Jien et al., 2021).

Soil Organic Carbon

The mean SOC content was also higher in organically amended soils compared to the control or fertilizer treatments, but the results were not significant. The lack of significant differences between organic and fertilizer treatments for SOC content is attributed to the short duration (1.5 months) of this study. Long-term studies have shown that the addition of organic amendments increases SOC over time (Sharma et al., 2008; Ngo et al., 2012; Doan et al., 2015; Agegnehu et al., 2015), and that the sustained increase of SOC in soil over time is dependent on the nature of the organic amendment (Ngo et al., 2012). Notably, SOC of the control soil (0.91%) in the present field trial study is less than that reported in the literature for Tanzanian soils (Ndakidemi and Semoka, 2006; Sugihara et al., 2010; Kamiri et al., 2013). Though with the amendments, the SOC values in this study are closer to the reported values, inferring lower inherent carbon in Mwanza's urban soil.

Total Nitrogen

The TN (total nitrogen), CEC, EC, and NO_3^- values of this present field trial study are comparable to other soil studies in Tanzania (Ndakidemi and Semoka, 2006; Sugihara et al., 2010; Kamiri et al., 2013). There were no significant differences in total nitrogen with respect to treatment. However, the study by El-Sharkawi (2012) reported similar values for loamy soils amended with urea fertilizer (0.19% TN) and organic treatments (0.21% for rice straw-manure compost and 0.22% for sludge treatment) over a 2 year study period. In this study, the increase in total nitrogen content was attained within a month and a half. Therefore, in the case of nitrogen requirement, organic treatments are comparable to fertilizer treatment.

Available Phosphorus

Phosphorus availability is generally a constraint to crop growth in tropical acidic soils of Tanzania and many other developing countries (Ndakidemi and Semoka, 2006; Szilas et al., 2007). However, in this study, P availability was not considered a limiting factor. Compared to other studies in Tanzania, the available P values in the soil for this study were higher (Ndakidemi and Semoka, 2006; Kamiri et al., 2013). Although in the soil study by Ndakidemi and Semoka (2006), the available P reported at one of the thirty sites was 54.6 mg P/kg, which is comparable to the 53.6 mg P/kg in the control soil in the present study.

The application of organic amendments has also been shown to increase available P significantly (Agegnehu et al., 2015). The available P in this study was significantly higher in poultry manure than fertilizer treatments. Poultry manure is known to have higher P content than other organic amendments, averaging at 2.7% P (Thangarajan et al., 2013). The study by Wei et al. (2015) reported Olsen P values for chicken manure compost at 6080 mg P/kg (0.680% P) as compared to 780 mg/kg (0.078% P) in food and vegetable waste compost. Whereas the composts used in this study were in the lower range at 150 mg P/kg (0.015% P) and 170 mg P/kg (0.017% P).

The soils are of volcanic origin therefore contain a lot of allophane (type of clay mineral) and therefore lots of P. but they are inherently still low in pH, but adding of ash increased pH and made the P inherent in the soil available. Soils of volcanic origin are not low in P, in fact they have a lot of P but its just not available

However, the soils around Mwanza region are of volcanic origin (National Bureau of

Statistics, 2015b), which are not low in P content but have limited P availability under the inherently low pH conditions. Therefore, the higher available P content in all treatments may be due to the relatively high pH levels of the field site soil (Gay-des Combes et al., 2017), which is attributed to the presence of wood ash. It has been demonstrated by Schiemenz and Eichler-Löbermann (2010) that ashes, due to their alkalinity, increase the plant available P pool in soil and can also be an effective source of P-fertilization in loamy sand. Carneiro et al. (2021) also found that the addition of biochar enabled slow release for plant uptake and protection against soil adsorption than soluble phosphorus fertilizer. Therefore, it is inferred that the wood ash present on the site is the source of stored phosphorus that was made available during the growing periods.

Soil Microbial Biomass - Carbon

Studies have also suggested that organic amendments increase SMB (soil microbial biomass) (Sharma, 2006; Bougnom et al., 2010; Sugihara et al., 2010; Ngo et al., 2012; Srivastava et al., 2016; Bass et al., 2016). Microbial biomass is sensitive to changing soil conditions, such as the addition of soil amendments (Odlare et al., 2008). In this study, the soils with organic amendments had significantly higher SMB-C than fertilizer treatments, which demonstrates the benefit of organic amendments to microbial growth in urban soils. According to Voroney et al. (2008), microbial biomass can serve as an early indicator of stresses on the ecosystem. The significant difference in microbial biomass results in this study also illustrates the potential for using it as a parametric indicator for short-term field trial studies.

The values of SMB-C obtained in this study are also higher than those reported in the literature (Sharma, 2006; Sugihara et al., 2010). The values of SMB-C reported for sandy loam soils in India, for example, ranged from 120.5 μg C/g in control soil to 167.2 μg C/g in soils treated with leaves and compost (Sharma, 2006).

However, the values for SMB-C in the present study are comparable to studies where soil and compost have been mixed with wood ash. The study by Gay-des Combes et al. (2017) on sandy loam soil, reported 1000 μg C/g in compost-treated soils and 1200 μg C/g in soils treated with a combination of compost and ash. In sandy clay loam soil, on the other hand, while both compost and ash treatments increased SMB-C, compost-plus-ash treatments had lower SMB-C than compost treatments only (Bougnom et al., 2010). Converting the extractable phospholipid fatty acids (PLFA) values reported by Bougnom et al. (2010) to SMB-C, using the relationship recommended by Bailey et al. (2002) and a K_{EC} of 0.45, the resulting SMB-C values are 929 μg C/g for compost amended soil and 769 μg C/g for compost-plus-ash amended soil.

Further, wood ash is similar to biochar as both are produced through a smouldering process that results in wood carbonization (Hansson et al., 2020). A study by Jien et al. (2021) showed a change in soil microbial communities with the addition of biochar that prompted organic matter decomposition and ammonia oxidation. In this study, the NH_4^+ values in this field trial study are much greater than those reported in other studies on Tanzanian soils (Sugihara et al., 2010; Srivastava et al., 2016), which is attributed to increased N-mineralization by the higher levels of soil microbial biomass present at the field site.

Therefore, the presence of wood ash played a role in the higher levels of SMB-C obtained from this field study and should be considered in further studies in urban agriculture in Mwanza, or Tanzania in general.

Cation Exchange Capacity

According to Buol et al. (1998), soil organic matter is also known to increase CEC, but there were no significant differences with respect to treatment in this study. Nonetheless, the values for CEC are interesting to compare because according to Ndakidemi and Semoka (2006), soils with 6.0 to 12.0 cmol/kg have poor exchangeable bases and limited capacity to supply nutrients to plants, and soils with < 12 cmol/kg are typical of weathered soils. The average values were greater than 12 cmol/kg in the poultry manure, one of the composts, and fertilizer treatments as compared to the control. Therefore, the addition of amendments improved cation exchange capacity of the soil comparably.

4.4.2 Amaranth and Cabbage Crop Growth

Amaranth and cabbage growth under fertilizer treatment were also comparable to growth under compost treatment for both growing periods. Growing amaranth is important to food security because amaranth is one of the cheapest dark green vegetables in the tropical market (Rastogi and Shukla, 2013). It has a high dietary value (Akanbi and Togun, 2002) due to high levels of iron, vitamin A and C, minerals, and protein in the leaves (Whitehead et al., 2002). Therefore, growing the crop for both leaves and seed can help support household nutrition for small-scale growers (Hoidal et al., 2019). Cabbage, on the other hand, is a commercial crop whose yield is a common indicator of profit for vegetable growers (Ji et al., 2017). Cabbage is a cool weather crop (Tiwari et al., 2003), and its production can be vulnerable to soil quality decline, particularly soil compaction (Mochizuki et al., 2007). Cabbage yield is also dependant on various factors, such as irrigation and environmental conditions (Ji et al., 2017), amendment use (Shrestha et al., 2020), as well as the containment and substrate in which cabbage is grown (Tiwari et al., 2003; Mitchell and Frisbie, 2017).

Amaranth is a fast growing leafy green vegetable (Rastogi and Shukla, 2013) that is grown during the wet season or under irrigation in the dry season (Akanbi and Togun, 2002). In this study, the amaranth was grown primarily using rainfall, with limited supplementary irrigation on days with no rain. In the first growing period, amaranth growth was poor. Before the amaranth growth was negatively affected by external environmental factors in the first growing period, which are discussed in Section 4.4.3, growth in one type of compost treatment was comparable to control treatment, and significantly greater than growth in poultry manure and the other type of compost. Whereas in the second growing period the amaranth grew rapidly over a period of thirty days. Heights of amaranth plants in other studies have been reported between 7 cm to 49 cm (Whitehead et al., 2002) and 20 cm to 30 cm (Akanbi and Togun, 2002). The heights at harvest after the second growth period in this study ranged from an average of 12 cm in one type of compost-treated soils to 34 cm in poultry manure treatment.

There are few studies that have investigated the effect of food waste compost, manure, and fertilizer separately on amaranth growth. The study by Aynehband et al. (2017) reported no significant differences between amaranth grown only under fertilizer treatment or under combined fertilizer and compost treatment compared to non-amended soil. However, there were significant differences in amaranth height and stem diameter under a combined fertilizer and vermicompost treatment compared to no amendment (Aynehband et al., 2017). The vermicompost had reportedly higher available P content, as did the poultry manure-treated soils in this study. Additionally, the study by Akanbi and Togun (2002) reported higher amaranth yields with compost made from maize stover and poultry manure than under fertilizer. Poultry manure is often favoured as a type of manure in tropical countries because of its high P content. In this study, growth under poultry manure treatment was comparable to compost treatment in the first growing period but outperformed all other treatments in the second growing period. The soil pH decreased over time and rainfall frequency increased which allowed for increased P and nutrient uptake by plants in the second growth period (Fernandes et al., 1994; Cerda et al., 2017). Growth under fertilizer and compost treatments was comparable. Therefore, organic amendments such as poultry manure and compost can be used just as effectively as inorganic fertilizers to grow amaranth greens.

Cabbage growth under amended soils in this study exceeded growth in control soils in the first growing period. These results are supported by Shrestha et al. (2020) who reported cabbage yields under rain and supplementary irrigation were 26% greater in soils amended with fertilizer, manure, and municipal composts than soils without any amendments. Cabbage growth under composts and fertilizer treatments was comparable, but growth in both fertilizer and compost treatments was significantly greater than poultry manure treatments.

According to Bass et al. (2016), compost addition can result in yield benefit due to improved water retention. Therefore, it was expected that since the organically amended soils have higher water holding capacities than fertilizer-treated soils, growth under no rain conditions would be greater in the organically amended soils. However, the method by which irrigation occurs has also been found to influence cabbage growth. Tiwari et al. (2003) reported that cabbage yields were 62.44% greater under drip irrigation than under furrow irrigation. On days when there was no rain, the supplementary irrigation provided to cabbages was through water poured locally around each plant, which is similar to drip irrigation, and so the lack of rain did not hinder overall cabbage growth in any treatment. In the second growing period, cabbage growth did not differ significantly between the amended and not amended soils (except INF* treatments).

4.4.3 Limitations to Crop Growth

Amaranth Defoliation

Amaranth crops suffered from defoliation and hindered height growth in the first growing period, with heights at harvest ranging from 1 cm in INF* treatments to 3.6 cm in control treatments. There were no adverse defoliation events in the second growing period.

It is speculated that the growth before 8 DAP (days after planting) in the first amaranth growing period was affected by consecutive days of strong winds 6 and 7 DAP, during which time winds reached 24 km/h speeds. However, high winds were also prevalent during the second round of amaranth growth 6 and 7 DAP, though wind speed reached a maximum of 21 km/h rather than 24 km/h. No studies were found that investigate the effect of wind speed on amaranth growth. There is, therefore, insufficient data to state that wind alone had a significant effect on amaranth growth during the first growing period.

The rain patterns during the two planting rounds of amaranth also differed. In the first growing period, there was limited rainfall, with scarce rain at the beginning of the growing period and continuous rain at the end of the growing period. In the second growing period, there was more frequent rainfall with rainy days spread out over the beginning of the growing period, though there was no rain towards the end of the growing period. An irrigation study by Masariramb et al. (2012) at varying field capacities reported that while amaranth growth was not affected at 85% water capacity, the crops grown at 65% and 40% water capacity showed signs of water stress with fewer leaves, smaller heights, and lesser stem girth. Therefore, water availability plays a role in amaranth growth.

The study by Whitehead et al. (2002) showed that amaranth growth is also affected by temperature, reporting further that mean daily soil temperatures at or above 25°C are required for maximum amaranth seed germination, mean air temperatures between 28°C and 30°C produce maximum leafy yield, and growth is negatively impacted when mean daily air temperatures decline to 18°C. Comparing growth and weather conditions, the low daily air temperatures after 15 DAP in the first round of amaranth growth may indeed have been the cause for the growth stagnation. Interestingly, the growth in control soils in the first planting were less affected by the stagnating effects of lower air temperatures than the amaranth growth in all other treatments. For the second round of amaranth growth, the daily air temperatures were between 18°C and 25°C, which corresponded to the slow growth observed before 15 DAP, whereas after 18 DAP the maximum air temperatures were higher (> 27°C), which corresponded to rapid amaranth growth.

The defoliation event that occurred before 8 DAP in the first round of amaranth growth did not hinder amaranth from growing steadily between 8 and 16 DAP. Defoliation has been shown to be a concern among farmers who use amaranth for leaves and seed, though it has been found that a single defoliation event with up to 50% leaf removal does not impact seed yield (Hoidal et al., 2019). In this study, however, other factors prevented the amaranth from reaching maturity in the first growing period and the crops from the second planting were harvested before seed production.

Fertilizer Misuse

One of the barriers cited by McIntire (2014) to the use of fertilizer in SSA was the lack of information on how to use fertilizers appropriately. The findings from the present study support this statement as the conflicting instructions received for urea fertilizer application had a negative impact on crop germination and crop growth. Fertilizer application with the seeds at the same time as planting proved to be the incorrect method of application as is indicated by the delayed germination in both amaranth (first planting) and cabbages (second planting). Incorrect fertilizer application did not have as much effect on amaranth seed germination as it did on cabbage seed germination, with only one cabbage seed germinating under this condition. Nitrogen fertilizer is highly soluble (Thangarajan et al., 2013), and the lack of rain at the beginning of the first growing period compared to the abundance of rain at the beginning of the second growing period may have contributed to the suppressed cabbage seed germination. The inorganic N released from the fertilizer in the soil would result in acidic conditions, which are known to hinder cabbage germination and growth (Mitchell and Frisbie, 2017).

