Sustaining peri-urban agriculture in rapidly urbanising cities in sub-Saharan Africa.

A model and survey based assessment of adaptations to maintain peri-urban agriculture in Kumasi under threat of climate change and urban sprawl.

Kai Feberwee

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Preface

In front of you is the digital edition of my Master thesis on peri-urban agriculture in sub-Saharan Africa. This digital edition is different in that it includes the full set of appendices, rather than exclusively the link to the drives.

This thesis was written between 2022 and 2023 over the course of 13 months as the final part of my master's degree in civil engineering. It started from an interest in urban agriculture and food security and a willingness to contribute to the discourse on these topics. In this research, I could combine several of my interests, with both urban agriculture and its applications in sub-Saharan Africa.

I am very grateful to Dr. Edo Abraham and Frank Annor for their supervision and their day-to-day help with research, modelling and writing. I also owe gratitude to Prof. Nick van de Giesen and Prof. Merle de Kreuk for their feedback on the final thesis.

Finally, I owe a debt of gratitude to Mr. Samuel Darbah and the students from Kwadaso Agricultural College in Kumasi for their help with the surveys and for the time they took to meet and discuss the research. Without them, this would not have been possible.

Kai Feberwee
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Abstract

Throughout sub-Saharan Africa, agricultural activities in urban and peri-urban areas are threatened by urban sprawl. These activities are important not just for the livelihoods of those who take part in it, but also for the food security of the city. Historically, in Kumasi 40% of the crops in the city are sourced from urban and peri-urban agriculture. However, Kumasi is also a city that is growing rapidly both in population and in area: since the 1980's population has more than quadrupled and the area has increased more than tenfold. Because of this, there is a need to find ways to maintain urban and peri-urban agriculture under the threat of urban sprawl and the climate change in the future and also work well in the Kumasi context.

We used the agro-hydrological model AquaCrop informed by 4.5 years of local weather data, soil data and crop data to model the effectiveness of adaptations in maintaining food security for three neighbourhoods in Kumasi. Local farmer management practices that were determined by a survey of 150 Kumasi farmers made a distinction in management practices between adaptations and crops. This model gave yields and irrigation water uses for five crop groups that are commonly cited as crucial for food security. Combined with population growth predictions and land use and land cover analysis this allowed us to make a statement about how well adaptations can meet current and future demand of crops and how much space is needed to meet demand. This model was supplemented with a survey of vendors and farmers to investigate barriers against- and preferences for adaptations.

Backyard gardening and sack gardening turned out to be the best options to maintain peri-urban agriculture. These adaptations use the least space, for the highest yields. From the survey of farmers and vendors, no strong objections were found against the implementation of these adaptations. Over 80% of surveyed farmers and vendors felt that backyard gardening was a good adaptation to maintain peri-urban agriculture in Kumasi. Backyard gardening and sack gardening are optimally suited for growing vegetables and legumes, which are the easily perishable crops and thus benefit from a short supply line, which many vendors cite as solutions for spoilage.

It is possible to ensure self-sufficiency for these crops with 5-9% of total land in the Feyiase neighbourhood, 11-20% in Ejisu and with 14-22% in the Kwadaso neighbourhood. It is therefore recommended to target at least a majority self sufficiency, by reserving a >50% fraction of this land for backyards and sack gardening spaces. At the same time, any available marginal lands should be allocated for the growth of cereals and tubers, to allow for the production of these subsistence crops, until the production of the remaining demand is fully met by rural import. With these adaptations and recommendations, it is possible for peri-urban agriculture in Kumasi to maintain its important role throughout the coming decades.

In order to determine if there are any deviations from these conclusions, future research should focus on including empirical crop data tailored to AquaCrop or use a model that is better suited to represent the chaotic nature of (peri-) urban agriculture. While the model results do not differ significantly from the crop yields as found in literature, a model informed by local crop data can be an even better representation of the situation in Kumasi. Furthermore, a study into the long-term effects of adaptation on nutrition can reinforce our conclusions on food security.

Finally, there is an opportunity to develop more high-tech agricultural methods like greenhouses and aquaponics. There is also an opportunity to incorporate wastewater reuse schemes, following examples from other countries, such a urine reuse, or low-tech treatment with sludge harvest. For this, it is recommended to set up educational programs and pilots.

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1. Introduction

1.1 Urban sprawl and peri-urban agriculture

Since the 1960's the population of the world has more than doubled and an increasingly large number of these individuals reside in urban areas. Since 2007, more than 50% of all people lived in cities and this fraction is only increasing. There are now more people on the world living in cities then there are in rural areas. In sub-Saharan Africa (SSA) in particular, projections of urban growth show massive increases (Gao & O'Neill, 2020).

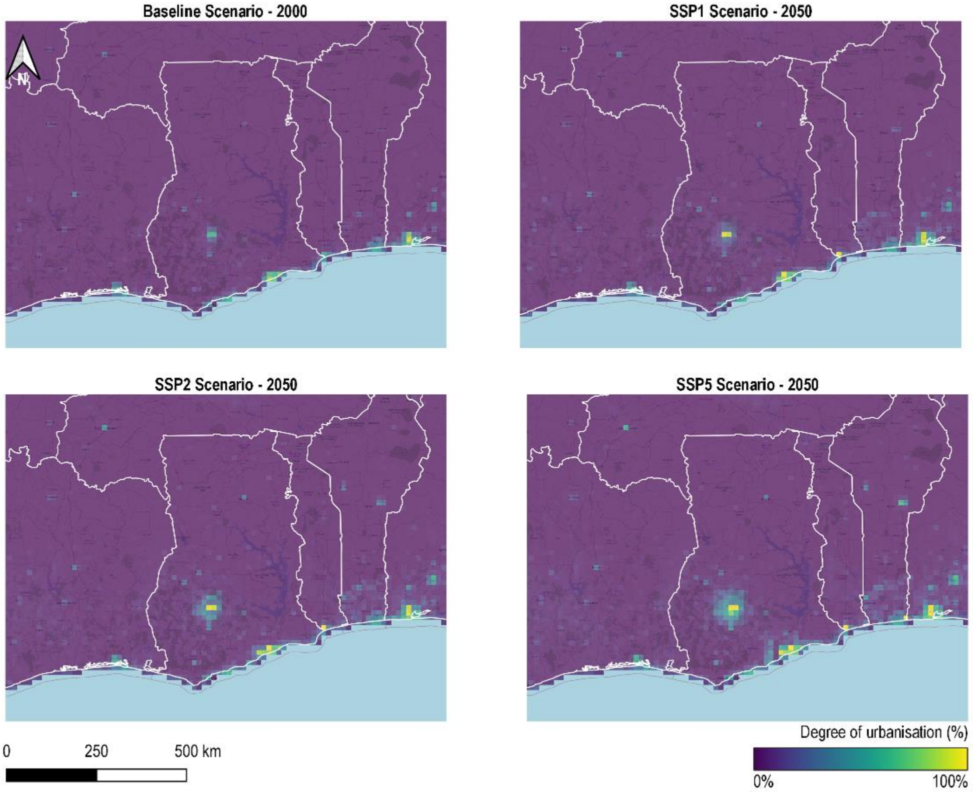


Figure 1. Projections for urbanisation in Ghana in 2050 based on SSP scenarios. Lighter pixels mean higher fractions of urbanised land (Maps based on data from Gao (2020)).

As Figure 1 shows, urban areas are not just growing in terms of population. To house the increasing number of residents, urban areas are expanding in horizontal direction, in what is known as urban sprawl. In this process, land on the edge of the urban area transforms from rural, towards urban. This land, with both urban and rural characteristics is called peri-urban land.

As a consequence of this urban sprawl, agricultural activities in peri-urban fringes suffer. In Kumasi in Ghana for example, vegetative cover has decreased from 48% to 9% between 1986 and 2016 (Kwadwo et al., 2019). In addition, complex land tenure rights in countries like Ghana leave peri-urban farmers unable to continue their activities and often force them to make place for residential development (McGregor et al., 2011).

This farmland shrinkage not only endangers the livelihoods of peri-urban farmers, but also threatens the food security of the city. Throughout SSA, small farmers on the fringes of the city have been important elements of the cities' food supply (Cofie et al., 2003). This can be in the form of easily perishable foods, like fresh vegetables and fruits, which is the case in Kumasi (Danso et al., 2014), or in the form of livestock rearing, which is widely applied in peri-urban Kampala (Sabiiti & Katongole, 2016).

On top of the threat of urban sprawl, climate change is an ever-present spectre that is haunting future development. In Kumasi, this manifests itself through increasing temperatures (Koranteng et al., 2019), leading to discomfort in the population, and through increased precipitation, leading to flooding (Korah & Cobbinah, 2017). Climate change and urban sprawl also reinforce each other. Korah and Cobbinah (2017) state that climate change is a driver of migration to cities, where rural residents resettle in flood prone areas, due to lack of space. At the same time, this urbanisation means that urban green space gets replaced by built-up area, reducing infiltration capacity and consequently, increasing runoff. On top of this, the decrease in urban green space reinforces the urban heat island effect, increasing the discomfort of high temperatures.

1.2 Research scope and goals

These issues mean that there is an interest in finding ways to maintain urban and peri-urban agriculture (UPA) in SSA. The goal of this research is to find and evaluate adaptations that (peri-) urban farmers in Kumasi can make to ensure that agriculture is maintained on the fringes of and inside Kumasi. The choice for Kumasi came from the important role that UPA plays there, as well as the urbanisation that this place has been through for the last thirty years. Finally, there already exists a network there, which simplifies cooperation with local partners.

The adaptations are assessed on their potential to limit the effects of urban sprawl and climate change on their ability to maintain food security for the city. After the adaptations are analysed and modelled, surveying of stakeholders allows for validation of the results, as well as understanding potential barriers against implementation. The issue is approached using the following research question:

What adaptations are suited to sustain peri-urban agriculture in Kumasi (against the threat of climate change and urban sprawl)?

The following sub-questions help to answer the main question:

- What is the nature of peri-urban agriculture in Kumasi?
- What threats to peri-urban agriculture are there and how do they impact livelihoods?
- What adaptations are available to maintain peri-urban agriculture?
- What elements are part of adaptation design and how do these elements influence what adaptations are well suited?
- How do farmers and vendors perceive threats and adaptations and what elements do they value in adaptations?

1.3 Relevancy

This research contributes to the discourse on urban and peri-urban agriculture in several ways. For one, it is the first time that the potential for self-sufficiency is researched based on modelling of local practices and based on surveys of local actors. Earlier work that tried to quantify the productivity of UPA did so based on countrywide mean yields and thus misses local dynamics of urban agriculture. Crop yields can vary wildly through a country due to different practices, climate and soils. By taking the actual practices from (peri-) urban farmers in Kumasi into account, as well as the local climate and soil system, this model will be a closer representation of reality. Moreover, this work also takes climate change into account with three scenarios for the mid-century in terms of population growth and changing climates. This allows for statements that are valid now, as well as in 25 years.

This work is also highly relevant in terms of policy. The modelling in this work provides quantifications for land that needs to be reserved in neighbourhoods so to maintain food security. It also shows which adaptations are better suited for specific crops in the modelled neighbourhoods. Finally, this work attempted to survey stakeholders in peri-urban agriculture on their opinions on the situations, which can also be used as a foundation for future policy.

1.4 Structure

This report is structured in the following way. Chapter two gives the background to the problem by first introducing several concepts and definitions that are commonly used throughout the work. In the later parts of this chapter, the study area is introduced, and the threats and adaptations are outlined.

Chapter three details the method that was used in this research. It includes the method for assessment of the adaptations, the workings of the agro-hydrological model AquaCrop and the set-up of the surveys of the stakeholders.

Chapter four presents the results of modelling and survey and discusses the implications of these results. Following this is the assessment of the adaptations and which adaptations work best to maintain UPA in Kumasi. It also includes a short literature study into safe wastewater reuse in UPA as a basis for future research. Any extended sets of results are found in the appendix of this work.

Finally, chapters five and six follow up with the conclusions and recommendations based on this research, as well as the answer to the main research questions.

2. Background

This chapter is dedicated to an explanation of some of the concepts that are used in this work, as well as a background to the study area in Kumasi. Finally, the findings from the literature review, that resulted into the identification of the threats to peri-urban agriculture in Kumasi and what adaptations there are, are given in chapters 2.3 and 2.4.

2.1 Concepts and definitions

In the preceding parts, several concepts were introduced without giving a proper definition and without explaining the relevant background in sub-Saharan Africa. This chapter deals with defining these concepts in relation to this research.

2.1.1 Urbanisation in sub-Saharan Africa

In sub-Saharan Africa, levels of urbanisation have increased massively over the past years. In 1960, less than a quarter of the Ghanaian population lived in cities. In 2020, this number has grown to over half. Even in countries with lower absolute levels, the growth of the last 60 years has been incredible. This trend becomes clear from Figure 2, where the degree of urbanisation for SSA in general, the Euro zone and Ghana specifically has been plotted. Before going deeper into the effects of urbanisation on peri-urban agriculture, it is important to have a clear definition of the concept of urbanisation and related terms.

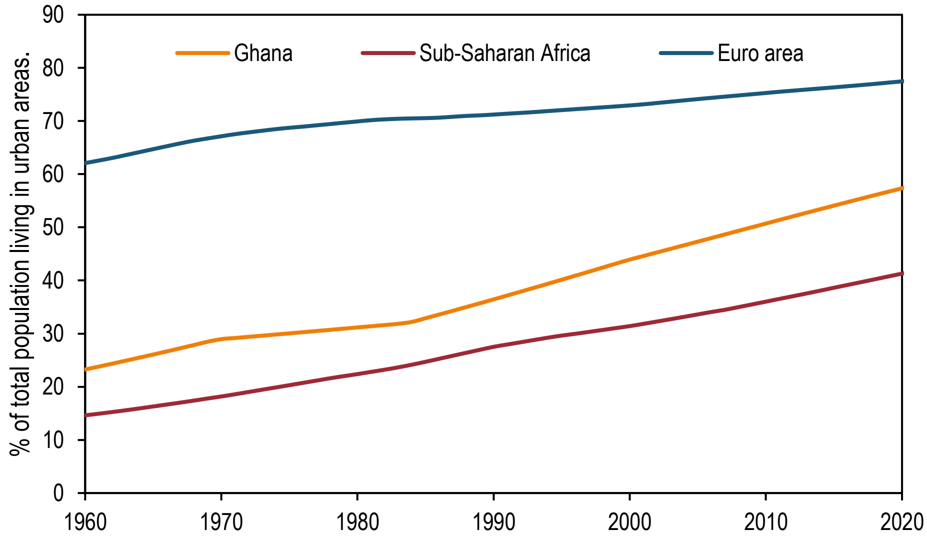


Figure 2. Degree of urbanisation for Ghana, SSA and the Eurozone (The World Bank, 2021b).

Urbanisation is defined as “the increase in the proportion of people living in towns and cities. (…). This usually occurs when a country is still developing.” (EEA, 2023).

This already reveals how urbanisation is something that is very much linked with the developing nations of sub-Saharan Africa. It also warrants a closer look at the concept of development. Development generally refers to economic growth. While this is an incomplete picture of the concept and often contested, the link between the economic element of development and urbanisation becomes clear from Potts (2018). They explicitly define urbanisation also in economic terms: a shift from livelihoods based on agriculture, to ones based on industry and services. Although both definitions are contested (Shifa & Borel-Saladin, 2018), for this work it suffices to take both elements into account and define urbanisation as the increase in the proportion of people living in towns and cities and the associated shift in livelihoods.

Distinct from urbanisation is urban growth. Whereas urbanisation refers to the part of the population that lives in cities relative to the total population, urban growth refers to the absolute increase of people living in the city (Shifa & Borel-Saladin, 2018). Both elements are contributions to urban sprawl, the increase of the size of the city in terms of area.

From this, one can see that these concepts are all linked together. In general, whenever this work refers to urbanisation, it can be assumed that it refers to urbanisation and its consequences.

From a first glance, urbanisation may not seem like a problem by itself. In fact, the shift in livelihoods away from subsistence agriculture towards a more service and industrial based economy has the potential to come with an increase in welfare. However, the urban sprawl that comes with urbanisation means that green space inside and surrounding the city is under threat. As a result, agricultural areas that are necessary for a stable food supply may have to make place for residential development. As has already been outlined earlier in this work, this process is already going on. Urban sprawl is thus a threat to food supply of the city itself. All in all, it is clear that the increase in urban population and its corresponding urban sprawl will increase the strain on all resources in the city.

This transformation is not just impacting the urban areas itself. The urban-rural interface, what we call peri-urban area, is particularly affected by urban sprawl (Cobbinah et al., 2015). Before going into depth into this impact, it is important to first have a clear image into what peri-urban, urban and rural mean in general and in the context of sub-Saharan Africa.

2.1.2 The distinction between urban, rural and peri-urban

A common definition of rural is often “not urban”. Although useful, this is not fully satisfactory. The Food and Agriculture Organisation of the United Nations (FAO) uses three characterisations for rural areas (FAO, 2018).

- Sparse settlement
- Non-built-up land cover
- Remoteness

This would make a rural area one with smaller, spread-out settlements, characterised by little swaths of built-up land cover, among more vegetated landcover like agriculture and forestry. Finally, remoteness refers to a lower accessibility of services and markets.

In contrast, urban areas are regions with a high density of population and buildings. This is generally associated with a large degree of impervious landcover, as well as a low degree of green space. To come back to the definition or rural, one can also say that urban areas generally have a high density of services and markets.

With urban and rural defined, this leaves peri-urban as obviously the part that links these two. Peri-urban areas are the zones in which the urban transforms into rural. It is characterised as a region where rural and urban land cover mix among each other. Take for example an important road leaving the city. In a peri-urban area, there could be larger residential development along this road, along with the important services. Around this core, there would be more green space and smaller homes and residential blocks, mixed with agricultural land use.

This point where urban turns into peri-urban and peri-urban into rural is not a hard boundary and the size of this zone is different for every city. An organically grown city that swallowed previously neighbouring villages generally will have a larger peri-urban fringe than newly developed cities. Besides, the peri-urban areas have different characteristics all over the world.

Much like urban agriculture is distinct between SSA and places like Europe – as explained a little below - the characteristics of a peri-urban area are very different. Take the western Netherlands for example: a peri-urban area in this country will likely evoke the idea of greenish suburbs, with perhaps a recreational green zone as a transition towards the pastures that are associated with the dairy industry. While the farmers will make their livelihoods here, the people who live in the suburbs likely commute to their job in the city.

In contrast, peri-urban areas in SSA often feature subsistence farming; people make do with whatever space they can find to grow some crops or to keep some livestock to feed their families. Others sell the products on markets in the same area. People still work and commute to the city, but this distinction in the agricultural part is important and something that will be explored later.

It is now clear what is meant with urban, rural and peri-urban, but the second element that was hinted at is maybe even more important. In the next part, the concept of urban and peri-urban agriculture is explained and what this means for this research.

2.1.3 Urban agriculture

Urban agriculture (UA) involves the growing of crops or holding of livestock in an urban setting. This ranges from larger scale community gardens to smaller private gardens, which also means that there is a large diversity in the types of people taking part in UA and in the types of crops that are grown.

Additionally, patterns are not the same throughout the world. For an audience in the Global North, the concept urban agriculture likely evokes imagery of high-tech vertical farming, hydroponics systems, or for a more informed person, the image of a small pot of basil on the balcony. Both high-tech and low-tech are a reality for urban agriculture in the Global North. At the same time, the role that UA fulfils is very different to the role it has in other parts of the world. In the Netherlands, UA often has an educational use (Van der Schans, 2010): high tech hydroponics as proof of concept and smaller community gardens to introduce schoolkids to the concept. Do note that this is not necessarily true for all places in the west. In food deserts in the United States, UA is distinctly hailed as a way to improve food security (McCauley, 2020).

In contrast, UA in developing countries is much more a tool for survival. In rapidly urbanising cities like Accra and Kampala people spend a large amount of their income to feed themselves (Orsini et al., 2013). Because of this, people living in urban and peri-urban areas use any available space to grow little bits of food that can either complement a diet or can be sold to buy other foodstuffs. In many peri-urban areas people rely completely on agricultural activity for their livelihoods (Zezza & Tasciotti, 2010).

There has been a lot of research on the positives of urban agriculture, citing the benefits for food security, extra income and community building as elements that make engaging in UA worth it.

Zezza and Tasciotti (2010) found that urban households that engaged in agricultural activities had a higher diversity in diets, as well as a larger caloric intake. As a later part will reveal, both these elements are associated with higher degrees of food security.

In addition to the food security argument, Orsini et al. (2013) mention the benefits to the economy of the urban poor. By growing crops themselves, they not only reduce the amount of money that is spent on food purchases, but they also stimulate the development of farming-adjacent activities, such as processing and packaging industries, in developing neighbourhoods.

Finally, McCauley (2020) and Orsini et al. (2013) specifically mention the benefits that UA brings to social inclusion in poor communities and in introducing green space. The former has been cited as an important factor in lifting up disadvantaged people in their communities, while the latter is hailed as crucial in maintaining biodiversity and mitigating the effects of climate change (Orsini et al., 2013).

Naturally, engaging in UA is not without risk. Research has shown that soil and air pollution have an impact on accumulation of potentially harmful substances in the crops that are grown (Shahid et al., 2019). Consequently, it is crucial that there is sufficient monitoring of potential pollutants and care should be taken in the handling of products.

The second risk is water availability. Although most of the global urban croplands are rainfed (Thebo et al., 2014), expansion of UA in regions that are more water scarce will mean that irrigation measures need to be in place. In specific schemes, irrigation is already practiced. In an increasingly water scarce future, competition for water resources may threaten the food supply from UA. Therefore, any identified adaptations should be future proof in term of water use.

In addition to this risk, there is a fair degree of criticism to UA's capability to relief food insecurity. In a widely cited study, Badami and Ramankutty (2015) found large area requirements to be able to grow enough vegetables for urban poor. In some cases, more than 100% of the urban area was needed to be able to supply inhabitants with vegetables. Equally, there also exists empirical evidence that shows agricultural production in urban and rural spaces alone by urban dwellers had no association with increased food security in Tamale in Ghana (Ayerakwa et al., 2020).

2.1.4 Food security

The FAO defines a person as food insecure "(…) when they lack regular access to enough safe and nutritious food for normal growth and development and an active and healthy life" (FAO, 2022b). Data shows that in 2020 worldwide, roughly 28% of the population experienced moderate to extreme food insecurity. In sub-Saharan Africa, this value is even larger, noting a value of almost 30% of the population (see Figure 3).

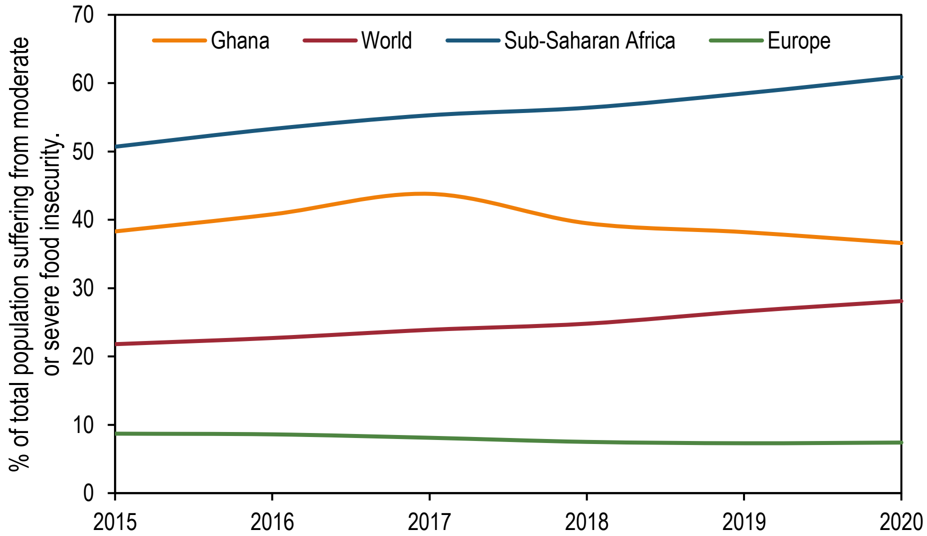


Figure 3. Prevalence of moderate to severe food insecurity in the population for Ghana, sub-Saharan Africa, Europe and the world (FAOSTAT, 2022).

Severe food insecurity is defined here as having no food at all for a day or more. This highlights a focus purely on quantity, but lesser degrees of food insecurity in the FAO definition and other authors also stress the need for variety and general nutrition (e.g. Upton et al. (2016)).

A crucial element in tackling this second element of food insecurity is diet. The EAT-Lancet Commission (2019) researched a planetary health diet that would optimise human health and environmental sustainability. In their summary report the commission states that, while keeping local possibilities in mind, the consumption of fruits, vegetables and legumes needed to be doubled, while reducing the consumption of food with added sugars and red meats by more than half in developed countries. They calculated the necessary daily intakes of important crop groups for a person to maintain food security in both quantity and quality. The intakes are shown in Table 1.

Table 1. EAT-Lancet recommended intakes for important crop groups (EAT-Lancet Commission, 2019).

Food group	Intake [g/day]	Intake min [g/day]	Intake max [g/day]	Intake [kcal/day]
Whole grains	232	232	232	811
Tubers and starchy vegetables	50	0	100	39
Vegetables	300	200	600	78
Legumes	75	0	100	284

Based on this, it is possible to split up food security in urban areas in three important components:

1) Sufficient **supply** of food in general.
2) Sufficient **access** to food for (urban) populations.
3) Strong **variety** of food for optimal nutrition, with focus on fruits, vegetables and legumes.

In urban areas the latter two elements are the main problem. For one, inadequate financial means in poor families do not allow them to purchase enough food, let alone varied food (Lopez-Carr, 2013). Supply is there, but not everyone can afford it. Moreover, the massive increases in urban populations over the last years can also jeopardise the supply of food for urban populations in general. Still, there is a tremendous opportunity in growing food in urban areas themselves. Not only does this simplify access, but it also allows to grow different perishables that are crucial for the EAT-Lancet diet. Finally, urban farms provide necessary green space to make cities more liveable (Cilliers et al., 2020).

With this, the final definition is clear. The meanings of urbanisation, peri-urban areas, urban agriculture and food security are all explained. This gives enough information to really zoom in on the study area and to apply these concepts on this specific location.

2.2 Study Area

Now that it is clear what the definitions of the commonly used concepts are, it is good to zoom in on the study area and what these concepts mean for Kumasi in specific. This part will go through a short description of Kumasi, into a deeper dive into livelihoods in the peri-urban fringe and food supply of the city, as a background to introduce the threats and adaptations in a future chapter.

2.2.1 Kumasi: history, climate and geography

Kumasi is the second largest city in Ghana and the capital city of the Ashanti region. In 2019 the population was estimated at 2.1 million people spread out over an area of 509km² (4,135 people/km²) (Anarfi et al., 2020). This population is the result of an enormous growth: since 1984, population has increased fourfold (496,268 in 1984). At the same time, the city is undergoing rapid sprawl; built up area has increased more than tenfold in the last 40 years (43.22 km² in 1984).

As the seat of the king of the Ashanti people, the city holds an important place in the mythology of the Ashanti, which is the dominant ethnic group in the region. Later, from the 19th century onwards, the region fell under British rule. The British colonisers had a large impact on Kumasi, razing the city to the ground in 1896 and rebuilding at the same spot (Adjei Mensah, 2014). During more than half a century of gradual redesign, Kumasi became known as the “garden city” of West-Africa. In the design of the city, special care was taken to ensure sufficient green space in the form of parks and agriculture. The massive urban sprawl in recent years however, has led to such a decrease in urban green space that experts believe Kumasi can no longer be called a garden city (Adjei Mensah, 2014).

Kumasi is located in the Tropical Savannah Köppen climate zone typified by tropical grasslands and distinct wet and dry seasons. Throughout the year, temperatures are fairly consistent. Records from the period 1991-2020 show a maximum in mean temperature in February (28.76°C) and a minimum in August (25.22°C). Precipitation features a dry season from December to February and fairly high precipitation in the remaining months with a peak in October. Full distributions of temperature and precipitation are represented in Figure 4.

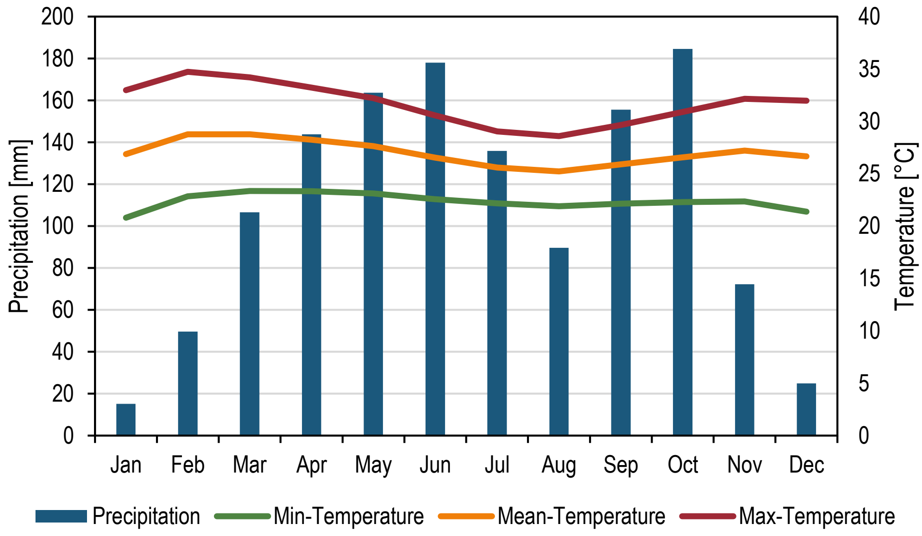


Figure 4. Climatology of the Ashanti region (1991-2020)
Based on climate data from (Harris et al., 2020).

Mean annual temperatures have been rising steadily for the last 100 years. The observed mean annual temperature in 2021 was 27.55°C, in contrast to 26.85°C in 2001 and 26.54°C in 1921. Moreover, the last 5 years feature some of the highest annual temperatures in the temperature record, all above 27°. Precipitation records show a different trend, with annual precipitation levels between 1250 and 1500 mm per year, which remained consistent over the recorded period.

The geography of Kumasi is characterised by the undulating terrain that is a consequence of the rivers flowing through the city. The streams generally flow in southward direction, including rivers like the Daban, Sisa and Wiwi. This creates a network of low grounds with streams and corresponding wetlands, alternating with higher grounds. The city overlays a clayey soil that impedes infiltration of rainfall, leading to high runoff generation. Moreover, the orientation of the river network means that the rivers first flow through the peri-urban area, followed by the urban and then the peri-urban fringe on the other side of the city again. This means that any waste that is collected in this process ends up in other neighbourhoods, increasing the risk of pollution and disease. The geography is visualised in Figure 5.