Differences in Compost

Growth in FWC-2 treatments, on the other hand, was consistently lower in the second planting for both amaranth and cabbage growth, whereas growth under FWC-1 treatments was higher. This difference could be attributed to the lower application rate of FWC-2 compared to FWC-1. According to Bass et al. (2016), compost is generally not stable over medium to long-term timescales, and so regular reapplication would be required over extended periods for significant SOC improvements. Additionally, a majority of African countries do not have standards for the application of manure or compost to land, which makes it difficult to monitor nutrient addition and provide guidelines for organic matter (Couth and Trois, 2012). The application rate of 2.5 kg/m^2 for FWC-1 and PM is deemed sufficient for amaranth and cabbage growth based on the results of this study. From experience in this study, food waste compost application is recommended before each cropping season at a rate of at least 2.5 kg/m^2. However, further research is needed to evaluate efficacy of application rates without the influence of wood ash and under differing cropping systems and rain-fed versus irrigation regimes.

4.5 Conclusions

The purpose of this study was to assess the effects of varying soil treatments (organic and inorganic) on urban soil quality and crop growth in Mwanza City. The findings of this study demonstrated that the application of organic amendments improves urban soil quality compared to the application of fertilizer. Soils amended with poultry manure and composts had higher soil water holding capacity and increased soil microbial biomass (carbon), which can be used as indicators for short duration field trials.

Additionally, crop growth under compost treatments was comparable to crop growth in fertilized soils and soils without amendments. Crop growth performed best with poultry manure treatments under frequent rain conditions. It was also found that improper use of fertilizer can significantly delay germination and crop growth. Therefore, the study concludes that the use of only fertilizers to improve crop yield should be discouraged in urban agriculture, particularly in Mwanza, Tanzania. Instead, use of organic amendments, such as composts from food waste or manure, should be encouraged. However, future research is required to evaluate standards for compost and manure application rates on urban agricultural soils in Tanzania. Further assessments of other cultivated urban soils are also required for soil parameters presented in this study as well as additional soil parameters, such as soil porosity and available/total potassium. Future studies should also examine the nutritional elements and contaminants in the crops grown in urban agriculture, specifically in cabbage and amaranth greens under differing amendment applications.

The soil in this study had wood ash present due to previous land use, which should be taken into consideration for future uses of this study. The presence of wood ash at the site prior to the field experiment had a pronounced effect on the pH of the soil, as well as the available P and SMB-C contents of the soil. Gay-des Combes et al. (2017) found that compost and ashes were complementary fertilizing pathways that promote soil fertility through positive effects on soil moisture, pH, organic matter, and microbial activity. Therefore, future studies could also explore the potential for organic amendments blended with wood ash, which increases soil pH, for improving crop productivity in tropical acidic soils.

Chapter 5

Simulations of Urban Soil Organic Carbon under Organic and Inorganic Amendment Scenarios in Mwanza,Tanzania using CENTURY

5.1 Introduction

Globally, the land area for agricultural use increased from 1961 to 2011 as the world population grew from approximately 3 billion in 1961 to 7 billion in 2011 (Lal, 2013a). Rapid urbanization along with population and income growth are the key forces driving the global food demand (FAO, 2016).

With the global population expected to increase to 9.2 billion by 2050 (Ronald and Adamchak, 2010), and urban populations expected to double in African countries (UNFPA, 2007), food security is a growing concern for the Africa continent. One of the primary causes of declining food security in sub-humid and semi-arid tropics of Africa is soil fertility depletion on smallholder farms (Wichelns, 2003).

Over much of the continent, farmers mix and balance organic and inorganic techniques to improve soil fertility (Fairhead and Scoones, 2005). However, many farmers struggle to replenish soil fertility because of lack of investment capacity (improved seeds and farming inputs) and secure land tenure (NEPAD, 2013). Additionally, East Africa suffers from accelerated soil erosion, which affects crop production and yield (Lal and Singh, 1998; Borrelli et al., 2017). Consequently, increases in agricultural output in Africa have come from increased harvested areas rather than higher yield (McIntire, 2014). However, rapid urbanization is also increasing competition for land (Ayambire et al., 2019), which is especially concerning for urban agriculture, which engages 29 million households in Africa (Lorenz, 2015).

Urban agriculture contributes to increased dietary diversity, which is a component of food security (Tasciotti and Wagner, 2015). Urban agriculture can also mitigate adverse environmental impacts of cities and promoting resource-use efficiency while enhancing climate change adaptation (Ayambire et al., 2019). Therefore, urban agriculture can contribute to SDGs (Sustainable Development Goals) 2 (Zero Hunger) and 11 (Sustainable Cities and Communities) as put forward by the United Nations (Sustainable and Goals, 2018; Ayambire et al., 2019). However, urban agriculture faces many challenges, such as water availability, labour, inputs (seeds, amendments), and land availability and security, as well as lack of support from local governments (Magigi, 2013). Urban agriculture is a prominent activity in major cities in Tanzania, including Dar es Salaam and Mwanza (Sawio, 1994; Flynn, 2001; Magigi, 2013). However, urban agriculture has received little attention in urban planning and zoning policies, and carries the negative connotation of 'persistence of peasant culture' in the perspective of local governments (Mwanza City Council, 2017).

5.1.1 History of African Agriculture

Before colonization, African farmers practiced shifting cultivation, which allowed the soil to maintain its fertility because the cultivated area would be left to fallow for three or more growing seasons (European Commission, 2013a; Bationo et al., 1998). Over the centuries, African farmers had also adapted various foreign crops to local conditions (Yudelman, 1975), such as maize that was introduced by the Portuguese in the 1500s and the Dutch in the 1600s to different parts of Africa (Monjane et al., 2011). However, production methods were governed by the natural environment (Yudelman, 1975). Additionally, before colonization, the African economy was based on a barter system as opposed to a monetized system (Ocheni and Nwankwo, 2012), relying largely on household agriculture (Yudelman, 1975) to provide cereals and vegetables for home consumption and for local barter (Anderson and Throup, 1985).

In the 1850s, the influx of missionaries, traders, and private research groups introduced new agricultural input to tropical Africa, which led to colonial involvement in African agriculture from the 1880s to the end of the colonization period (Yudelman, 1975). One of the aims of colonization was to export agricultural products from colonized countries to meet food and industry demands of the colonizers (Ocheni and Nwankwo, 2012). Therefore, during colonization, African farmers were displaced by settler farmers, consigned to lands with marginal agricultural potential, and encouraged to cultivate continuous and annual cropping systems (Bationo et al., 1998). However, concerns were voiced by agricultural departments as early as 1937 regarding the possibility of soil erosion as a result of over-cultivation (Anderson and Throup, 1985).

By the end of the colonial era, publicly financed research was being conducted in all the colonies or former colonies in tropical Africa (Yudelman, 1975). Research in East Africa included irrigation requirements of arabica coffee, sorghum and maize drought-resistance, the effect of activated charcoal on organic decomposition in dried and wetted soil, and maize and cassava resistance to streak viruses (Humphries, 1960). African farmers had begun using new farm implements and new seeds developed within the region, such as hybrid maize developed in Southern Rhodesia (now Zambia) (Yudelman, 1975). The global increase in fertilizer use since World War II increased crop yields globally, except in sub-Saharan Africa where fertilizer adoption was low (Lal, 2013a). And so, high population growth and continuous cultivation in areas that used to be under traditional shifting cultivation led to nutrient depletion from the soil, decline of arable land, decreased crop yields, and reduction in food produced per capita (European Commission, 2013a; Bationo et al., 1998). Soil erosion continues to be an ongoing concern in SSA (sub-Saharan Africa) where soil erosion for 2012 was estimated at 5-50 Mg ha^{-1} yr $^{-1}$ in areas within Tanzania (Borrelli et al., 2017). Changes in average soil erosion have been >5% over the period of 2001 - 2012 (Borrelli et al., 2017).

5.1.2 History of Tanzanian Urban Agriculture

The general history of African agriculture does not differentiate between rural versus urban areas. However, there are few accounts that provide historical data for urban agriculture. The earliest accounts of urban farming in Dar es Salaam, a city established in the 1860s, document urban cultivation of rice, coconut, maize, and cassava (Flynn, 2001).

The town of Mwanza, established in 1872, was founded as a commercial centre for cotton export (Mwanza City Council, 2008). The local municipal government was established in 1972, and the town gained city status in 2000 (Mwanza City Council, 2008). Agriculture currently engages 62.8% of the population (United Republic of Tanzania, 2017), and urban agriculture has been practiced in the region since the mid-1960s (Flynn, 2001).

The shortage of fertile land and water availability that continues to threaten the livelihood of African rural farmers (Malley et al., 2008) extends to urban farmers since urban soils are already deemed to be degraded (Lorenz, 2015). Additionally, in Tanzania, uncontrolled runoff results in water erosion, which leads to further loss of water and soil fertility (Kimaro, 2019). In Mwanza, the sandy to loamy soils are already low in fertility (National Bureau of Statistics, 2015b), and are susceptible to declining soil fertility and declined soil and crop productivity (Sanchez, 2002). Therefore, research for urban planning and agriculture needs to focus on land management strategies that can increase soil resilience (Tully et al., 2015), such as restoring the SOC pool through the use of organic amendments (Lal, 2011; Thangarajan et al., 2013).

According to Dewitte et al. (2013), the fundamental knowledge foundation from which African countries can shape policy and land management decisions is lacking. Long-term studies can be valuable to study changes in SOC dynamics and the effects of land use and soil management over time, but most studies are short in duration compared to agricultural soil use (Bortolon et al., 2011). In recent years, digital soil mapping has been promoted as a tool for compiling soil data, which can subsequently be used to develop evidence-based soil management recommendations and decisions (Sanchez, 2009; European Commission, 2013a; Hengl et al., 2015). Site-specific soil modelling can also be a useful tool for simulating soil properties under differing land management systems over long periods of time, which researchers have demonstrated using CENTURY SOC (soil organic carbon) modelling software (Cole et al., 1993; Dil and Oelbermann, 2014; Oelbermann et al., 2017; Smith, 2017). The objective of this study, therefore, was to use the CENTURY model to evaluate the impact of organic amendments (food waste compost and poultry manure) and inorganic amendments (wood ash and fertilizer) on SOC in cultivated urban soils in Mwanza, Tanzania.

5.2 Materials and Methods

The model, CENTURY, developed by a team at Colorado State University, is a regional scale model of C (carbon) and N (nitrogen) biogeochemical cycling to predict soil organic matter dynamics (Schimel et al., 1990; Parton et al., 1993). The model divides the SOC into several pools (active C, slow C, and passive C) with differing turnover rates (Cole et al., 1993). Knowledge of different SOC pools provides a better understanding of the relationship between SOC and land use, and can help with measuring the impacts of management practices (Guimarães et al., 2013). The use of the CENTURY model requires historical data of land management to simulate the current state of SOC and, in turn, project changes in SOC under differing land management strategies.

5.2.1 Study Site

The CENTURY model was used to simulate SOC stock to a 20 cm depth in the tropical urban agricultural soils of Mwanza, Tanzania. Mwanza region receives bimodal rainfall, with a short rainy season between October and December and a long rainy season between February/March and May (National Bureau of Statistics, 2012a, 2015b; Mwanza City Council, 2017). Maize (*Zea mays* L.) is the dominant crop grown in Mwanza region, followed by paddy (*Oryza glaberrima*), cotton (*Gossypium arboreum* L.) (National Bureau of Statistics, 2012a). The crops grown in the two seasons do not differ considerably, though larger areas are planted for cultivation in the shorter rainy season as compared to the long rainy season (National Bureau of Statistics, 2012a). The CENTURY model requires climate data to establish model parameters. Mean weather data from 1985 to 2015 gathered at the weather station at the Mwanza International Airport were acquired from CustomWeather (2020). The climate data used for the simulation are provided in Table 5.1.

The CENTURY model also requires site characteristics. The urban site chosen for modelling purposes is situated at 2°31'24.71"S 32°53'51.46"E and is comprised of sandy loam soil. It is regularly used for urban crop cultivation. Additional site characteristics used for modelling purposes are provided in Table 5.2 and were derived from the study in Chapter 4.

Table 5.1: Mean climate data for Mwanza, Tanzania derived from the data collected by the weather station at the Mwanza International Airport from 1985 to 2015

Month	Min Temp (°C)	Max Temp (°C)	Precipitation (mm)
January	19	28	31.0
February	19	28	19.5
March	19	29	50.5
April	19	28	73.5
May	19	28	32.1
June	18	28	3.0
July	17	28	0.3
August	18	29	4.0
September	19	29	7.6
October	19	29	40.5
November	19	28	59.8
December	19	27	60.1

Table 5.2: Site characteristics (0 – 20 cm) of an urban sandy loam soil in Mwanza, Tanzania

Site Characteristic	Values
Location	Mwanza, Tanzania
Latitude	2°31'25"S
Longitude	32°53'51"E
Altitude (m)	1140
Soil classification	Sandy loam
Sand (%)	72
Silt (%)	14
Clay (%)	13
Bulk density (g/cm^3)	1.48
pH	7.7
Soil OC (%)	1.26
Soil total N (%)	0.19
C:N ratio	6.9
SMB-C (μg C/g)	328.3

OC (organic carbon), N (nitrogen), SMB-C (soil microbial biomass - carbon)

5.2.2 Land Management in CENTURY Model

The CENTURY simulation also requires scheduling of historical land management and crop cycles to establish equilibrium soil carbon stock values and determine the impacts of land management changes on SOC over time. The time periods scheduled into CENTURY are referred to as blocks. A summary of the scheduling is provided in Table 5.3.

Block 1 was set from year -10,000 (to establish baseline SOC) to 1870, which was the beginning of colonial influence on agriculture. This block period was characterized by the growth of tropical grass in Mwanza region. In 1872, Mwanza was founded as a commercial centre for cotton export (Mwanza City Council, 2008). Block 2 begins in 1871, marking the beginning of the colonization period and land use change to agriculture in Mwanza. The practice of annual ploughing is built into the block, along with annual cultivation of cotton and unimproved maize. Archived maps of Tanzania (Figure 5.1) show that around the 1960s, Mwanza region still had significant production of cotton as a cash crop. Therefore, Block 2, set from 1871 – 1961. The practice of annual ploughing continues in all subsequent blocks.

By the end of the colonization period, the green revolution was well under way, using chemical pesticides and hybrid seeds (Evenson and Gollin, 2003). Though the implementation and crop yield success did not extend to African countries (Pingali, 2012), hybrid maize seeds did become more widely available (Brooks, 2014). Therefore, unimproved maize is replaced with hybrid maize for Block 3, which is set from 1961 (the year of Tanzanian independence) to 2000. Annual cultivation of rice is also added to the model, in addition to the existing annual cotton cultivation.

Table 5.3: Scheduling of land management practices and crop cycles in Mwanza, Tanzania for the CENTURY model

Date	Background Information	Management Practices
10,000 BC – 1870 (Block 1)	10,000 years to estimate equilibrium SOC	Tropical Grassland
1871 – 1960 (Block 2)	Period of colonial influence on agriculture 1872 Mwanza officially cotton export town	Crops: Cotton and unimproved maize annually Cultivation: Plowing (P) Harvest: Cotton (T), maize (GS) Erosion[1]: 0.5 $kg/m^2/month$
1961 – 2000 (Block 3)	1961 Tanzania gained independence	Crops: Cotton, rice, and hybrid maize annually Cultivation: P Harvest: Cotton (T), rice (T), maize (GS) Erosion: 1.0 $kg/m^2/month$
2001 – 2020 (Block 4)	2001 Mwanza promoted to city status	Crops: Hybrid maize biannually, rice annually Cultivation: P Harvest: Maize (GS), rice (T) Erosion: 2.0 $kg/m^2/month$
2021 – 2200 (Block 5)	Start of annual amendment application	Crops: Hybrid maize biannually, rice annually Cultivation: P Harvest: Maize (GS), rice (T) Erosion: 2.0 $kg/m^2/month$ Amendments Compared (17 g $N/m^2/y$)[2]: Poultry Manure (PM)[3] - 240 g $C/m^2/y$ Food Waste Compost[4] (FWC) - 246 g $C/m^2/y$ Inorganic Fertilizer - Nitrogen (IFN) Wood Ash (Ash)[5] - 254 g $C/m^2/y$

[1]Adapted from Ashagre et al. (2018)
[2]Amendments were applied to meet crop nitrogen requirement, upper end estimates used from Osmond and Riha (1996)
[3]Derived using values from Evanylo et al. (2008)
[4]Derived using values from own research (Chapter 3)
[5]Derived using values from Gay-des Combes et al. (2017).

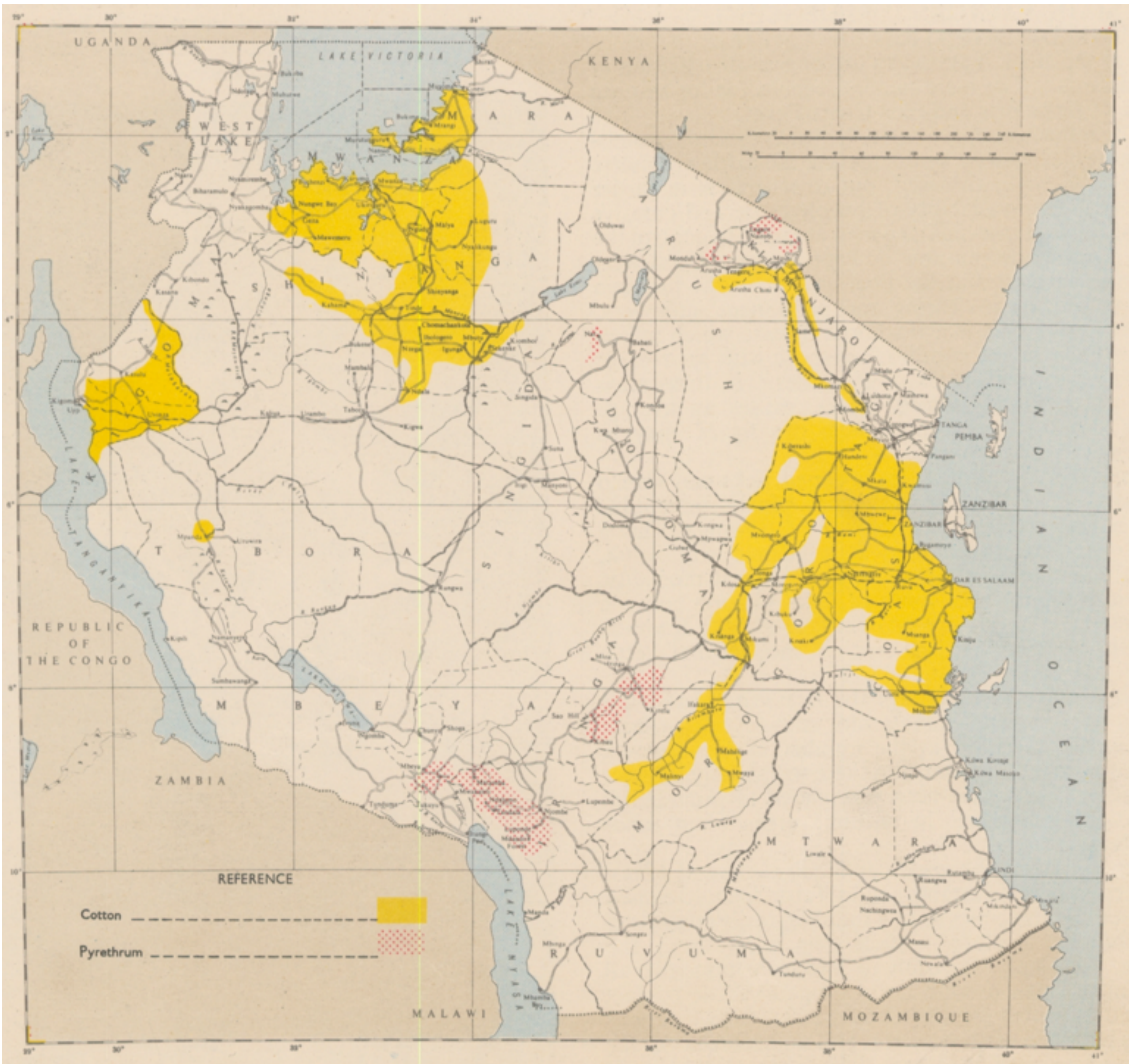


Figure 5.1: Map of main cash crops grown in Tanzania in 1967, used with permission from The Geological Survey of Tanzania (personal communication, 2018). The map, used to generate the cultivation history required for the CENTURY model, shows that cotton was the main cash crop grown around Mwanza region.

Block 4 was set from 2001 to 2020. Mwanza was established as a city in 2001. In the simulation model, cotton cultivation was replaced by hybrid maize to account for the reduced space in an increasingly urban environment. The cropping systems of cultivating hybrid maize twice a year and paddy rice annually continue into Block 5, which was set from 2021 to 2200. This block period was used to simulate the impact of organic amendments, poultry manure (PM) and food waste compost (FWC), and inorganic amendments, fertilizer-nitrogen (IFN) and wood ash (Ash), compared to no amendments (NA).

To account for the effects of urbanization as well as the impact of soil loss, erosion rates were added only to the month of January in Block 2 at 0.5 kg/m^2/year, Block 3 at 1.0 kg/m^2/year, Blocks 4 and 5 at 2.0 kg/m^2/year using information from studies on urban erosion by Hu et al. (2001) and Ashagre et al. (2018). The map of Tanzania (Figure 5.2) indicates annual soil loss around Lake Victoria ranged from 2-50 Mg/ha/year between 2001 and 2012.

Four soil carbon (C) parameters were simulated in CENTURY: SOC, and active C, slow C, and passive C fractions. The differences between the C fractions are presented in Table 5.4 with information derived from Parton et al. (2001).

Table 5.4: Characteristics of soil carbon fractions derived from Parton et al. (2001)

Carbon Fraction	% of SOC	Turnover Rate
Active	2 to 4	Few months to years
Slow	45 to 65	20 to 50 years
Passive	30 to 40	400 to 200 years

The differences in the C parameters between treatments were compared statistically using the mean values in the interval between 2100 to 2110, when the changes in SOC

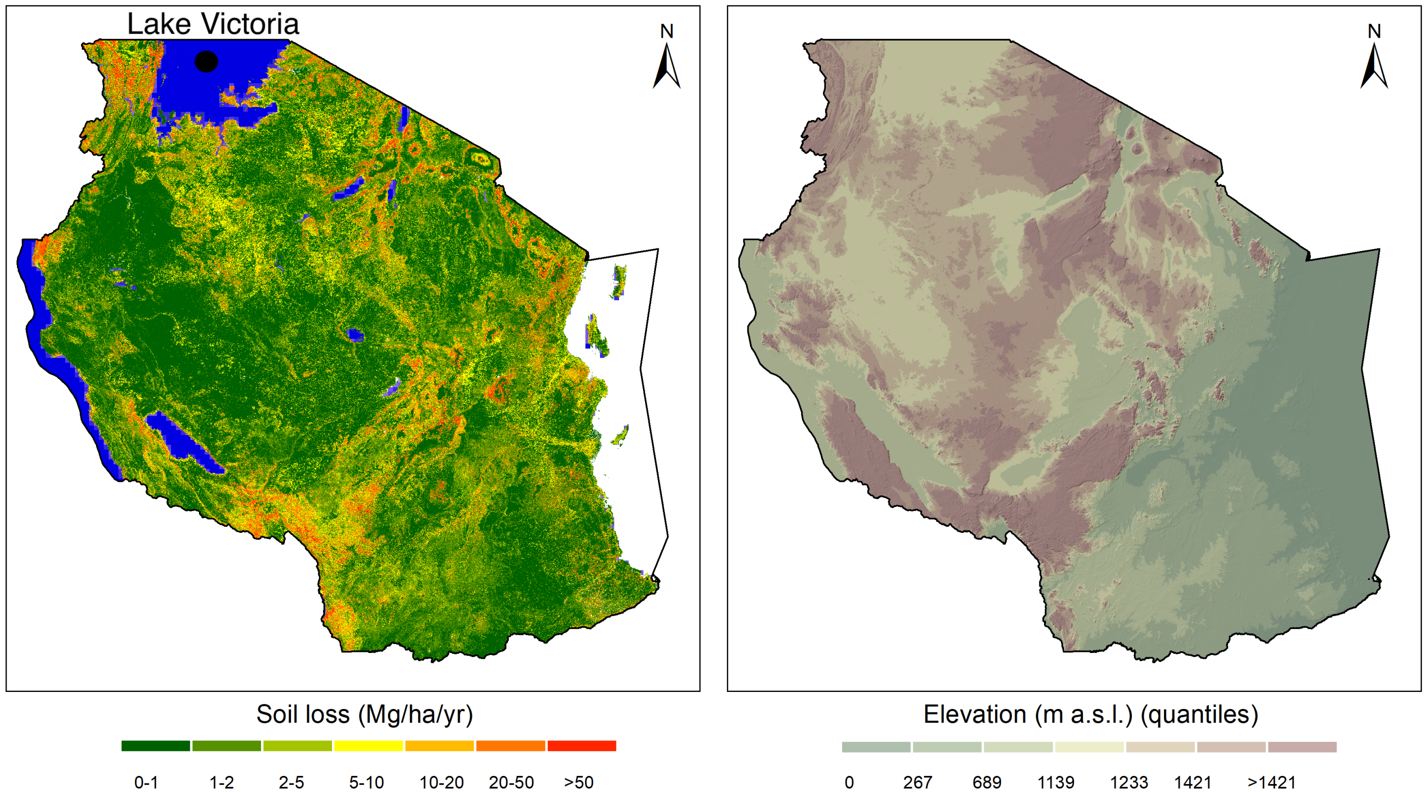


Figure 5.2: Map of annual soil loss in Tanzania between 2001 and 2012 alongside the corresponding land elevation. Reproduced with permission from Pasquale Borrelli, contributing author of *An assessment of the global impact of 21st century land use change on soil erosion*(Borrelli et al., 2017), under Creative Commons Attribution 4.0.

and C fractions had reached an equilibrium. The statistical analyses were conducted using one-way ANOVA in SPSS software. The data were transformed using natural logarithm functions to meet the normality (Shapiro-Wilk test) and homogeneity (Levene's test) assumptions required for factorial ANOVA. Estimated marginal means were compared post hoc using Tukey HSD tests for homogeneous data sets and Games-Howell tests in cases where the equal variance assumption was not met.

5.2.3 CENTURY Model Context and Validation

The CENTURY model was evaluated and compared with eight other soil organic matter models by Smith et al. (1997) using twelve datasets from seven long-term (minimum 20-year) experiments on three land uses (grassland, arable cropland, and woodland). Smith et al. (1997) reported that CENTURY performed simulations on all three land uses with consistently low errors, and the best performance for the model was on grass and crop systems.

Bortolon et al. (2011) reported that the use of the CENTURY model involves a high degree of complexity and uncertainty due to the limitations on acquiring the required historical information for cultivation time and sequence of management practices. The CENTURY model is dependent on site-specific parameters. Bricklemyer et al. (2007) showed that the CENTURY model over-estimated SOC content by an average of 10% using site-specific soils data. However, Oelbermann and Voroney (2011) found that the CENTURY model underestimated levels of SOC compared to measured values by an average of 7% using site-specific parameters and experimental studies spanning over 10 years in tropical and temperate climates. Therefore, a ± 10% error is accepted for CENTURY model use.

The limitations of CENTURY pointed out in the literature include the inability of CENTURY to accurately capture the change in SOC as a result of changes in pH (Smith et al., 1997), bulk density (Oelbermann and Voroney, 2011), and soil texture (Bricklemyer et al., 2007) over time.

5.3 Results

Prior to cultivation, the SOC of the land under tropical grass was 15,568 g C/m^2 (Figure 5.3). In 1871, the year before Mwanza was established as a cotton export town, cultivation in the area resulted in a spike in SOC followed by a rapid decline. The decline continues when cultivation remains continuous and no amendments are used. By 2020 the SOC declines to 4,045 g C/m^2 and by 2200 the SOC declines to 826 g C/m^2. However, when comparing potential amendments that could be used in urban agriculture, there are significant differences in SOC from 2021, the year marking the beginning of annual amendment application in the CENTURY model. To illustrate the effects of the amendments by 2050, the change in SOC from year 2021 is shown in Table 5.5.