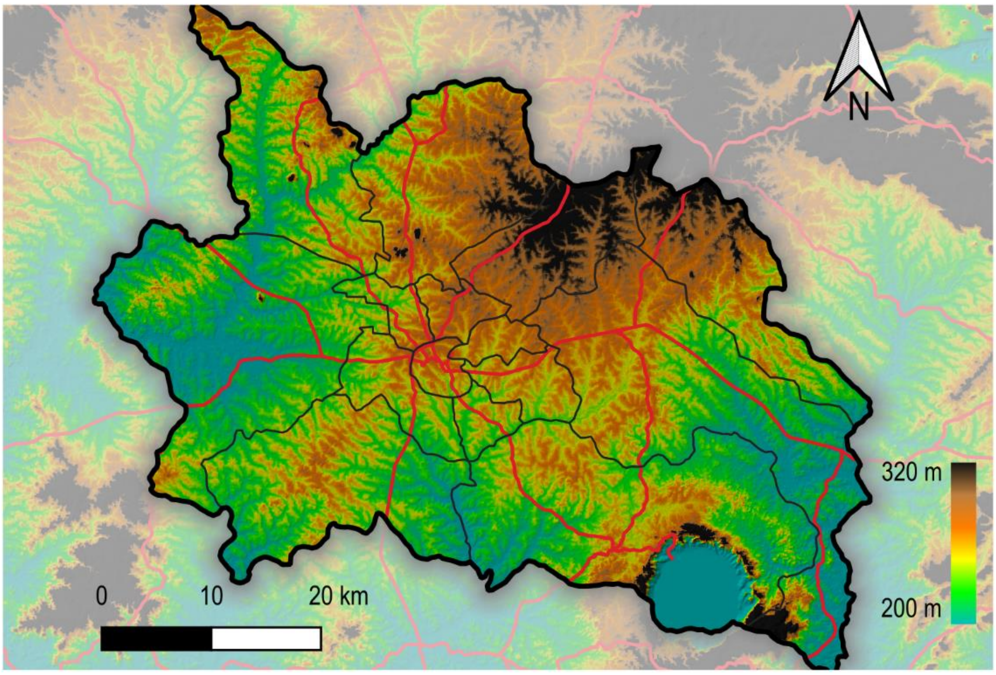


Figure 5. Geography of Kumasi and surrounding districts (Major roads shown in red). DEM data from (NASA JPL, 2013); District boundaries from (Ghana Statistical Service, 2019).

2.2.2 Livelihoods in urban and peri-urban Kumasi

As the capital of the wealthy Ashanti region, Kumasi is a city of commerce. The crossroads of the city do not just serve as a hub for transport of goods in Ashanti however, but also attract migrants from all over the country and other parts of West-Africa (Amoako & Cobbinah, 2011). Many of these migrants live in slums under poor environmental conditions. In these parts of the city, people’s livelihoods are dependent on informal economic activity, like street sales of food or other goods (Amoako & Cobbinah, 2011) & (Owusu-Sekyere & Amoah, 2020). In the peri-urban parts of the city, agriculture is a major form of livelihood (Cobbinah et al., 2015). The crops produced in this peri-urban interface are an important source of vegetables and tubers for the inhabitants of Kumasi. Moreover, the inhabitants of peri-urban areas are dependent on the sales of vegetables for their livelihoods.

Peri-urban areas are increasingly under threat from the urban sprawl of Kumasi. In the Feyiase neighbourhood for example, 52% of the inhabitants are now displaced residents from the city. The remaining 48%, who are indigenous to the area, are the ones who work in agriculture (Cobbinah et al., 2015). The influx of people leads to new residential development, usually at the expense of agricultural land in the peri-urban parts of Kumasi. Despite the importance of peri-urban agriculture for the city, the profitable nature of residential development often wins out in land use planning by traditional authorities (Cobbinah et al., 2015).

These threats force peri-urban farmers to diversify into either different farming strategies, to abandon farming altogether or, in extreme cases, migrate. In the case where farming is maintained, farmers try to exploit all types of marginal lands. This includes lands that are yet to be developed, but also lands next to drains or rivers (Abass et al., 2013). This type of agriculture is not sustainable, as the developments will displace the farmers over time, or due to flood risk. Moreover, intensification to maintain livelihoods involves heavy use of fertiliser and land depletion. Because of this, there is a need for additional adaptations in the forms of technology or planning.

2.2.3 Land tenure in Ashanti/Kumasi

A commonly cited issue in the theory of peri-urban agriculture is uncertain land tenure. Ghana has two types of land administration. Customary ownership, in which land and its resources are held in trust by traditional leaders, and “regular” state/private ownership (Mintah et al., 2021). Approximately 80% of the land is in hands of the former. These lands are officially administrated by the Asantehene (the ruler of the Ashanti people), who then divides it to divisional chiefs (Cobbinah et al., 2020). Traditional authorities thus hold the key in prospective land development in Kumasi and determine what types of development can take place. Cobbinah et al. (2015) state that because of this distribution, collaboration in land development is ineffective and that it leads to an imbalance between planning and development.

Currently, traditional authorities are also the ones who allocate lands to be used for farming in peri-urban communities. Crucial however, is that they keep the right to retract this permission for other types of development. Increasing urbanisation leads to stronger competition for land. Because of this, it is common that agricultural land planning loses out against more profitable residential development (Cobbinah et al., 2015).

2.2.4 Food basket

With the importance of UPA and the trials it faces clear, it is good to look at which crops are grown in the city. It is already established that UPA is an important source of perishables. Still, there is benefit in covering the full scope. For this we introduce the concept of the food basket. The food basket accounts for three elements in considering the diet of city dwellers:

- What is consumed (Traditional diets/current diets)
- What is available (Crops grown in vicinity)
- What ensures food security (EAT-Lancet Planetary Health Diet)

The first element looks at what people in the city eat. Frank et al. (2014) identified two dietary patterns among the urban population of Ghana. Firstly, a “purchase” pattern characterised by higher intakes of sugar, rice, meats and exotic vegetables. In contrast, the traditional pattern features plantain, leafy vegetables and garden eggs.

Already this indicates a shift in diet from traditionally grown foods to imported ones. This is corroborated by Drechsel et al. (2007), who researched urban-rural food flows in Kumasi. They distinguished between food grown in rural areas, grown in urban areas and imported from abroad. Imported foods are more frequent among wealthier urbanites and correspond to the components of the “purchase” dietary pattern. Logically, the traditional dietary pattern includes crops that are grown in and around Kumasi. According to Drechsel et al. (2007) urbanites get their tubers mostly from rural regions whereas 90% of leafy vegetable demand is met by (peri-)urban agriculture.

All in all, 40% of the food inflow into the Kumasi markets is sourced from the city and its peri-urban fringe itself. This already gives an indication for element two of the food basket. In Danso et al. (2014) the features of the major urban vegetable production sites in Kumasi are outlined. Combined with Drechsel et al. (2007), this leads to Table 2, detailing the food basket of Kumasi.

Table 2. Food Basket of Kumasi, split up into crop categories.

Category	Elements	Main Source
Tubers	Cassava, Plantain, Yam	Rural
Fruits	Papaya, Melon, Banana, Mango, Pear, Pineapple	All
Vegetables	Cabbage, Carrot, Cucumber, Eggplant, Lettuce, Pepper, Tomato	(Peri-)Urban
Cereals	Maize, Rice, Wheat	Rural for the former, import for the latter two
Legumes[1]	-	-

The 2019 EAT-Lancet report on the "transformation of the global food system" defines diets that are healthy both for the planet and humanity (EAT-Lancet Commission, 2019). In short, this means a higher consumption of vegetables and a lower consumption of red meat globally. For sub-Saharan Africa more specifically, the consumption of red meat is still below the health boundary they set, while the consumption of starchy vegetables is 7 times higher than the boundary Figure 6. The diets identified in Kumasi above support these findings. Furthermore, it shows that the transformation is already going on, although there is still space for more vegetables, fruit and legumes in the diet and the intake of sugary foods in the "purchase pattern" is a worrying trend.

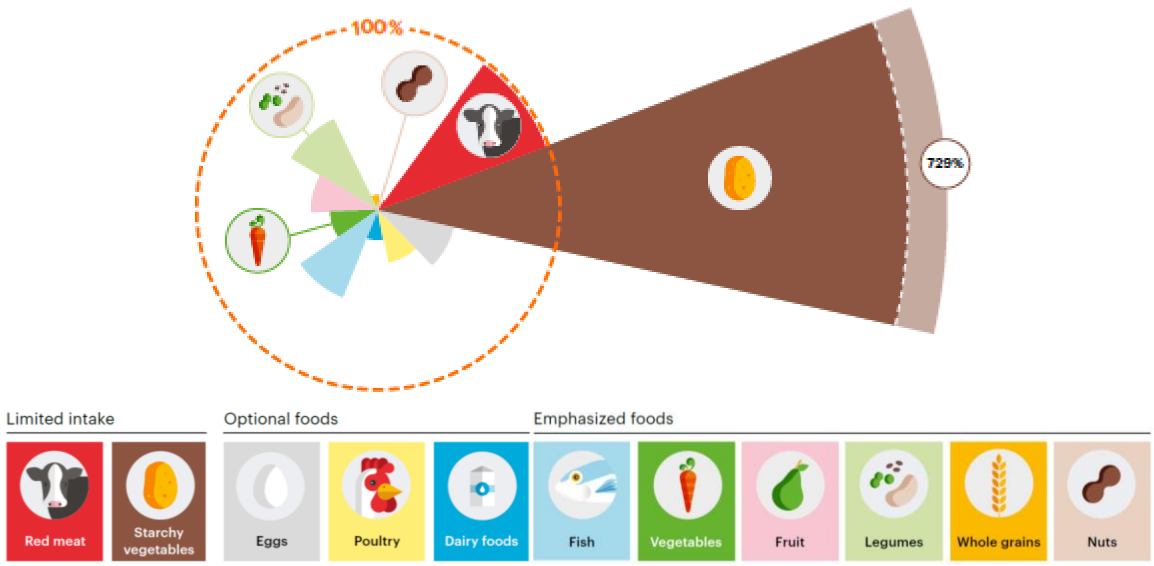


Figure 6. "Diet gap" between current patterns and planetary health diet in SSA as identified by EAT-Lancet Commission (2019).

[1] Not yet consumed widely, but a crucial element from the EAT-Lancet diet for planetary and personal health.

2.3 Threats to livelihoods

It has become clear that peri-urban agriculture is an important source of livelihood for marginalised people in Kumasi as well as the premier source for fresh vegetables in the city. It is also established that Kumasi is suffering from the consequences of climate change and urban sprawl. Before advancing towards adaptations, it is important to understand the types of threats better.

2.3.1 Urban sprawl

The population of Kumasi is growing with 4% annually, which admittedly is already decreasing when compared to the 5.4% that has been recorded in most of the past 30 years (Abass et al., 2018), but still far from sustainable. At the same time, the city is expanding massively in horizontal direction, which is easily visualised with the use of remote sensing data (Figure 7). Experts have stated that this horizontal expansion is not unifiable with sustaining the landscapes and livelihoods of formerly peri-urban neighbourhoods (Abass et al., 2018).

The spread comes with high competition for land, which leads to farmland being reassigned by authorities for residential development, which is generally more profitable for them. The reduction in arable land is not just visible from remote sensing, but also from statistics. According to the Ministry of Food and Agriculture, the cropped area for major cereals and tubers in one district has reduced twofold between 2001 and 2016 (Abass et al., 2018). Farmers that remain are now put under pressure to increase production. This intensification damages soil fertility; endangering future productivity.

All in all, the urban sprawl of Kumasi risks the livelihoods of peri-urban farmers by reallocating their land for residential development. This results in a smaller food supply for a continually growing population. Finally, the remaining farmers are forced to increase their short-term agricultural yield by intensification, in turn threatening the long-term fertility of the agricultural lands.

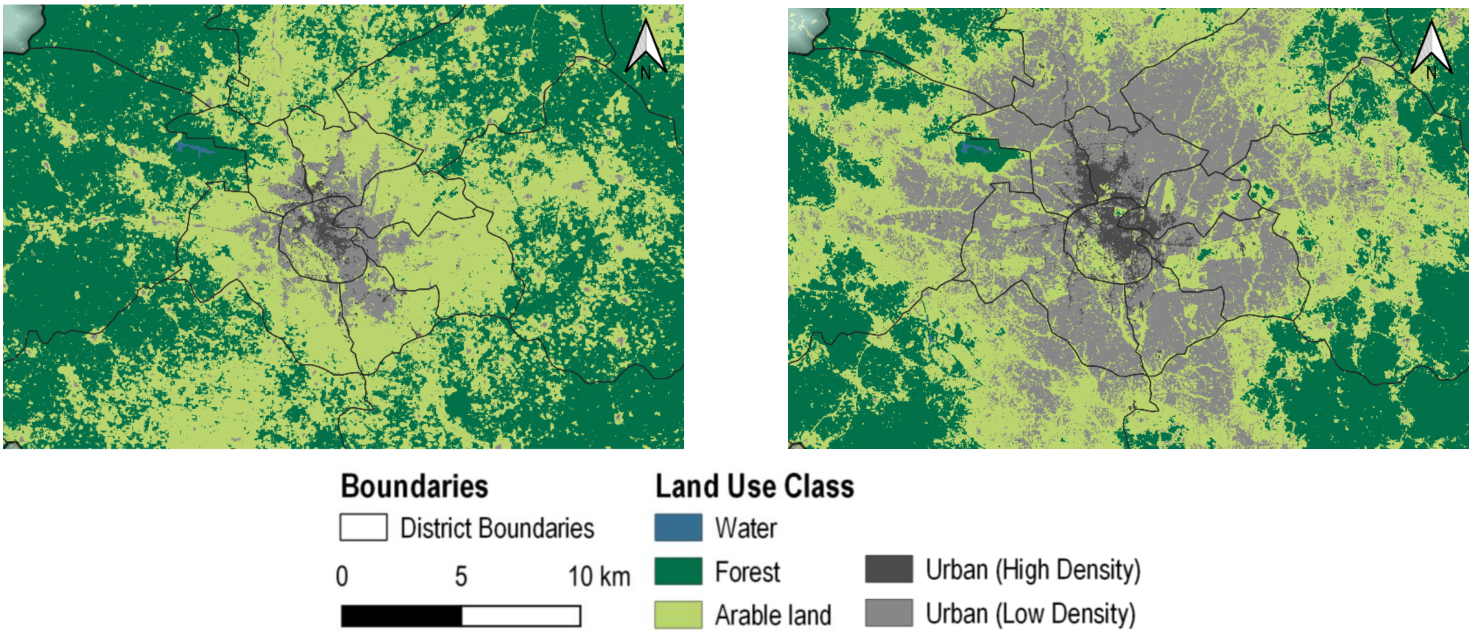


Figure 7. Land use change from 1986 (l) to 2021 (r) in Kumasi.
Land use data from (USGS, 2021); District boundaries from (Ghana Statistical Service, 2019).

It is not all bad news. Abass et al. (2018) also found that the reduction in productivity in the vicinity of Kumasi is associated with an increase in production of staples in other parts of the Ashanti region. At the same time, they noticed an increase in backyard gardening in the newly developed peri-urban regions. Going off the food basket from before, this means that the rural and urban production have the potential to become complementary, where the staple cereals and tubers are provided by fully rural production and the more perishable fruits and vegetables can be produced directly in the city. Still, there remains the issue of scale and the needed water and nutrients, especially considering the effects of climate change. A closer look at the adaptations that agriculture needs follows in the next section.

2.3.2 Climate change

The second major threat is climate change. Climate change is generally associated with increases in temperature and more irregular rainfall. In some ICCP scenario's, mean annual temperature in Kumasi will increase to above 28° in 2040 and may even rise to 31° in 2100. Precipitation estimates are accompanied by a large degree of uncertainty. Figure 8 shows the projections for SSP2. From here, it becomes clear how large the difference is between high estimates for precipitation and low estimates. This uncertainty means that, in the future, Kumasi must be prepared for either longer dry spells, or very intense rainfall.

Droughts are obviously a threat to rainfed agricultural production and prolonged periods without rain can reduce the discharge of the rivers, which is a risk to irrigated production as well. Besides, long dry spells can lead to overuse of groundwater, which is unsustainable. Conversely, floods associated with more intense rainfall of shorter duration endanger the production of crops in wetlands and low-lying areas.

The effect of increasing temperatures is already being felt throughout Kumasi. In an attempt to analyse the Urban Heat Island (UHI) effect in Kumasi, Koranteng et al. (2019) reported that a majority of respondents indicated that the outdoor temperature was uncomfortable. These same respondents ascribed the discomfort to a reduction in green space in the city. It is clear that the effects of climate change are already felt in the city. Moreover, the loss of green space resulting from the growth of the city exacerbates the issues.

There is also a link between the irregular precipitation associated with climate change and the change of land use in the city. Similarly to the temperature situation, experts noted that recently flooding is more frequent due to land use change (Campion & Venzke, 2013). Others stated that due to climate change, more places are now flood-prone (Korah & Cobbinah, 2017). This is a risk to peri-urban agriculture because agriculture either already takes place in the low-lying riparian zones, or because it is driven towards these marginal lands due to urban sprawl.

It is not simple to find things that deal with all the effects of climate change without global shifts. There are however some elements that make adaptation in the city simpler. Firstly, there is a need for clarity. The previous paragraph outlined some of the uncertainties related to climate change. If we do not know how the climate system will react, it is impossible to adapt to it. Therefore, there is a need for effective models that can predict weather patterns and the response of the hydrology in Kumasi. This way, there is a chance to design in such a way to mitigate the effects of floods and droughts. For farmers, there may be a need to change their crops to ones that are more drought resistant or use technological adaptations that use less water. A deeper dive into adaptations specifically related to agriculture follows in the next section.

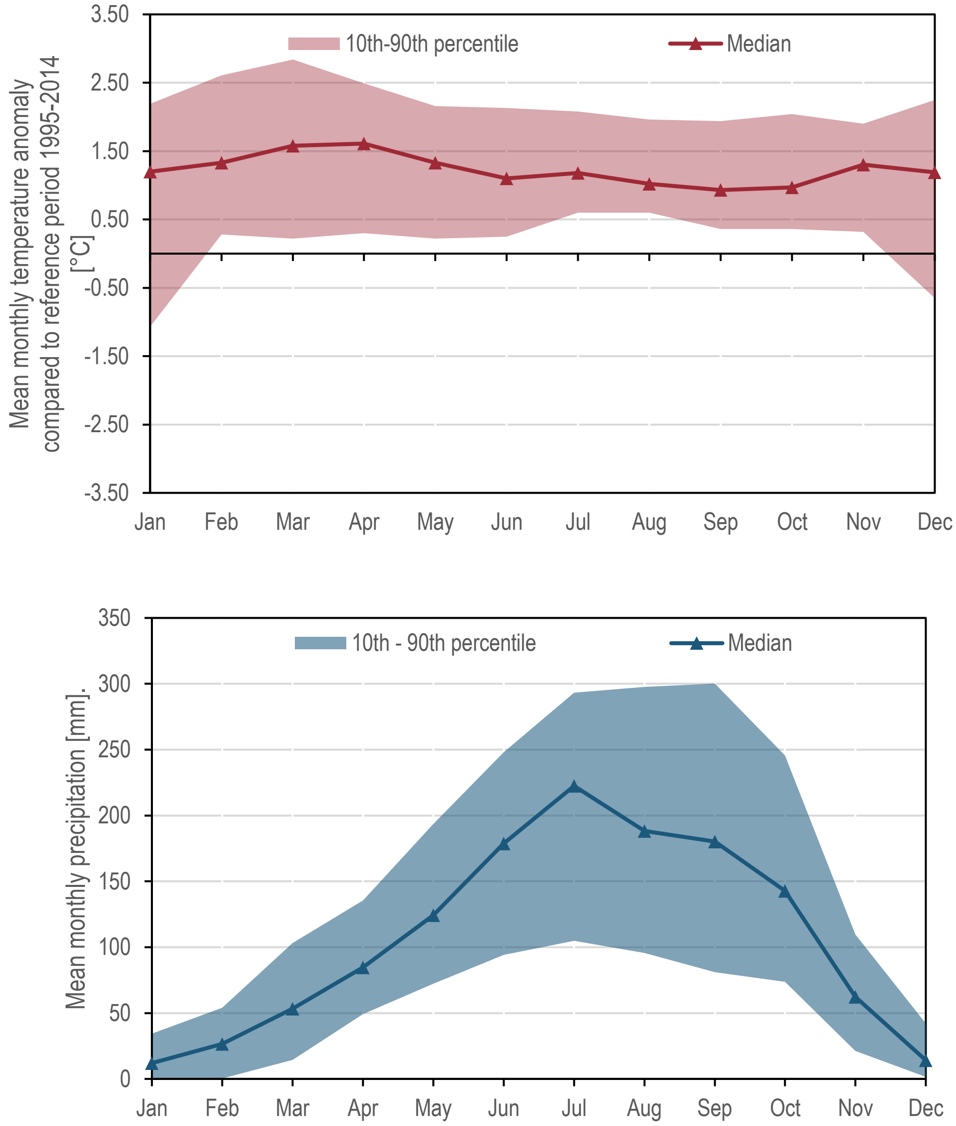


Figure 8. Climate effects on weather in Ashanti for the period 2040-2059 for SSP2-4.5 (The World Bank, 2021a).
Top: Mean monthly temperature anomaly. Bottom: Mean monthly total precipitation.

2.4 Adaptations to maintain (peri)-urban agriculture.

Peri-urban agriculture plays an important part in Kumasi's food supply and in the livelihoods of its inhabitants. It is also clear that peri-urban agriculture in its current form is not sustainable in the face of urban sprawl and climate change. Because of this, it is important to identify the options that farmers can take to deal with their problems. In this we make a distinction between "high" and "low" tech solutions. Among the low-tech solutions are backyard gardening, farming on marginal lands and container/sack gardening. High tech solutions include soil free farming methods (Aquaponics) and greenhouse technology. The adaptation strategies were identified by Ayambire et al. (2019).

2.4.1 Maintaining current strategies.

Before it is possible to evaluate the other adaptations, it is necessary to take a deeper look at the current schemes, to form a baseline for comparison. Section 2.2 gave an insight into the current schemes that are used by (peri-)urban farmers in Kumasi. Still, there is a noted difference between the strictly urban and peri-urban types of agriculture. In the very dense urban city centre of Kumasi, agricultural production occurs on government owned lands, located on school campuses for example (Danso et al., 2014). This contrasts with the earlier mentioned farming on empty lands, to be developed land, and general land on the fringes of the peri-urban.

The type of agriculture is also different. Urban production on campus lands is mostly focussed on irrigated vegetable production (Danso et al., 2014). Traditionally, the peri-urban production is more mixed between vegetables, cereals and tubers in a rainfed rotation scheme (McGregor et al., 2011). Under the threats described however, many of these farmers have shifted to irrigated vegetable production with multiple harvests per year (McGregor et al., 2011). This scheme is reported to be more profitable, allowing for more diverse livelihoods for peri-urban dwellers (Danso et al., 2002).

Naturally, maintaining the current systems of agriculture does little in adapting to the changing circumstances in Kumasi. If urban sprawl keeps growing out of control, urban farmers will be forced to abandon agriculture and try to make a living in other ways. The only way for UPA to remain in its current form under the spread of urban sprawl is by extensive political intervention in zoning land specifically for crop production. This way agriculture can continue, while the city is developed around it. It is not a flawless plan however, experts have noted an extensive amount of informal development (Cobbinah et al., 2020), which might bypass the planned zoning. Moreover, a growing population means a growing requirement of food. This will force farmers to use more intensive methods, which depletes the soils of nutrients and depletes nearby water resources that may already be lacking due to climate change.

All in all, continuing on the current path is only viable under very specific political circumstances. Even if zoning planning makes sure that there remains space, informal development and agricultural intensification threaten UPA in this scheme. Still, the option remains as a baseline if similar conclusions follow from other adaptations.

2.4.2 Backyard Gardening

Backyard gardening is the production of crops or holding of small livestock in a private space. This production is different to the current strategy in that the backyard production is mostly for personal consumption. Backyard gardening is already widespread in Africa and has widely ascribed positive effects on the environment and on livelihoods of those taking part in it (Ayambire et al., 2019).

Due to its subsistence nature, backyard gardening is limited to fewer crops and forced towards a diverse production, as people cannot subsist from just one crop. This means that there is a preference towards the growing of vegetables, although there is also opportunity to grow some cereals or tubers. In specific cases, people even tend fruit trees that not only provide a crucial part of the EAT-Lancet diet, but also serve to mitigate the UHI effect (Armar-Klemesu & Maxwell, 2022).

Naturally, the addition of urban green in backyard gardens combats the temperature element of climate change. Moreover, sufficient garden space in between impermeable development provides plenty of space for infiltration of rainfall, which benefits both the groundwater in the city and reduces prevalence of floods.

This strategy is fairly resistant to urban sprawl. In newly developed neighbourhoods backyard gardening is already more frequent than before (Abass et al., 2018). Provided that the urban sprawl keeps the horizontal character that it has now, there is no reason to assume that backyard gardening is under threat. This way, there remains space for backyard gardening between residential buildings. If urban development changes to a denser manner however, this strategy is no longer viable.

All things considered; backyard gardening is a promising strategy in adapting to the problems facing agriculture in Kumasi. The strategy provides resilience to climate change and backyard gardening has actually increased under the sprawl that has happened in the past years. Although some questions remain about the subsistence nature and the scale of food production, the initial assessment is that backyard gardening will score highly.

2.4.3 Farming on marginal lands

Although the high competition for land in peri-urban areas is noted as a threat to agriculture, there still remain certain marginal lands that are less desirable for general urban development. Marginal lands are defined as places where it is harder or impossible to grow crops in conventional schemes, due to high slopes, low fertility or other limiting elements (Ayambire et al., 2019). This mostly includes lands along roadsides, along the many water bodies in the city or other wetlands. Despite how it seems from the definition, agricultural production is actually somewhat viable on these lands. The easy accessibility of water makes these lands effective for irrigated agriculture and already farmers flock there to cash in on the possibilities (Ayambire et al., 2019).

Marginal lands are not limiting in the types of crops that grow on them. It is possible to grow cereals and the easy access to water in wetlands provides a prime location to grow irrigated vegetables. In the case of production in wetlands however, experts have noted a need for crops that do not damage the capacity of wetlands to provide ecosystem services (Ayambire et al., 2019). This may mean that there is less room to extensively use fertilisers, or to overuse water resources, which is a little contradictory to the concept that marginal lands are lands with low fertility.

Naturally, farmers on marginal lands are not excluded from the threats. For one, climate change threatens lands next to waterways with flooding. Conversely, low rainfall threatens the water supply for irrigated agriculture.

The value of this adaptation is in dealing with the second threat of urban sprawl. As marginal lands are less desirable for development, it is possible to maintain agriculture for longer. With the immense growth of Kumasi however, even marginal lands are now invaded by residential development (Ayambire et al., 2019). As such, the value in resolving the threat of urban sprawl is massively reduced.

Farming on marginal lands is already practiced in Kumasi and building upon this base is easier than setting up new strategies from scratch. However, it became clear that this strategy does little to mitigate the threats and even becomes less viable when climate change and urban sprawl become stronger. The initial assessment of this strategy is therefore that this is not a feasible strategy to deal with the problems that agriculture in Kumasi is facing.

2.4.4 Container/sack Gardening

Container gardening (also known as sack gardening) is similar to backyard gardening in that it is currently mostly used on private spaces for personal consumption. This strategy involves the growing of crops in sacks that are normally used for packaging (Peprah et al., 2014). It is mostly practiced in areas where land is scarce. The positive effects of sack gardening are similar to those of other strategies in increased consumption of vegetables, more urban green and better financial circumstances for the farmers (Gallaher et al., 2015).

Due to the nature of container gardening, crops are mostly limited to leafy vegetables, that adapt well to the conditions in the sacks. In Ghana, authors have also noted the possibility to grow peppers, tomatoes and garden eggs (Peprah et al., 2014). Like most of the strategies, the focus on vegetables makes sense. Cultivation of vegetables complements the production from other parts of Ashanti and urban production of vegetables is widespread. In potential commercial applications of more large-scale container farms, there is opportunity to grow fresh herbs, to take advantage of the emerging purchase food patterns in the city.

For other elements of the assessment, container gardening can be easily compared to backyard gardening and maybe even considered as one singular strategy. In terms of dealing with the threats however, the two strategies differ. Whereas backyard gardening provides urban green space to mitigate the effects of climate change, container gardening works to grow crops even where there is no space. Therefore, there is little effect on mitigating climate change due to sack gardening.

In terms of dealing with sprawl, it was established that backyard gardening can be sustained, provided that urban sprawl continues in its current, not dense, fashion. In contrast, container gardening can be maintained to a higher degree than regular backyard gardening under denser urban sprawl. The main feature of container gardening is the vertical structure. By nature, this takes up less space than conventional backyard gardening.

From this, container gardening can be seen as a strong adaptation to maintain urban agriculture in Kumasi under the threat of climate change and urban sprawl. It takes up little space, requires almost no investment to set up and provides large benefits to those taking part in it. The initial assessment is therefore that container gardening is a good candidate for maintaining UPA.

2.4.5 Aquaponics

In their paper, Ayambire et al. (2019) praised soil-free farming as a method that efficiently uses land and water to maintain UPA. They noted three types: film farming, aeroponics and hydroponics. For this research however, the focus is on a specific type of hydroponics that combines hydroponics with aquaculture to grow both fish and crops in a symbiotic manner called aquaponics. The reference document for this is a technical paper by the FAO that goes into great depth for this concept by Somerville et al. (2014).

In its simplest form, aquaponics uses a system of fish tanks, filters and growth beds that results in two agricultural products, crops and fish. Effluent from the fish tank is fed through the filters into the growth bed, from where it flows, via another retention tank, back into the fish tank. This way, the normally polluted effluent is not released to the environment. Moreover, the nutrients from the effluent are used by the plants, which means that no outside fertilisers are needed. Despite the start-up costs and the not insignificant requirement of expert knowledge, the benefits of aquaponics are compelling in that that they are very efficient in places where water and land is scarce, exactly the environment that is often found in the rapidly urbanising cities of SSA.

Aquaponics systems are diverse in the types of crops that can be grown. The FAO technical paper by Somerville et al. (2014) has guidelines for a wide variety of leafy vegetables like lettuce and cabbage, as well as fruiting vegetables like tomatoes, peppers and eggplants. Moreover, aquaponics units are very well suited to grow fresh herbs like basil and parsley, which are elements of the purchase consumption pattern. On top of this, the yield of fish that aquaponics systems also give are a compelling benefit. Fish is another emphasised food group from the EAT-Lancet diet. As such, aquaponics systems provide foods that are important parts of diverse diet.

As a “high” tech strategy, aquaponics should be one of the candidates that adapts to the threats the best. From a first glance, this seems to be the case. Aquaponics uses little water, which means that there is no need to exhaust limited water resources. Besides, the space requirement is limited in a way where the space that is needed is not necessarily large but comes with some conditions that we will go deeper into in a later chapter.

From first sight, it seems that aquaponics is the prime solution to maintain UPA in Kumasi. It satisfies the need to deal with the two main threats, provides a diverse set of crops as well as fish and is sustainable in that it needs little water and nutrients. It is important to keep in mind that a fair degree of knowledge, as well as technology is necessary to introduce it. The first assessment of this solution is hopeful, but full analysis will have to show whether this hope is justified.

2.4.6 Greenhouses

The final adaptation and second “high” tech strategy is the adaptation of greenhouses. In their paper on greenhouse farming in Ghana, Forkuor et al. (2022) hailed them for their resource efficiency, reduced climate impact and consequently, higher yields. In the same paper, they also stressed the benefit of greenhouses in mitigating the two main threats that were identified earlier. Negative elements included poor design for Ghanaian climate and lack of correct materials. However, some research has already been done on alternative building materials that are available locally, like bamboo or the use of nets, rather than glass (Forkuor et al., 2022). More extensive research on design and environments for greenhouses for Ghana specifically can be found in Elings et al. (2014) & Elings and Warmenhoven (2020).