From 2021, the SOC in amended soils is greater than the SOC in soils without any amendments, following the sequence of FWC > PM > Ash >IFN > NA. The changes in SOC for FWC, PM, and Ash amended soils can be divided into three trends: a rapid increase from 2021 to 2080 (Figure 5.4), a plateau with an incremental incline from 2080 to 2109 (Figure 5.5), and a gradual decline from 2109 to 2200 (Figure 5.6). The SOC for

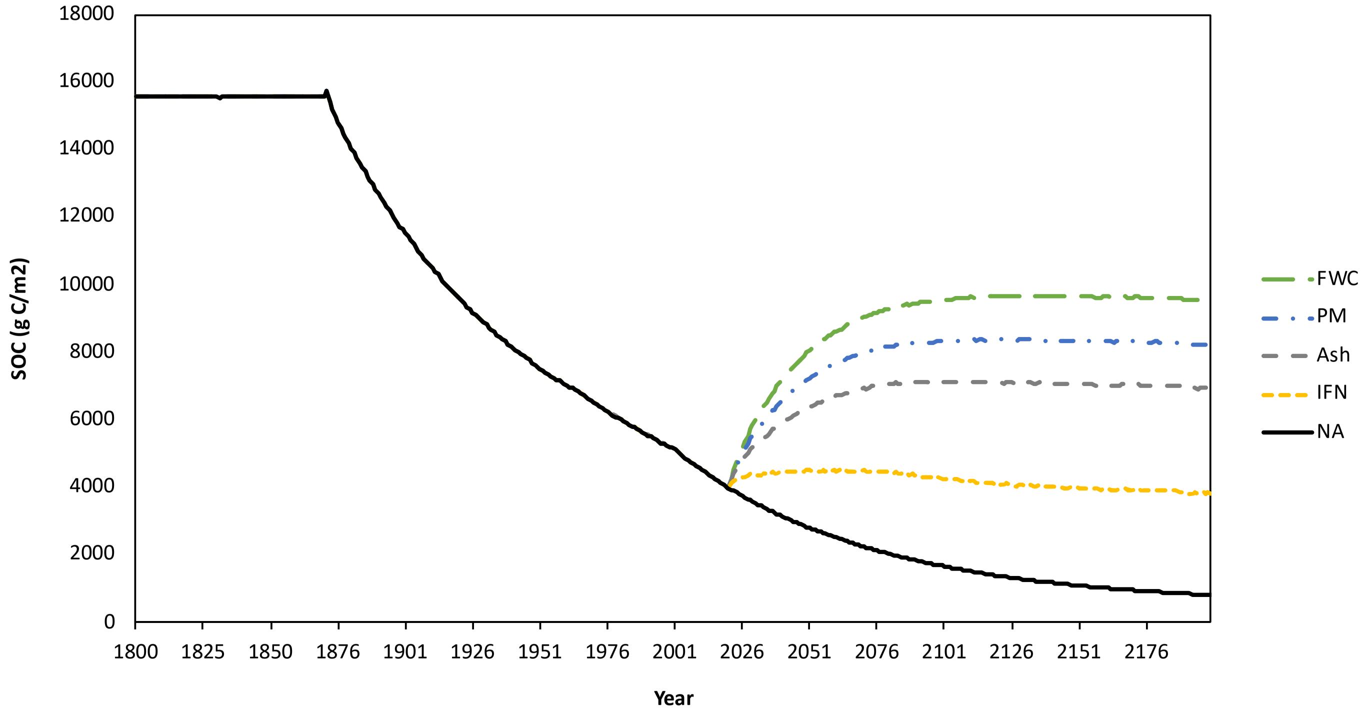


Figure 5.3: Soil organic carbon (SOC) (g C/m^2) stocks simulated in CENTURY soil organic matter model from 1800 to 2200. Year 2021 marks the beginning of soil amendment impacts on SOC of urban sandy loam soils in Mwanza, Tanzania.
FWC (food waste compost), PM (poultry manure), Ash (wood ash), IFN (inorganic fertilizer (nitrogen)), NA (no amendment).

Table 5.5: Changes in soil organic carbon (g/m^2) between 2021 and 2050 to a depth of 20 cm under differing land management practices as simulated by the CENTURY soil organic matter model for Mwanza, Tanzania.

Management Practice[1]	**Year 2050 SOC (g C/m^2)**	**Change from Year 2021 SOC (g C/m^2)**
Ash	6379	2381
FWC	7996	4002
PM	7198	3203
IFN	4512	518
NA	2840	-1154

[1]Ash (wood ash), FWC (food waste compost), PM (poultry manure), IFN (inorganic nitrogen fertilizer), and NA (no amendment)

the three time periods (2021-2080, 2080-2109, and 2109-2200) is graphed separately with equation trends for comparing rates of change between the different amendments.

For the interval between 2100 and 2110, where SOC and C fraction values are in equilibrium, there were statistically significant differences ($p<0.001$) in SOC across amendments, following the sequence: FWC > PM > Ash > IFN. For the active C fraction, there were statistically significant differences ($p<0.001$) between IFN and Ash, FWC, and PM, as well as between Ash and both FWC and PM. The highest accumulation of active C was in Ash amended soils followed by FWC and PM amended soils, and finally in IFN amended soils, following the order Ash > FWC = PM > IFN. The changes in the active C fraction are shown in Figure 5.7.

In the slow C fraction, the differences and sequence are the same as total SOC; there are significant differences ($p<0.05$) between all amendments, following the sequence FWC > PM > Ash > IFN. The changes in the slow C fraction are shown in Figure 5.8. Whereas

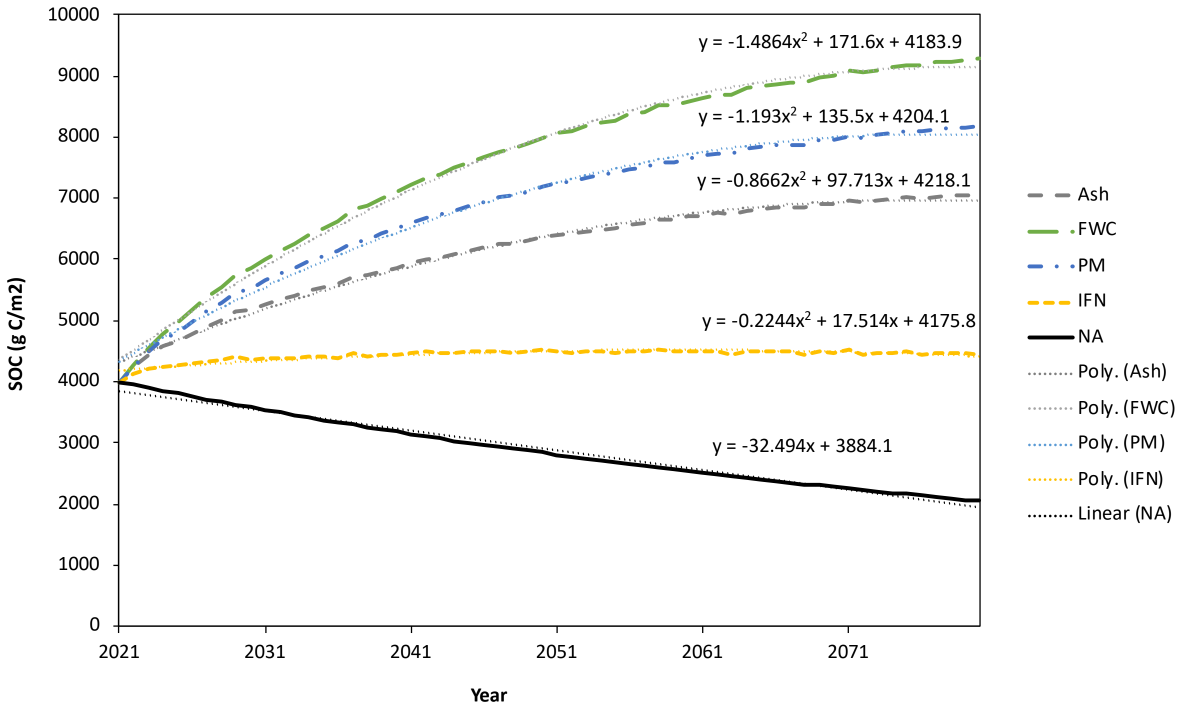


Figure 5.4: The changes in soil organic carbon (SOC) simulated in CENTURY model from 2021 to 2080, showing a rapid increase in SOC for FWC (food waste compost), PM (poultry manure), and Ash (wood ash) amended soils as compared to IFN (inorganic nitrogen fertilizer) amended soils. SOC declines steadily without amendments (NA). Equations best fitting the SOC trend for each amendment are displayed for comparison.

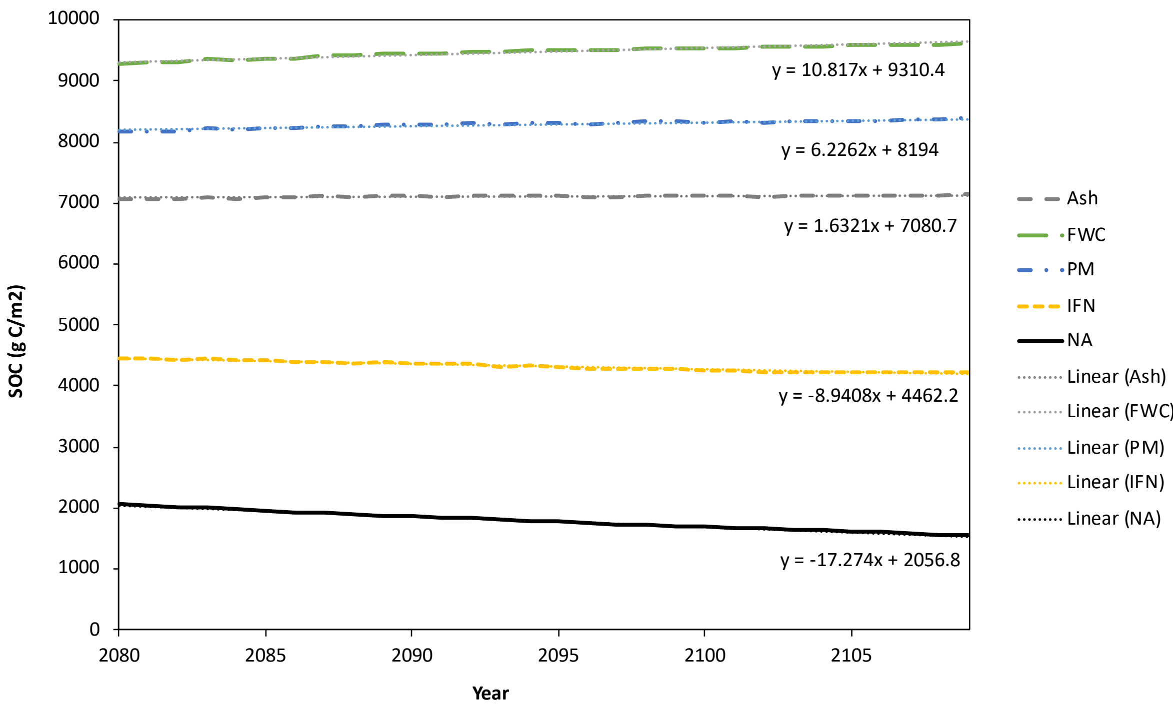


Figure 5.5: The changes in soil organic carbon (SOC) simulated in CENTURY model from 2080 to 2109, where SOC values for FWC (food waste compost), PM (poultry manure), and Ash (wood ash) amended soils have equalized, with incremental increases as compared to IFN (inorganic nitrogen fertilizer) and not amended soils for which SOC values are in steady decline. Equations best fitting the SOC trend for each amendment are displayed for comparison.

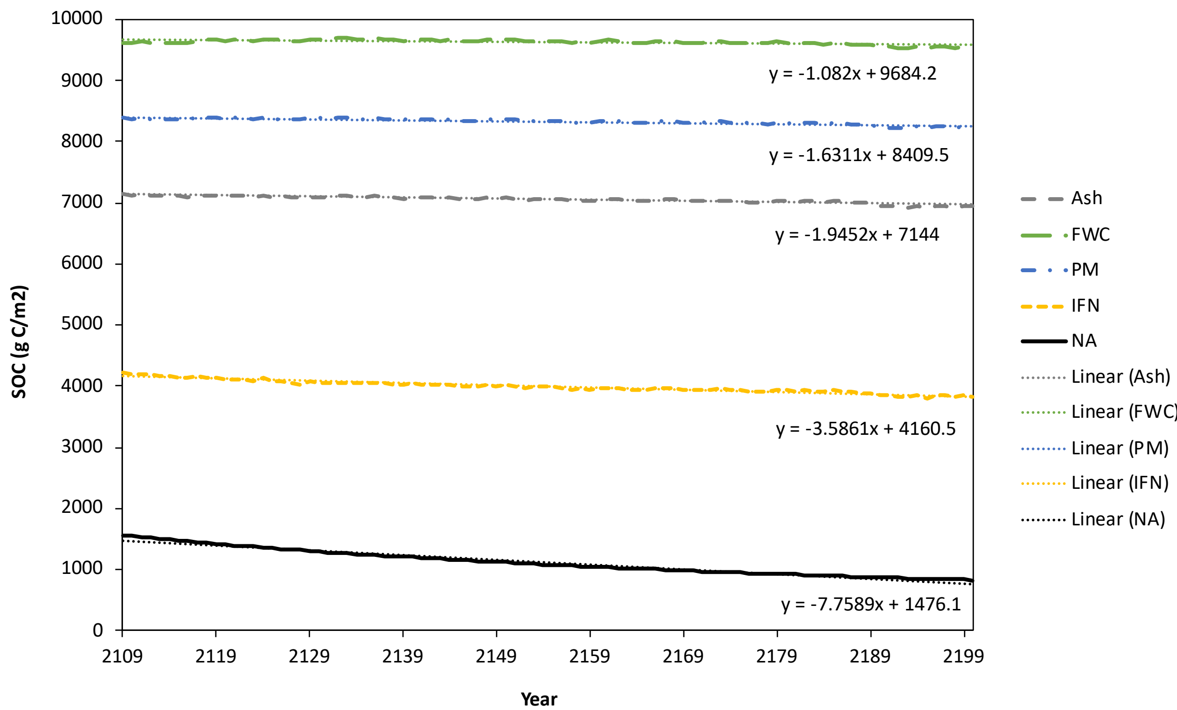


Figure 5.6: The changes in soil organic carbon (SOC) simulated in CENTURY model from 2109 to 2200, showing a gradual decline in SOC for FWC (food waste compost), PM (poultry manure), Ash (wood ash), and IFN (inorganic nitrogen fertilizer) amended soils. SOC continues to decline steadily without amendments (NA). Equations best fitting the SOC trend for each amendment are displayed for comparison.

in the passive C fraction, there are no significant differences between Ash, FWC, and PM amended soils, but there are significant differences ($p<0.001$) between IFN and Ash, FWC, and PM, with the lowest accumulation of passive C fraction in the IFN amended soils. The order of accumulation in passive C fraction is Ash = PM = FWC > IFN. The changes in the passive C fraction are shown in Figure 5.9. The mean values for SOC and the three C fractions (active, slow, and passive) across the four simulated amendments are provided in Table 5.6.

The highest accumulation of C was in soils amended with FWC, PM, or Ash. However, the accumulation of C varied within each fraction across amendment application. For example, the greatest C gain for FWC and PM amendments occurred in the slow C fraction, whereas the greatest gain for Ash amendments occurred in the active C and passive C fractions.

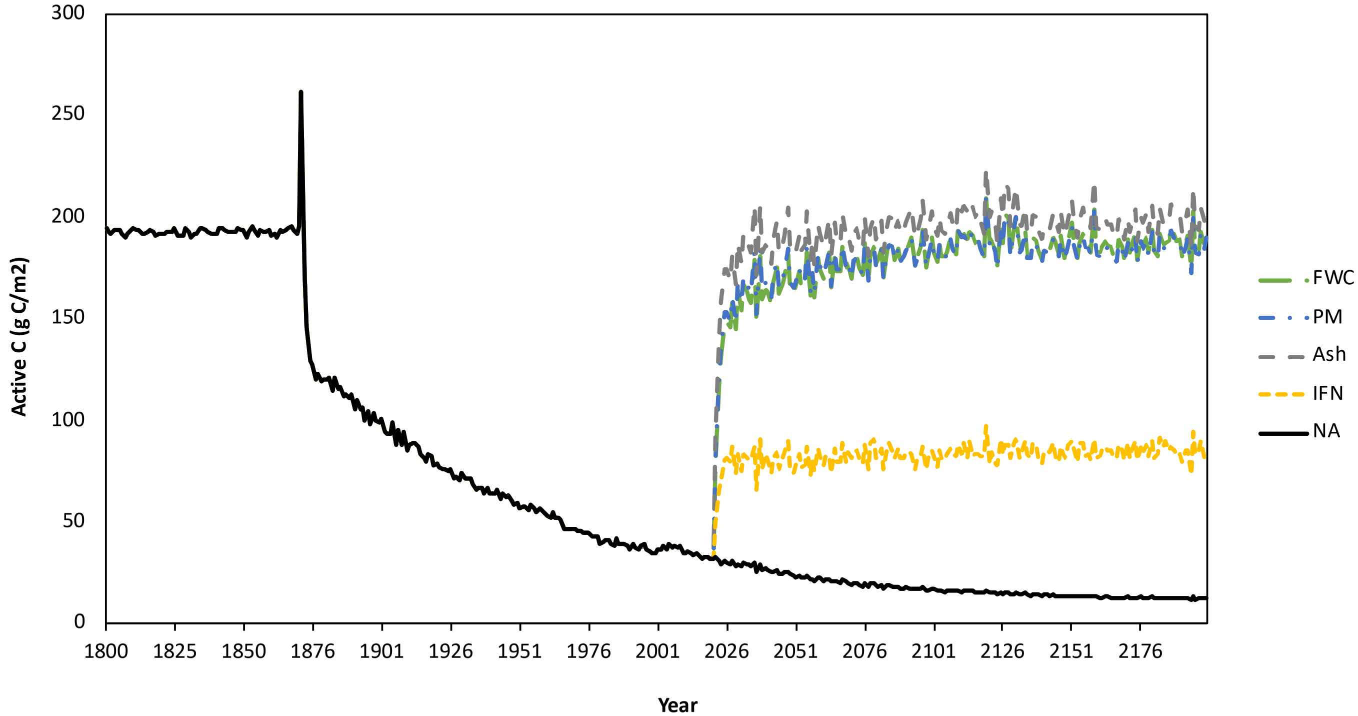


Figure 5.7: Active carbon (C) (g C/m^2) fraction simulated in CENTURY soil organic matter model from 1800 to 2200. Year 2021 marks the beginning of soil amendment impacts on active C fraction of urban sandy loam soils in Mwanza, Tanzania.
FWC = food waste compost, PM = poultry manure, Ash = wood ash, IFN = inorganic fertilizer (nitrogen), and NA = no amendment.

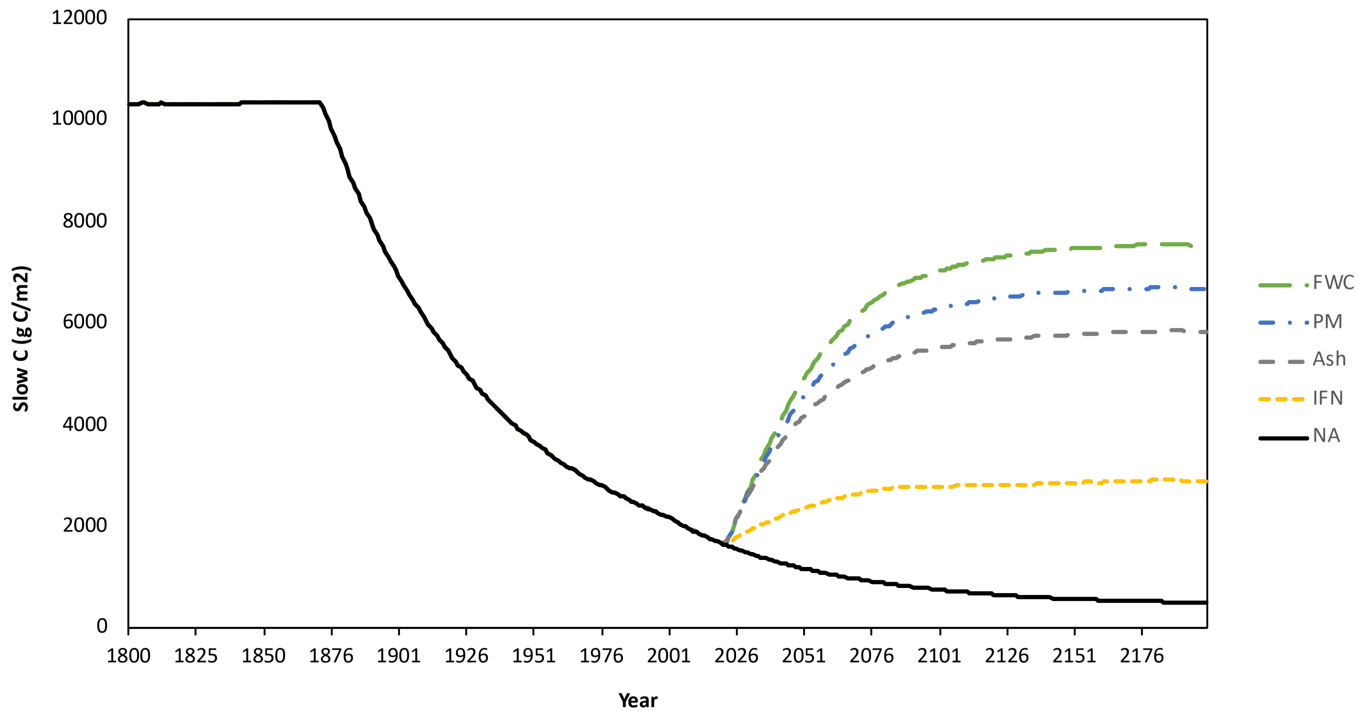


Figure 5.8: Slow carbon (C) (g C/m^2) fraction simulated in CENTURY soil organic matter model from 1800 to 2200. Year 2021 marks the beginning of soil amendment impact on slow C fraction of urban sandy loam soils in Mwanza, Tanzania.
FWC = food waste compost, PM = poultry manure, Ash = wood ash, IFN = inorganic fertilizer (nitrogen), and NA = no amendment.

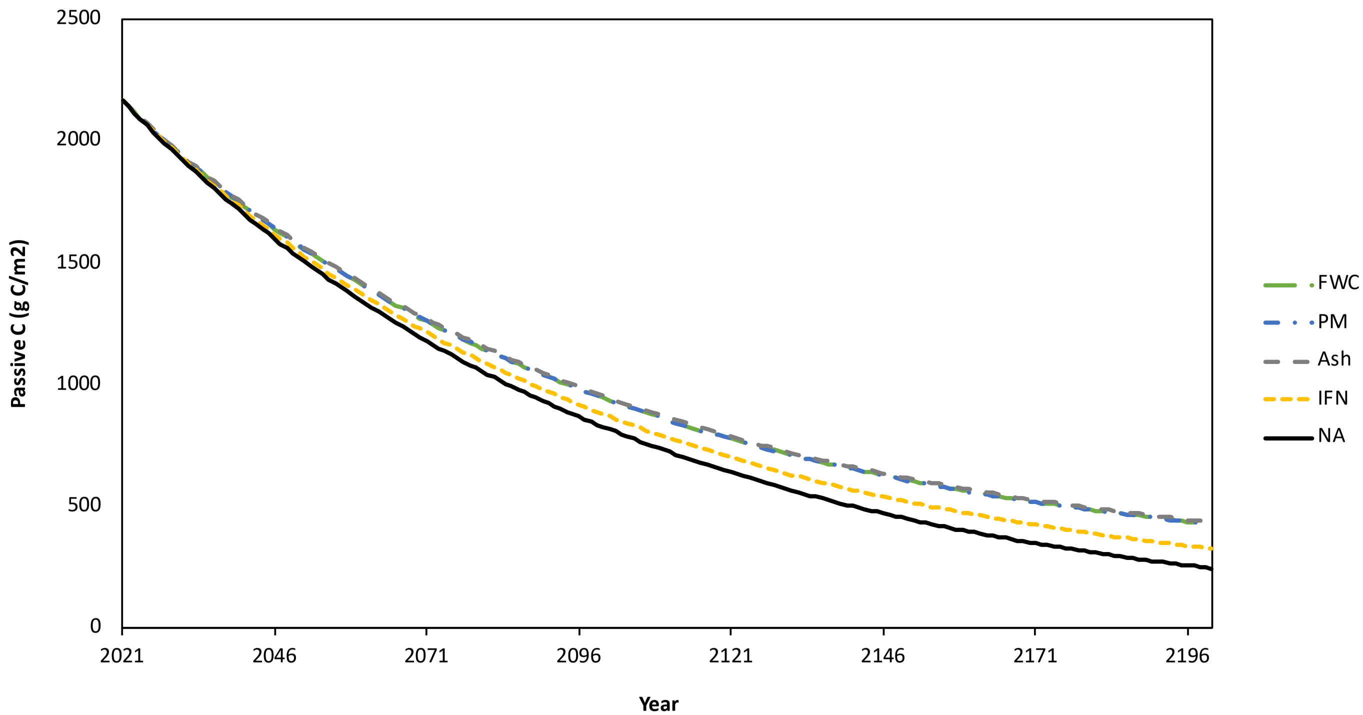


Figure 5.9: Passive carbon (C) (g C/m^2) fraction simulated in CENTURY soil organic matter model from 1800 to 2200. Year 2021 marks the beginning of soil amendment impact on passive C fraction of urban sandy loam soils in Mwanza, Tanzania.
FWC = food waste compost, PM = poultry manure, Ash = wood ash, IFN = inorganic fertilizer (nitrogen), and NA = no amendment.

Table 5.6: Mean values of soil organic carbon (SOC) fractions (g C/m^2) from the years 2100 to 2110 simulated by the CENTURY soil organic matter model for sandy loam soils in Mwanza, Tanzania

Management Practice	**SOC (g C/m^2)**	**Active C (g C/m^2)**	**Slow C (g C/m^2)**	**Passive C (g C/m^2)**
Ash	7119 (13)^a	197 (5)^a	5554 (28)^a	910 (28)^a
FWC	9581 (30)^b	185 (5)^b	7095 (51)^b	901 (28)^a
PM	8348 (20)^c	184 (5)^b	6334 (40)^c	901 (28)^a
IFN	4232 (16)^d	83 (3)^c	2798 (8)^d	832 (30)^b

^{a,b,c} Values with different letters (a,b,c) in the same column indicate a significant difference between treatments. Values with the same letters indicate no significant difference between treatments. Standard error is in parenthesis.
Statistical analysis determined using one-way ANOVA: SOC $F(3,36) = 169308.18$, $p < 0.001$; Active C $F(3,36) = 1717.45$, $p < 0.001$; Slow C $F(3,36) = 42203.33$, $p < 0.001$; Passive C $F(3,36) = 8.36$, $p < 0.001$. Tukey tests were performed for post hoc estimate marginal means comparison, except for IFN comparisons within the slow C fraction for which Games-Howell tests were used for unequal variance assumption. The threshold for statistical significance was $p<0.05$).

5.4 Discussion

The simulated implementation of agricultural practices in 1871 confirmed that when natural grasslands are converted to agricultural lands, large losses occur in soil C storage (Cole et al., 1993; Lal, 2007). Subsequent SOC decline occurred through the historical cultivation of continuous cotton-maize, cotton-rice-maize, and hybrid maize-rice cropping, with no additions of soil amendments. Similar declining trends have been reported in other studies where CENTURY was used to evaluate the impact of differing land management practices on SOC in tropical areas (Bortolon et al., 2011; Oelbermann and Voroney, 2011), which are compared in Table 5.7. Compared to the other studies, the decline in the present study was 1.5 times steeper, which is attributed to a combined effect of the high soil erosion factor and the lack of soil input over the historical cultivation period. In the three comparative studies, fertilizer addition was included in at least one cultivation period in the historical land management after land conversion. Additionally, the soil erosion factors included in the study by Bortolon et al. (2011) were ten-fold lower than the soil erosion factors used in this study. Soil erosion is a pressing problem worldwide, but more so in sub-Saharan African countries (Borrelli et al., 2017) and in urban environments (Zhang and Huang, 2015; Grafius et al., 2016; Ashagre et al., 2018; Hewett et al., 2018). A study of two Tanzanian cities by Ashagre et al. (2018) reported that the highest soil erosion occurs November to January, and following the long dry season (June to September) when significant erosion is caused by rainfall on bare ground or areas burnt in preparation for the planting season.

Table 5.7: Comparison of decline in soil organic carbon (SOC) stock after land conversion between different studies using CENTURY simulations for tropical locations. The SOC decline was determined as a linear function for comparative purposes: before land conversion and after historical cultivation divided by the number of years under historical cultivation.

Location	**Native Vegetation**	**SOC (native vegetation) (g/m^2)**	**Decline ($g/m^2/y$)**
Brazil[1]	Subtropical forest	4300-5800	36-50
Costa Rica[2]	Tropical forest	5700	23
Tanzania[3]	Tropical grassland	15000	73

[1]Bortolon et al. (2011)
[2]Oelbermann and Voroney (2011)
[3]This study

5.4.1 Nitrogen Fertilizer

As was observed in the results, fertilizer application does not increase soil organic carbon as much as the other simulated amendments, especially organic amendments. The higher level of SOC from simulated inorganic fertilizer application compared to no amendment is attributed to increased root biomass as a result of better crop productivity (Ebhin Masto et al., 2006).