Like the other solutions, greenhouses provide a space for many different types of vegetables, with a small difference. Whereas the previous solutions placed an emphasis on leafy vegetables and herbs, literature about greenhouses mostly covers fruiting vegetables, like tomatoes and peppers. Still, there is plenty of opportunity for leafy vegetables. Like the other strategies, this means that greenhouses work well to complement rural crop production.

Greenhouse technology is similar to aquaponics in that the controlled environment allows for more efficient use of water resources and nutrients, when compared to more conventional schemes. This means that greenhouse technology is also resistant to climate change. In terms of dealing with sprawl, we are again looking at a similar concept as aquaponics, there is not necessarily a large space requirement, but the space comes with conditions.

All in all, greenhouse technology deals with the threats in a similar manner as the other “high” tech solution. In contrast to aquaponics however, greenhouses seem to need less expert knowledge, because in its base form, growing crops in greenhouses is similar to growing crops outside. There is however a fairly high need for materials to build the greenhouse in the first place. Its initial assessment is therefore that this adaptation is of high value, but more in-depth analysis will have to show if the technology and material requirement is too limiting.

2.4.7 Other adaptations

Naturally, the list of adaptations is not exhaustive. On top of the ones already identified, there remain several other options from literature that may be useful adaptations in general. For the context of this research however, they are not taken into account for various reasons.

The first of these additional adaptations comes from Ayambire et al. (2019). They posit that Building-Integrated farming models (BIFMs) can be a benefit to food security with a small spatial footprint. BIFMs utilise walls and rooftops as the space to cultivate crops on. They give examples from Canada, where a large farm can supply 10,000 people per week of vegetables and herbs.

This is also where the limitations come in. Not only are all current examples from applications in the global North, Ayambire et al. (2019) specifically state that the systems require rooftops and walls with sufficient structural integrity. They state that cities in sub-Saharan Africa, including Kumasi, lack this important element and for this reason this adaptation is currently unviable and will not be taken into account in the model.

Another adaptation with the, in theory, potential to limit the effects of the threats is urban agroforestry. According to Taylor and Lovell (2021), combined systems of trees and regular crops are better in an ecological sense and also a cultural one. In their view, this system that they call urban food forestry provides better yields than conventional urban agriculture, due to symbiotic benefits from the trees and the crops below them. Moreover, the added trees reduce the effects of UHI and provide benefits for the urban residents psychologically.

The reason that this adaptation is not taken into account in the model is due to some of the limitations of AquaCrop. The literature on AquaCrop modelling of fruit trees is very limited and the crop database does not include extensive parameters for these. On top of this, Taylor and Lovell (2021) state that in places with uncertain land tenure, people are less likely to invest into plants that do not provide yields immediately. As this uncertain tenure is exactly what occurs in Kumasi, this adaptation is less suited for this case and therefore not taken into account further in this research. However, there is potential, as this is a low-tech method to combat the threats.

3. Method

This chapter is dedicated to the steps that are necessary to answer the research questions. The background already gave the threats, how peri-urban agriculture in Kumasi works currently and what adaptations are available. Now rests the task to find out how the adaptations help to reduce the effects of the threats and how popular they are among the population of Kumasi.

The first part of this chapter details the indicators that are used to assess the adaptations. Next is the explanation of the AquaCrop model, that is used to assess food security. Finally, the goals and methods of the survey are explained, which is used to gauge the opinion of the Kumasi residents about the adaptations.

3.1 Adaptation performance

To recall: the goal of this work is to identify adaptations for UPA in Kumasi that are resilient against the threats of climate change and urban sprawl. From literature study, five adaptations were designated.

- Backyard/home gardening
- Sack/container gardening
- Farming on marginal lands
- Greenhouses
- Aquaponics

Identification of the adaptations is a first step, but not sufficient to make a statement. For this, a deeper look into how adaptations perform for specific indicators is necessary.

3.1.1 Indicators related to threats.

As the adaptations are meant to maintain UPA against the threats of climate change and urban sprawl, there need be indicators that say how well the adaptations deal with these threats. Therefore, the following indicators are used to evaluate the usefulness of an adaptations.

- Food security/space requirement: how do the agricultural yields of adaptations compare to demand and how much space is needed to meet demand.
- Irrigation water demand: How much additional water is needed to grow crops.

These elements are intrinsically linked. Generally, whenever more water is used, yields will be higher. Consequently, where yields are higher, less land is needed to feed people. Still, food security is the starting point. The Eat-Lancet diet is again useful in deciding how to maintain food security in the future. In the summary report, recommended daily intakes of several food groups are given (Table 1)

To be able to determine the total demand in a district – now and in the future - the populations of the districts are combined with projections for population growth for the specific SSP scenarios (Kc & Lutz, 2017). With the population in the districts and the daily demand for specific food groups per person per day it is possible to make a statement about the demand for these foods in a district.

Next up is the space requirement. Modelling of adaptations and crops will show the yields for specific crops that correspond with the food groups from Table 1. Based on the demand that was found earlier, it is now possible to determine how much area needs to be under cropping to feed the population of a district.

In addition, it is already possible to show how much space is available in a district in the present. Spatial analysis of satellite data with GIS allows for classification of different types of land use in Kumasi. With this, it is possible to make a distinction between regular arable lands and marginal lands in districts and it is possible to quantify the area of each. Because of uncertainties in land use planning and informal development, it is impossible to extrapolate this to future scenarios, but it gives an indication of what types of land are already plentiful in districts, which may favour some adaptations. The results of this spatial analysis are visible in Chapter 4.2.

Finally, there is the irrigation water demand. While some crops may inherently require more irrigation, there may be a difference in water demand for specific adaptations. Naturally, adaptations that use less water are more desirable in a future where water resources are potentially scarce.

With this, the most important indicators for adaptation performance are clear. Still, there remain several indicators that are also important in deciding which adaptations are best suited to maintain peri-urban agriculture in Kumasi.

3.1.2 Indicators related to implementation of adaptations.

These three elements are the most important in terms of dealing with the threats. Nevertheless, this does not mean that these indicators are only things that are important in adaptation design. More practical aspects related to the implementation of the measures are central in a design that reflects the situation on the ground. These practical aspects include:

- Material cost: what is needed for construction and is this available
- Financial cost: are the financial means there to be able to afford adapting and what is needed.
- Knowledge: do farmers need training to work with new systems and is this network available
- Politics: is there a need for policy and awareness before this can be implemented.

Because of the scope of the project, these elements are approached in a more qualitative manner. Information on these indicators is found in literature and examples from earlier implementation in other regions/countries. The answers to the survey of farmers and vendors can also give an estimate into the effectiveness of the adaptation in relation to these indicators. The scope of this survey is outlined in the next sections.

3.2 AquaCrop

The modelling of yield and irrigation water demand for the adaptations uses the AquaCrop model. AquaCrop is a crop water productivity model developed by the FAO in 2016 (FAO, 2022a). With climate data, soil data and management practices as input, AquaCrop calculates the crop development, water balance and agricultural yields for several types of crops, which can then be used to assess the agricultural productivity and irrigation water use for different agricultural schemes and crops.

AquaCrop is designed to simulate organised agriculture, on large fields with structured management and irrigation. If we recall the essence of urban agriculture in Kumasi, there is a distinct contradiction. Urban agriculture is chaotic; vegetables, legumes and cereals are grown close to each other in small patches of whatever land is available. Those who take part in it may do it in their spare time, without the knowledge that comes with experience.

Why use AquaCrop then? For one, it provides a strong balance between going in depth and simplicity. There is no field data available for things like fertility or crop performance. The qualitative assessment from AquaCrop provides a simple method to incorporate this anyway, highlighting how this balance helps in modelling. Moreover, in comparing adaptations among each other, the model should suffice if the input is equal.

3.2.1 AquaCrop – How does it work?

AquaCrop is built on, but not fully the same as, the simplified crop yield response to water from Steduto et al. (2012). This formula relates the crop yield directly to the amount of transpired water. All information in this part about the workings of AquaCrop can also be found in Steduto et al. (2012).

$$\left(\frac{Y_x - Y_a}{Y_x}\right) = K_y\left(\frac{(ET_x - ET)}{ET_x}\right) \tag{1}$$

With:

Y_x = Maximum yield	[ton/ha]
Y_a = Actual yield	[ton/ha]
K_y = Yield response factor	[-]
ET_x = Maximum evapotranspiration	[mm]
ET_a = Actual evapotranspiration	[mm]

AquaCrop is a little different from Equation 1 in that it splits up the actual evapotranspiration in non-productive soil evaporation and productive crop transpiration. Biomass and yield are thus only a product of the latter. The agricultural productivity in AquaCrop is described with the following equation:

$$B = WP * \sum Tr \tag{2}$$

Where:

B = Produced biomass	[kg/m²]
WP = Water productivity parameter	[kg/m²/mm]
Tr = Crop transpiration summed over the growth period	[mm]

Biomass does not always correspond to usable product, however. For a crop like tomato, the fruits only make up a fraction of the full plant. This fraction is called the Harvest Index: the ratio of yield to biomass. With this the final equation for the output of the model is complete.

$$Y = HI * B \tag{3}$$

Where:

Y = Crop yield	[kg/m²]
HI = Harvest index	[-]
B = Produced biomass	[kg/m²]

On a surface level this seems a sufficient explanation of the workings of AquaCrop. It is however also important to understand how AquaCrop comes to the values for crop transpiration before we continue.

For the development of the crop, AquaCrop uses a parameter called (green) canopy cover (CC). Canopy cover is the fraction of a unit surface of land that is covered by vegetation when looking from directly above. In the early stages of development, CC develops following a sigmoid function from a starting level (CC_0) to a maximum level (CC_x). When the crop reaches the stage of senescence, CC starts to decline exponentially. In the model, the development of the CC is dependent on the climate (temperature and CO_2), water balance and nutrient availability.

At the same time, the roots of the crop develop from a minimum effective rooting depth (Z_n) to a maximum effective rooting depth (Z_x). This Z_x is equal to the depth of a specific restrictive soil layer in the case where one is present. Otherwise, it is equal to maximum rooting depth determined by the crop. The availability of water to the crop is determined by the rooting depth. At the same time, rooting depth expansion is also impacted by water stress, creating feedback.

A visualisation of the CC development and the root zone development is visible in Figure 9.

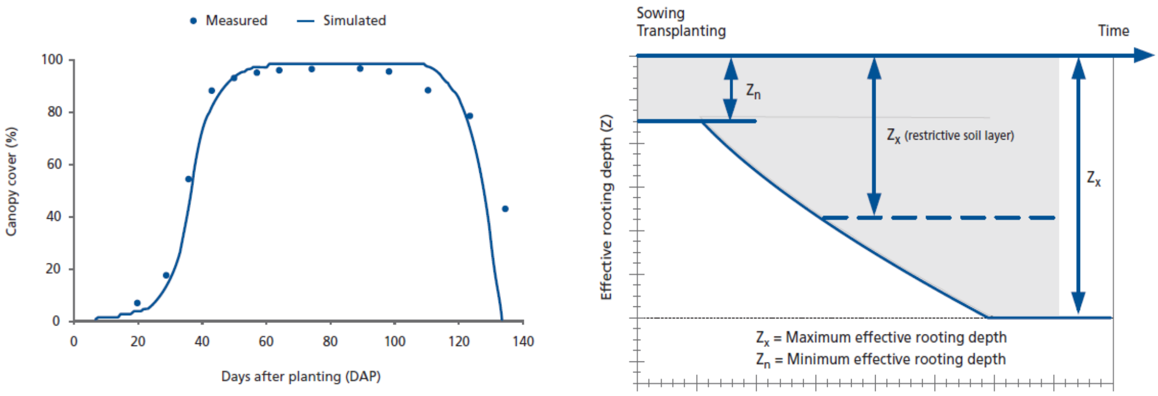


Figure 9. Examples of crop development over time from AquaCrop Manual. Left.: Crop canopy development. Right: Root zone development (Steduto et al., 2012).

How does this then relate to the transpiration? From the canopy cover comes the available area that can transpire. By multiplying the CC with the reference evapotranspiration (ET_0) and a crop transpiration coefficient ($K_{c,\ Trx}$) we get the crop transpiration. From here, the transpiration is fed in equation 2, leading to the biomass and concurrently the yield**.** The crop transpiration coefficient is dependent on the level of stress that the crop feels. Via this, stress is one of the factors that influences end yields.

In AquaCrop, crops can suffer water stress, temperature stress and fertility stress. In the case of water stress, which is the most elaborate element, the soil water balance is the determining factor. When the depletion of the water in the root zone reaches a certain first threshold, the development of CC is limited. From here, recovery is still possible. When the depletion grows further, the second and third thresholds for stomatal closure or early senescence respectively are reached, leaving lasting damage and severely impacting crop yields. These stresses are a result of a shortage of water. Conversely, there is also aeration stress. This occurs when the water levels in the root zone become too high. It also results in stomatal stress and stress in the development of CC. Finally, water stress can influence the Harvest Index. In the case of little water stress, the harvest index is increased, increasing the yield relative to biomass. This is because less energy is used for leaf growth, rather than fruit and flower development. I.e., fruits and flowers get priority in resources before the leaves. In the case of severe water stress the harvest index is reduced due to an inability to develop fruits/grains altogether.

Temperature stress is much simpler. When temperatures are outside of the comfortable range for the crop, the canopy expands slower. Temperature effects on transpiration are already considered by ET_0.

Finally, soil fertility stress is modelled in a simplified manner. AquaCrop does not simulate a nutrient balance but introduces coefficients that limit canopy development or increase canopy senescence based on a qualitative assessment of soil fertility. Due to the need for validation based on local data, soil fertility is not considered in this model.

All in all, the workings of AquaCrop are simple. Climate feeds the water balance, which determines the crop canopy development. Crop canopy development determines the transpiration of the crop which not only feeds back into the water balance, but also controls the generation of biomass and consequently, yield. Figure 10 shows an outline of the flow of the model.

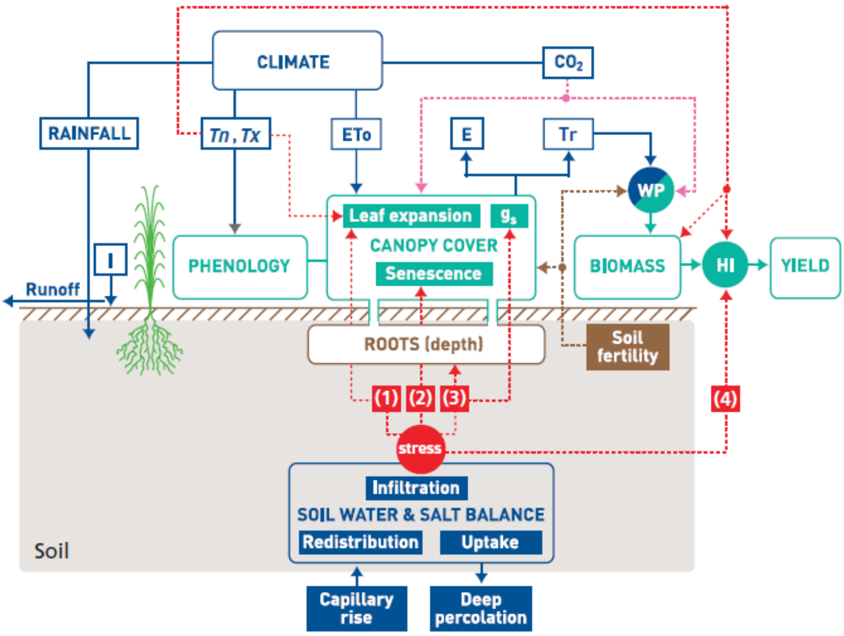


Figure 10. AquaCrop model flowchart (Steduto et al., 2012).

Now that it is clear how AquaCrop works, it is good to look at what is needed to make it work. On the upper boundary of the system as outlined in Figure 10 is the climate. For the water balance, the rainfall and the reference evapotranspiration are necessary data, the latter of which is transformed into crop transpiration and soil evaporation. For the crop development, daily minimum and maximum temperature and atmospheric CO_2 concentrations are the controlling factors.

On the lower boundary is the soil system. This influences the water balance via properties like soil field capacity and permanent wilting point. In the presence of a groundwater table, AquaCrop takes deep percolation and capillary rise into account for the soil water balance as well.

In between these two boundaries is the crop system. For AquaCrop to accurately model specific crops, empirical data on the length of growing stages, certain parameters for CC development and sensitivity to stresses is needed. The built-in database from FAO data is already quite extensive and literature has calibrated data for many more crops in specific applications. This space is also where the crop response to fertility is calibrated.

Finally, there is a management aspect. Field and irrigation management influences runoff, fertility and other disrupting elements. In the irrigation input, AquaCrop can generate irrigation schedules based on a set of requirements based on root zone water depletion. Or, if available, the model can work with a pre-set schedule. Field management includes runoff management, mulches, weed management and the fertility of the soil.

The output screen of AquaCrop (Figure 11) shows the development of the canopy during the growing season and the moments of stress. On the same screen, the water balance with the thresholds for stresses are shown. Other output elements are the actual yield, the relative generated biomass compared to the maximum possible biomass in absence of stress and the final harvest index. In the case of irrigation, another output element is the irrigation dates and amounts. In this model, we are mostly interested in the yield output, relative biomass and the irrigation information. The other output parameters may be useful to identify issues with specific schemes, if necessary.

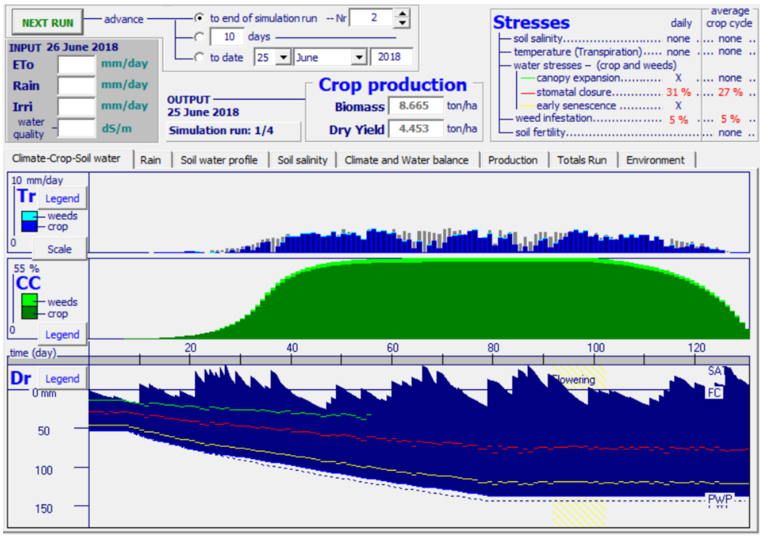


Figure 11. AquaCrop output screen. In this example high soil moisture levels lead to aeration stress in the mid-season.

3.2.2 AquaCrop– input for the model

In the background for AquaCrop two boundaries were mentioned from where AquaCrop requires input: the climate at the upper boundary and the soil system at the lower boundary. Next to this, AquaCrop requires information about the crop development and the management practices. This part goes through these boundaries and how the input for the model was generated.

To reiterate from earlier, the climate input consists of temperature data (T_{max} and T_{min}), precipitation (P), reference evapotranspiration (ET_0) and global CO_2 concentrations. The latter is included in the program in the form of the Mauna Loa observatory data. Thus remains the need for a dataset with the remaining necessary information. This is sourced from the data from the Trans-African Hydro-Meteorological Observatory (TAHMO) (van de Giesen et al., 2014). This dataset has weather data for several Kumasi weather stations for the period starting in May 2017 to December 2021. Any missing data is interpolated linearly, whenever it was impossible to fill it in with data from the other stations.

While the precipitation and the temperature data are directly implemented into AquaCrop, the ET_0 is not included in the TAHMO dataset. AquaCrop can calculate an estimate for the ET_0 using temperature, radiation, wind speeds and humidity. All these parameters are available in the TAHMO dataset.

Of course, there is an interest in the workings of the adaptations under climate change. Therefore, the combination of the TAHMO data and the climate projections from The World Bank (2021a) are used to generate a dataset for three SSP scenarios. The climate change datasets are generated by assigning a multiplication factor per month. Equation 4 gives an example of the calculation of a multiplication factor for minimum temperature in January.

$$k_{tmin,jan} = \frac{T_{min,jan,SSP}}{T_{min,jan,TAHMO}} \qquad (4)$$

Where:

$k_{tmin,\,jan}$ = multiplication factor for minimum temperature for January. [-]

$T_{min,jan,ssp}$ = monthly mean minimum temperature for January from the SSP prediction. [°C]

$T_{min,jan,TAHMO}$ = monthly mean minimum temperature for January from the TAHMO dataset. [°C]

By calculating the multiplication factors for every month and for every variable (temperature and precipitation) and consecutively multiplying the data from the daily TAHMO observations with the corresponding multiplication factor for that specific month, a new daily dataset for five arbitrary years of data in the period 2040-2050 is created for three SSP scenarios. This data can then be used in AquaCrop for the modelling of the adaptations in the future. While this does assume that the variance of data will be the same in the future, which might not necessarily be the case, the lack of long-term data to perform a full weather generation is not available. Therefore, this is an option that finds a balance between accuracy and simplicity.

With this, the required data for the upper boundary is complete. There remains the question of the input from the soil system, crop data and management practices.

A crucial element of the AquaCrop model is the crop physiology. It includes crop development, yield formation and the responses to the various stresses. A full list of Crop parameters is included in the full set of AquaCrop input in Appendix A. AquaCrop input.

While AquaCrop has a database of crop parameters, not all crops of interest are included in this database. Moreover, these parameters can be optimised with the help of empirical data. Therefore, wherever possible, the crop parameters in this model come from literature. Five crops that represent the food groups from the EAT-Lancet diet will be modelled using AquaCrop. The full set of crops and their source is included in Table 3. An important element from the EAT-Lancet diet that is missing is the inclusion of fruits. Due to the lack of proper AquaCrop data for fruit tree modelling, this food group is excluded from the model.

With this information, the crop phenology is clear. Only the management and the soil system information remain as necessary information for the model.

Table 3. Sources of crop parameters for AquaCrop model.

Crop Type	In AquaCrop database?	Empirical data available from:	Source used
Cassava	Yes	-	AquaCrop Database
Cabbage	No	Burkina Faso	Wellens et al. (2013)
Dry Bean	Yes	-	AquaCrop Database
Maize	Yes	Ghana	AquaCrop Database[2]
Tomato	Yes	Ghana	Darko et al. (2016)

On the lower boundary of the AquaCrop model is the soil system. This includes both the soil composition and the groundwater table. The soil properties are crucial for the soil water balance, because it affects capacity and drainage. Amoateng et al. (2018) researched the soil compound associations found in Kumasi. In the Western part of the city, the main soil association is the Bekwai-Akomadan-Oda Compound Association, which is characterised by a well-draining silty clay. In contrast, the more eastern and southern parts of the city have the Bomso-Offin Compound Association. This soil consists of a more sandy clay loam that is moderately well draining.

The input for groundwater is rather simple. The groundwater table in Kumasi is too deep to have an impact on the AquaCrop model. This eliminates capillary rise from the SWB.

The final part of the model input is the **farmer management**. As this is informed by survey, this is included in the next section.

[2] Empirical data not used due to large uncertainties in empirical data.

3.2.3 Model input– Farmer survey part I

Naturally, it is difficult to make conclusions informed by a model that bases its input purely on literature and guesswork. Because of this, the model input is based upon a farmer survey that consists of two parts.

The farmer management model input consists of the first part of the farmer survey. Farmers are questioned about their crops, planting behaviour and use of irrigation and fertiliser. The questions are specifically framed to relate to the information that is required for the AquaCrop model. While this does mean that the answers are of a more qualitative sort, it makes it simpler to directly incorporate the survey answers into the model. Three examples of questions of this part of the survey are:

- What types of agricultural products do you produce?
- What method do you use to irrigate your crops?
- How do you qualify the fertility of your land relative to others you know?

The target group of the survey consists of farmers throughout the peri-urban parts of Kumasi. Because different adaptations are to be compared, it is desirable that the respondents of the survey involve a set of farmers with a variety of practices, including home gardeners, farmers on marginal lands and people who farm on regular fields. This way, there should be a distinct difference between the model input for each adaptation and consequently, different outputs for irrigation water demand and agricultural yield.

The locations of the survey are also important. From the food basket, it was clear that different products are sourced from different parts of the city. Leafy vegetables are commonly grown in irrigated schemes more centrally in the city, whereas other products are sourced from peri-urban neighbourhoods or from outside the city. Therefore, the survey should include a diverse set of neighbourhoods from all parts of Kumasi. At the same time, there is an interest in neighbourhoods that specifically feel the threat of urban sprawl. These neighbourhoods include:

- Kwadaso, a neighbourhood just west of the city centre
- Feyiase, a neighbourhood on the south edge of Kumasi, cited in literature as a place with high migration.
- Ejisu, a neighbourhood on the East edge of Kumasi, known for its recent development.

Of course, for a set of results to have meaning, the survey should have a sufficient sample size. The minimum sample size equation as established by Krejcie and Morgan (1970) provides a useful guide for determining how many farmers to survey.

$$s = \frac{X^2NP(1-P)}{d^2(N-1)+X^2P(1-P)} \tag{5}$$

Where:
s = Required sample size [-]
X^2 = the table value of Chi-square for 1 degree of freedom at the desired confidence level (for 95%: $X^2 = 3.841$) [-]
N = population size [-]
P = population proportion (0.5 for maximal sample size) [-]
d = degree of accuracy (margin of error) [-]

The first variable that is required is the population size. In this context the persons of interest are involved in agriculture in the peri-urban interface in Kumasi. The reference for this information comes from the 2010 Population and Housing Census (PHC) from the

Ghana Statistical Service (GSS). This survey gives information on district level on the number of households in a district that are engaged in crop farming. The survey makes a distinction between urban households and rural households. Considering that the urban parts of these districts overlap with the peri-urban fringe of the Kumasi metropolitan area, this value is a good approximation for the total population size. In addition to the two districts, one community of the larger Kumasi Metropolitan district is also considered. The nature of this community fits well with the characteristics of the peri-urban area and it is therefore useful in this research.[3]

Table 4. Households engaged in agriculture in three districts around Kumasi (Ghana Statistical Service, 2010).

District	Total households in district	Households engaged in crop farming (Rural)	Households engaged in crop farming (Urban)
Bosomtwe	22,895	9,255	1,477
Ejisu – Juaben[4]	33,078	12,870	2,177
Kwadaso	9912	-	772
Total population size:			4426

In many applications, d is set at 0.05, to limit the chance that the results are incorrectly representing the population. From here, the total population size and X^2 value give the minimal required sample size of 353 farmers. In this research, there are insufficient resources to survey that many people.

Therefore, the sample size of farmers is set at **150**, as this is the maximum that is possible with the resources that are available. When going through Equation 5 backwards, this shows that, while maintaining the 95% confidence level, the margin of error is equal to 0.079. In other words, there is a 95% chance that the results are within an ≈8% boundary of the real value: a satisfactory boundary for the results to remain meaningful.

As mentioned before, the distribution over the city is important for the results. Therefore, to maintain a representative sample, the total sample size is distributed proportionally over the three neighbourhoods. The full distribution is shown in Table 5.

With this first part of the farmer survey and the AquaCrop model explained earlier, the modelling phase is covered.

[3] Since 2018, Kwadaso is considered a district in the same way that Ejisu and Bosomtwe are. As the information in this chapter comes from the 2010 PHC, this part uses the terminology from that census.
[4] In 2018, Ejisu-Juaben was split up into the Ejisu municipal and the Juaben municipal district. Like above, the information from the 2010 census is used in this research.

3.3 Farmer survey part II and vendor survey

Another important part of the adaptation design is acceptance and barriers. While adaptations might work well in a technical sense, a preference for specific elements by the residents of Kumasi may mean that another adaptation is better suited in a practical sense. The input from farmers, who must work with adaptations, and vendors, who bring the products to the customers are therefore of interest in deciding what adaptations are best suited.

3.3.1 Farmer survey part II – Acceptance and barriers

Because of this, the second part of the farmer's survey is designed in such a way to research preferences for specific schemes or preferences for elements that they find most important in adapting. This way, adaptation design is informed not just by modelling and literature, but also by opinions from those who are the ones that have to adapt.

The goal of this part of the survey is to figure out if there exist any barriers against adaptations or if certain adaptations are preferred. In addition, this gives an opportunity to ask farmers which of the elements that make up an adaptation design are important to them, do they value yield most highly, or are they more concerned about implementation costs. Three example questions from the survey are:

- Please rank the adaptation in terms of how useful you believe they are against the threats.
- Please rank these elements in how important you find them in determining what adaptations to make.
- Are you able and willing to switch to growing crops in sacks and why?

The full question list is included in Appendix B. Survey Questions.

The target group and locations are the same as part I of the farmer survey and are given in the section above.

3.3.2 Vendor survey – supply, acceptance and barriers

Not just farmers are impacted by the threats to UPA. The markets in central and peri-urban Kumasi are the places where the crops reach the consumers. The opinion of vendors on adaptations is another element that is of interest in the adaptation design. Products from different agricultural schemes may be associated with good or bad quality. Vendors know what types of crops their customers want to purchase and what elements are important for them. They can therefore inform how well adaptations are suited to the needs of themselves and of their customers.

Earlier, in the introduction of the food basket concept, the sources of common agricultural products were revealed. Most of these were sourced from (Drechsel et al., 2007), this source is fairly outdated. Therefore, the survey of the vendors also provides an opportunity to investigate the sources of the products on the markets and to update the knowledge on how much peri-urban agriculture contributes to food security in the city.

Similarly to the farmer survey, vendors are first informed about the risks and about the study. They then get to answer some introductory questions about gender and age group again. From here, the questions about the sales of agricultural products and their sources are given. Finally, they are given similar questions to the ones from the farmer survey. The only difference being that they are asked about what impacts adaptations have on their sales, rather than the impact on their practice. Three example questions are:

- How many leafy vegetables do you sell per week and where do they come from?
- Do you notice recent changes in supply from urban and peri-urban sources?
- Would you sell/eat products grown in backyards and why?

The full question list is included in Appendix B. Survey Questions.

The target group of this survey is made up of crop vendors on several markets in Kumasi. This includes vendors that sell just one type of product, to ones that sell the full complement of cereals, tubers and vegetables.

Although a major goal from this survey was to recreate the data from Drechsel et al. (2007) their choice of markets included a select amount of markets in central Kumasi. Seeing as this research is mostly focused on peri-urban agriculture, markets in the same neighbourhoods as the farmer survey are a more logical option. These markets include:

- Kwadaso market (For the Kwadaso neighbourhood, in the Eastern part of the city)
- Feyiase market (Close to the Feyiase neighbourhood, south of Kumasi)
- Ejisu market (In the town of Ejisu, just west of Kumasi)

In the case of the vendor survey, there is less of a focus on surveying sufficient vendors, but more so on capturing the spatial variety. Accordingly, the focus is on four markets in and around Kumasi. The budget of respondents for market survey is **100** vendors. These are divided equally over the markets in the neighbourhoods.

Table 5. Distribution of planned respondents over the neighbourhoods and markets.

Distribution of survey respondents

Neighbourhood/Town	# of Farmers	# of Vendors
Ejisu	70	~34
Feyiase	50	~34
Kwadaso	30	~34
Total:	150	100

4. Results and discussion

This section is dedicated to the results of the AquaCrop modelling, the results of the spatial analysis and the outcomes of the farmer and the vendor survey.