While the high solubility of inorganic fertilizers is advantageous for helping plants take up nutrients (Thangarajan et al., 2013), there are disadvantages to fertilizer use, including the energy-intensive manufacturing process that contributes to greenhouse gas emissions (Vermeulen et al., 2012). Additionally, nitrogen fertilizer use in agricultural expansion has increased the atmospheric N_2O emissions, a gas that is 265 times more potent than carbon dioxide (Smith, 2017). Long-term or repeated fertilizer use can also decrease abundance and biodiversity of soil organisms (Tully et al., 2015) and increase soil acidification (Vanlauwe and Giller, 2006; Tully et al., 2015). Additionally, Lal (2013a) argues that there is a strong relation between soil degradation and use/misuse of fertilizers. The start of this trend is evident from the simulated year 2080, at which point the SOC in fertilizer-amended soils declines and continues to decline at a faster rate than organically-amended soils from simulated year 2100.

5.4.2 Organic Amendments

Increases in SOC were greatest in organically amended soils. Tropical soils rely on SOC for promoting biological diversity, which helps maintain soil quality (Guimarães et al., 2013). However, sustained increases in SOC over time are dependent on the nature of organic amendment (Ngo et al., 2012), as was the case in the present study with simulated FWC, PM, and Ash amendments. Additionally, organic material consists of a wide range of C compounds with varying rates of decomposition (Ajwa and Tabatabai, 1994), which need to be explored to understand which SOC pool are most impacted by the amendments.

The accumulation of active C fraction, comprised of soil microbes and microbial products (Parton et al., 2001), was greatest in ash-amended soils, followed by FWC and PM amendments. Wood ash is strongly alkaline (Gay-des Combes et al., 2017). The higher pH in ash-amended soils has shown to increase microbial activity (Jokinen et al., 2006; Saarsalmi et al., 2010). In this fraction, the decomposition of organic matter is primarily regulated by factors that impact the microbial community (Berg and McClaugherty, 2008). Microbial biomass is sensitive to changing soil conditions, such as soil amendments (Odlare et al., 2008), which serves as an early indicator of stresses on the ecosystem (Voroney et al., 2008). In Chapter 4, the results from the field trial showed that soil microbial biomass carbon was highest when amended with poultry manure and compost on soils that were already imbued with wood ash. According to Gay-des Combes et al. (2017), compost and ashes are complementary fertilizing pathways for promoting soil fertility. In this simulation study, the compost and ashes were simulated separately, but future work could investigate the potential impact of compost-ash blends on SOC pools.

The results for the slow C fraction followed a similar trend to the results for the total SOC, with highest accumulations in FWC-amended soil, followed by PM amendment, and then Ash amendment. The slow C fraction, also referred to as the humic substances of the soil, progressively decreases when soils are converted from natural ecosystems to farming use (Guimarães et al., 2013). The fraction is made up of resistant plant matter and stabilized soil microbial products (Parton et al., 2001). The distinction between the impacts of FWC, PM, and Ash on the slow fraction can be explained by the differences in lignin content for the simulated amendments, which was highest for FWC followed by PM, and none in the Ash. While increased lignin concentrations correlate with decreased decay rates (Berg and McClaugherty, 2008), once degraded, lignin serves as a parent material for humic substances (Flaig, 1964), which is the slow C fraction.

The passive C fraction, comprised of physically and chemically stabilized organic matter (lignin) that is resistant to decomposition, is the long-term stable carbon fraction (Parton et al., 2001). The passive C fraction decreased significantly after land conversion, though, with the input of amendments, there was a slower decline in the fraction. There were, however, no differences between the impacts of Ash, FWC, and PM amendments on the passive C fraction, inferring that all three are capable of increasing the stable fraction at a similar rate.

Soil carbon fractions from this study were compared with other studies that also used CENTURY to simulate agricultural land management in tropical locations, such as no-till, agroforestry, sole cropping, biochar application, and manure application. Carbon fraction values for comparison were selected approximately 10 years after the land management changed had been initiated, where possible. The comparisons are summarized in Table 5.8. The SOC values from the present study align most with the values presented by Oelbermann and Voroney (2011) in Costa Rica with FWC and PM application being comparable to agroforestry and Ash and INF being comparable to sole-cropping. Whereas the active C fraction from the present study is higher in FWC, PM, and Ash than the agroforestry management (Oelbermann and Voroney, 2011).

Martínez-Blanco et al. (2013) identified decreased soil erosion as one of the nine potential benefits of compost application. Even with soil erosion built into the model, the SOC and C fractions for Ash, FWC, and PM-amended soils increased from 2021 to 2109 (88 years). The effect of soil erosion is only detectable in the CENTURY simulations for Ash, FWC, and PM amendments from year 2110, though the decline in SOC from that point is diminutive.

A 9-year study conducted by Annabi et al. (2011) found that application of urban composts derived from municipal solid waste, co-composted sewage sludge and green waste, or biowastes resulted in higher soil microbial activity and increased SOC, as well as enhanced aggregate stability, which enabled resistance of the soil to water erosion. While vegetation

Table 5.8: Comparing carbon fraction (Soil organic carbon (SOC), active carbon (C), slow C, and passive C) values between different studies using CENTURY simulations, 10 years after change in land management (*unless otherwise stated)

Land Management	**SOC (g/m^2)**	**Active C (g/m^2)**	**Slow C (g/m^2)**	**Passive C (g/m^2)**
No-till[1]	2660 - 3480 (+)	-	-	-
Agroforestry[2]	5800 (+)	72 (+)	2700 (-)	2600 (+)
Sole crop[2]	5200 (-)	32 (-)	2800 (-)	2600 (+)
FWC [3]	6000 (+)	154 (+)	2795 (+)	1934 (-)
PM [3]	5652 (+)	158 (+)	2733 (+)	1935 (-)
Ash [3]	5266 (+)	177 (+)	2697 (+)	1937 (-)
IFN [3]	4380 (+)	75 (n)	1941 (+)	1926 (-)

(+) indicates an upward trend, (-) indicates a downward trend, (n) indicates a neutral (straight) trend

*Exception to the 10-year rule: the values obtained from this study are a ten-year average over 150 years from the start of the relevant land management. [1]Bortolon et al. (2011)

[2]Oelbermann and Voroney (2011)

[3]This study, where FWC = food waste compost, PM = poultry manure, Ash = wood ash, and IFN = inorganic fertilizer (nitrogen).

cover in Tanzanian cities from the March to May growing period reduces surface runoff, and subsequently, soil erosion (Ashagre et al., 2018), the addition of organic and wood ash amendments in urban agriculture can help counter soil erosion through increased SOC accumulation.

5.4.3 Implications in Urban Agriculture

According to Magigi (2013), urban land problems develop because of restrictive by-laws that prohibit food production. For example, in 1966 Mwanza's town council prohibited crop cultivation and in 1982 urban authorities were authorized to destroy crops over 1 m high (Flynn, 2001). Continuing urbanization and population growth within cities will not decrease the importance of urban agriculture in Africa (De Bon et al., 2010). Urban land use planning for improved urban soil quality and food security will require instruments for making better informed decisions (Magigi, 2013). This study has shown that use of the CENTURY soil organic matter model can be used to project and evaluate impacts of land management practices on SOC pools. Additionally, the results assert that the use of organic amendments in urban agriculture will allow urban soils to accumulate and sequester carbon, enhance soil microbial activity, counter soil erosion, and improve soil quality for crop production. Therefore, the study supports the conclusion set forth by Ayambire et al. (2019) that city by-laws should make provisions for urban agriculture and encourage the use of conservation land management practices, such as the use of organic amendments.

5.5 Conclusions

The use of amendments on urban sandy loam soils in Mwanza City was evaluated through a 180-year simulation using the CENTURY SOC model. Historical data about Mwanza region used in the simulation showed that SOC declined rapidly after conversion from natural tropical grassland and through continuous cultivation of cotton, rice, and maize as well as urbanization and soil erosion until amendment applications were modelled for 2021.

The annual addition of food waste compost, applied at a rate to meet crop nitrogen requirements, increased SOC the most compared to poultry manure, wood ash, and inorganic (nitrogen) fertilizer. Organic waste amendments enabled the highest SOC accumulation of the resistant carbon fraction that is stored within the soil for up to 50 years. This carbon fraction is lost over time when natural lands are converted for farm use. However, the results of this study demonstrate that the carbon fraction can be restored with the annual use of organic amendments on cultivated urban soils in MWanza, Tanzania. The restoration of the slow C fraction of can help counter soil degradation and sequester atmospheric carbon. Additionally, the use of organic amendments and wood ash amendment indicated a counteracting effect on the soil erosion parameters built into the model.

There are some limitations to using the CENTURY model without adequate site parameters and historical data of land management and changes to land use. To integrate the use of CENTURY in land management, the numeric values of SOC from the model may be refined through further studies and access to more specific geographic historical land management data. Nonetheless, this study has demonstrated that the CENTURY model is an effective tool to compare amendment input strategies and the resulting SOC trends can form baseline projections for decisions regarding land use in urban areas. The CENTURY model can, therefore, be used by decision makers to inform land use policies and initiatives for sustainable urban development under SDG 11. Further, use of organic amendments (food waste compost, specifically) should be integrated into urban land management policies to enable sustainable urban agriculture (SDG 2) and increase soil carbon (SDG 13).

Chapter 6

Conclusions

6.1 Major Research Findings

This dissertation represents a unique approach to exploring the multidisciplinary perspectives surrounding urban agriculture in a developing city in SSA (sub-Saharan Africa). Urban agriculture is an integral aspect of Mwanza, Tanzania for urban culture and livelihood. People who cultivate urban land do so not only for subsistence and income, but also for enjoyment and tradition. There are currently various constraints to cultivation, including constricted space, lack of land tenure, reliance on rainy seasons for crop irrigation, and declining soil fertility. A growing concern among urban farmers is a disease spreading across the maize (*Zea mays*) crops, which makes research on urban agriculture even more critical to urban food security in developing countries. With climate change and urbanization, the constraints are expected to increase with projected increases in extreme climate events related to rainfall (Luhunga and Songoro, 2020) and the increased likelihood of plant pathogens (Velásquez et al., 2018).

Urban farmers also tend toward use of organic amendments, such as manure or crop residue, to replenish cultivated soil. This provides an opportunity to create a nutrient cycle for urban agriculture in developing cities. With increased urbanization, the increase in organic (food) wastes is inevitable. The contribution of the hospitality sector (restaurants and hotels) to the organic waste stream has yet to be explored for developing countries (Pirani and Arafat, 2014), especially with respect to promoting sustainable waste management. This dissertation provided insight into waste management of the hospitality sector in Mwanza City, which may be indicative of this sector in Tanzania, and East Africa generally. Wastes produced by the hospitality sector are currently disposed of in a land dump, as opposed to a sanitary landfill. This means that the gases and leachate produced from decomposition of organic waste mixed with other wastes are neither captured nor prevented from entering the surrounding environment (Hoornweg and Bhada-Tata, 2012), and therefore, contribute to greenhouse gas emissions (Kaza et al., 2018).

Major Findings Chapter 2

- Urban farmers vary in age, gender, education, level of agriculture expertise, and agriculture practices, but all use hand tools, specifically the hand-hoe;
- Urban agriculture is an integral component to culture and livelihood even in a developing city where urban agriculture is not included in land-zoning policies and has historically been discouraged by government through by-laws;
- Urban farmers are concerned for soil fertility of cultivated urban land and have a positive attitude towards organic amendments for soil improvement.

However, organic (food) wastes from hotels and restaurants are separated before waste collection as a result of kitchen wastes not containing a high percentage of non-organic wastes. Restaurants and hotels also currently pay for waste management services and are willing to separate organic wastes from other wastes, though they are not willing to pay additional fees for separate collection. The attitude toward waste segregation presents an opportunity for a waste diversion strategy. In developing cities, like Mwanza, the infrastructural and financial capacity of municipalities are limited (UN-Habitat, 2014). Therefore, a low-cost rapid composting method was proposed, which produces mature compost in 30 days, using the limited space available at pre-existing waste transfer stations within the city. The low-cost, rapid composting method can be integrated into any city that has similar waste management layouts as Mwanza City, which many developing cities do in SSA (Kaza et al., 2018).

Major Findings Chapter 3

- Insights into hospitality sector waste management in a developing city, whereas previous studies have focused on municipal solid waste from residential sector;
- Opportunities identified for waste diversion in hospitality sector as most hotels and restaurants reported separating (or willingness to separate) organic waste from other wastes for waste collection;
- A low-cost, rapid composting method that can be integrated into waste management strategies for cities that have limited financial and infrastructural capacities and make use of waste transfer stations.

While not many urban farmers had heard of, or used, food waste compost in their cultivation activities, the response to compost samples shown to interview respondents was overall positive. Food waste composts from the low-cost rapid composting method and from a commercial compost producer in Tanzania were comparable, though they were lower in nutrients (nitrogen, phosphorus, carbon) than manure-based organic amendments. Nonetheless, under a short-term field trial, food waste compost amendment performed comparably to poultry manure, when applied at the same rate, and inorganic nitrogen fertilizer for promoting crop growth. Moreover, within a month and a half, the soil under organic amendment (food waste compost and poultry manure) showed improved water holding capacity and soil microbial biomass (carbon) as compared to soils treated with inorganic nitrogen fertilizers. Additionally, the misuse of fertilizer led to delayed seed germination, which presents a risk for farmers.

Studies have demonstrated the positive impacts of compost and organic amendment on soil physical, chemical, and biological characteristics in long-term studies (Martínez-Blanco et al., 2013); however, this dissertation adds to the claim with confirmed physical and biological improvements in the short-term. Therefore, water holding capacity and soil microbial biomass should be considered as indicators to promote investments in organic amendments for urban agriculture, and can extend to rural agriculture.

Major Findings Chapter 4

- Short-term field trial demonstrated improved water holding capacity and soil microbial biomass (carbon) under organic amendments (food waste composts and poultry manure) compared to inorganic nitrogen fertilizer;
- Crop growth is comparable under organic amendments and inorganic nitrogen fertilizer treatment;
- Misuse of nitrogen fertilizer can result in delayed (or no) seed germination, which poses a risk for farmers who lack proper knowledge or training.

In the short-term field trial, there was an increase in soil organic carbon across all treatments. However, the CENTURY model illustrated that over the next 100 years, annual application of food waste compost and poultry manure (organic amendments) increase soil organic carbon significantly more than inorganic nitrogen fertilizers or no amendment use. While the results of the modelled simulation are prone to a margin of error, they do provide a trajectory for what governments and researchers can expect to observe in the upcoming decades. Given the conflicting needs of land and differing land management strategies, a tool like CENTURY can provide guidance for forming appropriate land management policies that meet the needs of the people as well as sustainable development. One focus of African agriculture, for example, is encouraging family farming, which accounts for 90% of agricultural activity in Africa (NEPAD, 2013; Oxford Business Group, 2019). The objectives set out by the Alliance for a Green Revolution Africa and OCP Africa are to keep African soils in a state of maximum productivity by helping farmers better understand their soils and providing access to better performing seeds and fertilizers (Oxford Business Group, 2019). This dissertation showed that the continued use of inorganic fertilizers may maintain SOC at higher levels than not using any amendments, but the use of organic amendments will increase soil organic carbon, especially in the slow carbon fraction, which is naturally lost over time after land conversion.