Because the survey results are both input of the AquaCrop model and complementary to it, they are split up over the elements of this chapter. The first section goes over the management input for the AquaCrop model first, which is made up of the first part of the farmer survey. Part 4.1.2 will then detail and discuss the output of the model. Section 4.2 is dedicated to the indicators of the adaptations concerning the threats and implementations, with the former building on the model output. Section 4.3 follows this with the remaining survey results concerning the threats, market supply and barriers against adaptations. The final assessment of the adaptations is then given in chapter 4.4. Finally, a short text is dedicated to a study into the potential of wastewater reuse in peri-urban agriculture in Kumasi.

4.1 AquaCrop model results

The first element of the results is the set of results from the AquaCrop model. To recall from the previous chapter. AquaCrop is a crop productivity model from the FAO that calculates yields and irrigation water need based on inputs of climate data, soil data, crop data and management practices.

The first three of these elements have been dealt with in the method section. Because the management input is a result of the survey, its results follow below. The second half of this part will give the outputs of yield and water need for the crops in the two modelled neighbourhoods.

4.1.1 Management input for AquaCrop model – results from farmer survey part I

Before it is possible to look at the output from AquaCrop, it is necessary to collect the responses to the farmer survey that are related to management. The farmer survey has 146 results from 3 neighbourhoods**.** A full distribution of the planned and actual sample sizes is included in Table 13.

Based on the answers of the survey, the practices are divided based on the type of land (backyards, fields, marginal lands and sacks[5]) and into the type of crop. The management that is used as model input is used by the majority of farmers in that neighbourhood. This way, a profile is made of a typical farmer for each specific crop, adaptation and neighbourhood. One example of the management practice input for AquaCrop can be found in Table 6 with the full set in Appendix C. Aggregated survey responses. If a specific crop is not grown by any farmer in a neighbourhood in one of the schemes, this crop is excluded from the modelling as the lack of management data makes it impossible to distinguish between adaptations. This does not mean that these crops are not grown now or in the future, just that the modelling cannot be informed by reality. One crop group that was added despite not having any responses is the legumes. Although these are not grown widely currently, they are modelled anyway to correctly represent the high emphasis from the EAT-Lancet diet. Management input for this crop is taken as the average of the other crops. In the future, specific research into legumes and their application in Kumasi might be necessary to draw more accurate conclusions.

[5] Management input for sack gardening is the same as for backyard gardening, but with higher crop density.

Table 6. Example of management practices based on farmer survey results.

Management practices: Feyiase - Fields

Crops	Planting Month	Irrigation method	Mulches	Fertility	Weeds	Runoff management
Cassava	March	Rainfed	Organic	Good to very good	No	Increase runoff
Cabbage	March	Sprinkler	No	Very good	No	No
Maize	March	Rainfed	No	Very good	No	No
Tomato	March	Surface	No	Very good	Yes	No

The responses to the survey indicate that there is a difference in practices for different crops and for different parts of Kumasi. Farmers in and around Feyiase for example are less likely to use interventions on their crops than in the other surveyed neighbourhoods. In the case of mulches, 26% of Feyiase backyard gardeners state that they employ this tactic. In contrast, 50% of Kwadaso backyard gardeners and 56% of those in Ejisu do so. In terms of runoff management, the neighbourhoods vary wildly. Only 30% of Kwadaso farmers influence runoff on their fields, either by limiting it through bunds, or by increasing it through acts like compaction. In the other surveyed neighbourhoods, these practices are more common, with 50% and 66% of farmers in Feyiase and Ejisu respectively answering that they influence runoff on their fields. This may be due to socio-economic factors, the different soils or due to the proximity of the agricultural college in Kwadaso and potential outreach programs, which might help farmers with applying different interventions, as well as better irrigation.

This impact of colleges and universities on irrigation practices seems to be visible in other survey results. Whereas in Feyiase only 1 farmer stated that they use piped water for irrigation, 8 farmers, or 21% of respondents in Kwadaso do so. However, in Ejisu, which is not particularly close to the agricultural college, 26% of farmers use piped water, most of these grow vegetables. In terms of irrigation practices, Kwadaso notes higher numbers of farmers who use high-efficiency irrigation methods: 28% uses either sprinklers or drip irrigation in contrast to only 12% in Feyiase and 21% in Ejisu. The number of farmers that do not irrigate at all are similar however: 41%, 41% and 45% for Kwadaso, Ejisu and Feyiase respectively.

To validate these hypotheses about the survey results. A small informal interview was conducted with the survey team from Kwadaso Agricultural college, which included a professor and 4 students from the college. One of the questions in this interview was related to the impact of potential outreach from the college. From the interview, it seemed that some farmers that grow on one of the university campuses in the Kwadaso area had training at the agricultural college. Moreover, the technical extension officer at the campus lands gives advice to the farmers, which might explain their more frequent use of mulches and high-efficiency irrigation techniques. This does not explain the higher frequency of these methods in the Ejisu neighbourhood, although the neighbourhood is somewhat close to the Kwame Nkrumah University, which might employ similar outreach in the Ejisu neighbourhood.

Even though the three different neighbourhoods have different soils, fertility does not seem to be a problem. Only two of the farmers classify the fertility of their land as very poor, all from Ejisu. Most farmers in the three neighbourhoods classify the fertility of their land as either very good or good, however.

Naturally, soil fertility and fertiliser use are linked. Only 2 out of 36 (6%) respondents from Kwadaso noted that they do not use fertiliser, larger numbers are visible in Ejisu, where 36 out of 50 farmers state that do not use fertilisers on at least some of their crops. Similarly, 23 farmers from Feyiase state that they do not use fertiliser, about one third of the respondents. The majority of farmers that do use fertiliser use synthetic types, approximately half of the respondents in the case of all three neighbourhoods. The remainder is split evenly between compost and animal waste.

The disparity in fertiliser use may again be caused by differences in soils or in potentially nutrient rich irrigation water. A full picture about this is not clear from the survey, however. Although farmers from Feyiase are more likely to use surface water for irrigation, similar numbers of farmers feel that the irrigation water has an effect on fertility: 34% and 27% for Feyiase and Kwadaso respectively. Ejisu is different in this aspect, as 90% of farmers here believe that irrigation water has an effect on fertility. Surface water is here also the main source of irrigation water.

This set of different farmer management practices for different neighbourhoods and adaptations forms one of the pillars of the AquaCrop modelling of the yield and irrigation water demand. The results of this modelling are given in the next section.

4.1.2 AquaCrop model – Output of agricultural yield and irrigation water demand

With the input of management from the survey and the input from chapter 3.2.2 (climate, crop and soil data) it is possible to run AquaCrop for the full set of 3/5 years, depending on the crop and planting date.[6] The output includes yield, relative biomass and total irrigation depth in mm. The tables below show the results for the different adaptations for Feyiase in SSP1. The results for the baseline and the other climate scenarios are included in Appendix D. Model results**.**

These results show that there are small differences in yields for the different schemes and thus for different adaptations. This is because different management practices influence the soil water content and consequently the crop development. The simulations indicate that for cassava and maize, yields are (a little) higher in backyards than they are in regular fields. From the management input, it can be seen that backyard gardeners in Feyiase increase the runoff for their tubers, which farmers on fields do not. It is likely that this intervention prevents aeration stress in wet periods, thus leading to higher average yields.

In terms of irrigation depth, one can see that farmers on fields in Feyiase do not irrigate their cereals, whereas backyard gardeners do so, leading to an average seasonal irrigation water use of 96.75mm. This additional water use also leads to higher relative biomass: in fields, only 86% of maximal biomass is generated, whereas in backyards, 99% is achieved.

The higher irrigation water need in backyards is also seen in the growing of tomatoes. The model finds almost twice the irrigation water need for tomatoes grown in backyards when compared with regular fields, even though the irrigation method is the same. This is explained by the later planting dates from the survey. Farmers on fields stated that they plant their tomatoes around may. In contrast, backyard gardeners gave February as the most common planting month for their tomatoes. As rainfall in Kumasi has a local peak in June (Figure 4), less additional water is needed in these schemes with later planting dates. Do note that for both schemes the relative biomass is 1. This means that the achieved yields are equal to the maximal possible yield.

[6] As the first year of the dataset starts from May onwards, crops planted before May only have 4 years at maximum of data.

Table 7. Output for AquaCrop model for SSP1 and Feyiase neighbourhood.

Fields

Scenario		Cassava	Cabbage	Maize	Tomato	Bean
SSP1	Yields [ton/ha]	22.43	-	12.90	6.31	4.14
	Relative biomass [-]	0.83	-	0.86	1	0.96
	Irrigation depth [mm]	0	-	0	82.5	0
	Yield [kg/m²]	2.24	-	1.29	0.63	0.41

Backyards

Scenario		Cassava	Cabbage	Maize	Tomato	Bean
SSP1	Yields [ton/ha]	22.99	6.44	14.80	6.30	4.14
	Relative biomass [-]	0.86	1	0.99	1	0.96
	Irrigation depth [mm]	0	247.25	96.75	148.5	0
	Yield [kg/m²]	2.30	0.64	1.48	0.63	0.41

Marginal Lands

Scenario		Cassava	Cabbage	Maize	Tomato	Bean
SSP1	Yields [ton/ha]	21.77	6.44	14.87	6.30	4.14
	Relative Biomass [-]	0.84	1	0.99	1	0.96
	Irrigation depth [mm]	0	137	0	148.5	0
	Yield [kg/m²]	2.18	0.64	1.49	0.630	0.41

Sacks

Scenario		Cassava	Cabbage	Maize	Tomato	Bean
SSP1	Yields [ton/ha]	-	7.08	-	6.59	4.25
	Relative Biomass [-]	-	1	-	1	0.94
	Irrigation depth [mm]	-	218.25	-	151.25	0
	Yield [kg/m²]	-	0.71	-	0.66	0.42

Naturally, there are not just differences between schemes in one neighbourhood, but also between neighbourhoods in general. Table 8 and Table 9 show the same results as above, but for Kwadaso and Ejisu.

From these additional simulations, it can be seen that there is a difference in yield and irrigation water use between Kwadaso, Ejisu and Feyiase and a difference between yields for different schemes within Kwadaso and within Ejisu. The latter is again caused by different management strategies, while the former is a consequence both of different management as well as the different soil types between the neighbourhoods. This difference in soil, while it may seem insignificant, actually has a large impact on the yield. The clayey soil in the Western part of Kumasi impedes drainage and thus is beneficial in drier periods. It also results in lower irrigation water needs, despite similar irrigation methods. However, modelling results show that a major problem with yield is aeration stress caused by excessive rainfall in a short period. This means that the poorly draining clayey soil has higher levels of aeration stress than the more sandy soil and thus on average lower yields.

In both Kwadaso and Feyiase, yields are highest in the sack gardening schemes. In this scheme crop density is higher than in the other three, regular planting methods. This leads to a potential higher yield per m² in the model. This is a consequence of the way AquaCrop works and may not be a perfect representation of reality. No literature about sack gardening explicitly states that yields are higher than in conventional agricultural schemes, so it is not clear if the higher crop density directly translates to higher yields the way it does in AquaCrop.

Table 8. Output of AquaCrop model for SSP1 and Kwadaso neighbourhood.

Fields

Scenario		Cassava	Cabbage	Maize	Tomato	Bean
SSP1	Yields [ton/ha]	20.66	5.74	13.18	5.29	4.22
	Relative biomass [-]	0.77	0.89	0.88	0.77	0.98
	Irrigation depth [mm]	0	86.25	0	57.75	0
	Yield [kg/m²]	2.07	0.57	1.32	0.53	0.42

Backyards

Scenario		Cassava	Cabbage	Maize	Tomato	Bean
SSP1	Yields [ton/ha]	17.33	6.04	13.37	5.78	4.22
	Relative biomass [-]	0.65	0.94	0.89	0.87	0.98
	Irrigation depth [mm]	0	52	0	0	0
	Yield [kg/m²]	1.73	0.60	1.34	0.58	0.42

Marginal Lands

Scenario		Cassava	Cabbage	Maize	Tomato	Bean
SSP1	Yields [ton/ha]	-	-	13.19	-	4.22
	Relative biomass [-]	-	-	0.88	-	0.98
	Irrigation depth [mm]	-	-	0	-	0
	Yield [kg/m²]	-	-	1.32	-	0.42

Sacks

Scenario		Cassava	Cabbage	Maize	Tomato	Bean
SSP1	Yields [ton/ha]	-	6.59	-	6.08	4.41
	Relative biomass [-]	-	0.93	-	0.87	0.98
	Irrigation depth [mm]	-	71.5	-	0	0
	Yield [kg/m²]	-	0.66	-	0.61	0.44

Table 9. Output of AquaCrop for SSP1 and Ejisu neighbourhood.

Fields

Scenario		Cassava	Cabbage	Maize	Tomato	Bean
SSP1	Yields [ton/ha]	21.58	5.60	12.74	6.11	3.70
	Relative biomass [-]	0.84	0.87	0.5	0.88	0.83
	Irrigation depth [mm]	0	87	0	57.75	0
	Yield [kg/m²]	2.16	0.56	1.27	0.61	0.37

Backyards

Scenario		Cassava	Cabbage	Maize	Tomato	Bean
SSP1	Yields [ton/ha]	18.76	5.60	12.81	6.31	3.70
	Relative biomass [-]	0.70	0.87	0.93	1	0.86
	Irrigation depth [mm]	0	33.25	0	72.50	0
	Yield [kg/m²]	1.88	0.56	1.28	0.63	0.37

Marginal Lands

Scenario		Cassava	Cabbage	Maize	Tomato	Bean
SSP1	Yields [ton/ha]	-	6.43	12.83	6.30	3.92
	Relative biomass [-]	-	1	0.86	1	0.88
	Irrigation depth [mm]	-	57.75	205.75	268.67	0
	Yield [kg/m²]	-	0.64	1.28	0.63	0.33

Sacks

Scenario		Cassava	Cabbage	Maize	Tomato	Bean
SSP1	Yields [ton/ha]	-	6.17	-	6.59	3.97
	Relative biomass [-]	-	0.87	-	1	0.85
	Irrigation depth [mm]	-	35.75	-	72.50	0
	Yield [kg/m²]	-	0.62	-	0.66	0.40

4.2 Indicators for adaptation assessment

With the agricultural productivity clear per adaptation and per neighbourhood, it is possible to quantify how each adaptation will contribute to the food security of the neighbourhood and how much land is necessary in each neighbourhood to be self-sufficient. The first element of this section is dedicated to this analysis. In addition to this, there are several elements of adaptations that influence the implementation of these, a qualitative analysis based on literature and implementations elsewhere is also included in the second half of this section.

4.2.1 Performance of adaptations related to threats.

The yield results from the model provide the basis to determine the adaptation's ability to guarantee food security. For this, it is first necessary to quantify the demand per district. With the information from Table 1**Error! Reference source not found.**, the population numbers f rom the PHC and the projections from Kc and Lutz (2017), it is possible to quantify the daily demand per food group and district. An example projection for demand per food group scenario and district are shown in Table 10. All information that was used to get to these demands, as well as the tables for the other scenarios and neighbourhoods are included in Appendix D. Model results.

Table 10. Total daily demand for crop groups for SSP1 and Feyiase neighbourhood.

District	Food group	Intake (kg/day)	Intake min (kg/day)	Intake max (kg/day)
	Total daily demand per district per food group - SSP1			
Feyiase	Whole grains	12,751	12,751	12,751
	Tubers and starchy vegetables	2,748	-	5,496
	Vegetables	16,489	10,993	32,978
	Fruits	10,993	5,496	16,489
	Legumes	4,122	-	5,496

The demands per neighbourhood are only part of the picture. As stated in the previous chapter, insight in the amount of space that is (currently) available is also important. For this, remote sensing data provides the outcome. With the help of data from Sentinel-II data and QGIS, the classification of land uses in Kumasi, divided into urban land, arable land and marginal lands provides the available space in each neighbourhood for agriculture. Do note that this classification is different to the one from Figure 7, as that one had a lower resolution and thus was less accurate. For Kwadaso, the full district was considered. For Feyiase, the overlap between the Bosomtwe district line and the 10-kilometre buffer around the central city district provides a good boundary of this neighbourhood. Finally, as Ejisu is fully outside the 10-kilometre buffer, a 15-kilometre buffer was used, as this was a good approximation of the peri-urban land in and around Ejisu. The result of the classification is visualised in Figure 12, with some values for the available space in Table 11.

Starting with the currently available space, compared to the current demand, the results show that in the neighbourhoods, there is currently not enough space to meet the demand of the food groups locally with just one of the categories of land (marginal vs regular arable land/backyards). The combination of both types of land does provide enough space currently to feed the populations of the neighbourhoods.

In the future, due to climate change, yields of some crops, like legumes and vegetables, are increased. In contrast, the rainfed crops, like tubers and cereals, see reduced yields in the future. At the same time, the projected population growth in the districts mean that the space that is required for self-sufficiency can increase by as much as 40% for a crop group like legumes.

Table 11. Available space per district.

District	Marginal Lands (km²)	Backyards, gardens and other agriculture (km²)	Total (km²)
Ejisu	14.5862	30.5128	94.61
Feyiase	6.6	18.2	44.36
Kwadaso	5.2644	25.5625	64.11

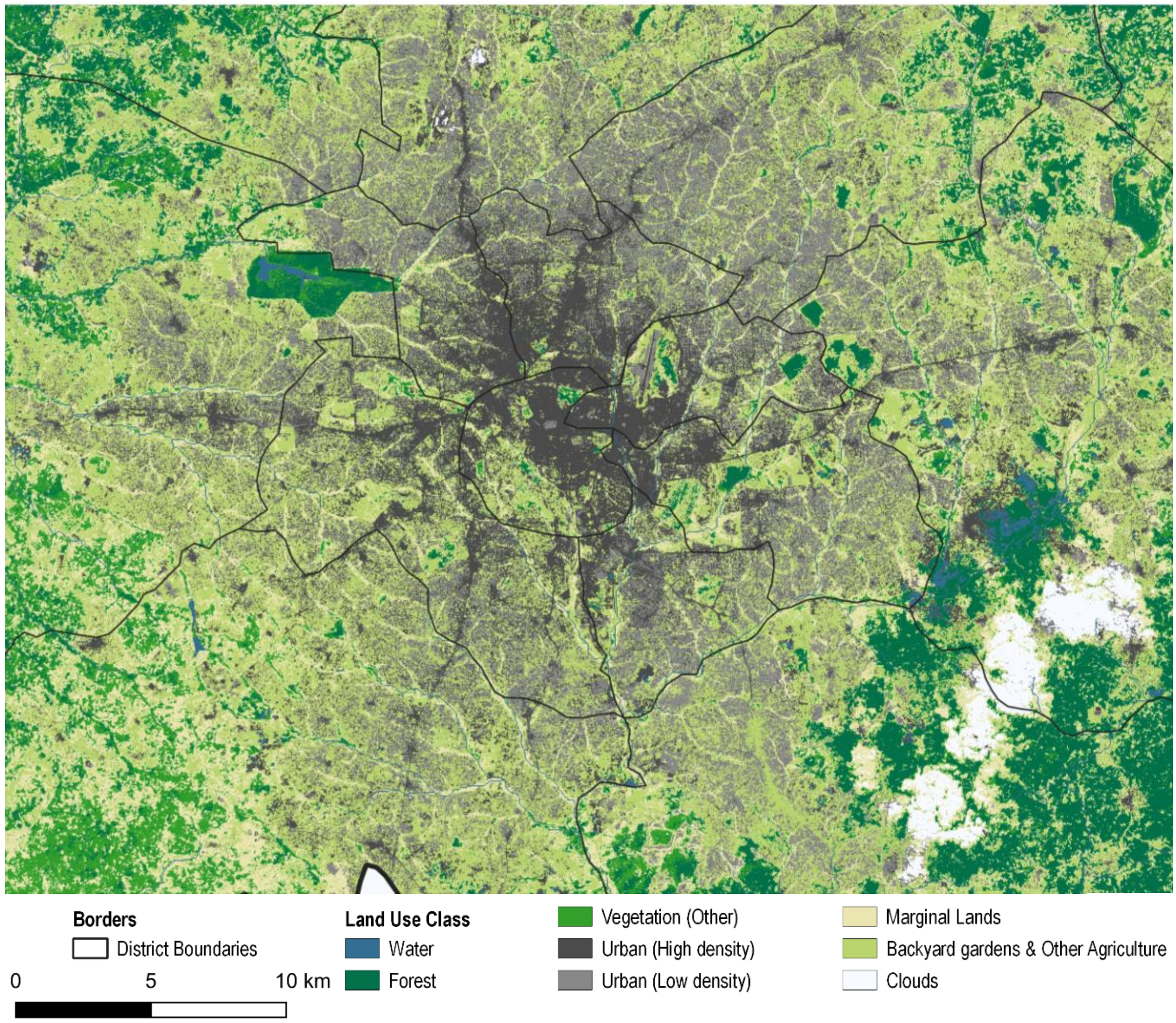


Figure 12. High resolution land use classification of Kumasi.
Land use data from (ESA, 2021); District boundaries from (Ghana Statistical Service, 2019).

This means that trade-offs are necessary to be able to maintain food security in the neighbourhoods. One of these methods is by using the adaptations that use the least space per specific crop group. Sack gardening and backyard gardening use less space for vegetables and legumes than farming on fields and marginal lands. In contrast, the gains in space for these adaptations are negligeable for cereals and tubers. As such, growing these crops on marginal lands or on fields is more efficient.

From this information, several things can be deduced. For one, backyard gardening and sack gardening are useful adaptations to limit land use for agriculture, while maintaining good yields of vegetables. Moreover, they are useful adaptations to start growing legumes in, so to add this crucial element to local diets. At the same time, these adaptations are less suited for growing cereals and tubers.

By growing vegetables in backyards (and sack gardening schemes where space is very limited) one can guarantee a local supply of these crucial elements of diets. The results show that in the most extreme case (SSP2), between 9.2 and 14.5 km^2 of gardening space in Kwadaso is needed to provide 100% of the population with vegetables. To put this into perspective, this is equal to 36 to 55% of potential arable land currently available in the neighbourhood, or between 14 and 22% of total area in the neighbourhood. In terms of land per household, it would mean that every household needs between 11 and 18m^2 of land to grow vegetables on.

For the Feyiase neighbourhood, self-sufficiency for vegetables requires between 2.25 and 3.8 km². This is 12 to 20% of arable land in the neighbourhood and approximately 5 to 9% of the total available land, or again between 11 and 16m² per household. This also holds for Ejisu, where between 11 and 20% of total neighbourhood area is needed to fulfil the demand, or 12 to 19m² per household.

In addition, by using marginal lands for the crops that are more optimal in these schemes, about 5 km² and 1.28 km² of these lands are enough to provide the populations of Kwadaso and Feyiase respectively, of their full cereal need. For Kwadaso, this is approximately 100% of the available marginal lands as classified above, while for Feyiase, this is 20% of available marginal lands in the district. In Ejisu, there is more marginal land available than in the other neighbourhoods. As such, there is more than enough space available to meet the demand of cereals and tubers with production on these lands. Approximately 8.5 km² is required for tubers and cereals combined, where 15.6km² is available. The full space requirement per district, crop type and adaptation for one scenario is shown in Table 12. The full set of tables is included in

Finally, there is the important aspect of irrigation water need. In Kwadaso, backyard and sack gardening for vegetables uses less water than fields, with crops grown in sacks needing a little more than those grown in backyards.

This is reversed in Feyiase, where backyards need a little more water than sacks. Another interesting aspect here is the water use of other crops. Tubers are rainfed in every adaptation, but backyard gardeners in Feyiase do water their cereals and consequently, there is a higher irrigation water need in this adaptation. Still, this is not correlated to an increase in yield when compared to other adaptations. As such, growing cereals in backyards in Feyiase should be discouraged.

Overall, the water use of adaptations is not excessive and accompanied by increases in yields. Accordingly, the results of the research into irrigation water use does not change the assessment made earlier based purely on the yields and space requirement of adaptations.

With this part done, there remains two more elements in deciding the usefulness of adaptations. The next section goes into indicators related to implementation, such as cost and policy. Finally, chapter 4.3 looks at the survey results and the opinion of farmers and vendors. The full assessment and recommendations about the adaptations then follows in chapter 4.4.

Table 12. Space requirement comparison(100% self-sufficiency - SSP2)

District	Crop type	Total demand in season (kg)	Space (Fields) (km²)	Space (Backyards) (km²)	Space (Marginal) (km²)	Space (Sacks) (km²)	Season duration (days)
Ejisu	Whole grains (Maize)	7,989,807	6.27	6.20	6.19	-	132
	Tubers and starchy vegetables (Cassava)	4,696,203	2.10	2.42	-	-	360
	Leafy vegetables (Cabbage)	6,809,495	11.76	11.77	10.24	10.68	87
	Fruiting vegetables (Tomato)	8,767,082	13.89	13.44	17.95	12.86	131
	Legumes (Dry Bean)	2,250,264	5.92	5.91	6.33	5.66	115
Feyiase	Whole grains (Maize)	1,918,857	1.42	1.29	1.28	-	132
	Tubers and starchy vegetables (Cassava)	1,127,855	0.49	0.48	0.49	-	360
	Leafy vegetables (Cabbage)	1,635,390	-	2.46	2.46	2.23	87
	Fruiting vegetables (Tomato)	2,462,483	3.78	3.78	3.78	3.61	131
	Legumes (Dry Bean)	540,430	1.30	1.30	1.30	1.27	115
Kwadaso	Whole grains (Maize)	6,831,632	5.01	4.93	5.01	-	132
	Tubers and starchy vegetables (Cassava)	4,015,457	1.84	2.22	-	-	360
	Leafy vegetables (Cabbage)	5,822,413	10.09	9.77	-	9.16	87
	Fruiting vegetables (Tomato)	8,767,082	15.71	14.53	-	13.97	131
	Legumes (Dry Bean)	1,924,073	4.39	4.39	4.39	4.20	115

4.2.2 Performance of adaptation related to implementation.

Besides the indicators that are related to the threats, there are elements of the adaptations that are more related to the implementation of those. These are important because adaptations that are very beneficial to combating the threats may be less practical due to being very expensive or by being contingent on government intervention. This chapter includes a short analysis of several indicators related to implementation and how they affect the usefulness of the adaptations.

The first indicator is material need. For this, we look at what materials are needed for an adaptation and if these are easily available in Kumasi/Ghana. If less materials are needed, an adaptation is obviously more desirable. Adversely, if a lot of materials are needed and if these are not easily available, adaptations are less desirable.

Backyard gardening is an adaptation that uses very little special materials when compared to other adaptations. The materials that are needed are the ones that are needed for farming anyway. In their research into backyard gardening in Ouagadougou and Tamale Bellwood-Howard et al. (2018) specifically noted seeds, fertiliser, crop protection and fencing materials as the most important inputs for backyard gardeners. These are all elements that are needed for all adaptations anyway. Following this, backyard gardening is an adaptation with a comparatively low material need.

The next adaptation in sack gardening is a little different. The NGO Solidarités International has made a handbook with resources to set up sack gardening schemes (Solidarités International, 2016). In this handbook they also outline the materials that are needed. For a sack gardening scheme, one needs to make the actual gardening bags, as well as a nursery. The resulting list is similar to the one for backyard gardening and includes, seeds, fertiliser, crop protection and fencing material. In addition, one needs the actual sacks, a plastic pipe the size of the bag, soil, and stones to buttress the sacks. From this, the conclusion is that sack gardening has a larger material cost than regular backyard gardening. However, the needed materials are readily available, as the sacks are easily obtained. The increase in material is therefore a small problem.

Following this is farming on marginal lands. As another more “conventional” farming scheme the material use is the same as backyard gardening, where the only necessary materials are those that are needed for agriculture anyway. Moreover, due to the potential access to roadsides, it may even mean that less transport material is needed, as crops can be sold directly. It is therefore a desirable adaptation in the sense of material needs.

The second to last adaptation is greenhouse technology. The description of different greenhouse designs in Ghana from Elings et al. (2014) show that all designs, whether it be glass, plastic or net houses, are heavy in material use. Greenhouses need a steel structure to support the plastic panels or the nets. Depending on the environment, additional soil and fertiliser may also be necessary. Finally, for optimal productivity, electricity access is needed for good ventilation. From this, one can see that greenhouses require a significant investment of materials. Moreover, Forkuor et al. (2022) also state that the materials that are needed are not readily available. While this seems like a problem, they also stress the potential of bamboo to use as a structural material to use a more locally available material. With this the need is lowered, but still significant.

Finally, there is the adaptation to aquaponics and the one that likely is the heaviest in terms of material requirement. The materials that are needed for this can be sourced from the FAO guidelines from Somerville et al. (2014). Their material list is too expansive to fully describe here, but it contains a set of IBC tanks, that are readily available in Ghana and a network of PVC pipes, which can also be found for sale online. Remaining materials include concrete blocks, frames for support and pumps to circulate the water. This final element means that electricity is a requirement of the adaptations. All in all, there is a large material requirement, but some of these materials are easily accessible in the Ghana context.

The next indicator is the financial cost. Closely related to the material cost, this indicator shows if it is difficult to adapt because large initial investments are needed, or because maintenance is expensive. Naturally, cheap adaptations are more desirable than adaptations that are more expensive.

Backyard gardening is a cheap adaptation in that the initial investment is small and that the maintenance is not higher than other adaptations. As with the materials, the main cost is in the elements that are needed for every form of agriculture in terms of soil, fertiliser and seeds.

Similarly, for sack gardening, the costs are in the seedlings and fertiliser. Another addition is the cost for the sacks. Research into sack gardening in Kenya showed that many farmers still purchase their sacks (Gallaher et al., 2015). These sacks are still rather cheap with an average cost of $0.25 USD per sack. In the Kenya example, farmers had 3-7 sacks in their household giving a total cost of $0.75-$1.75 for the sacks. Other resources, such as soil and rocks are often gathered illegally for free, although there might be costs associated with gathering these elements through legal means.

As with the previous two adaptations, farming on marginal lands is another cheap adaptation. There are no special elements necessary to farm on these lands. One thing to keep in mind is that, according to Ayambire et al. (2019), marginal lands can be less suited for agriculture due to high slopes and/or low fertility. If this is the case, cost of maintenance of agriculture on this land is higher due to the need for more fertiliser and/or means to hold water better on the field.

The remaining adaptations are the two most expensive ones. Starting with greenhouses. This adaptation is very costly when compared to the previous three. Obviously, the initial investment of constructing a greenhouse is larger than cropping in backyards, sacks or on marginal lands. Online, greenhouse construction is offered starting at $4000 USD ramping to over $10,000 USD (Forkuor et al., 2022). Moreover, the need for electrification in some types of greenhouses means that maintenance costs are also high.

Lastly, the adaptation to aquaponics is another expensive one. In their paper, Somerville et al. (2014) included a cost-benefit analysis of an aquaponics unit for domestic food consumption. Their estimate for an initial investment is $700 USD and they estimate the running costs at $26.45 USD. It is remarkably cheaper than constructing a greenhouse, but it assumes already present water and electricity connections. The maintenance costs associated with these can be significant.

The following indicator is knowledge. If adaptations have a high knowledge requirement, that means that people need additional training to be able to effectively practice agriculture in these schemes. If no additional training is needed, an adaptation is obviously better suited to maintain UPA in Kumasi.

As with the previous indicators, backyard gardening is an adaptation with little necessary investment for knowledge. If farmers are switching from fields to growing crops in newly developed backyards, they already have the knowledge necessary to grow crops. However, if people move to new neighbourhoods and are encouraged to grow crops in backyards as addition to their other livelihoods, some training may be useful, so people do not give up growing crops in backyards, because of lack of knowledge.

Next up is sack gardening, this is not as straightforward as some of the other schemes. In their guidelines Solidarités International (2016) stress the need for education. Their learning objectives include teaching people how to construct sacks, how to transplant into the sides of sacks and what elements are crucial for success. According to their guidelines, three sessions of 2 to 3 hours are needed at least. This makes it not very intensive in training, but more so than adaptations that are ready from the get-go.

Farming on marginal lands is easily addressed, as another simple scheme, people need no training on top of the regular knowledge that is necessary to be a farmer. One element to keep in mind is the characterisation of marginal lands from Ayambire et al. (2019). If the lands are less suited for agriculture, farmers may need some help in adapting to this specific land. Moreover, due to the proximity to roads and wetlands, some farmers may need training on the risks associated with pollution. This makes this adaptation not very knowledge heavy when compared to the high-tech solutions coming up.

The first of the high-tech adaptations in greenhouses is again knowledge heavy. According to Forkuor et al. (2022), very little farmers have technical expertise that is necessary for greenhouse farming. They give little elaboration on the specifics of what knowledge is required however. Although there is overlap with regular soil-based agriculture, it is likely that this adaptation does require some additional training before it can be implemented.

Lastly, aquaponics is another adaptation that requires additional training. According to Somerville et al. (2014) educational capacity is a determining factor in how well aquaponics systems can perform. They specifically stated understanding of the ecosystem, knowledge of nutrition and knowledge of general aqua- and horticulture as the things that are necessary. However, they do mention that the inclusion of local adaptations to the technology will simplify the training of those who have to use the system. Still, all in all, this is likely the adaptation that will require the most work in training the farmers.

In an earlier chapter, it was established that for peri-urban agriculture to remain in its current form in Kumasi, extensive changes are necessary in policy to protect the green spaces in (peri-)urban Kumasi. From this, it seems that adaptations that deal with the threats without changes in policy are better suited to the Kumasi context than ones that do need them.

Backyard gardening is policy intensive in the sense that the success of this adaptation is dependent on the type of development that occurs in Kumasi. If the future residential development is dense, with little green space, there should space allocated for community gardens, for backyard gardening to be possible. Otherwise, with lower density development, some outreach, or motivation may still help with introducing people to backyard gardening. From this, it seems that backyard gardening is fairly policy intense.

This is also true for sack gardening, which uses similar spaces as backyard gardening. An extra element here is that neighbourhoods may need centralised nurseries for people to pick up plants, soil and sacks. The government or local community can allocate spaces for these nurseries. This means that sack gardening is also quite dependent on policy.

Farming on marginal lands is not an adaptation strategy that requires large investments in policy. As with the other adaptations however, high demand for land also means that residential development should be prevented from encroaching on marginal lands to be able to maintain agriculture on these spaces.

As a high-tech adaptation, greenhouses are heavy in policy in the sense that other elements, like finance and knowledge do not appear out of nowhere and should be provided by institutions. Local government can sponsor agricultural outreach programmes or provide loans for greenhouse investment.

Finally, the second high-tech adaptation of aquaponics work similar in terms of policy as the greenhouse development. Outreach programmes and loans can compensate for the high knowledge and financial barriers. Similarly to the sack gardening scheme, a communal nursery for fingerlings[7] and the crops may be a necessary investment to allow for more widespread aquaponics applications in neighbourhoods. Again, there is a role for local government or other institutions in setting this up.

4.3 Survey results

In chapter 4.1, the survey results from the first part of the farmer survey were shown and discussed. Naturally, the other parts of the survey and the vendor survey are also of interest. In this part, the results from these surveys and their implications are discussed. Ultimately, it was not possible to survey the full amounts of neighbourhoods as planned, due to a lack of resources. The distribution of responses and the comparison to the planned sample sizes for the full survey is given in Table 13**.** The full aggregated answers to the surveys are given in Appendix C. Aggregated survey responses.

Table 13. Actual survey sample sizes.

Neighbourhood/Town	# of Farmers		# of Vendors	
	Planned	Actual	Planned	Actual
Ejisu	70	55	~34	36
Feyiase	50	55	~34	10
Kwadaso	30	36	~34	68
Total:	150	146	100	114

In the following sections, the results of the survey are given. The results are split up corresponding to the sections of the survey, starting with the demographics of the respondents, followed by their perception of the threats, supply and ending with their feelings about the adaptations.

4.3.1 Demographics of respondents

The first set of questions in the survey were related to the demographics of the respondents. The distribution of age, gender and experience is not the same in every neighbourhood and the conclusions that can be drawn from this are fairly interesting.

In general, the age of the farmers is quite old, half of the surveyed farmers are either in the 40-50 or 50+ group. The spatial distribution of age is not equal, however. Out of the Feyiase farmers, 50% of respondents is in the 50+ age group, compared to 17% from the Kwadaso area and only 1% from the Ejisu area.

This age difference is also reflected in the levels of experience from farmers. 36% of Feyiase farmers state that they have been a farmer for more than 20 years. In contrast, only 20% of Kwadaso farmers and 7% of Ejisu farmers have the same level of experience. Over the total number of respondents, experience is fairly evenly split between >20 years, 10-20 years, 5-10 years and <5 years, with about a quarter of the respondents answering for either category. The difference in age and experience between neighbourhoods may be a cause of the difference in management practices. This is further explored in a later section.

The spatial difference is also present in the gender distribution. Feyiase respondents are 51% male and 49% female. In Kwadaso, 86% of the respondents is male, with the same distribution in Ejisu: 80% male. This also means that over the full set of respondents, the majority identifies as male: 70%.

[7] Fingerlings are juvenile fish that have developed a little and are typically as large as human fingers.

For the vendors, 97% of total respondents is female, with all neighbourhoods showing the same trends. Age distribution is a lot more spread out than for the farmers. With similar numbers for all age groups. In terms of experience, a small majority of vendors could be considered very experienced: 53% of vendors have been one for over 10 years. For a large majority of vendors, it also is their main trade: only 30% of them grow their crops themselves. That mean that the 70% that do not grow their crops themselves, get their crops from either farmers or from wholesale. In terms of spatial differences, there are little remarkable results. Vendors from Feyiase, Kwadaso and Ejisu show the same demographic patterns concerning age and experience.

4.3.2 Perception of threats by farmers and vendors

The results of the survey show that the threats as they are identified from literature are very much perceived as such by the farmers and vendors of Kumasi. Out of all the surveyed farmers 95% felt that things needed to change for agriculture to be maintained in Kumasi. According to these same farmers, the most important elements in this change are education and land ownership. In contrast, they feel that government land planning is less important: with 41% of farmers answering that they find it only somewhat important to not important at all.

There is very little difference in the answers to this part of the survey between the neighbourhoods. Both Kwadaso and Feyiase farmers feel similarly about the threats and what elements are important. The distribution of the response to the question about important elements for the full set of farmers is visualised in Figure 13.

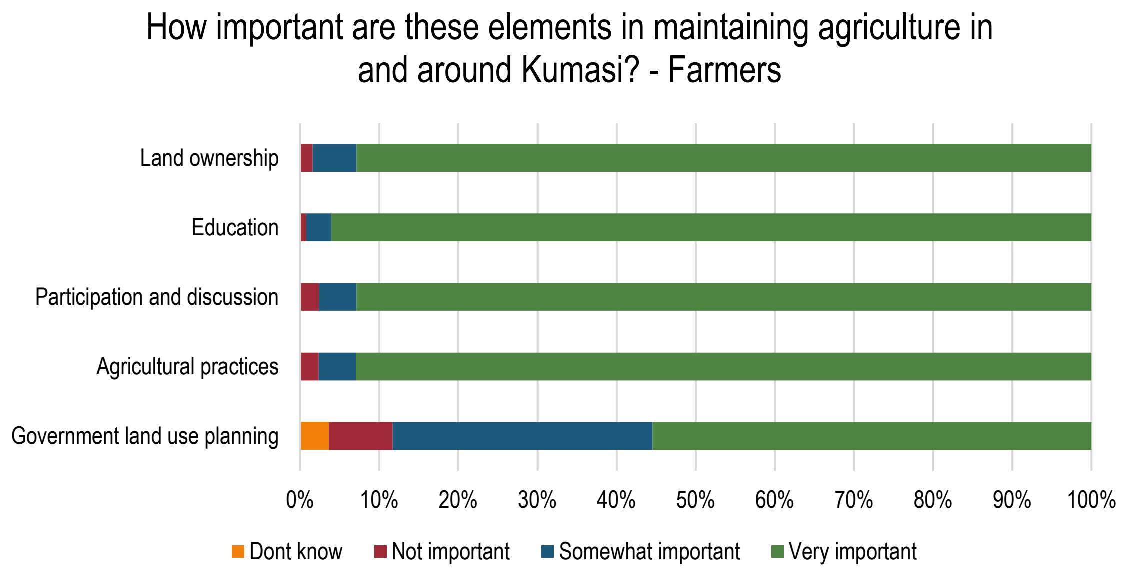


Figure 13. Farmer survey results: what elements are important in adapting.

The opinion on agriculture is shared by the vendors; 93% of the respondents here believe that things need to change for agriculture to be maintained. The vendors see climate change as a larger threat than urbanisation, with 95% citing the former as a threat and 87% for the latter. Many vendors also relate these threats to their own supply and 76% are afraid that they can no longer meet the demand of their customers in the future.

For the vendors, there are also little spatial differences. Similar numbers of vendors in all neighbourhoods feel that climate change and urbanisation are a threat to urban agriculture. Vendors in all neighbourhoods also feel the same way about the impact on future demand, with the numbers matching the one above.

Now that it is clear how farmers and vendors look at the threats, it is good to zoom in on the vendors specifically. The next section is dedicated to the supply of important crop categories on markets and to supply in general.

4.3.3 Supply of crops on four markets in and around Kumasi

In Chapter 2.2.4. the table from Drechsel et al. (2007) proved an important resource in determining both the food basket and in quantifying the contribution of peri-urban agriculture in Kumasi. This resource is very outdated, however. A short section of the vendor survey is dedicated to asking questions about the supply on the Kumasi markets and the sources of the products.

Vendors were asked how many kilos of a crop category (vegetables, cereals, etc.) they sold per week and where they got these products from. They were asked to answer with the name of the neighbourhood, village or region. From this, a profile of the sources of the products on the markets could be made, leading to the charts in Figure 14.

When compared with the table from Drechsel et al. (2007), there are some differences and similarities. The fruiting vegetable category from Figure 14 shows very similar numbers to the results from literature for tomato. For the leafy vegetables however, the 90% sourced from urban production that literature found is not represented in the results from the survey. Vendors of leafy vegetables on the Ejisu and Kwadaso area markets apparently source their leafy vegetables mostly from rural areas, with the second largest category being other markets. In the interview with the representatives of the Kwadaso Agricultural College, they stated that most of the vegetables that are grown in an urban setting are mostly consumed by the people who grow them. According to the representatives, while some of these crops may be sold to university staff or students, it is unlikely that the crops end up at the markets. This is a likely explanation for the difference between this survey and the one from Drechsel et al. (2007). The latter also interviewed households, which will include the vegetables from campuses.

While the survey results for tuber and starchy vegetable sales match fairly well to some crops from this category (plantains, cocoyam), it is less accurate for cassava. Still, the overall conclusion that these are sourced from rural areas is not problematic, as this supports the idea that urban and peri-urban land can be used for vegetable production.

Finally, the results for cereals show a large degree of uncertainty, due to two vendors answering “Kumasi” as the source of their product. It is likely that this refers to other markets, but this is not verifiable. Still, there is a lack of cereals from peri-urban sources on markets, despite earlier literature stating that ~35% of maize comes from urban and peri-urban sources and even though many surveyed peri-urban farmers state that they do grow cereals. A possible explanation can also be found in the farmer survey. When asked what they do with their yields, 88% of the surveyed farmers state that they use it to feed their families. A large majority of these do manage to sell some remains, but from this it seems that cereals are very much a subsistence crop, one that does not get sold unless yields are high enough.

Another element that was explored is the issue of spoilage. Looking back at the theory of urban agriculture, one of the main benefits was the easy access to perishable foods. If spoilage is an issue, it would be better to further promote vegetable production in the urban and peri-urban areas.

Virtually all vendors answered yes to the question if spoilage is a problem, with a majority finding it a large problem. This pattern is the same through the neighbourhoods, with all answering among similar lines. The only difference here is that 78% of Ejisu vendors found it a large problem, whereas 60% of Kwadaso vendors thought so.

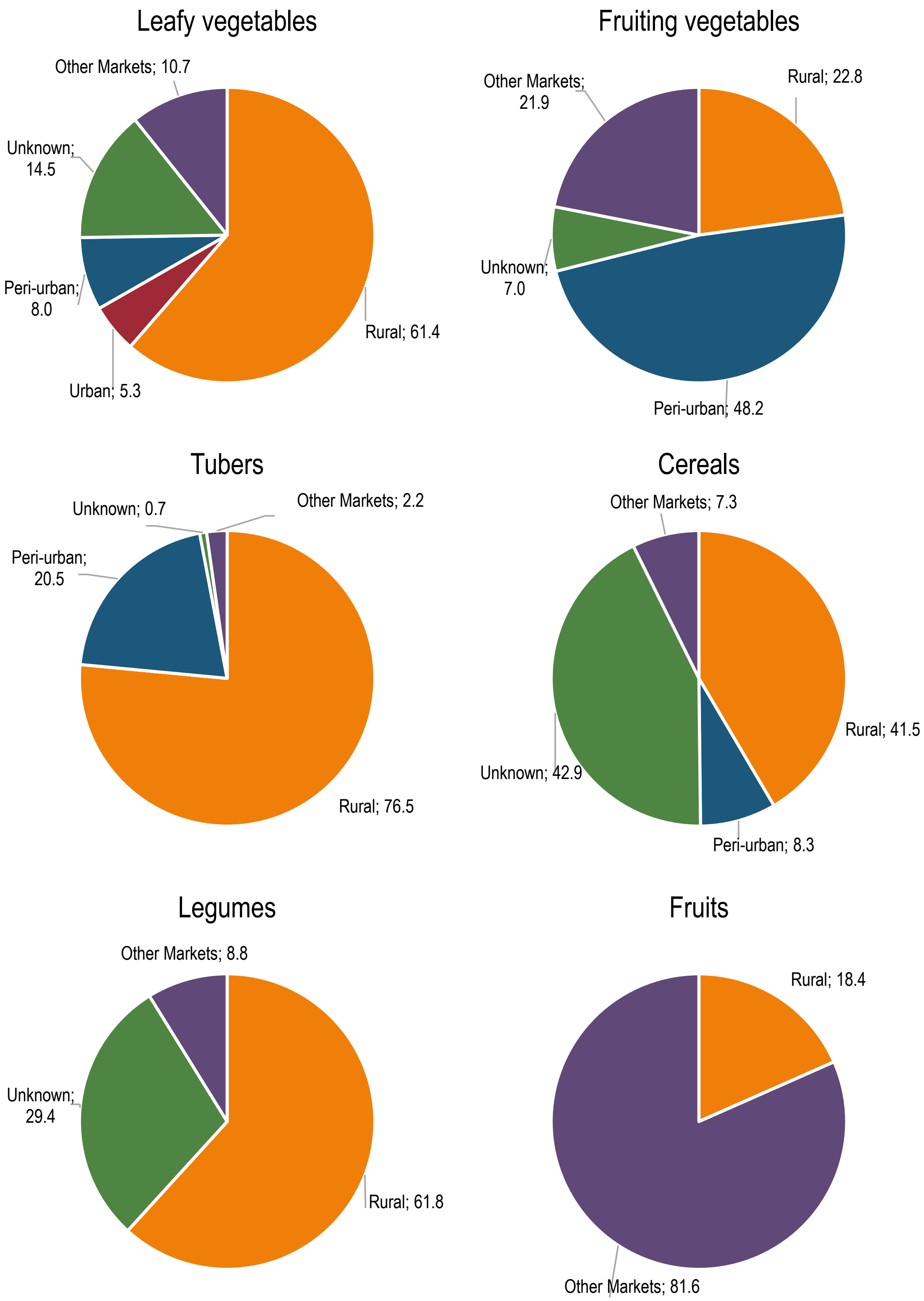


Figure 14. Vendor survey results: Where are the crops on the surveyed markets sourced from.

When asked about the main causes of spoilage. Vendors had the option to select one or more of three answers: “Lack of cooling facilities”, “it takes too long to get food to the markets” and “products are of insufficient quality”. Most vendors found the second option the largest cause of spoilage, with 80 out of 104 respondents selecting that option. 64 vendors also selected the lack of cooling facilities, with a smaller amount, 19 respondents, selecting the insufficient quality option.

With these causes of spoilage, there seems to be opportunity to improve the supply from the direct vicinity and so to reduce the waste that is generated because products need to come from far or because of lack of cooling.

4.3.4 Acceptance and barriers against adaptations

Having established that vendors and farmers feel similarly about the threats as the literature does, it would be expected that, barring other external circumstances, they would be receptive to novel methods that are better suited to maintain agriculture.

Earlier, the perception of the threats by the farmers and vendors were shown. Seeing that they feel that things need to change, some questions were dedicated to asking which elements are important in adaptations and how they feel about the adaptations specifically. Farmers found no element more important than others, rating things like yield, crop variety, water use, knowledge and materials all very important. Interestingly, 13% rate financial cost as only “somewhat important”. The farmers who did so mainly came from the Feyiase neighbourhood. Virtually every one of those were also willing to change practice in general. They are mainly interested in backyard gardening, sack gardening and marginal lands, with some still citing expenses as the reason for not wanting to choose a high-tech adaptation.

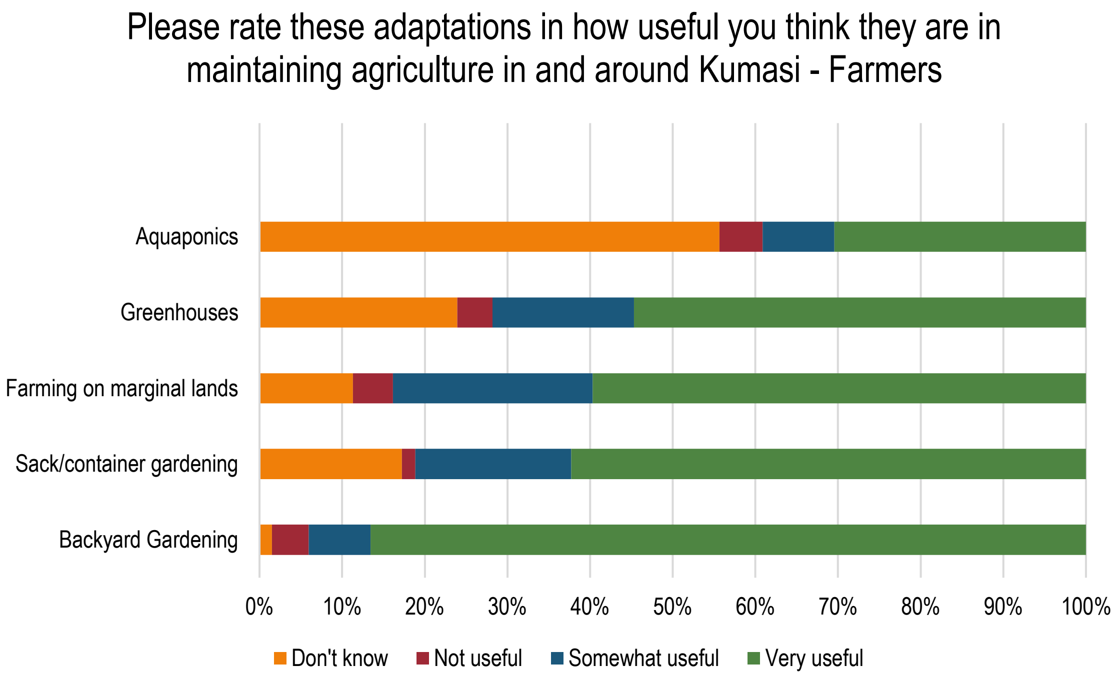
Farmers were also asked to answer how useful they think specific adaptations will be. The full results are shown in Figure 15. The farmers are overall positive about most of the adaptations, with over 50% answering “Very useful” or “Somewhat useful” for 4/5 adaptations. Farmers are most positive about backyard gardening and sack gardening as adaptations and less so about the high-tech adaptations of greenhouses and aquaponics, where a small majority answered “Don’t know” for the latter.

The question about important elements was a little different for the vendors, they were asked which elements they found most important to trust a product. The most important elements by far were the source of the irrigation water and the location of the field, with 83 and 81 out of 117 respondents selecting these options. In contrast, the third most important element, the type of product, was only selected by 41 vendors. There is very little difference between the neighbourhoods, with vendors in all the surveyed markets answering similarly.

In addition to this, vendors were also asked how useful they think specific adaptations are to see if they have a different perspective on this than farmers. Vendors look differently at sack/container gardening than farmers, likely due to being unfamiliar with it, as the largest category is “Don’t know” for the full set of vendors. In terms of sack gardening, Ejisu vendors seem to be more knowledgeable than Kwadaso vendors, as the former mostly answered “somewhat useful” (39%). This is only marginally larger than the “Don’t know” category, with 36% of Ejisu vendors still seemingly lacking knowledge of this adaptation. Similarly, vendors seem to be even less knowledgeable about aquaponics than farmers, with almost 90% answering “Don’t know”. In contrast, vendors are much more lyrical about marginal lands; 66% of vendors answered “Very useful” for this adaptation, whereas only 55% of famers did.

Vendors were also asked how confident they were in the quality of products from the adaptations. The answers to this question closely matched those of the question about the usefulness of adaptations. In general, whenever vendors feel that an adaptation is useful, they also feel confident in the quality of the products.

It seems that vendors in Kwadaso are more apprehensive about these high-tech adaptations than those in Ejisu, although the sum of the people that answered, “Very confident” and “Somewhat confident” is generally similar, vendors from Ejisu generally say that they are very confident, whereas Kwadaso farmers are more cautious; they answer somewhat confident more often. One adaptation for which this is visible is the adaptation to greenhouses. While vendors from both neighbourhoods are confident in general, Ejisu farmers answered very confident in 60% of cases, compared to 47% for Kwadaso vendors.



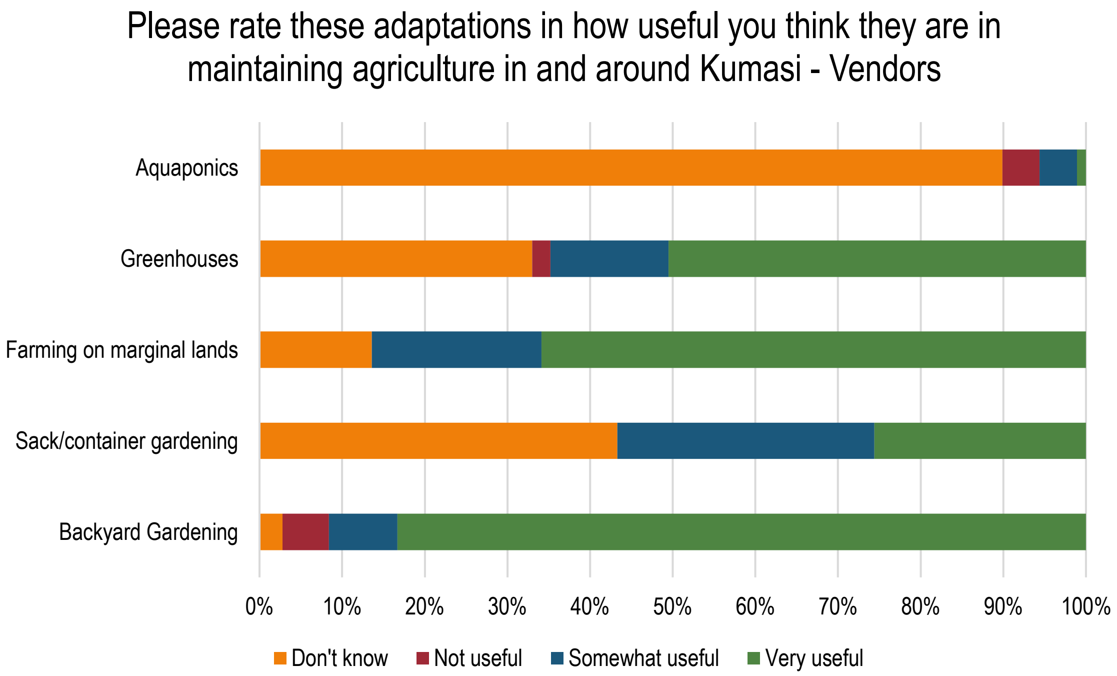


Figure 15. Survey results: How useful are these adaptations in maintaining agriculture in and around Kumasi.

Next up is the willingness to adapt. From the survey, it appears that the majority of farmers are willing to change the type of agriculture that they practice to one of the adaptations. Overall, increased backyard gardening is the most popular as an adaptation, possibly because its practices are closest to “regular” farming. The high-tech solutions are less popular, with a majority not willing to switch to these practices. In the explanations of their answers, most farmers cited expenses as the reason for not willing to switch to this adaptation. As a matter of fact, the majority of farmers that answered “no” to the question if they are willing to change their practice in general also cited finances as the main reason for not being able or willing to.

Table 14. Willingness to switch practices for full sample of farmers.

Would you be willing to switch to growing crops in one the adaptations?

	Change in general	Backyards	Sacks/ containers	Marginal Lands	Greenhouse	Aquaponics
Yes	88	69	50	36	43	9
No	44	14	28	25	39	56
Total	132	82	78	61	82	65

It is interesting to research if the willingness to adapt is related to the demographics of the respondents. For this, the X^2 contingency test for categorical variables is a useful method to understand the relation between two variables. This test checks “(…) the goodness of fit to the data of the null model of independence of variables” (Whitlock & Schluter, 2009, p. 243). In one example here, the two variables are farmer age and willingness to adapt. The null hypothesis is that these two variables are independent: the probability of being willing to adapt does not differ according to age. The alternative hypothesis is of course that farmer age and willingness to adapt are not independent.

The analysis of the two variables shows that the two variables are indeed not independent. The X^2 contingency test resulted in a P-value in the order of $P<10^{-3}$, thus indicating that the willingness to adapt differs according to the age of the farmer. The responses indicate a higher willingness to adapt for older farmers, with 32 out of 34 farmers in the 50+ age group indicating their willingness to adapt. In contrast 19 out of 30 and 17 out of 30 farmers are willing to adapt in the 0-30 and 30-40 age groups respectively. This is another question that was explored in the interview with the experts from Kwadaso Agricultural College. According to them, young farmers are less dedicated to farming as a livelihood than older ones. Another reason is land tenure, older farmers are better established on their lands and are thus more willing to take risks or invest to improve their livelihoods.

Similarly, there exists a relationship between willingness to adapt and neighbourhood. 80% of Feyiase farmers are willing to change practices in contrast to 40% of Kwadaso farmers. Statistical analysis revealed a P-value of 2.63E-3 highlighting the link. According to the interview, farmers on the campus lands can be removed from the land if the university demands it. Like the previous answer, farmers who are uncertain if they can remain on their land are unwilling to invest in better practices.

The most popular adaptation for farmers and vendors both is backyard gardening. A large majority, 69 out of 82 farmers state that they would be willing to switch to growing crops in backyards. When asked why, the majority stated convenience, the cheap prices and the benefits it would bring to their homes, family and community. The survey results indicate that this sample of farmers feel the same way about backyard gardening as the literature does, which is a good indicator for this adaptation.

When asked if they would sell or eat products grown in backyards, vendors wholeheartedly answered yes. They supported the views from the farmers about cost and convenience but added that they felt that products from backyards are organic, healthy and well maintained. Some even stated that they already grow products in backyards themselves and that they sell some of it. In the interview, the representatives from KAC were asked why crops from backyards have this image of being organic and cheap. They stated that due to the small-scale nature, no chemical fertilisers are used by the farmers. According to the representatives, vendors perceive these products as cheap because farmers have to sell them quickly, due to storage problems. This gives vendors bargaining power, which allows them to buy these products for cheap and then sell them with a large markup.

All in all, these results indicate that there exist no barriers from two crucial groups in Kumasi against adapting in the form of backyard gardening. This, combined with the effectiveness of this adaptation in terms of food security, and in practical matters shows that backyard gardening is a very well-suited practice to maintain urban and peri-urban agriculture in Kumasi.

Sack gardening is an adaptation that farmers felt would be more useful to maintain agriculture than vendors. 61% of farmers answered that they would be willing to switch to growing crops in sacks. Many gave the reduction in necessary space as the reason for their trust in this adaptation. Others repeated the points from backyard gardening and said that it would be good for their family and community. Some were more sceptical however, stating excess chemicals, or potential low yields as the reason.

Vendors are also fairly confident in sack gardening, with 72% stating that they would be willing to sell/eat products from this scheme. The explanations that they gave were mostly related to reductions in general cost, cost of transportation and labour. There is a slight contradiction in the answers, where some vendors feel that the crops grown in this scheme are of poor quality due to use of chemicals and excessive fertiliser, while other specifically mention that the crops will be healthy and organic. Many vendors are practical in their answers, saying that they are fine with it, as long as it is cheap, of good quality or both.

From these results, the conclusion is again that there exist no strong barriers against sack gardening as an adaptation, with some caveats. While the majority of farmers and vendors are fine with the adaptation, concerns that they have about quality, unfounded or not, need to be addressed either in the form of education or otherwise.

The adaptation of farming on marginal lands is somewhat popular among farmers. 36 out of the 88 that were willing to switch practices said that they would be willing to switch to growing crops on marginal lands. Most of these said that it is good to use lands that are otherwise left unused and cited the low cost of transportation as a positive. One farmer specifically mentioned wetlands as a good place for rice cultivation.

Almost all the surveyed vendors were willing to buy/eat crops grown in marginal lands. The foremost reason they gave for this was that the crops were cheap, easy to transport and of good quality. Some vendors specifically stated that the soil would be rich and that the crops would therefore be of good quality. One vendor stated that growing crops on marginal lands would cut down costs on water supply. This specific vendor is one of the few who grow the crops that they sell themselves, which explains why this is a concern for them.

As with the previous adaptations, no clear barriers seem to exist for the adaptation of farming on marginal lands. While there may be other concerns related to implementation – as discussed in an earlier chapter, the opinion of the farmers and vendors is clearly in favour of the adaptation.

The opinions on greenhouses are very mixed. Vendors are enthusiastic about the products, but farmers are not willing to switch to these schemes. In contrast to the low-tech solutions, the majority of farmers is not willing to switch to growing crops in greenhouses. Almost all of them stated that the costs are the main reason for not wanting to do so, with one farmer citing lack of knowledge as their reason. Some of these did remark that greenhouses are more efficient but would still not be able to switch due to the price. In contrast to aquaponics, 52% of farmers are still willing to switch to greenhouses. They stated that the products would be bigger and healthier and that the plants would be free from pests.

Vendors are very willing to sell/eat products from greenhouses, 77% of respondents answered that they were willing to do so. The main reason given here was the health of the crops and the fact that they are free from pests and diseases. Some vendors did state that they were only willing to buy the products if they were affordable echoing the responses from those who are not willing to buy products from this adaptation, who also cited expenses as the main reason for not doing so.

This adaptation is the first one where one population group is in clear opposition. Farmers are fearful that adapting in this way is too expensive. A way to manage these fears can lie in the form of policy, where loans and/or subsidies can overcome this barrier; especially because greenhouses are very valuable in terms of yield and land requirement. Overall, there remains potential if these concerns are addressed.

Aquaponics is the least popular adaptation by far. With only nine farmers being willing to switch. None of these two gave an explanation for their answer. Among the farmers that answered no, the most frequent explanations were that they had no knowledge, or that it would be too expensive.