As urban cultivation and urbanization continue, the decrease in soil organic matter is a concern not only for soil degradation but also for the increase in atmospheric emissions of soil carbon (Lal, 2013b). Therefore, this study emphasizes the urgency to transition to land management strategies, specifically use of organic amendments, such as food waste compost, that increase soil organic matter in urban areas and can help meet the goal of sustainable development in cities and communities.

Major Findings Chapter 5

- Without amendments, the soil organic carbon in urban cultivated soils can be expected to decline steadily over the next 100 years;
- With annual inorganic fertilizer application, soil organic matter will be maintained but with annual application of wood ash, poultry manure, or food waste compost, soil organic carbon will increase;
- Annual application of organic amendments (food waste compost or poultry manure) can promote accumulation of the resistant carbon fraction, which is lost over time when natural lands are converted for farm use, and can help counter soil degradation and sequester atmospheric carbon.

The four chapters together demonstrate that the pathway to integrated soil fertility management in Mwanza, Tanzania is through investment in organic amendments, specifically food waste compost. Tying back to the SDGs, the use of organic amendments in urban agriculture can help achieve sustainable agriculture (SDG 2) as organic amendments improve soil quality while promoting crop growth. Understanding the needs of urban farmers is key to empowering small-scale/family farmers (SDG 2) and ensuring acceptance of food waste compost for use in urban agriculture. Redirecting the flow of food wastes generated by the hospitality sector away from land dumps and toward urban agriculture can help achieve nutrient recycling within the city, contributing to building sustainable cities (SDG 11). Finally, the sequestration of carbon in the soil through organic amendments is action against climate change (SDG 13).

Therefore, this research provides the groundwork for urban planners and policy-makers in developing countries to not only accept urban agriculture as a core component of urban culture, but to also build capacity for urban agriculture and contribute to sustainable development by making provisions for organic amendment use in urban agriculture. The implications of the results are not limited to Mwanza City. Developing cities, particularly in SSA, have similar presence of urban agriculture, lack of organic waste diversion from the hospitality sector, and municipal waste management that involves depositing mixed wastes in land dumps following waste accumulation at transfer points. With further location-specific research, the results of this study can be applicable to other developing cities.

6.2 Key Research Contributions

The issues of rapid urbanization, food security, soil degradation, and waste production are complex, but can be addressed through interdisciplinary research. The studies in this dissertation employed a mixed methods approach to understanding the value of urban agriculture in a rapidly growing Tanzanian city. The studies also give credence to the dissertation hypothesis presented in Section 1.6.1 in Chapter 1, the gist of which is: if there is an inclination for urban farmers to improve their cultivated soils using organic amendments like food waste compost and if soil quality can be improved with food waste compost, then the production and application of food waste compost can be the pathway to sustainable cities through organic waste management and conservation agriculture. The key research contributions of this dissertation (Figure 6.1) relate back to the conceptual framework from Chapter 1.

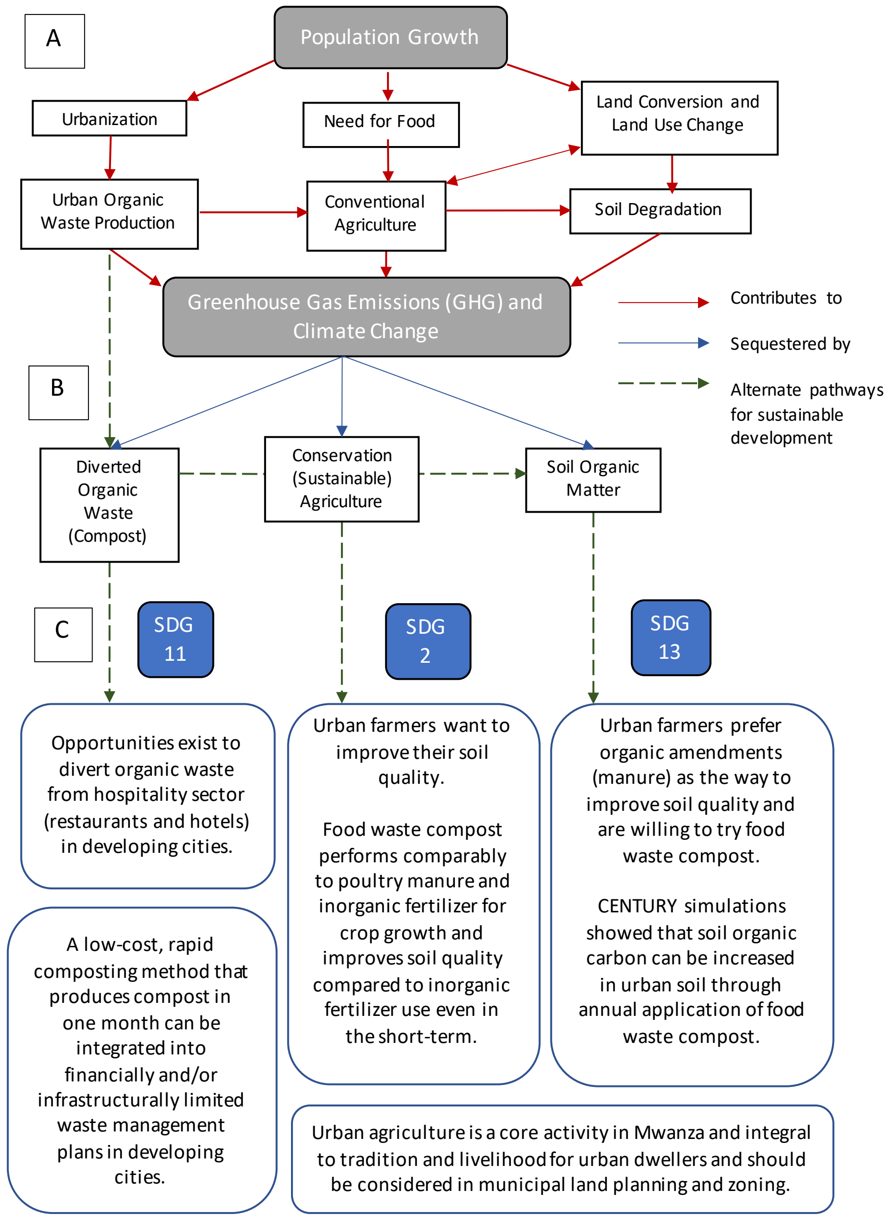


Figure 6.1: The conceptual framework is now divided into three parts. Part A represents the current issues of population growth and anthropogenic contributions to GHG (greenhouse gas) through urbanization, waste production, conventional agriculture, and soil degradation. Part B depicts the alternate pathways to curb GHG emissions lead to diversion of urban organic wastes to conservation agriculture, increasing soil organic carbon, and contributing to the SDGs (Sustainable Development Goals). Part C highlights the key contributions from this dissertation under the associated SDG.

6.3 Recommendations for Future Research

Even though the SDGs formed the framework for this research - with a focus on SDG 2 (Sustainable Agriculture), SDG 11 (Sustainable Cities), and SDG 13 (Action on Climate Change), it is unlikely that international climate policies will successfully limit global temperature rise to +2°C (Thornton et al., 2011). In the short and medium term, there is a need for better climate change adaptation and mitigation strategies (Mkonda et al., 2018) that can extend beyond one developing city and be implemented at larger scales through coordinated efforts.

Therefore, further research recommendations that stem from this dissertation include:

- The adoption of CENTURY simulation modelling as a land management planning tool for urban developing cities, specifically for zoning urban agriculture areas and promoting organic amendment use;
- Engaging urban stakeholders, including urban farmers and food waste producers, in decision-making for land use policies and adoption of climate adaptation strategies;
- Pilot-scale studies for rapid composting throughout the year to evaluate the opportunities and constraints of the low-cost, rapid composting method with actual waste generation rates and food waste composition, which may vary seasonally;
- Evaluating the social, environmental, and economic benefits and drawbacks of the pilot-scale rapid composting within developing cities;

- Varied (short and long term) field trial studies at additional urban sites with differing soil compositions to provide a more comprehensive evaluation of the effects of food waste composts versus inorganic fertilizers on urban soil quality and crop growth;
- Evaluating the effects of varying blended compositions of organic and inorganic fertilizers to optimize crop growth and improve soil quality for urban cultivated land;
- Investigating the dynamics between urban agriculture, food waste production, and the impacts of COVID-19 in Mwanza City.

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APPENDICES

Appendix A

Supplementary Materials

A.1 Semi-Structured Interview Questions

A.1.1 Kiswahili: Maswali ya Mahojiano

Umri:

Jinsia:

Ngazi ya elimu:

Idadi ya watu ndani ya nyumba:

Idadi ya watu wanaoshiriki katika kilimo:

Ukubwa wa shamba:

Ukubwa wa njama:

Umiliki wa shamba:

Kodi (Mwenyeji) au Mwenyewe

Mazoea ya Kilimo

Ulianza kilimo lini? Ulikua kwenye shamba au?

Unafanya kilimo kila mwaka au kila sasa? Tafadhali eleza.

Niambie kuhusu shughuli zako za kila siku za kilimo. Unautaratibu wa kila siku?

Unatumiaje zana yoyote kusaidia kwa shughuli za kilimo?

Kuna mazoea ya kilimo ambayo unayotumia?

Kuna mazoea yoyote ambayo yamepitishwa familia yako au yanayotumika ndani ya nchi?

Unalima mazao gani? Wanabadilika kulingana na msimu?

Una sababu maalum za kuchagua mazao haya?

Mabadiliko

Umeona mabadiliko gani iliyokutana wakati wa miaka yako ya kilimo?

Unaongea na wakulima wengine?

Wakati gani unaweka mbegu kwenye ardhi? Unajuaje ni wakati mzuri?

Unafanya nini na mavuno? Mavuno yamekuwaje kwa misimu iliyopita?

Udongo

Ni viashiria gani unatumia kupima afya ya udongo na uwezekano?

Unawezaje kupima uzazi wa udongo?

Unajisikiaje kuhusu udongo katika mashamba yako?

Ungependa kuiboresha?

Unatumiaje pembejeo ya udongo mara kwa mara kwenye udongo? Unatumia nini?

Umejaribu marekebisho tofauti ya udongo?

Mashamba yako yanaathirika sana katika miaka kavu?

Una bajeti ya miradi ya kuboresha ardhi?

Unafikiriaje nini njia bora zaidi ya kuboresha afya ya udongo na mavuno ya mazao?

Ni mazao gani inakupa faida zaidi?

Unahusikaje na magugu na wadudu?

Binafsi / Baadaye

Unapenda nini zaidi kuhusu kilimo?

Nini ngumu zaidi kuhusu kilimo kwa ajili yenu?

Je! Ni kilimo tu chanzo chako cha mapato?

Unao malengo au mipango kwa shamba lako?

Mbolea kutoka kwa taka ya chakula (Mboji)

Ungehisije kuhusu kutumia mbolea kutoka kwa taka ya chakula?

A.1.2 English: Interview Questions

Respondent Descriptors

Age:

Sex:

Education Level:

Number of Household Members:

Number of Members who participate in agriculture:

Farm Ownership: (e.g., rent or own?

Farm size:

Plot sizes:

Agriculture Practices

When did you start farming? Did you grow up on a farm?

Do you farm all year around or at certain periods? Please explain.

Tell me about your daily activities of farming?

Do you have a daily routine?

Do you use any tools to help with the farming activities?

Are there any particular agricultural practices that you use?

Are there any practices that have been passed down your family or are locally used?

What kind of crops do you grow? Do they change based on season?

Did you have any special reasons for choosing these crops?

Change

What was the biggest change you encountered during your years farming?

Do you communicate with other farmers?

When do you start seeding? How do you know when to start?

What do you do with the harvest produced?

What has the harvest been like in the past few seasons?

Soil

What key indicators do you use to gauge soil health and viability?

How do you gauge soil fertility?

How do you feel about the soil in your fields?

Would you like to improve it?

Do you regularly apply inputs on the soil? Do you use fertilizers, manure, or compost?

Have you experimented with different soil amendments?

Are your fields greatly affected in dry years?

Do you have a budget for land improvement projects?

What do you think is the most effective way to improve soil health and crop yields?

What has been your most consistent crop in terms of making a good profit?

How do you deal with weeds and pests?

Personal/Future

What is the most satisfying part of farming for you?

What is the hardest part of farming for you?

Is farming your only source of income?

What goals or plans do you have for your farm?

Compost

How would you feel about using compost from urban food waste?

A.2 Hospitality Waste Generator Questionnaire

A.2.1 Kiswahili: Orodha ya Maswali ya Uchunguzi

Jinsi Mnavyo Kusanya na Kutupa Takataka

Tafadhali chagua kwamba sambamba na jibu lako

1. Takataka unakusanya wapi?

a. Ndani

b. Nje

c. Au sehemu nyingine (eleza wapi):

2. A) Unatumia pipa ya takataka?

a. Ndiyo

b. Hapana

Kama ndiyo, unatumia pipa ngapi na size gani?

Kama hapana unaweka wapi?

2. B) Unaridhika na jinsi unaweweka takataka (fikiria juu ya harufu, nafasi, na kusafisha)?

a. Ndiyo

b. Hapana

Eleza kwa ufupi

3. A) Takataka iliokusanywa unatupa wapi?

a. Inachukuliwa na wahusika

b. Kuna sehemu ya kutupa

c. Unachimbia kwenye ardhi

d. Unachomo moto

Eleza kwa ufupi unatumia eneo gani:

4. Takaka iliokusanywa unatupa marangapi?

a. Kila siku

b. Kwa weeki mara tatu

c. Kwa weeki mara mbili

d. Winginevyo (eleza kwa ufupi marangapi):

5. Takataka kama inachukuliwa na wahusika ni marangapi?

a. Kila siku

b. Kwa weeki mara tatu

c. Kwa weeki mara mbili

d. Winginevyo (eleza kwa ufupi marangapi):

6. Unadhani nani anahusika kuchukua hio takataka?

a. Municipality

b. Biashara binafsi

c. Watu binafsi

d. Winginevyo (eleza kwa ufupi):

7. Unalipia kutupa takataka?

a. Ndiyo

b. Hapana

Kama ndiyo (na kama unataka kujibu), shilingi ngapi unalipa kwa mwezi?

Kama hapana, eleza kwanini?

Maoni

8. Kama unataka kuona mabadiliko, nini ungependa kuona mabadiliko?

Takataka ya Chakula

9. Kiyasi gani ya takataka ni takataka ya chakula?

10. Unaonaje takataka ya chakula (fikiria juu ya harufu na kusafisha)?

11. Unatafautisha takataka na takataka ya chakula?

a. Ndiyo

b. Hapana

Kama ndiyo, eleza kwa ufupi

12. Kama ukipewa pipa ya kusanya takataka ya chakula, utaweza kukusanya kwenye pipa hiyo?

a. Ndiyo

b. Hapana

c. Sifahamu

Kama hapana au sifahamu, eleza kwa ufupi:

13. Unaweza kulipa huduma za kuchukuliwa takataka ya chakula tu?

a. Ndiyo

b. Hapana

c. Labda

d. Sifahamu

14. Unaweza kulipa huduma za kuchukuliwa takataka ya chakula tu lakini mara kwa mara?

a. Ndiyo

b. Hapana

c. Labda

d. Sifahamu

Maelezo ya ziada

A.2.2 English: Waste Generator Survey

Current Waste Practices and Services

Please select the choice that corresponds to your answer:

1. Where do you store your waste?

a. Inside

b. Outside

c. Other (please specify):

2. A) Do you use bins to store your waste?

a. Yes

b. No

If yes, how many and what sizes of bins do you use?

If not, where do you store your waste?

2. B) Are you satisfied with your method of storing waste (i.e. cleanliness, cleaning requirement, space-wise)?

a. Yes

b. No

Please explain why or why not?

3. A) How do you get rid of your waste?

a. It is collected

b. At a communal drop off

c. Bury

d. Burn

3. B) Please describe where:

4. How often do you take out / drop off your waste?

a. Everyday

b. 3 times/week

c. 2 times/week

d. Other (please specify):

5. If your waste is collected, how often is it collected?

a. Everyday

b. 3 times/week

c. 2 times/week

d. Other (please specify):

6. According to you who is responsible for managing the people's waste (i.e. collecting, transporting, disposing)?

a. Municipality

b. Private Sector

c. Residents

d. Other (please specify):

7. Do you pay for solid waste collection?

a. Yes

b. No

If yes (and if you want to answer), how much do you pay per month?

If no, please explain why?

Opinion

8. Is there anything you would like to see changed with respect to waste storage, waste collection, or waste service?

Organic Waste (Food Waste)

9. How much of your total waste is organic/food waste, if you were to estimate?

10. How do you feel about the organic/food waste portion of your waste?

11. Do you store your organic/food waste separately from other waste?

a. Yes

b. No

If yes, please explain briefly:

12. If a separate bin were provided only for organic/food wastes, would you put only your organic/food wastes into that bin?

a. Yes

b. No

c. I don't know

Please explain why:

13. Would you be willing to pay for the collection of only organic/food waste?

a. Yes

b. No

c. Maybe

d. I don't know

14. Would you be willing to pay for collection of only organic/food waste if the collection was frequent?

a. Yes

b. No

c. Maybe

d. I don't know

Additional Comments

Appendix B

Procedure for Exporting Soil Samples from Tanzania

B.1 Introduction

Due to regulations passed in 2017, all export of soil and rock samples from Tanzania now require testing by the Ministry of Energy and Minerals and an export permit to carry soils out of the country.

Exporting soil and rock samples from Tanzania is an involved and arduous process. However, the documentation and resources explaining the intricacies and steps of the process are limited. The aim of this supplementary chapter is to first present available soil analysis resources available within Tanzania for both farmers and researchers, and, more importantly, to delineate the application process for exporting soils outside of Tanzania.

B.2 Methods

The information presented in this chapter was collected through direct observation. After conducting a field trial in Mwanza, Tanzania to investigate the affect of soil amendments to soil parameters for short duration crops, the soil samples required analysis. The soil characteristics that needed to be analyzed were: bulk density, soil pH, soil texture, available phosphorus (P), total nitrogen (N), organic carbon (C), electric conductivity (EC), cation exchange capacity (CEC), nitrate (NO3-), ammonium (NH4), soil moisture, and soil microbial biomass.

A majority of the analyses were conducted at the Agriculture Research Institute (ARI) – Ukiriguru, which is located within the vicinity of Mwanza city. However, the institute did not have the capacity to conduct nitrate (NO3-), ammonium (NH4), soil moisture, and soil microbial biomass analyses.

Sokoine University of Agriculture (SUA) in Morogoro was consulted regarding analyses that the ARI – Ukiriguru was unable to perform. While the list of analyses available at SUA was extensive, there was one critical analysis (soil microbial biomass) that they were unable to perform. Therefore, the decision was made to export the remaining soil samples for further analysis at the University of Waterloo in Canada. The steps for the application process for the soil export permit were recorded through the process.

Information presented in this chapter was primarily collected through direct observation and first-hand account of the processes.

B.3 Results and Discussion

B.3.1 Soil Analysis within Tanzania

Soil samples taken around the Mwanza city area can be analyzed at the Agricultural Research Institute - Ukiriguru (ARI - Ukiriguru). These samples can be analyzed upon request of researchers or farmers that want to have a better understanding of the characteristics of their soils. The institute requests 1 kg of soil per sample and recommends two depths: 0 – 30cm, and 30 – 50 cm for sample analyses. The costs for analyses at ARI - Ukiriguru are relatively affordable, providing an array of analyses for 25,000/- Tsh (Tanzanian shillings) total per sample. This translates to USD $11 total per sample*. This cost covers sample preparation, soil texture, pH, EC, CEC, available P, total N, organic C, and exchangeable bases. These analyses are accompanied with a comprehensible explanation of the results for each farmer that requests an analysis. The institute also offers to perform bulk density analysis and can provide a field technician to take samples provided the technicians are paid expenses for the day, which was 50,000/- Tsh in 2018 at the time the researcher requested bulk density sampling. The institution was unable to perform analyses of soil moisture, soil microbial biomass, nitrate, and ammonia. The remaining samples were air-dried and sieved to less than 2 mm for transport. However, due to the lack of an export permit, the soils were transported within the country to Sokoine University of Agriculture.

Sokoine University of Agriculture (SUA) is better known for its soil laboratory facilities. The university is located in Morogoro, Tanzania which falls between the capital city of Dodoma and the largest city and international port of entry, Dar es Salaam. The list of analyses services provided by SUA is more extensive and includes analyses of plant matter as well. Soil analyses that are additional to the ones provided by ARI - Ukiriguru include extractable minerals, lime requirement, suspended solids, nitrate and ammonia, soil moisture, and ashing. A comparison of the costs of select analyses at ARI-Ukiriguru and at SUA are shown in Table B.1. However, the university does not currently have the capacity to perform soil microbial biomass analyses, which was a critical parameter for analysis. Therefore, the soils were transported to Dodoma, Tanzania's capital city, to begin the soil export permit application.

Table B.1: Cost comparison of select soil analyses at ARI-Ukiriguru and SUA in Tanzanian Shillings (Tsh) and equivalent US Dollars (eUSD). The conversion rate at the time of the research was 2,250 Tsh to 1 eUSD.

Analysis	ARI (Tsh)	ARI (eUSD)	SUA (Tsh)	SUA (eUSD)
Particle Size Analysis	4,000	1.78	3,750	1.67
Available P	2,500	1.11	5,250	2.33
Total N	3,500	1.56	9,000	4
Organic C	2,500	1.11	7,500	3.33
CEC	5,000	2.22	9,000	4
Bulk Density	1,000	0.44	2,550	1.13
Soil Moisture	n/a	n/a	3,000	1.33
N-NO3	n/a	n/a	9,000	4
N-NH4	n/a	n/a	9,000	4
Soil Microbial Biomass	n/a	n/a	n/a	n/a

B.3.2 Exporting Soils from Tanzania

Though there are regional offices for the Ministry of Energy and Minerals in cities around Tanzania, and letters of transporting soil samples within the country can be obtained from these offices, the process to export soil samples from Tanzania can only be completed in

Dodoma, the capital city. Soil samples can be transported within the country through ground transportation, by car or bus, without any trouble. However, transporting soil samples by air even within the country requires justification and support from the local Ministry of Energy and Minerals office.

In Dodoma the process is started by the person requesting the permit (hereafter referred to as the applicant) at the Regional Office in Kizota. In Swahili this office is called Ofisi ya Afisa Madini Mkazi (hereafter referred to as the Kizota Office). Other locations that are part of the process include the Geological Survey Tanzania Lab in Dodoma town, the banks (all of which are located within a few meters of each other on Nyerere St.), District Head Office (in Swahili: Ofisi ya Mkuu wa Wilaya, hereafter referred to as District Office), Tanzania Revenue Agency (TRA), and University of Dodoma (UDOM).

There are various choices of local transportation within Dodoma city and to and from Kizota, the cheapest of which are motorbikes (called boda boda) where the passenger rides behind the driver and there is not much room for baggage. The next option is a rickshaw (called a bajaj), which is a less expensive mode of transport than the last option of a taxi. The recommended mode of travel is by bajaj, which offers a relatively low-cost mode of transportation with room for accompanying baggage, such as the packages of soil samples.

B.3.3 The Export Permit Application Process

Following are the steps for the export permit application process:

1) The first step is the Kizota office where the process is started. At the Kizota office a sample of the soil samples is taken and sealed for soil testing at the GST Lab, primarily

to check for rare minerals. Use local transportation to get to the Kizota Office. The road leading to the office is off the main highway onto dirt roads. At the office, the officers require a letter of introduction and justification from the organization for which the soil or rock samples are being exported. They also require a little portion of two or more of the soil samples, which they put into a container that has to be bought by the person requesting the analysis.

The number of containers that are submitted for soil testing depends on the number of locations from which the soils were taken or the number of different types of soils that are within the sample set. For one type of soil taken from one location, they only require one container to be filled with about 50g of soil in total from two or more soil samples. Though only 50g in total is required for soil testing, they may end up taking more as a scale may not available to measure the amount taken. Before the soil is put in the container, two holes are made in the container and two on the lid, so that after the soil is placed in the container, it can be sealed with wire and metal tags, each with a ministry commission tag number. These numbers are written in a book and the applicant signs for these tags.

2) Using local transportation, the container of soil samples has to be taken to the GST Lab in Dodoma town. Upon receiving the container, the sample reception at the GST Lab provides the applicant with an account number and amount of money (in Tsh) to be deposited. Using local transportation again the applicant has to go to the prescribed bank, deposit the money (95,000/- Tsh per sample for testing) and bring back the bank receipt. The bank receipt is then attached to a form filled out at the Sample Reception at the GST Lab and then taken to the Accounts department, which is in the building across the road, from where an official receipt is issued. The GST Lab also takes the applicants contact

information, particularly the local phone number so that they may contact the applicant once the testing is complete. The amount of time it takes for the testing is not guaranteed but may take one to three days. The GST Lab contacts the applicant when the results are ready.

3) When the results are ready at the GST Lab, the applicant receives a call and collects the results and the accompanying letter after verifying that all the information on the documentation, such as names and dates, are correct. These documents are then taken back to the Kizota Office where the officers prepare an invoice for payment, which has to be taken to the prescribed bank. This payment is for the export permit application (USD$ 100), royalty for export (USD $ 10), and processing fee (USD $1), totalling USD$ 111. At the prescribed bank, a copy of an identification document such as a passport or local voting or ID card is required to complete the deposit. Once the funds have been deposited, the receipt from the bank has to be taken back to the Kizota Office's accounts department.

4) At the Kizota Office the applicant then fills out an export permit application form while the accounts department issues a receipt and a receipt number that has to be included in the application form. The applicant must also fill out details regarding the soil samples, including in how many packages the soil will be transported and the commercial value of the samples. The paperwork is then taken to the officers who prepare the export permit application, which includes a copy of the initial introduction/justification letter from the applicant's organization, the GST Lab test results and letter, the application form, and a signature page. While this application is being prepared, the applicant makes holes in the bucket (bought and brought by the applicant) and packs the soil samples into the bucket. Depending on the number of soil samples that the applicant has, the applicant can buy a

small bucket (10 L) or a big bucket (20 L) from town.

5) Next the bucket is taken to the TRA office where four representatives are required to complete the sealing process and sign the application form: one person from the District Office who checks the contents of the bucket in detail, one person from the Ministry of Energy and Minerals to apply the sealing tags, one person from the TRA to verify the sealing process, and the applicant as well. The buckets are tied with string between two of the holes, and the other two holes were sealed with wire and metal tags. Upon instruction from the TRA and Ministry of Energy and Minerals representatives, the top of the buckets are also sealed with a red seal on top of the string to ensure that the package is not reopened once sealed. Five copies of the permit application documents are signed, and one copy each is given to each representative: TRA, Ministry of Energy and Minerals, District Office, and the applicant.

6) The last copy has to be taken to UDOM where the export permit is finally issued and signed, after which it can be picked up by the applicant. The permit is only valid for 30 days from the date the permit was issued and signed.

7) At the Dar es Salaam international airport, the sealed container of soil samples has to be taken to the cargo area minerals office. There the officers provide two documents: an assessment and a clearance to travel. They keep the original export permit document and provide the applicant with a photocopy for travel purposes. The original export permit document is then returned back to the Ministry of Minerals and Energy head office to be filed.

The amount of time it takes for each step in the process and a breakdown of costs associated the steps are compiled into Table B.2 for ease of reference. Only costs associated with the process have been included in the cost breakdown; costs for accommodation and daily living expenses have not been included.

Table B.2: Time requirement and cost of each step associated with the export permit application process.

Step	Time Requirement	Costs (Tsh)	Details of Cost
Step 1	2 - 3 hours	2,000	Container
		5,000	Transport* to Kizota office from Dodoma center
Step 2	1 - 2 hours	5,000	Transport to GST from Kizota office
		2,000	Transport to and from bank
		95,000	Analysis of one sample
Step 3	3 - 4 hours	15,000	Transport
		USD 111.00	Permit application and processing fee
Step 4	2 - 3 hours	6,000	Bucket for packing in soil samples
		5,000	Local Transport
Step 5	3 - 4 hours	10,000	Local Transport
Step 6	1 - 2 hours***	15,000	Transport to and from UDOM

B.4 Conclusion

Institutions within Tanzania for research on soil and agriculture have the capacity to conduct various soil and plant analyses. The price ranges for the analyses offered are reasonable for researchers, though may be steep for farmers to use as a resource for gauging soil fertility of their cultivated land. For research on soil within Tanzania, it is recommended that experiments be designed to align with the availability and accessibility of local resources.

However, due to the limited capacity of local institutions, it is reasonable to expect that researchers conducting soil research in Tanzania from countries outside of Tanzania may wish to export soil samples for more in-depth analyses. However, the export process is lengthy and arduous because all export process now have to go through ministry offices in Dodoma. Researchers are advised to take into consideration the length and costs of the tasks involved. Therefore, the steps provided in this chapter can serve as a useful guide for researchers planning soil-related research that requires export of soils from Tanzania.