Among vendors, the most frequent answer to the question if they would be willing to eat/sell products from aquaponics schemes was “Don’t know” (71%). Of those who gave a decisive answer, a small majority answered that they would be willing to sell/eat those products (17%). Most vendors were very practical and stated that they would be fine with doing so if the products were of good price and quality and were not contaminated. Many other simply answered that they had no knowledge of it. A few vendors erred on the side of caution and answered that they do not believe that the products will be of good quality.

While aquaponics systems are efficient and well performing related to the threats, the lack of knowledge impacts people’s opinion of this adaptation. The interview with the KAC experts revealed that there are currently no education programs in Ghana altogether. The survey team stated that they had difficulties in explaining this adaptation to people. A common answer that they received in response was that people could not conceive that this would work. There is potential in the answers of many vendors, where they will sell the products if they are not too expensive. Some centralised aquaponics pilots can therefore help in introducing the concept and hopefully, spreading the knowledge, allowing for more widespread adaptation.

4.4 Final adaptation assessment and recommendations

We have looked at the contributions of adaptations to food security, the land use, how well they can be implemented and finally, how the residents of Kumasi feel about them. With this, it is possible to make a statement about what adaptations are best suited to maintain peri-urban agriculture in Kumasi.

The replies to the survey showed that there are gains to be made in the supply of vegetables and legumes from urban and peri-urban sources. Not only has the supply from these places reduced when compared to earlier research, but the vendor survey also found that spoilage is a large problem. With the main cause of spoilage being the time it takes to get crops to the market, adaptations that guarantee local supply can make a difference in this issue as well.

Accordingly, preferred adaptations are ones that perform well for growing vegetables in the urban and peri-urban setting. At the same time, a low irrigation water need, to reduce climate impact, as well as easy implementation are other elements that are important. Finally, the popularity of adaptations among the population is also crucial.

Backyard gardening is probably the most viable adaptation. The model results show that this adaptation performs well in terms of yield and irrigation water use, especially when it comes to growing vegetables and legumes. On top of this, the adaptation is the one with easy implementation, due to the low costs in terms of finance and materials, and low expert knowledge that is required. Above all, this adaptation is very popular among the surveyed population of farmers and vendors. As such, the only conclusion here is that backyard gardening is an adaptation that is well suited to maintain peri-urban agriculture in Kumasi.

Sack gardening is related to backyard gardening in that the implementation is similar. Like the previous, sack gardening performs well in terms of yield of vegetables and legumes, with high yields and low space requirements for self-sufficiency. Sack gardening performs even better than regular backyard gardening when looking at the latter. It is more limited in the implementation however, with the need for more materials and centralised nursery set-ups. The adaptation is also popular among the respondents of the survey, although there remain some concerns about quality. All in all, the conclusion here is that sack/container gardening is a useful adaptation in maintaining peri-urban agriculture in Kumasi.

Farming on marginal lands is a more poorly performing adaptation in that it works less well for the growth of vegetables than the previous two. However, this adaptation performs well for the growth of cereals, which are also an emphasized crop in the EAT-Lancet diet. As such, this adaptation can be complementary to the backyard and sack gardening ones for a full diet. The survey results indicated that cereals are an important subsistence crop and there remain questions about the viability of switching to vegetables without starving many farmers that are dependent on these cereals. By using the backyard and sack spaces for vegetables and marginal lands for (communal) cereal growth, this transition can be made easier. As such, farming on marginal lands is a discouraged for the long term, but perhaps necessary adaptation for the short term to maintain peri-urban agriculture in Kumasi.

Greenhouse technology is a high-tech adaptation that was not modelled. However, the analysis of the implementation found that there are many steps that remain to be taken before the adaptation is viable. Not just is there a shortage of usable materials, the uncertainty of electricity access makes this adaptation discouraged based on these indicators alone. Respondents were also apprehensive, with many fearing the large costs associated with it. The conclusion here is that greenhouse gardening is not a useful adaptation to maintain peri-urban agriculture in Kumasi.

Finally, there is aquaponics. Like greenhouses, the implementation of this adaptation is made difficult both by the nature of the adaptation and by local circumstances. Lack of materials, expert knowledge and electricity access mean that it is not viable to rely on aquaponics to maintain peri-urban agriculture. These thoughts are corroborated by the survey replies, where many respondents did not know what the survey team was talking about. The lack of education or trials currently also meant that it is necessary to first set up these elements before the adaptation can be relied on for larger scale production. This leads to the conclusion that aquaponics is not a useful adaptation to maintain peri-urban agriculture in Kumasi.

4.5 Reflections on the method and limitations

As with any work, the method that was used comes with limitations. In this part, some of these limitations are addressed, as well as the implications on the validity of the results.

4.5.1 Limitations and uncertainties of the model

As with any model, there is always a chance that there remain uncertainties in the input data. In this model, the input consists of the TAHMO weather data, soil and crop data and farmer management. The latter is a result of the survey and thus addressed in the next section.

The main concern about uncertainty in the weather data comes in the form of missing days. As there is missing data in the TAHMO dataset, any missing days were interpolated linearly. It is possible that due to this interpolation, rainfall and temperature were over- or underestimated on specific days. However, there were little incidents with missing data and as such, it is unlikely that this has a high effect.

Crop data provides uncertainty in that the factors that determine crop development are dependent on the location and the specific crop variety. In the AquaCrop manual it is therefore recommended to calibrate the crop data using empirical data from the location. As this was impossible for this research, data from Ghana, or similar climates were used to calibrate the AquaCrop crop data. Wherever this data was not available, the AquaCrop database was used uncalibrated.

An earlier chapter already mentioned the limitations of AquaCrop. To restate, AquaCrop is a program made to simulate organised agriculture. This is at odds with the chaotic nature of UPA in Kumasi. As such, the modelling with AquaCrop might miss nuances that are present in real life and thus there remains the risk that the real-life yields will be different than those modelled. As stated before however, when comparing the adaptations with one another, the output provides an equal comparison. If more accurate modelling is required for other applications, further research, informed by empirical data, could provide the necessary detail.

Still, to gauge the ability of the model to represent reality, it can be useful to compare its output to literature and to the output of the survey. The results are visible in Table 15, where the mean yields of the model, survey and literature are given.

Table 15. Model output comparison with survey and literature.

Crop type	**Yield (kg/m²)**			**Source**
	Model	Survey	Literature	
Whole grains (Maize)	1.32	2.97(1.58)[8]	1.23	(Akolgo et al., 2020)
Tubers and starchy vegetables (Cassava)	2.16	0.34	2.1	(Acheampong et al., 2022)
Leafy vegetables (Cabbage)	0.58	0.63	0.37	(Amoah et al., 2017)
Fruiting vegetables (Tomato)	0.57	0.32	0.75	(Lamptey & Koomson, 2021)
Legumes (Dry Bean)	0.38	-	-	

From the results in Table 15, it seems that there are differences between the modelled yields, surveyed yields and the yields as found in literature. Although the model and the literature match well for cereals and tubers, there is a large difference with the survey. This is explained by the nature of the survey questions. Farmers were asked to quantify the size of their land and their average yield. For some farmers, this led to either extremely high yields, or extremely low ones. One farmer stated that they make 600 tons of cereal on 2 acres of land, leading to an average yield of 74 kg/m². When this farmer is taken out of the calculation, the mean yield is much closer to the modelled and surveyed value.

[8] Value is 1.58 with the large outlier removed.

For the tubers category, the difference is not as easily explained. One cause can be due to the way crop categories are included in the questions. Whereas the model uses one example crop, in this category cassava, the crop category also includes other tubers and starchy vegetables, such as plantain and yam. It might be that the yields of these other crops reduce the mean yield of this category in the survey results. Otherwise, it may again be a consequence of the way the survey questions were asked.

Finally, the differences in the yields between the two vegetable categories are small. From literature, mean yields have a high variance, with some reporting yields lower than the modelled yields and others reporting higher yields. As such, the modelled yields are within the limits set by literature and the model should be a good representation of real life yields.

4.5.2 Limitations and uncertainties of the survey

A major limitation in the survey is the freedom with which the respondents can answer the questions. Without a focus group discussion or interview, it is impossible to gauge the respondent’s feelings towards the questions or their interpretation of them. As such, it is possible that a respondent understands a question differently and accordingly answers in a way that was not intended. Wherever possible, respondents were asked to explain their choices. In addition, the survey team helped fill in the survey to the best of their ability. In the interview with the representatives from KAC, the survey team stated that farmers left with a better understanding of the concepts talked about in the survey and that many farmers were grateful for the interaction. They also stated that they took their time to explain the survey. Based on this, it is unlikely that there were any misunderstandings with the questions. Moreover, during inspection of the data, there were little indicators that any answers were answered wrong. The fact that many survey answers support findings from literature also backs up this claim.

Another limitation of this study is in the survey locations. Although care was taken to select a diverse set of neighbourhoods with different characteristics, in a city the size of Kumasi there remains a risk that these locations are not representative of others. While it is likely that the results are representative for the city, the conclusions should only be valid for the actual neighbourhoods that were modelled and surveyed, and any policy informed by this work should keep this into account.

All in all, there exist some elements that undermine the validity of the results, but they have been addressed in the best way possible. As such, the conclusions and recommendations of this study are still valid.

4.6 Wastewater reuse in urban agriculture – potential for the Kumasi case.

Having established the potential future water scarcity in the city and the problems that cities have with concentrating waste, one can imagine that a solution to both these problems is very valuable. Reuse of wastewater is receiving attention as a way to valorise waste streams all over the world, in countries like Brazil, South-Africa and India (Rodriguez et al., 2020). Already in Kumasi, peri-urban farmers (unknowingly) use wastewater for irrigation of their crops, although this arguably does not happen in a safe manner. This means that there is tremendous opportunity to incorporate more organised and safe methods of wastewater reuse in the adaptations.

This chapter includes the state-of-the-art of wastewater reuse in Kumasi and around the world. It is to be used as a basis for any recommendations for future research.

4.6.1 Wastewater reuse: The basics.

As a resource, wastewater is incredibly valuable because it contains multiple types of useful matter, like water, nutrients and energy. Because of this, (treated) wastewater and its by-products are used globally in agriculture. In 2006, the WHO released a set of guidelines for the safe reuse of wastewater and excreta in agriculture (World Health Organization, 2006). The guidelines detail some of the allowed concentrations of chemicals and necessary treatment options before reuse can be safe.

This treatment aspect is very important for the safe reuse of wastewater. Globally, 80% of wastewater is released back into the environment without any treatment (Rodriguez et al., 2020). While not all wastewater is necessarily unsafe for reuse, consumers are especially put at risk with crops that are consumed raw. Because of this, it is almost always worth it to invest in some type of treatment.

Treated water is not the only resource that we get from wastewater. Some treatment processes generate a by-product called sewage sludge. This sludge can be processed into either biogas, which is used for energy generation, or biosolids. Biosolids contain many nutrients that are useful for crop development and are therefore a very potent fertiliser. Biosolids are not the only source of nutrients. Earlier in the treatment process of wastewater, phosphorus can be recovered and also put to use as a fertiliser (Rodriguez et al., 2020).

Now that it is clear what resources wastewater contains and what guidelines exist globally for the safe reuse, it is useful to look at how wastewater is used specifically in the Kumasi context.

4.6.2 Wastewater reuse in Kumasi.

The sanitation sector of Kumasi is paradoxically at the same time well and poorly developed. The central parts of the city have dense network of water pipelines that are serviced by the Ghana Water Company Limited (GWCL). Over the years, the demand for water has increased to such a degree however that the production cannot keep up. In 2015, production was only high enough to cover 73% of the demand. Moreover, the dense network of connections thins out very rapidly going into the suburbs; water access here is less developed (Maoulidi, 2010).

Throughout the city, public facilities are the main type of sanitation services. While there are a few small sewer networks, most facilities are connected either to septic tanks or to specialised systems like aqua-privies. In poorer neighbourhoods, bucket or pit latrines are still very common. All in all, Maoulidi (2010) estimated that 43% of Kumasi residents had access to improved sanitation facilities. It is a logical conclusion that wastewater ends up in the surface water in Kumasi.

Vegetable farmers in Kumasi often use the water from the many streams in the city to irrigate their crops. In research by Arimiyaw et al. (2020) farmers stated that even if piped water would be readily available, they would not be able to afford to use it for irrigation purposes. On top of the fact that the stream water is free, they noted that the nutrients contained in it would help their crops grow. In the same research, farmers stated that they felt that the use of this water was risk free and that there would not be any health implications. To paraphrase a statement from a farmer: If the water would be contaminated, it would not produce healthy crops like this. However, (arguably older) research by Amoah et al. (2006) found that most of the vegetable samples that they collected were contaminated with faecal coliforms. Moreover, in their research into surface water quality, Takyi et al. (2022) found high levels of heavy metals in the Kumasi rivers. They also corroborate the contaminations with faecal coliforms from earlier results.

There seems to be a contradiction in the replies in the study by Arimiyaw et al. (2020). The farmers are aware of the nutrient content of the water that they use but are (wilfully) ignorant of some of the risks that come with using this irrigation water. This is of course not the complete picture. For many of these farmers, this water is the only affordable option and when their livelihoods depend on the sale of the crops, one can imagine that there is a necessity.

All in all, this shows that: (1) the untreated wastewater that is discharged on the surface water in Kumasi is used to irrigate vegetables. (2) the wastewater is contaminated to such a degree that it introduces a risk particularly in the vegetables that are consumed raw. From this, one can conclude that there is opportunity to improve the reuse of wastewater in Kumasi to make it safer, while maintaining the easy accessibility and nutrient content. To see what opportunities there are, it is important to look at what is done in other places and what is possible.

4.6.3 Wastewater reuse: State of the art.

Having established the situation in Kumasi, it is good to look at examples from other countries to see how wastewater can be reused efficiently and safely. This way, its role in providing cheap and nutrient rich water for agriculture can be maintained, while also ensuring the safety of those who consume the products.

In Brazil, researchers looked into which treatment methods were well suited to allow for reuse of wastewater with applications in hydroponics systems (Marangon et al., 2020). As hydroponics is one the adaptations, this research is very relevant to the Kumasi case.

From their research, Marangon et al. (2020) found that Upflow Anaerobic Sludge Blanket (UASB) Reactors and stabilisation ponds (SP) were best suited as biological treatment options, with the former having the advantage of higher yields of sludge and the production of biogas. Although the SP does not generate biogas and has lower yields of sludge, its effectiveness in developing countries with a warm climate is often praised together with their capacity to remove pathogens for little investment (Tilley et al., 2014). In contrast to the results from Brazil, the UASB is less suited for the context of peri-urban Kumasi because of the need for constant electrification, training and special materials. (Tilley et al., 2014).

After the biological treatment, post-treatment is conducted with constructed wetlands or maturation ponds. These two systems are again low-cost and low tech: very well suited for the Kumasi context. From here, the treated wastewater is safe to be used in either hydroponics, fish farming, or combined aquaponics systems. The by-products from the treatment process are then used as fish food or as fertiliser.

All in all, Marangon et al. (2020) found that this combination of systems has positive effects on livelihoods, food security and sanitation, while at the same time being sustainable. Before getting fully lost in the positive effects however, it is crucial to keep implementation in mind. A more inclusive study into the financial needs, technical knowledge and implementation in specific regions like Kumasi is recommended.

Another paper, by Miller-Robbie et al. (2017) researched reuse of nutrients and treated wastewater in urban agriculture in a food-energy-water-health (FEW-Health) nexus strategy for Hyderabad in India. This allows for an integrated approach in infrastructure design in a sustainable way. The authors specifically state that their research focuses on rapidly developing cities, with little existing treatment infrastructure and where irrigation with untreated wastewater is widely applied. Their conclusions are therefore very useful for the Kumasi context.

Another reason why the work from Miller-Robbie et al. (2017) is useful for the Kumasi context, is that they take greenhouse gas emissions into account. Their work specifically looks at trade-offs in greenhouse gas emissions, reductions due to urban agriculture and wastewater reuse and the health benefits associated with the treatment. Because the goal of this research is to look at adaptations that are resilient against climate change, their conclusions are important for the recommendations in this research.

In the end, they found that implementing wastewater treatment had a significant effect on reductions of greenhouse gas emissions and pollution levels of the discharged wastewater, when compared to untreated discharge. Another interesting conclusion is that in their set-up, the reuse of nutrients was less effective. However, they state that due to the limitations of their study, more research was necessary to capture the dynamics of multiple seasons. What we can derive from this study, is that the implementation of treatment in the wastewater reuse process in Kumasi will help to reduce GHG emissions and thus benefit the battle against climate change.

Another interesting development is the reuse of separated urine. Urine contains nitrogen, potassium and phosphorus, three crucial nutrients for crops and is safe to use after storage for 1-6 months, depending on the consumer (Tilley et al., 2014).

Chrispim et al. (2017) researched the applications of urine on lettuce and maize on the campus of the University of São Paolo. By installing special urinals, separated urine was collected that was stored and later used for irrigation of the crops.

The researchers found that application of urine was associated with larger plants and a higher plant density. Soil metrics were also improved when compared to the control group. The authors conclude that reuse of urine as fertiliser benefits both the crops and the access to sanitation in places where this may be lacking.

In Kumasi, campus lands are used for irrigated production of vegetables. A set-up like the one from Chrispim et al. (2017) can therefore be a strong solution.

Not everything is positive however. Experts have expressed concerns about reduced soil quality due to excessive wastewater reuse, with soil salinity being the main one. In a meta-analysis of 21 papers, Gao et al. (2021) researched the changes in soil salinity associated with repeated irrigation with treated wastewater. They concluded that irrigation with treated wastewater is associated with significant accumulations of soil salinity and concurrently, an average reduction in yield of approximately 7%. This could be a problem if wastewater reuse is to become a main source of irrigation water in Kumasi.

The findings of Gao et al. (2021) do allow for some nuance however. They also found that in clayey soils, the effects were less pronounced and yields could increase. This is exactly the type of soil in the Western part of Kumasi and as such, wastewater irrigation can still be viable there. On top of this, the degree of treatment also mattered. While primary and tertiary treated wastewater increased salinity and decreased yields, this effect was reversed for secondary treated wastewater. From this, it is clear that the treatment method has a pronounced effect and by taking this into account, the risks associated with wastewater reuse can be reduced.

All in all, these examples show the possibilities for the reuse of treated wastewater, or related products in agriculture. This way, the farmers can continue using this cheap source of water and continue to benefit from the nutrients, while ensuring the safety of the consumers.

4.6.4 Conclusions and recommendations for wastewater reuse

This research established the importance of the waste/surface water for the irrigation of crops. At the same time, it has been shown that the contamination of the wastewater presents a risk for the consumers of the crops.

The examples from other countries show potential methods that allow for the continued reuse of wastewater in urban agriculture in a safe manner. Firstly, by applying some low-tech treatment options, water is safe enough for reuse without the need for things like constant electrification. It is crucial to keep in mind that different degrees of treatment can affect the yields and the soil salinity of the fields. At the same time, the harvested sludge is a potent fertiliser, providing farmers with additional necessary nutrients.

Another option comes in the form of urine reuse, the research from São Paolo shows that the separated urine is beneficial for crops and the potential to apply this in the Kumasi case. Another option is the installation of urine separating toilets in public facilities in neighbourhoods, which allows for reuse outside of campus lands.

Based on this, there are several recommendations for future research into this topic. Firstly, to identify potential pilot sites for treatment options following the research from Chrispim et al. (2017). This can be combined with investigations into pilots for aquaponics systems. Due to the salinity problems associated with sandy and silty soils, it is recommended to trial this in places with a more clayey soil, in the Western fringe of Kumasi.

A second recommendation is to investigate the urine reuse scheme, with the likely best location being one of the campuses. A small sanitation facility can be enough for a pilot, with the potential for upscaling.

Finally, it is recommended to investigate acceptance issues in wastewater irrigation. While it may be a potent solution in a technical sense, people may not want to purchase and eat crops that are irrigated using wastewater. Therefore, a household survey is necessary to investigate these barriers.

5. Conclusion

Throughout sub-Saharan Africa, urban areas are growing immensely in terms of population, but also in terms of surface area. The growth of the city threatens agricultural activities on the urban fringe, which is called peri-urban area. In cities like Kumasi in Ghana, urban and peri-urban agriculture (UPA) is an important source of food for the people of the city: peak season production accounts for 40% of the food inflow on Kumasi markets. Because of this, there is a need for interventions that make sure that urban and peri-urban agriculture can fulfil its role for the food security of the city, while dealing with the threats of urban sprawl and climate change.

The goal of this work was to answer the main research question:

What adaptations are best suited to sustain peri-urban agriculture in Kumasi (against the threat of climate change and urban sprawl)?

Urban and peri-urban agriculture in Kumasi comes in many forms. On the large green campus lands in the city centre, farmers grow vegetables. They make use of the streams on these lands for irrigation, which allows them to have multiple harvests per year. The crops are used to feed the farmers themselves and sometimes university staff and students.

To the edges of the city, peri-urban agriculture develops more chaotically; farmers use whatever green space is available to grow whichever crops they need to feed themselves. This can be in the form of backyards, or in small fields. Their crop variety is also large. Farmers grow cereals, tubers, vegetables and some even hold livestock. They use the crops to guarantee a varied diet for themselves and they sell remains for extra income.

These farmers on the fringe of the city are especially threatened by the urban sprawl of Kumasi. Due to complex land tenure systems, they are easily displaced to allow for profitable residential development. At the same time, climate change threatens the rainfed cropping with extended droughts, or extremely wet periods.

Several adaptations were identified that could make sure that urban and peri-urban agriculture are maintained despite these threats. First among these is backyard gardening. In new low-density development, green space for backyards allows residents to grow some vegetables, allowing for a varied diet.

The second option is sack gardening, where the use of produce sacks allows for verticality. This method is especially suited for place where space is even more limited. Like backyard gardening, vegetables are the main sets of crops that work best in this method.

The third option involves the growing of crops along roadsides or on wetlands, commonly known as marginal lands. Because these lands are less desirable for other development, they are prime lands to maintain agriculture on.

There are also more high-tech solutions, the first of which is greenhouse technology. Because greenhouses give a high yield with a low footprint, they are especially suited for places where space is limited. They do require large investment and maintenance however, which makes them less suited for applications in sub-Saharan Africa.

This is also the case for the last solution, which is aquaponics technology. The combination of the high efficiency growing of vegetables with the raising of fish means that this adaptation contributes massively to the food security of those who use it. It does mean that there are big investments and maintenance necessary for this to be maintained, which makes it difficult to apply in the Kumasi context.

To be able to efficiently assess the adaptations, there are several indicators that show how well suited they are to maintain UPA in Kumasi. They are related to either the performance of the adaptations in relation to the threats, or the implementation of these. Naturally, these include food security (how large are the yields), water use (how much irrigation water is needed) and land use (how much space is needed to feed the population). Among the indicators related to implementation are material cost, financial cost, knowledge requirement and policy. Finally, the opinion of the residents on the adaptations is also important. This is tested via a survey of farmers and vendors.

The survey of farmers and vendors showed that the respondents feel the same way about threats as experts do. The majority of the surveyed farmers and vendors feel that urbanisation and climate change threaten agriculture in and around Kumasi and believe that something needs to change for agriculture to be maintained.
The most promising adaptation according to the respondents and the modelling is backyard gardening. Not only does this adaptation provide high yields for vegetables and legumes, but it is also popular among the farmers and vendors.

Sack gardening is also popular as an adaptation among the surveyed population. Like backyard gardening, the modelling of this adaptation gave high yields on a low footprint for the emphasised crops, making sack gardening a well-suited adaptation.

Growing crops on marginal lands is less popular. Not only are some respondents apprehensive about is, but modelling of yield also shows lower yields than some of the other adaptations for the emphasised crops like vegetables. Marginal lands are better suited for tubers and cereals than the previous adaptations however, showing that they can be complementary.

Finally, the two high-tech adaptations are not very popular among the surveyed populations. Fears for high cost and general ignorance about the workings of the adaptations lead to apprehension about these adaptations. Moreover, the need for materials, financial investment and significant training mean that the foundations are not yet there for these adaptations. However, this does mean that no steps should be taken to lay these foundations down, as they have the potential to provide even better yields than the previous low-tech adaptations.

Overall, literature research, modelling and the survey show that the adaptations that are best suited are likely backyard gardening and sack gardening. The latter especially where space is even too limited for backyard gardening to efficiently work. Because these adaptations work best with vegetables and legumes. It is best to grow these crops locally and to source the other crops, like tubers and cereals from outside of the city. This is also supported by the findings from the survey about spoilage, where most of the vendors state that they have problems with crops perishing.

Currently, many urban and peri-urban farmers grow cereals and tubers as subsistence crops. To make the transition towards sourcing these from outside easier, local marginal lands should be used to grow cereals and tubers, while the other lands shift towards vegetables grown in backyards and sacks. This way, a varied diet is maintained, which achieves the main goal: maintaining the important role of UPA in the food security of Kumasi, while also allowing for the urban sprawl associated with the growth of the city.

Specific recommendations for policy and further research based on these conclusions follow in the next section.

6. Recommendations

Based on the conclusions, there are several recommendations for both policy and for further research. This way, the results from this research can be tested in a real Kumasi context and be actually put into practice. This section goes over the recommendations, starting with those for further research, followed by the recommendations for policy.

6.1 Recommendations for further research

Due to limitations of the study, not every angle can be followed as deeply as the others. More focused, follow-up investigation on specific elements of this work can provide better, more accurate data that will hopefully corroborate the conclusions from this research. Several follow-up opportunities were already identified and are outlined below.

The first recommendation for future research is related to the study into safe reuse of wastewater. Due to the current reuse of wastewater in agriculture in Kumasi, there is an interest in methods that allow for this practice to continue in a manner that is both safe and efficient. In chapter 4.6 several examples from other countries showed the potential for schemes like these in the Kumasi context. Accordingly, it is recommended to research both the potential for wastewater treatment options and urine reuse in the Kumasi context. The sources collected in chapter 4.6 can provide a starting point for this work.

The second recommendation follows from the survey results. Many of the surveyed urban and peri-urban farmers state that they grow cereals to feed themselves. However, the conclusions from the yield modelling showed that growing cereals in the city is suboptimal and that peri-urban farmers could better grow vegetables for a fully complementary growing scheme that would benefit the variety element of food security. However, if this means that the quantity element of food security is threatened by this, the conclusion is obviously invalid. Because it was impossible for this research to go into depth into the short- and long-term implications of this shift, it is recommended to do further research into this topic by tracking the food security of these farmers quantitively. At the same time, this research could investigate any other shocks that are associated with the shifts in growing schemes based on this research.

Finally, there is potential for future research to complement this work with empirical data from farmers from Kumasi. As outlined in section 4.5 the AquaCrop modelling of this work used general crop parameters, informed by literature as well as possible. Moreover, the management and irrigation practices were based on a constructed profile of an average farmer. It is possible to generate a crop model in AquaCrop based on actual Kumasi parameters and by working in tandem with field trials, it is possible to generate a set of optimised practices for the specific crops and adaptations. With this, the contribution of peri-urban agriculture to Kumasi food security can be even better.

6.2 Recommendations for policy

This work is not just a pilot study for future research and the conclusions already have implications for policy in Kumasi currently. In this section, the recommendations for actual policy in Kumasi are outlined. These recommendations are for investments, spatial planning and education in particular.

The first and most important recommendation is related to the adaptations and the production of vegetables and legumes in the researched neighbourhoods. The modelling and survey results in Chapter 4.2 indicated that between 14-22% of Kwadaso space and between 5-9% of Feyiase space was necessary for self-sufficiency for vegetables. The recommendation of this research is a target of at least a majority of vegetables in the neighbourhood to be grown inside the neighbourhood itself. In Feyiase, this is possible with only a small fraction of the neighbourhood land. In Kwadaso, there is more competition for land and therefore, significant spatial planning may be necessary, with additional control to discourage informal development. Still, with this target, issues with spoilage on markets can be reduced, climate change effects on the urban heat island are mitigated by the green space and people guarantee a diverse diet.

In terms of education and investment, it is recommended to work with NGO’s and education institutions in setting up trials and pilots for the high-tech solutions. Because greenhouses and aquaponics are very efficient, but currently unfeasible due to lack of knowledge, these trials can provide the foundation from which a larger system can be built. It is even possible to combine these pilots with the research into wastewater reuse as mentioned above for even easier implementation. Overall, with sufficient investment and training, these adaptations can guarantee a diverse supply of food with little need for space and water.

These recommendations should provide enough of a basis to make sure that peri-urban agriculture in Kumasi can be maintained under the threat of climate change and urban sprawl. Moreover, the blueprint can be applied in other cities in sub-Saharan Africa. The AquaCrop model informed by a survey can be done in countries where a local network is available.

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Appendix

This part includes a select set of supplementary data to the research. This data, as well as the full set of data for the model can be downloaded from a drive by following the link below. In part A, the input files for AquaCrop are explained. These actual files can be downloaded from the drive. Part B includes the full set of survey questions, with the aggregated answers included in Part C. Finally, Part D shows the summarised AquaCrop model results as well as the full spatial model results. The full AquaCrop model results can also be downloaded from the drive.

https://drive.google.com/drive/folders/18h4LaCqVLsugwOwRm07oIqfE6OSxpLbs?usp=drive_link

Appendix A. AquaCrop input

This part outlines the types of files that were used in the AquaCrop model, as well as the aggregated climate data. The full dataset of input files can be downloaded via the drive link. Due to restrictions in the TAHMO data, this data cannot be shared. The full dataset is available via the TAHMO portal at https://tahmo.org/ after requesting access via their forms.

A1. Climate files and aggregated climate data.

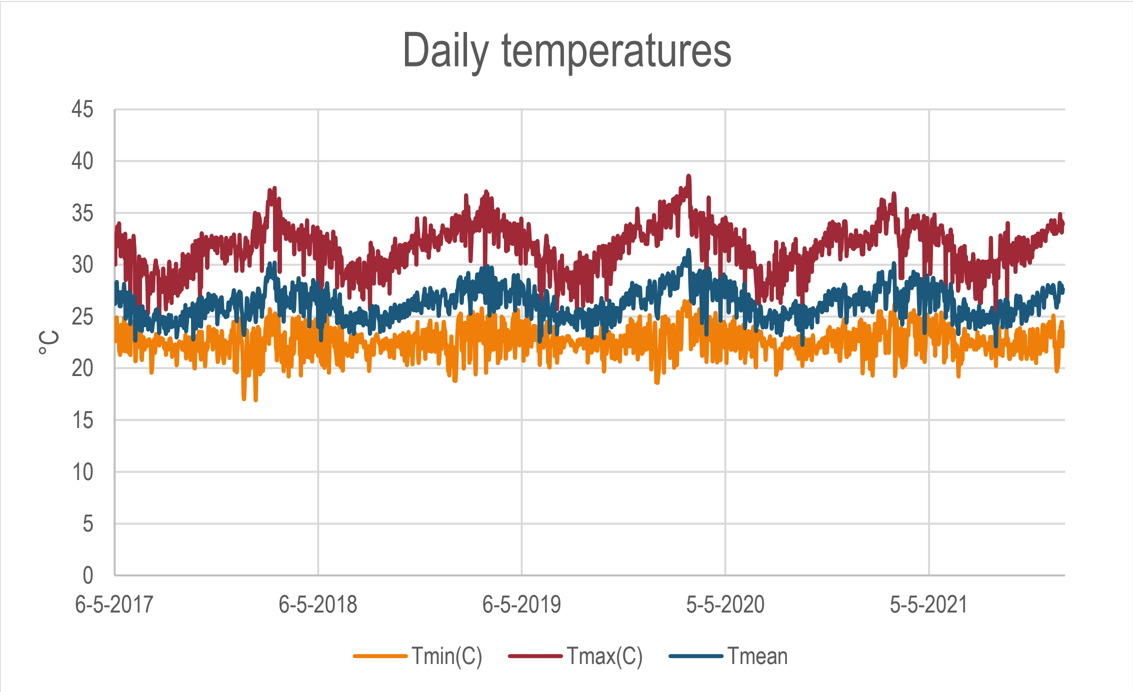
Climate File (*.CLI)		
Line	Description	Format
1	First line is a description of the file content	String of characters
2	Version number of AquaCrop	Real (1 digit)
3	The name of the air temperature file (*.TMP)	String of characters
4	The name of the ETo file (*.ETo)	String of characters
5	The name of the rainfall file (*.PLU)	String of characters
6	The name of the CO2 file (*.CO2)	String of characters

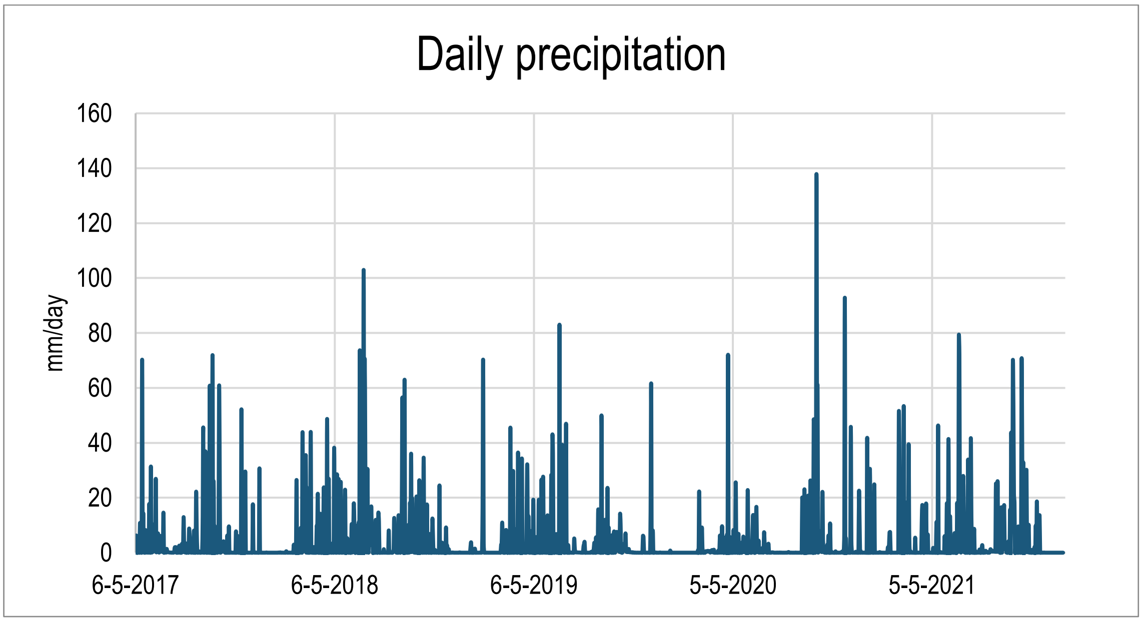
Temperature File (*.TMP)		
Line	Description	Format
1	First line is a description of the file content	String of characters
2	A number (1 to 3) used as a code to specify the time aggregation of the weather data: 1 : Daily weather data 2 : 10-day weather data 3 : monthly weather data	Integer
3	First day of record (1, 11 or 21 for 10-day or 1 for months)	Integer
4	First month of record	Integer
5	First year of record (1901 if the characteristics are not linked to a specific year)	Integer
6	Empty line	-
7	Title of variables ('Tmin (°C) TMax (°C)')	String of characters
8	Dotted line ('====================================')	String of characters
9	For each day 10-day or month of the record: - (average) minimum air temperature (°C) - (average) maximum air temperature (°C)	 Real (1 digit) Real (1 digit)

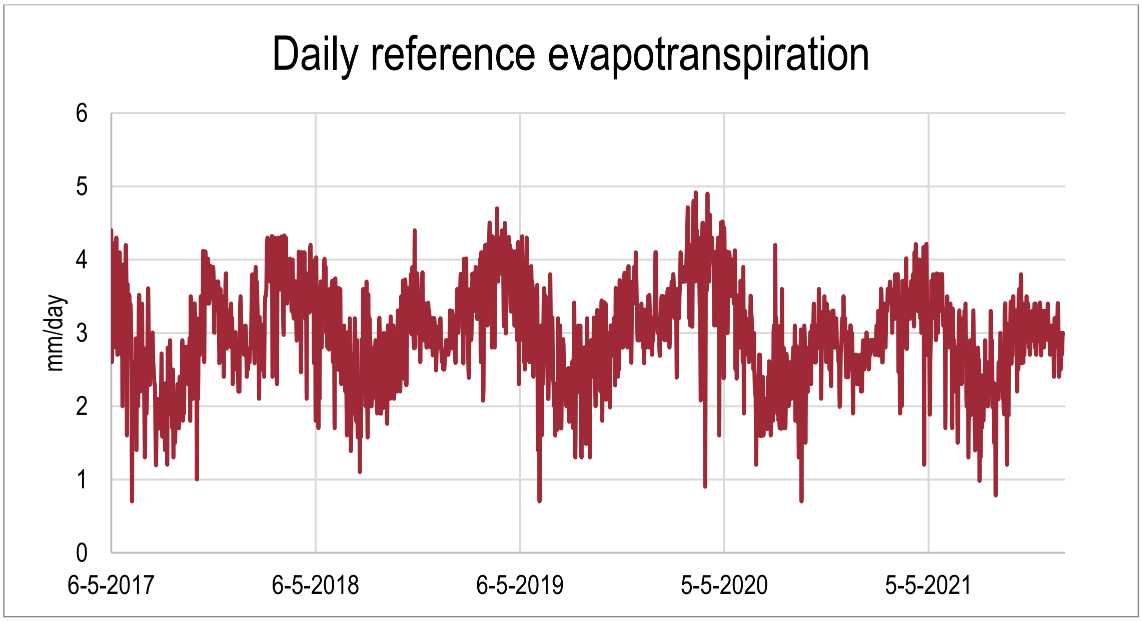
ETo File (*.ETo)		
Line	Description	Format
1	First line is a description of the file content	String of characters
2	A number (1 to 3) used as a code to specify the time aggregation of the weather data: 1 : Daily weather data 2 : 10-day weather data 3 : monthly weather data	Integer
3	First day of record (1, 11 or 21 for 10-day or 1 for months)	Integer
4	First month of record	Integer
5	First year of record (1901 if the characteristics are not linked to a specific year)	Integer
6	Empty line	-
7	Title of variables ('Average ETo (mm/day)')	String of characters
8	Dotted line ('====================================')	String of characters
9	Average ETo (mm/day) for each day, 10-day or month of the record	Real (1 digit)

Rainfall file (*.PLU)		
Line	Description	Format
1	First line is a description of the file content	String of characters
2	A number (1 to 3) used as a code to specify the time aggregation of the weather data: 1 : Daily weather data 2 : 10-day weather data 3 : monthly weather data	Integer
3	First day of record (1, 11 or 21 for 10-day or 1 for months)	Integer
4	First month of record	Integer
5	First year of record (1901 if the characteristics are not linked to a specific year)	Integer
6	Empty line	-
7	Title of variables (‘Total Rain (mm)’)	String of characters
8	Dotted line (‘=====================================’)	String of characters
9	Total Rain (mm) for each day, 10-day or month of the record	Real (1 digit)

CO_2 File (*.CO2)		
Line	Description	Format
1	First line is a description of the file content	String of characters
2	Title of variables (‘Year CO2 (ppm by volume)’)	String of characters
3	Dotted line (‘=====================================’)	String of characters
4 and next	For each record specify: - year - corresponding [CO2] in ppm by volume	Integer Real (2 digits)




Daily precipitation
mm/day
160
140
120
100
80
60
40
20
0
6-5-2017
6-5-2018
6-5-2019
5-5-2020
5-5-2021


Daily reference evapotranspiration
mm/day
6
5
4
3
2
1
0
6-5-2017
6-5-2018
6-5-2019
5-5-2020
5-5-2021

A2. Crop Files

Crop file (*.CRO)		
Line	**Value**	**Description**
1	-	File name
2	xx	AquaCrop Version
3	xx	File protection
4	xx	Type of crop
5	xx	Transplanted/Sown?
6	xx	Determination of crop cycle : by calendar days/GDD
7	xx	Soil water depletion factors (p) are adjusted by ETo
8	xx	Base temperature (°C) below which crop development does not progress
9	xx	Upper temperature (°C) above which crop development no longer increases with an increase in temperature
10	xx	Total length of crop cycle in growing degree--days
11	xx	Soil water depletion factor for canopy expansion (p-exp) - Upper threshold
12	xx	Soil water depletion factor for canopy expansion (p-exp) - Lower threshold
13	xx	Shape factor for water stress coefficient for canopy expansion (0.0 = straight line)
14	xx	Soil water depletion fraction for stomatal control (p - sto) - Upper threshold
15	xx	Shape factor for water stress coefficient for stomatal control (0.0 = straight line)
16	xx	Soil water depletion factor for canopy senescence (p - sen) - Upper threshold
17	xx	Shape factor for water stress coefficient for canopy senescence (0.0 = straight line)
18	xx	Sum(ETo) during stress period to be exceeded before senescence is triggered
19	xx	Soil water depletion factor for pollination (p - pol) - Upper threshold
20	xx	Vol% for Anaerobiotic point (* (SAT - [vol%]) at which deficient aeration occurs *)
21	xx	Considered soil fertility stress for calibration of stress response (%)
22	xx	Response of canopy expansion is not considered
23	xx	Response of maximum canopy cover is not considered
24	xx	Response of crop Water Productivity is not considered
25	xx	Response of decline of canopy cover is not considered
26	xx	dummy - Parameter no Longer required
27	xx	Minimum air temperature below which pollination starts to fail (cold stress) (°C)
28	xx	Maximum air temperature above which pollination starts to fail (heat stress) (°C)
29	xx	Minimum growing degrees required for full crop transpiration (°C - day)
30	xx	Electrical Conductivity of soil saturation extract at which crop starts to be affected by soil salinity (dS/m)
31	xx	Electrical Conductivity of soil saturation extract at which crop can no longer grow (dS/m)
32	xx	Dummy - no longer applicable
33	xx	Calibrated distortion (%) of CC due to salinity stress (Range: 0 (none) to +100 (very strong))
34	xx	Calibrated response (%) of stomata stress to ECsw (Range: 0 (none) to +200 (extreme))
35	xx	Crop coefficient when canopy is complete but prior to senescence (KcTr,x)
36	xx	Decline of crop coefficient (%/day) as a result of ageing, nitrogen deficiency, etc.
37	xx	Minimum effective rooting depth (m)
38	xx	Maximum effective rooting depth (m)
39	xx	Shape factor describing root zone expansion
40	xx	Maximum root water extraction (m3water/m3soil.day) in top quarter of root zone
41	xx	Maximum root water extraction (m3water/m3soil.day) in bottom quarter of root zone
42	xx	Effect of canopy cover in reducing soil evaporation in late season stage
43	xx	Soil surface covered by an individual seedling at 90 % emergence (cm2)
44	xx	Canopy size of individual plant (re-growth) at 1st day (cm2)
45	xx	Number of plants per hectare
46	xx	Canopy growth coefficient (CGC): Increase in canopy cover (fraction soil cover per day)
47	xx	Maximum decrease of Canopy Growth Coefficient in and between seasons - Not Applicable
48	xx	Number of seasons at which maximum decrease of Canopy Growth Coefficient is reached - Not Applicable
49	xx	Shape factor for decrease Canopy Growth Coefficient - Not Applicable
50	xx	Maximum canopy cover (CCx) in fraction soil cover
51	xx	Canopy decline coefficient (CDC): Decrease in canopy cover (in fraction per day)
52	xx	Calendar Days: from transplanting to recovered transplant
53	xx	Calendar Days: from transplanting to maximum rooting depth
54	xx	Calendar Days: from transplanting to start senescence
55	xx	Calendar Days: from transplanting to maturity
56	xx	Calendar Days: from transplanting to flowering
57	xx	Length of the flowering stage (days)
58	xx	Crop determinancy unlinked with flowering

59	xx	Building up of Harvest Index (% of growing cycle)
60	xx	Building up of Harvest Index starting at sowing/transplanting (days)
61	xx	Water Productivity normalized for ETo and CO2 (WP*) (gram/m2)
62	xx	Water Productivity normalized for ETo and CO2 during yield formation (as % WP*)
63	xx	Crop performance under elevated atmospheric CO2 concentration (%)
64	xx	Reference Harvest Index (HIo) (%)
65	xx	Possible increase (%) of HI due to water stress before flowering
66	xx	Impact on HI of restricted vegetative growth during yield formation
67	xx	Effect on HI of stomatal closure during yield formation
68	xx	Allowable maximum increase (%) of specified HI
69	xx	GDDays: from transplanting to recovered transplant
70	xx	GDDays: from transplanting to maximum rooting depth
71	xx	GDDays: from transplanting to start senescence
72	xx	GDDays: from transplanting to maturity
73	xx	GDDays: from transplanting to flowering
74	xx	Length of the flowering stage (growing degree days)
75	xx	CGC for GGDays: Increase in canopy cover (in fraction soil cover per growing-degree day)
76	xx	CDC for GGDays: Decrease in canopy cover (in fraction per growing-degree day)
77	xx	GDDays: building-up of Harvest Index during yield formation

A3. Irrigation and Field Management files

Irrigation file (*.IRR)		
Line	**Description**	**Format**
1	First line is a description of the file content 2	String of characters
2	Version number of AquaCrop	Real (1 digit)
3	A number (1 to 5) used as a code to specify the irrigation method: 1 : Sprinkler irrigation 2 : Surface irrigation: Basin 3 : Surface irrigation: Border 4 : Surface irrigation: Furrow 5 : Drip irrigation	Integer
4	Percentage of soil surface wetted by irrigation. This percentage is generally closely linked with the irrigation method. Default = 100	Integer
5	A number (1 to 3) used as a code to specify the irrigation mode: 1 : Specification of irrigation events; 2 : Generation of an irrigation schedule; 3 : Determination of net irrigation water requirement;	Integer
	Code = 1 (in line 5): Specification of irrigation events	
6	Empty line	-
7	Title (‘Day Depth (mm) ECw (dS/m)’)	String of characters
8	Dotted line (‘====================================’)	String of characters
9	For the 1st irrigation event: • The number of days after sowing/planting • Integer • The net irrigation application depth (mm) • The Electrical Conductivity (dS/m) of the irrigation • water The net irrigation application depth refers to the net irrigation amount. Extra water applied to the field to account for conveyance losses or the uneven distribution of irrigation water on the field should not be added.	Integer Real (1 digit)
10	Repeat for each successive irrigation event	
	Code = 2 (in line 5): Generation of an irrigation schedule	
6	A number (1 to 3) used as a code to specify the time criterion: 1 : Fixed interval; 2 : Allowable depletion (mm water); 3 : Allowable depletion (% of RAW); 4: Keep a minimum level of surface water layer between soil bunds	Integer
7	A number (1 to 2) used as a code to specify the depth criterion: 1 : Back to Field Capacity; 2 : Fixed net application depth.	Integer
8	Empty line	-
9	Title (‘From day … ECw (dS/m)’)	String of characters
10	Dotted line (‘====================================’)	String of characters

	For the 1st rule:
	• The number of days after sowing/planting from which the rule is valid (has to be 1 for the 1st rule);
	  ○ Value linked with the time criterion:
	  ○ the fixed interval (days) between irrigations (for example 10 days);
	  ○ the amount of water (mm) that can be depleted from the root zone (the reference is soil water content at field capacity) before an irrigation has to be applied (for example 30 mm); or the percentage of RAW that can be depleted
	  ○ before irrigation water has to be applied (for example 100 %);
	  ○ the minimum depth (mm) of surface water that should be maintained (between the soil bunds).
	• Value linked with the depth criterion:
		Integer
		Integer
		Integer

	o Extra water on top of the amount of irrigation water required to bring the root zone back to Field Capacity. The specified value can be zero (exact back to FC), positive (an over-irrigation) or negative (an under-irrigation); or o The fixed net irrigation application depth. • The Electrical Conductivity (dS/m) of the irrigation water. The fixed net irrigation application depth refers to the net irrigation amount. Extra water applied to the field to account for conveyance losses or the uneven distribution of irrigation water on the field should not be added. The values specified remain valid till the date for which a new rule (in the next line) is specified or to the end of the cropping period when no values at later dates are specified.	Real (1 digit)
12…	If applicable specifies values for 2nd , 3rd , 4th , .. rule	Real (1 digit)
	Code = 3 (in line 5): Determination of net irrigation requirement.	
6	The depletion (% RAW) below which the soil water content in the root zone may not drop (0 % RAW corresponds to Field Capacity). The total amount of irrigation water required to keep the water content in the soil profile above the specified threshold is the net irrigation water requirement for the period. The net requirement does not consider extra water that has to be applied to the field to account for conveyance losses or the uneven distribution of irrigation water on the field.	Integer

Field Management File (*.MAN)

Line	Description	Format
1	First line is a description of the file content.	String of characters
2	Version number of AquaCrop	Real (1 digit)
3	Percentage (%) of ground surface covered by mulches in the growing period	Integer
4	Effect (%) of mulches on the reduction of soil evaporation, which depends on the type of mulches	Integer
5	Degree of soil fertility stress (%) The effect of the selected soil fertility stress on crop production depends on calibration since the biomass – stress relationship (calibrated in the Crop characteristic menu), determines the corresponding biomass production that can be expected under well watered conditions for the selected soil fertility stress. The expected biomass production is expressed as a percentage of the maximum biomass production for unlimited soil fertility. In the absence of a calibration, the adjustment of biomass production to the specified soil fertility stress will not be simulated.	Integer
6	Height (m) of soil bunds	Real (2 digits)
7	A number (0 to 1) used as a code to specify if surface runoff is affected/prevented by field surface practices: 0 : surface runoff is not affected 1 : surface runoff is affected or completely prevented (Default = 0)	Integer
8	Percent increase/decrease of soil profile CN value (is zero (not applicable) when surface runoff is not affected or completely prevented by surface practices)	Integer
9	Relative cover of weeds (%)	Integer
10	Increase/decrease of relative cover of weeds in midseason (%)	Integer
11	shape factor of the CC expansion function in a weed infested field	Real (2 digits)

A4. Soil profile files.

Soil profile file (*. SOL)		
Line	**Description**	**Format**
1	First line is a description of the file content	String of characters
2	Version number of AquaCrop	Real (1 digit)
3	CN: the Curve Number (dimensionless)	Integer
4	REW: The Readily evaporable water from top layer (mm)	Integer
5	Number of soil horizons	Integer
6	Variable no longer applicable	-
7	Line with symbols for the soil physical characteristics	
8	Line with units for the soil physical characteristics	
9	Soil physical characteristics for soil horizon 1: • thickness of the soil horizon (m) • soil water content at saturation (vol%) • soil water content at Field Capacity (vol%) • soil water content at Permanent Wilting Point (vol%) • saturated hydraulic conductivity (mm/day) • penetrability (%) for root zone expansion rate • mass percentage (%) of the gravel fraction • parameter 'a' for estimation of capillary rise • parameter 'b' for estimation of capillary rise • description	 Real (2 digits) Real (1 digit) Real (1 digit) Real (1 digit) Real (1 digit) Integer Integer Real (6 digits) Real (6 digits) String of characters
10	Soil physical characteristics for soil horizon 2 (if present)	as for line 9
11	Soil physical characteristics for soil horizon 3 (if present)	as for line 9
12	Soil physical characteristics for soil horizon 4 (if present)	as for line 9
13	Soil physical characteristics for soil horizon 5 (if present)	as for line 9

Appendix B. Survey Questions

This section includes the full farmer and vendor survey question lists, in the same order as they were given to the respondents. Files with the questions are also available via the drive link.

B1. Farmer survey questions

Opening statement

I have read and understood the opening statement. I consent to participate in this study and to answer the questions in this questionnaire

- Yes
- No

I understand that for the duration of the research, my answers to the study will be processed and stored on the TU Delft servers and that they will only be accessible by the research team.

- Yes
- No

Introductory questions

What age group are you in

- 0-20 years old
- 20-30 years old
- 30-40 years old
- 40-50 years old
- 50+ years old
- Prefer not to tell

What is your gender?

- Female
- Male
- Other
- Prefer not to tell

Where do you live (Neighbourhood, suburb, village, etc.)

Is your farm in the same neighbourhood as where you live?

- Yes
- No

In case of no, in what neighbourhood is your farm?

How long have you been farming for?

- <5 years
- 5-10 years
- 10-20 years
- >20 years
- Don’t know

Production

What types agricultural products do you produce?

- Cereals (maize, rice, millet, sorghum, wheat, etc.)
- Tubers and other starches (cassava, yam, plantain, cocoyam etc.)
- Fruits (banana, pineapple, citrus etc.)
- Fruiting vegetables (tomato, eggplant, peppers, etc.)
- Leafy vegetables (lettuce, cabbage, chard, etc.)
- Animal products (milk, eggs, meat, fish, etc.)
- Other:

Can you give an estimate of how large your farming space is?

What methods do you use to grow crops?

- Rainfed cropping
- Irrigated agriculture
- Soil free farming (Aquaponics, hydroponics etc.)
- Greenhouses
- Other:

How often do you plant your crops per year?

- 1
- 2
- 3
- 4
- >4

In what months do you generally plant your crops?

Can you give an estimate of an average yield that you get?

Can you give an estimate of a high yield that you get?

What do you do with your crops?

- Feed myself and/or my family
- Sell for extra cash
- First feed myself and sell what's left
- Other:

Land types and security

How would you characterise the space where you practice agriculture?

- Marginal lands (roadsides, wetlands, along watercourses)
- Government owned land
- Personally owned/rented land: backyards
- Personally owned/rented land: fields
- Currently idle land
- Other:

How secure do you feel that this land remains available to farm on in the future?

- Very secure
- Somewhat Secure
- Somewhat insecure
- Very insecure
- Don't know

What is the main reason for feeling insecure?

- Land tenure – I do not own the land
- Climate change – Water may be scarce
- Profitability – I do not make enough money
- Urbanisation – The land may be used for other development
- Other:

Irrigation and drainage

What method do you use for irrigation?

- Watering cans
- Sprinkler
- Drip
- Surface irrigation (Furrow, basin or border)
- I do not irrigate my crops
- Other:

How do you know when irrigation is necessary?

- Experience/feeling
- Scheduling based on models
- Scheduling based in weather predictions
- Pre-set scheduling
- Other:

What water source do you use for irrigation?

- Surface water (river, lake, pond etc.)
- Harvested rainwater
- Groundwater
- Domestic water
- Wastewater
- Other:

How do you rate the average quality of irrigation water?

- Very poor
- Poor
- Good
- Very good
- Other:

Do you believe that irrigation water has an effect on fertility?

- Yes, a significant effect
- Yes, a small effect
- No
- Other:

Do you notice drainage problems on your field?

- Yes, water drains too fast.
- Yes, water drains not fast enough
- No, I have no drainage problems
- Other:

Does drainage capacity influence the choice of location to grow crops?

- Yes, I chose this location because the soils hold water well
- Yes, I chose this location because water drains quickly
- No, drainage capacity did not influence my choice of location
- No, I cannot afford to be critical of location
- Other:

How secure do you feel in the availability of water resources in the future?

- Very secure
- Somewhat Secure
- Somewhat insecure
- Very insecure
- Don’t know

Field management

Do you use mulches?

- Yes, organic mulches
- Yes, plastic mulches
- Yes, Other:
- No

How do you qualify the fertility your land relative to others you know?

- Very good
- Good
- Poor
- Very poor
- Other:
- Don’t know

What types of fertiliser do you use?

- Compost
- Animal waste
- Human waste
- Synthetic fertiliser
- I do not use fertiliser
- Other:

Do you use means to influence runoff on the fields?

- Yes, want to increase runoff
- Yes, I decrease runoff
- No, I do not influence runoff
- Other:

Are weeds a problem on your field?

- No, because I clear them regularly
- No, I do not have to clear weeds regularly
- Yes, because I have no time to clear weeds
- Yes, despite my efforts to remove them
- Yes, but I feel no need to remove them
- Other:

Adaptation

Do you feel that things need to change for agriculture to be maintained in and around Kumasi?

- Yes
- No
- Don’t know

Please rank these elements in order of importance in what needs to change for agriculture to be maintained in and around Kumasi.

	Not important	Somewhat important	Very important	Don't know
Government land use planning				
Agricultural practices				
Land ownership				
Better education				
Better participation and discussion				

Please rank these adaptations in order of most usefulness in maintaining agriculture against urban sprawl in Kumasi.

	Not useful	Somewhat useful	Very useful	Don't know
Backyard gardening				
Sack/container gardening				
Farming on marginal lands (roadsides, wetlands, etc.)				
Greenhouses				
Aquaponics				

Please rank the elements in order of what you find most important in adapting urban agriculture.

	Not important	Somewhat important	Very important	Don't know
Agricultural yield				
Variety of crops				
Water use				
Cost				
Knowledge requirement				
Material requirement				

Barriers

Would you be willing to change the type of agriculture you practice to one of the schemes above?

- Yes
- No

In case of no, could you explain why.

Would you be willing to switch to growing crops in greenhouses?

- Yes
- No

Could you explain why.

Would you be willing to switch to growing crops in sacks/containers?

- Yes
- No

Could you explain why.

Would you be willing to switch to growing crops in backyards?

- Yes
- No

Could you explain why.

Would you be willing to switch to growing crops on marginal lands?

- Yes
- No

Could you explain why.

Would you be willing to switch to growing crops and raising fish in aquaponics?

- Yes
- No

Could you explain why.

B2. Vendor survey questions

Opening statement

I have read and understood the opening statement. I consent to participate in this study and to answer the questions in this questionnaire.

- Yes
- No

I understand that for the duration of the research, my answers to the study will be processed and stored on the TU Delft servers and that they will only be accessible by the research team.

- Yes
- No

Introductory Questions

What age group are you in?

- 0-20 years old
- 20-30 years old
- 30-40 years old
- 40-50 years old
- 50+ years old
- Prefer not to tell

What is your gender?

- Female
- Male
- Other
- Prefer not to tell

Where do you live (Neighbourhood, suburb, village, etc.)

Is your shop in the same neighbourhood as where you live?

- Yes
- No

In case of no, in what neighbourhood is your shop?

How long have you been a vendor for?

- <5 years
- 5-10 years
- 10-20 years
- >20 years
- Don’t know

Sources of products

Do you grow the products that you sell yourself?

- Yes
- No

Please give an estimate of how many leafy vegetables you sell per week (kilos)

Where do your leafy vegetables (lettuce, cabbage, etc.) come from?

Please give an estimate of how many fruiting vegetables you sell per week (kilos)

Where do your fruiting vegetables (tomato, eggplant, etc.) come from?

Please give an estimate of how many tubers you sell per week (kilos)

Where do your tubers (cassava, plantain, etc.) come from?

Please give an estimate of how many cereals you sell per week (kilos)

Where do your cereals (maize, rice, etc.) come from?

Please give an estimate of how many legumes you sell per week (kilos)

Where do your legumes (beans, lentils, etc.) come from?

Please give an estimate of how many fruits you sell per week (kilos)

Where do your fruits (mango, pineapple, citrus etc.) come from?

Supply issues

Do you notice recent changes in supply from urban and peri-urban sources?

	Supply has increased	Supply is the same	Supply has decreased	Don't know
Last year				
Last two (2) years				
Last five (5) years				

Are you scared that supply might be changing (further) in the future?

- Yes, I am afraid that I cannot longer meet demand
- No, I am confident that I can meet the demands
- Other:

Do you feel that the supply suffers from spoilage?

- Yes, it is a large problem
- Yes, but it is a small problem
- No, it is not a problem

What do you feel is the largest cause of spoilage?

- It takes too much time to get food to the market
- Lack of cooling facilities
- Products are of insufficient quality
- Other:

Adaptations and barriers

What is the most important factor for you to trust the product?

- Source of the irrigation water
- Location of field
- Type of product
- Visual of the market
- Visual of the product
- Other:

Do you believe climate change is a threat to urban agriculture in Kumasi?

- Yes
- No

Do you believe urbanisation is a threat to urban agriculture in Kumasi?

- Yes
- No

Do you believe that things need to change to maintain urban agriculture in Kumasi against the threats?

- Yes
- No

Please rank these adaptations in order of most usefulness in maintaining agriculture against urban sprawl in Kumasi

	Not useful	Somewhat useful	Very useful	Don't know
Backyard gardening				
Sack/container gardening				
Farming on marginal lands (roadsides, wetlands, etc.)				
Greenhouses				
Aquaponics				

Please indicate for the following adaptations how confident you are in the quality of the products

	Not useful	Somewhat useful	Very useful	Don't know
Backyard gardening				
Sack/container gardening				
Farming on marginal lands (roadsides, wetlands, etc.)				
Greenhouses				
Aquaponics				

Would you be willing to pay extra for products that are sourced from the schemes above if that means that supply is more guaranteed?

- Yes
- No
- Don’t know

Would you sell/eat products that are grown in backyards?

- Yes
- No
- Don’t know

Could you explain why.

Would you sell/eat products that are grown in sacks/containers?

- Yes
- No
- Don’t know

Could you explain why.

Would you sell/eat products that are grown on marginal lands?

- Yes
- No
- Don’t know

Could you explain why.

Would you sell/eat products that are grown in greenhouses?

- Yes
- No
- Don’t know

Could you explain why.

Would you sell/eat products that are grown in aquaponics systems?

- Yes
- No
- Don’t know

Could you explain why.

Appendix C. Aggregated survey responses

This section includes the aggregated survey responses to the two surveys for the full sample set of respondents. These results can also be downloaded from the online drive, as well as aggregated survey responses split up by the neighbourhoods for which they were classified in. The third part of this appendix shows the table of modelling input for the AquaCrop model, as based on the survey responses.

C1. Vendor survey

What age group do you belong to?	#	%
0-20	2	1.77
20-30	21	18.58
30-40	28	24.78
40-50	25	22.12
50+	18	15.93
Prefer not to tell	19	16.81
Total:	**113**	**100**

What is your gender?	#	%
Female	110	97.35
Male	2	1.77
Prefer not to tell	1	0.88
Total	**113**	**100**

How long have you been a vendor for?	#	%
<5 years	15	13.76
5-10 years	33	30.28
10-20 years	34	31.19
>20 years	24	22.02
Don't know	3	2.75
Total	**109**	**100**

Do you grow the products that you sell yourself?	#	%
Yes	29	30.21
No	67	69.79
Total	**96**	**100**

Where do your products come from?

	Leafy Vegetables		Fruiting Vegetables		Tubers		Cereals		Legumes		Fruits	
Source	kg	[%]	kg	[%]	kg	[%]	kg	[%]	kg	[%]	kg	[%]
Rural	1035	61.4	875	22.8	2050	76.5	1400	41.5	210	61.8	50	18.4
Urban	90	5.3	0	0.0	0	0.0	1400	41.5	0	0.0	0	0.0
Peri-urban	135	8.0	1850	48.2	550	20.5	280	8.3	0	0.0	0	0.0
Unknown	245	14.5	270	7.0	20	0.7	45	1.3	100	29.4	0	0.0
Other Markets	181	10.7	840	21.9	60	2.2	247	7.3	30	8.8	222	81.6
Total	**1686**	**100.0**	**3835**	**100.0**	**2680**	**100.0**	**3372**	**100.0**	**340**	**100.0**	**272**	**100.0**
# of vendors:	39		33		19		17		10		7	

How has supply changed over the last years?

Last year	#	%	Last two years	#	%	Last Five years	#	%
Supply has reduced	58	50.88	Supply has reduced	11	11.22	Supply has reduced	3	3.30
Supply is the same	16	14.04	Supply is the same	25	25.51	Supply is the same	25	27.47
Supply has increased	38	33.33	Supply has increased	58	59.18	Supply has increased	52	57.14
Dont't know	2	1.75	Don't know	4	4.08	Don't know	11	12.09
Total	**114**	**100**	**Total**	**98**	**100**	**Total**	**91**	**100**

Are you scared that supply might be changing (further) in the future?	#	%
Yes, I am afraid that I can no longer meet demand	86	76.11
No, I am confident that I can meet the demands	27	23.89
		0.00
		0.00
Total	**113**	**100**

Do you feel that supply suffers from spoilage?	#	%
Yes, it is a large problem	74	64.91
Yes, but it is a small problem	39	34.21
No	1	0.88
		0.00
Total	**114**	**100**

What do you think is the largest cause of spoilage?	#	%
Lack of cooling facilities	64	39.02
It takes too long to get food to the markets	80	47.78
Products are of insufficient quality	19	11.59
Lack of warehouses	1	0.61
Total	**164**	**100**

What are the most important factors for you to trust a product		
	#	%
Source of the irrigation water	83	32.9
Location of the field	81	32.1
Type of product	41	16.3
How the product looks	23	9.13
How the market looks (wholesale)	24	9.52
Other	0	0
Total	**252**	**100**

Is climate change a threat to agriculture in Kumasi?		
	#	%
Yes	108	95.6
No	2	1.77
Don't Know	3	2.65
Total	**113**	**100**

Is urbanisation a threat to agriculture in Kumasi		
	#	%
Yes	96	86.5
No	12	10.8
Don't know	3	2.7
Total	**111**	**100**

Do things need to change for agriculture to be maintained in Kumasi?		
	#	%
Yes	103	93.6
No	2	1.82
Don't know	5	4.55
Total	**110**	**100**

How useful do you think these adaptations are in maintaining (peri-)urban agriculture in an around Kumasi

Backyard gardening			Sack/Container gardening			Farming on marginal lands			Greenhouses			Aquaponics		
	#	%		#	%		#	%		#	%		#	%
Very useful	90	83.3	Very useful	23	25.6	Very useful	58	65.9	Very useful	46	51	Very useful	1	1.14
Somewhat useful	9	8.33	Somewhat useful	28	31.1	Somewhat useful	18	20.5	Somewhat useful	13	14	Somewhat useful	4	4.55
Not useful	6	5.56	Not useful	0	0	Not useful	0	0	Not useful	2	2	Not useful	4	4.55
Don't know	3	2.78	Don't know	39	43.3	Don't know	12	13.6	Don't know	30	33	Don't know	79	89.77
Total	**108**	**100**	**Total**	**90**	**100**	**Total**	**88**	**100**	**Total**	**91**	**100**	**Total**	**88**	**100**

How confident are you in the quality of the products sourced from these adaptations?

Backyard gardening			Sack/Container gardening			Farming on marginal lands			Greenhouses			Aquaponics		
	#	%		#	%		#	%		#	%		#	%
Very confident	90	84.91	Very confident	22	25.88	Very confident	55	61.11	Very confident	47	52.81	Very confident	2	2.30
Somewhat confident	13	12.26	Somewhat confident	30	35.29	Somewhat confident	20	22.22	Somewhat confident	20	22.22	Somewhat confident	5	5.75
Not confident	3	2.83	Not confident	7	8.24	Not confident	1	1.11	Not confident	1	1.12	Not confident	6	6.90
Don't know	0	0	Don't know	26	30.59	Don't know	14	15.56	Don't know	21	23.59	Don't know	74	85.06
Total	**106**	**100**	**Total**	**85**	**100**	**Total**	**90**	**100**	**Total**	**89**	**100**	**Total**	**87**	**100**

Would you be willing to pay extra for products that are sourced from the schemes above if that means that supply is more guaranteed?		
	#	%
Yes	101	98.06
No	2	1.94
Don't know	0	0.00
Total	**103**	**100**

Would out eat/sell products from the following adaptations

Backyard gardening			Sack/Container gardening			Farming on marginal lands			Greenhouses			Aquaponics		
	#	%		#	%		#	%		#	%		#	%
Yes	103	98.10	Yes	75	72.12	Yes	84	89.36	Yes	67	77.01	Yes	12	16.67
No	1	0.95	No	20	19.23	No	2	2.13	No	8	9.20	No	9	12.50
Don't know	1	0.95	Don't know	9	8.65	Don't know	8	8.51	Don't know	12	13.80	Don't know	51	70.83
Total	**105**	**100**	**Total**	**104**	**100**	**Total**	**94**	**100**	**Total**	**87**	**100**	**Total**	**72**	**100**

C2. Farmer Survey

What age group are you in?	#	%
0-20 years old	1	0.68
20-30 years old	29	19.86
30-40 years old	33	22.60
40-50 years old	38	26.03
50+ years old	35	23.97
Prefer not to tell	10	6.85
Total	**146**	**100**

What is your gender?	#	%
Female	33	36.3
Male	58	63.7
Prefer not to tell	0	0
Total	**146**	**100**

How long have you been farming for?	#	%
< 5 years	29	20.42
5-10 years	43	30.28
10-20 years	39	27.46
>20 years	31	21.83
Don't know	0	0
Total	**142**	**100**

Is your farm in the same neighbourhood as where you live?	#	%
Yes	117	81.25
No	27	18.75
Total	**144**	**100**

What methods do you use to grow crops?	#	%
Rainfed	129	79.14
Irrigated	30	18.40
Soil free farming	3	1.84
Greenhouses	1	0.61
Other	0	0.00
Total	**163**	**100**

What do you do with your crops	#	%
Feed myself and/or my family	13	8.97
Sell for cash	39	26.90
First feed myself/family and sell the remains	93	64.14
Other	0	0.00
Total	**145**	**100**

How would you characterise the space where you practice agriculture?	#	%
Marginal lands	9	5.84
Government owned land	42	27.27
Personally owned land: Backyards	38	24.68
Personally owned land: fields	61	39.61
Currently idle land	4	2.60
Other	0	0.00
Total	**154**	**100**

How secure do you feel that this land remains available to farm on in the future?	#	%
Very secure	64	43.84
Somewhat secure	40	27.40
Somewhat insecure	31	21.23
Very insecure	9	6.16
Don't know	2	1.37
Total	**146**	**100**

What are the main reasons for feeling insecure?	#	%
Land tenure - I do not own the land	17	50.00
Climate change - Water may be scarce	3	8.82
Profitability - I do not make enough money	2	5.88
Urbanisation - The land may be used for other development	12	35.29
Other	0	0.00
Total	**34**	**100**

What method do you use for irrigation?	#	%
Watering cans	32	20.78
Sprinkler	23	14.94
Drip irrigation	7	4.55
Surface irrigation	25	16.23
I do not irrigate my crops	67	43.51
Other	0	0.00
Total	**154**	**100**

How do you know when irrigation is necessary?	#	%
Experience/feeling	53	33.76
Scheduling based on models	10	6.37
Scheduling based on weather predictions	89	56.69
Pre-set dates	5	3.18
Other	0	0.00
Total	**157**	**100**

What water source do you use for irrigation?	#	%
Surface water	99	60.74
Harvested rainwater	36	22.09
Groundwater	4	2.45
Piped water	23	14.11
Wastewater	1	0.61
Other	0	0.00
Total	**163**	**100**

How would you rate the average quality of irrigation water compared to others you know?	#	%
Very good	57	40.71
Good	42	30.00
Decent	8	5.71
Poor	2	1.43
Very poor	2	1.43
Don't Know	29	20.71
Total	**140**	**100**

Do you believe that irrigation water has an effect on fertility?	#	%
Yes, a significant effect	45	32.14
Yes, a small effect	29	20.71
No	66	47.14
Total	**140**	**100**

Do you notice drainage problems on your land?	#	%
Yes, water drains too fast	42	29.37
Yes, water drains too slow	33	23.08
No, I have no problems with drainage	68	47.55
Other	0	0.00
Total	**120**	**100**

Does drainage influence the location that you use to grow crops?	#	%
Yes, I chose this location because the soil holds water well	40	28.57
Yes, I chose this location because water drains quickly	34	24.29
No, drainage capacity did not influence my choice of location	23	16.43
No, I cannot afford to be critical of the location	43	30.71
Other	0	0.00
Total	**140**	**100**

How secure do you feel about the availability of water resources in the future?	#	%
Very secure	93	64.58
Somewhat secure	38	26.39
Somewhat insecure	7	4.86
Very insecure	3	2.08
Don't know	3	2.08
Total	**144**	**100**

Do you use mulches?	#	%
Yes, organic mulches (compost, straw, wood chips, etc.)	48	33.33
Yes, plastic mulches	0	0.00
No	96	66.67
Other	0	0.00
Total	**144**	**100**

How do you qualify the fertility of your land relative to others you know?	#	%
Very good	95	65.07
Good	45	30.82
Poor	2	1.37
Very poor	2	1.37
Don't know	2	1.37
Other	0	0.00
Total	**146**	**100**

What types of fertiliser do you use?	#	%
Compost	35	18.82
Animal waste	32	17.20
Human waste	0	0.00
Synthetic fertiliser	83	44.62
I do not use fertiliser	36	19.35
Other	0	0.00
Total	**186**	**100**

Do you influence runoff on your field?	#	%
Yes, I want to increase runoff	35	24.31
Yes, I decrease runoff	42	29.17
No	67	46.53
Other	0	0.00
Total	**144**	**100**

Are weeds a problem on your field?	#	%
No, because I clear weeds regularly	74	51.75
No, I do not have to clear weeds regularly	17	11.89
Yes, because I have no time to clear weeds	8	5.59
Yes, despite efforts to remove them	30	20.98
Yes, but I feel no need to remove them	14	9.79
Other	0	0.00
Total	**143**	**100**

What types of agricultural products do you produce?	#	%
Cereals	73	34.11
Tubers	56	26.17
Leafy vegetables	30	14.02
Fruiting vegetables	34	15.89
Fruits	14	6.54
Animal products	7	3.27
Oil Palm	2	0.93
Total	**214**	**100**

Do you feel that things need to change for agriculture to be maintained in and around Kumasi?	#	%
Yes	132	94.96
No	6	4.32
Don't know	1	0.72
Total	**139**	**100**

Which elements are most important for an adaptation to be useful?

	Agricultural yield		Variety of crops		Water use		Cost		Knowledge		Materials	
	#	%	#	%	#	%	#	%	#	%	#	%
Very important	119	90.15	117	88.64	117	92.13	105	84.00	117	94.35	116	91.34
Somewhat important	9	6.82	7	5.30	6	4.72	16	12.80	4	3.23	7	5.51
Not important	2	1.52	5	3.79	1	0.79	0	0.00	0	0.00	1	0.79
Don't know	2	1.52	3	2.27	3	2.36	4	3.20	3	2.42	3	2.36
Total	**132**	**100**	**132**	**100**	**127**	**100**	**125**	**100**	**124**	**100**	**127**	**100**

How useful are the adaptations in maintaining peri-urban agriculture in Kumasi?

	Backyard gardening		Sack/container gardening		Farming on marginal lands		Greenhouses		Aquaponics	
	#	%	#	%	#	%	#	%	#	%
Very useful	116	86.57	76	62.30	74	59.68	64	54.70	35	30.43
Somewhat useful	10	7.46	23	18.85	30	24.19	20	17.09	10	8.70
Not useful	6	4.48	2	1.64	6	4.84	5	4.27	6	5.22
Don't know	2	1.49	21	17.21	14	11.29	28	23.93	64	55.65
Total	**134**	**100**	**122**	**100**	**124**	**100**	**117**	**100**	**115**	**100**

What elements do you find most important in adapting urban agriculture.

	Government land use planning		Agricultural practices		Land ownership		Education		Participation and discussion	
	#	%	#	%	#	%	#	%	#	%
Very important	76	55.47	119	92.97	117	92.86	122	96.06	117	92.86
Somewhat important	45	32.85	6	4.69	7	5.56	4	3.15	6	4.76
Not important	11	8.03	3	2.34	2	1.59	1	0.79	3	2.38
Don't know	5	3.65	0	0.00	0	0.00	0	0.00	0	0.00
Total	**137**	**100**	**128**	**100**	**126**	**100**	**127**	**100**	**126**	**100**

Would you be willing to switch your farming practices to one of the adaptations?

Switch in general			Greenhouse			Sack/Containers			Backyards			Marginal Lands			Aquaponics		
	#	%		#	%		#	%		#	%		#	%		#	%
Yes	88	66.67	Yes	43	52.44	Yes	50	64.10	Yes	69	83.13	Yes	36	59.02	Yes	9	13.85
No	44	33.33	No	39	47.56	No	28	35.90	No	14	16.87	No	25	40.98	No	56	86.15
Total	**132**	**100**	**Total**	**82**	**100**	**Total**	**78**	**100**	**Total**	**83**	**100**	**Total**	**61**	**100**	**Total**	**65**	**100**

C3. Management practices input for AquaCrop.

Feyiase

			Regular			
Crops	**Planting Month**	**Irrigation method**	**Mulches**	**Fertility**	**Weeds**	**Runoff management**
Cassava	February	Rainfed	Organic	Good to very good	Yes	No
Cabbage	-	-	-	-	-	-
Maize	January	Rainfed	No	Good to very good	No	No
Tomato	May	Surface	No	Very good	No	No
Dry bean	February	Rainfed	No	Very good	No	No
			Backyards			
Crops	**Planting Month**	**Irrigation method**	**Mulches**	**Fertility**	**Weeds**	**Runoff management**
Cassava	February	Rainfed	No	Good to very good	No	Increase runoff
Cabbage	January	Drip	No	Very good	No	Reduce runoff
Maize	January	Surface	No	Very good	No	No
Tomato	February	Surface	No	Very good	No	No
Dry bean	February	Rainfed	No	Very good	No	No
			Marginal			
Crops	**Planting Month**	**Irrigation method**	**Mulches**	**Fertility**	**Weeds**	**Runoff management**
Cassava	March	Rainfed	No	Good to very good	No	No
Cabbage	February	Surface	Organic	Very good	No	No
Maize	March	Surface	No	Good	No	No
Tomato	February	Surface	No	Very good	No	No
Dry bean	February	Rainfed	No	Very good	No	No

Kwadaso

			Regular			
Crops	**Planting Month**	**Irrigation method**	**Mulches**	**Fertility**	**Weeds**	**Runoff management**
Cassava	March	Rainfed	Organic	Good to very good	No	Increase runoff
Cabbage	March	Sprinkler	No	Very good	No	No
Maize	March	Rainfed	No	Very good	No	No
Tomato	March	Surface	No	Very good	Yes	No
Dry bean	March	Rainfed	No	Very good	No	No
			Backyards			
Crops	**Planting Month**	**Irrigation method**	**Mulches**	**Fertility**	**Weeds**	**Runoff management**
Cassava	March	Rainfed	No	Good to very good	Yes	Decrease runoff
Cabbage	March	Sprinkler	Organic	Very good	No	No
Maize	March	Surface	Organic	Very good	No	Increase runoff
Tomato	March	Rainfed	No	Very good	No	No
Dry bean	March	Rainfed	No	Very good	No	No
			Marginal			
Crops	**Planting Month**	**Irrigation method**	**Mulches**	**Fertility**	**Weeds**	**Runoff management**
Cassava	-	-	-	-	-	-
Cabbage	-	-	-	-	-	-
Maize	March	Surface	No	Good	No	No
Tomato	-	-	-	-	-	-
Dry bean	March	Rainfed	No	Very good	No	No

Crops	Planting Month	Irrigation method	Mulches	Fertility	Weeds	Runoff management
Regular						
Cassava	March	Rainfed	No	Good	No	Increase runoff
Cabbage	March	Sprinkler	Organic	Good to very good	Yes	Increase runoff
Maize	February	Rainfed	No	Good to very good	Yes	Decrease runoff
Tomato	March	Sprinkler	Organic	Moderate to good	Yes	Increase runoff
Dry bean	March	Rainfed	Organic	Good	Yes	Increase runoff
Backyards						
Crops	**Planting Month**	**Irrigation method**	**Mulches**	**Fertility**	**Weeds**	**Runoff management**
Cassava	March	Rainfed	No	Very good	Yes	Decrease runoff
Cabbage	April	Surface	Organic	Very good	Yes	Decrease runoff
Maize	March	Rainfed	Organic	Very good	Yes	Decrease runoff
Tomato	May	Surface	Organic	Good	No	Decrease runoff
Dry bean	March	Rainfed	Organic	Good	Yes	Decrease runoff
Marginal						
Crops	**Planting Month**	**Irrigation method**	**Mulches**	**Fertility**	**Weeds**	**Runoff management**
Cassava	-	-	-	-	-	-
Cabbage	May	Surface	Organic	Good	No	Decrease runoff
Maize	October	Surface	No	Good	Yes	Decrease runoff
Tomato	October	Surface	No	Very good	No	No
Dry bean	October	Rainfed	No	Good	Yes	Decrease runoff

Appendix D. Model results

This section includes the results of the modelling of AquaCrop, as well as the calculations made for the space requirements of the adaptations. The AquaCrop results are aggregated in means of the full model sets. The full results per modelling year are included in the drive.

D1. Yield model results

Mean crop yields, relative biomass and irrigation water need of the 4/5-year dataset.

Feyiase

	Crop	Current Yields [ton/ha]	Current Brel [-]	Current Irrigation depth [mm]	Current Yield [kg/m²]	SSP1 Yields [ton/ha]	SSP1 Brel [-]	SSP1 Irrigation depth [mm]	SSP1 Yield [kg/m²]	SSP2 Yields [ton/ha]	SSP2 Brel [-]	SSP2 Irrigation depth [mm]	SSP2 Yield [kg/m²]	SSP5 Yields [ton/ha]	SSP5 Brel [-]	SSP5 Irrigation depth [mm]	SSP5 Yield [kg/m²]
Fields	Cassava	22.82	0.90	0.00	2.28	22.43	0.83	0.00	2.24	23.08	0.83	0.00	2.31	24.02	0.83	0.00	2.40
	Cabbage	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Maize	14.58	0.98	0.00	1.46	12.90	0.86	0.00	1.29	13.56	0.85	0.00	1.36	12.48	0.83	0.00	1.25
	Tomato	6.03	1.00	74.00	0.60	6.31	1.00	82.50	0.63	6.52	1.00	81.50	0.65	6.75	1.00	91.50	0.67
	Bean	4.05	0.99	0.00	0.40	4.14	0.96	0.00	0.41	4.17	0.94	0.00	0.42	4.25	0.93	0.00	0.42
Backyards	Cassava	23.43	0.94	0.00	2.34	22.99	0.86	0.00	2.30	23.70	0.86	0.00	2.37	24.66	0.86	0.00	2.47
	Cabbage	6.15	1.00	177.00	0.61	6.44	1.00	247.25	0.64	6.65	1.00	243.50	0.67	6.88	1.00	245.75	0.69
	Maize	14.74	1.00	22.50	1.47	14.80	0.99	96.75	1.48	14.89	0.99	136.25	1.49	15.00	0.99	166.75	1.50
	Tomato	6.02	1.00	62.50	0.60	6.30	1.00	148.50	0.63	6.52	1.00	170.25	0.65	6.74	1.00	166.50	0.67
	Bean	4.05	0.99	0.00	0.40	4.14	0.96	0.00	0.41	4.17	0.94	0.00	0.42	4.25	0.93	0.00	0.42

Feyiase

		Current				SSP1				SSP2				SSP5			
	Crop	Yields [ton/ha]	Brel [-]	Irrigation depth [mm]	Yield [kg/m^2]	Yields [ton/ha]	Brel [-]	Irrigation depth [mm]	Yield [kg/m^2]	Yields [ton/ha]	Brel [-]	Irrigation depth [mm]	Yield [kg/m^2]	Yields [ton/ha]	Brel [-]	Irrigation depth [mm]	Yield [kg/m^2]
Marginal Lands	Cassava	22.61	0.91	0.00	2.26	21.77	0.84	0.00	2.18	22.79	0.85	0.00	2.28	23.46	0.84	0.00	2.35
	Cabbage	6.15	1.00	70.75	0.61	6.44	1.00	137.00	0.64	6.65	1.00	157.50	0.67	6.88	1.00	178.75	0.69
	Maize	14.75	1.00	0.00	1.48	14.87	1.00	0.00	1.49	14.96	0.99	0.00	1.50	15.02	0.99	0.00	1.50
	Tomato	6.02	1.00	62.50	0.60	6.30	1.00	148.50	0.63	6.52	1.00	170.25	0.65	6.74	1.00	166.50	0.67
	Bean	4.05	0.99	0.00	0.40	4.14	0.96	0.00	0.41	4.17	0.94	0.00	0.42	4.25	0.93	0.00	0.42
Sacks	Cabbage	6.77	1.00	160.75	0.68	7.08	1.00	218.25	0.71	7.32	1.00	228.00	0.73	7.57	1.00	241.50	0.76
	Tomato	6.29	1.00	67.00	0.63	6.59	1.00	151.25	0.66	6.82	1.00	167.25	0.68	7.05	1.00	174.00	0.70
	Bean	4.23	0.99	0.00	0.42	4.25	0.94	0.00	0.42	4.27	0.92	0.00	0.43	4.34	0.91	0.00	0.43

Kwadaso

Scenario	Crop	Fields: Cassava	Fields: Cabbage	Fields: Maize	Fields: Tomato	Fields: Bean	Backyards: Cassava	Backyards: Cabbage	Backyards: Maize	Backyards: Tomato	Backyards: Bean
Current	Yields [ton/ha]	21.39	5.13	12.15	4.78	3.55	17.80	5.11	12.36	5.29	3.55
	Brel [-]	0.84	0.83	0.82	0.74	0.87	0.71	0.83	0.84	0.83	0.87
	Irrigation depth [mm]	0.00	50.25	0.00	14.50	0.00	0.00	54.50	0.00	0.00	0.00
	Yield [kg/m²]	2.14	0.51	1.22	0.48	0.36	1.78	0.51	1.24	0.53	0.36
SSP1	Yields [ton/ha]	20.66	5.74	13.18	5.29	4.22	17.33	6.04	13.37	5.78	4.22
	Brel [-]	0.77	0.89	0.88	0.77	0.98	0.65	0.94	0.89	0.87	0.98
	Irrigation depth [mm]	0.00	86.25	0.00	57.75	0.00	0.00	52.00	0.00	0.00	0.00
	Yield [kg/m²]	2.07	0.57	1.32	0.53	0.42	1.73	0.60	1.34	0.58	0.42
SSP2	Yields [ton/ha]	21.77	5.77	13.64	5.58	4.38	18.13	5.96	13.86	6.03	4.38
	Brel [-]	0.77	0.87	0.91	0.78	0.98	0.66	0.90	0.92	0.87	0.98
	Irrigation depth [mm]	0.00	114.50	0.00	68.50	0.00	0.00	97.25	0.00	0.00	0.00
	Yield [kg/m²]	2.18	0.58	1.36	0.56	0.44	1.81	0.60	1.39	0.60	0.44
SSP5	Yields [ton/ha]	22.74	6.20	13.65	5.77	4.54	18.96	6.25	13.84	6.25	4.54
	Brel [-]	0.78	0.90	0.90	0.78	0.98	0.67	0.90	0.92	0.86	0.98
	Irrigation depth [mm]	0.00	98.75	0.00	80.25	0.00	0.00	92.50	0.00	0.00	0.00
	Yield [kg/m²]	2.27	0.62	1.36	0.58	0.45	1.90	0.63	1.38	0.62	0.45

			Marginal Lands					Sacks		
		Crop	Cassava	Cabbage	Maize	Tomato	Bean	Cabbage	Tomato	Bean
Kwadaso	Current	Yields [ton/ha]	-	-	12.15	-	3.55	5.67	5.54	3.72
		Brel [-]	-	-	0.82	-	0.87	0.84	0.83	0.89
		Irrigation depth [mm]	-	-	0.00	-	0.00	53.50	0.00	0.00
		Yield [kg/m²]	-	-	1.22	-	0.36	0.57	0.55	0.37
	SSP1	Yields [ton/ha]	-	-	13.19	-	4.22	6.59	6.08	4.41
		Brel [-]	-	-	0.88	-	0.98	0.93	0.87	0.98
		Irrigation depth [mm]	-	-	0.00	-	0.00	71.50	0.00	0.00
		Yield [kg/m²]	-	-	1.32	-	0.42	0.66	0.61	0.44
	SSP2	Yields [ton/ha]	-	-	13.64	-	4.38	6.35	6.27	4.58
		Brel [-]	-	-	0.91	-	0.98	0.87	0.86	0.98
		Irrigation depth [mm]	-	-	0.00	-	0.00	118.75	0.00	0.00
		Yield [kg/m²]	-	-	1.36	-	0.44	0.64	0.63	0.46
	SSP5	Yields [ton/ha]	-	-	13.65	-	4.54	6.78	6.48	4.74
		Brel [-]	-	-	0.90	-	0.98	0.89	0.85	0.98
		Irrigation depth [mm]	-	-	0.00	-	0.00	102.25	0.00	0.00
		Yield [kg/m²]	-	-	1.36	-	0.45	0.68	0.65	0.47

		Fields					Backyards				
	Crop	Cassava	Cabbage	Maize	Tomato	Bean	Cassava	Cabbage	Maize	Tomato	Bean
Ejisu Current	Yields [ton/ha]	22.99	5.35	12.72	5.83	3.56	20.13	5.35	12.70	6.03	3.56
	Brel [-]	0.91	0.87	0.86	0.88	0.86	0.78	0.87	0.86	1.00	0.86
	Irrigation depth [mm]	0.00	49.50	0.00	39.50	0.00	0.00	20.50	0.00	72.25	0.00
	Yield [kg/m²]	2.30	0.54	1.27	0.58	0.36	2.01	0.54	1.27	0.60	0.36
SSP1	Yields [ton/ha]	21.58	5.60	12.74	6.11	3.70	18.76	5.60	12.81	6.31	3.70
	Brel [-]	0.84	0.87	0.85	0.88	0.86	0.70	0.87	0.93	1.00	0.86
	Irrigation depth [mm]	0.00	87.00	0.00	57.75	0.00	0.00	33.25	0.00	72.50	0.00
	Yield [kg/m²]	2.16	0.56	1.27	0.61	0.37	1.88	0.56	1.28	0.63	0.37
SSP2	Yields [ton/ha]	22.32	5.79	12.75	6.31	3.80	19.39	5.79	12.89	6.52	3.81
	Brel [-]	0.81	0.87	0.84	0.88	0.86	0.69	0.87	0.86	1.00	0.85
	Irrigation depth [mm]	0.00	123.75	0.00	100.75	0.00	0.00	53.00	0.00	69.25	0.00
	Yield [kg/m²]	2.23	0.58	1.27	0.63	0.38	1.94	0.58	1.29	0.65	0.38
SSP5	Yields [ton/ha]	23.27	5.99	12.75	6.53	3.92	20.19	5.99	12.95	6.75	3.92
	Brel [-]	0.82	0.87	0.84	0.88	0.85	0.70	0.87	0.86	1.00	0.85
	Irrigation depth [mm]	0.00	122.00	0.00	77.50	0.00	0.00	39.25	0.00	82.00	0.00
	Yield [kg/m²]	2.33	0.60	1.27	0.65	0.39	2.02	0.60	1.30	0.67	0.39

			Marginal Lands					Sacks		
		Crop	Cassava	Cabbage	Maize	Tomato	Bean	Cabbage	Tomato	Bean
Ejisu	Current	Yields [ton/ha]	-	6.15	12.71	6.01	3.92	5.90	6.30	3.72
		Brel [-]	-	1.00	0.86	1.00	0.98	0.87	1.00	0.86
		Irrigation depth [mm]	-	33.25	111.00	174.00	0.00	28.25	72.50	0.00
		Yield [kg/m²]	-	0.61	1.27	0.60	0.39	0.59	0.63	0.37
	SSP1	Yields [ton/ha]	-	6.43	12.83	6.30	3.34	6.17	6.59	3.97
		Brel [-]	-	1.00	0.86	1.00	0.88	0.87	1.00	0.85
		Irrigation depth [mm]	-	57.75	205.75	268.67	0.00	35.75	72.50	0.00
		Yield [kg/m²]	-	0.64	1.28	0.63	0.33	0.62	0.66	0.40
	SSP2	Yields [ton/ha]	-	6.65	12.92	6.51	3.56	6.38	6.81	3.97
		Brel [-]	-	1.00	0.86	1.00	0.89	0.87	1.00	0.85
		Irrigation depth [mm]	-	63.50	208.25	255.33	0.00	63.25	69.75	0.00
		Yield [kg/m²]	-	0.66	1.29	0.65	0.36	0.64	0.68	0.40
	SSP5	Yields [ton/ha]	-	6.87	12.99	6.74	3.77	6.60	7.05	4.09
		Brel [-]	-	1.00	0.86	1.00	0.89	0.87	1.00	0.85
		Irrigation depth [mm]	-	60.25	171.75	240.67	0.00	44.75	82.25	0.00
		Yield [kg/m²]	-	0.69	1.30	0.67	0.38	0.66	0.70	0.41

D2. Spatial model analysis results

Intake requirements for the major crop groups, based on the EAT-Lancet planetary health diet.

Intake requirements - Planetary Health Diet				
Food group	**Intake(g/day)**	**Intake min (g/day)**	**Intake max (g/day)**	**Intake (kcal/day)**
Whole grains	232	232	232	811
Tubers and starchy vegetables	50	0	100	39
Vegetables	300	200	600	78
Fruits	200	100	300	126
Legumes	75	0	100	284

Population numbers for the Kumasi districts, based on projections for Africa as a whole.

Neighbourhood	Current - Population (2021)	SSP1 – Population (2050)	SSP2 – Population (2050)	SSP5 – Population (2050)
Africa (Millions)	1393	1764	2011	1808
Ejisu	180,723	228,855	260,900	234,564
Feyiase	43,403	54,963	62,659	56,334
Kwadaso	154,526	195,681	223,081	200,562

Demand for crops per district, based on the population numbers and daily intakes from planetary health diet.

District	Food group	Current			SSP1		
		Intake (kg/day)	Intake min (kg/day)	Intake max (kg/day)	Intake (kg/day)	Intake min (kg/day)	Intake max (kg/day)
Ejisu	Whole grains	41928	41928	41928	53,094	53,094	53,094
	Tubers and starchy vegetables	9036	0	18072	11,443	-	22,886
	Vegetables	54217	36145	108434	68,657	45,771	137,313
	Fruits	36145	18072	54217	45,771	22,886	68,657
	Legumes	13554	0	18072	17,164	-	22,886
Feyiase	Whole grains	10069	10069	10069	12,751	12,751	12,751
	Tubers and starchy vegetables	2170	0	4340	2,748	-	5,496
	Vegetables	13021	8681	26042	16,489	10,993	32,978
	Fruits	8681	4340	13021	10,993	5,496	16,489
	Legumes	3255	0	4340	4,122	-	5,496
Kwadaso	Whole grains	35850	35850	35850	45,398	45,398	45,398
	Tubers and starchy vegetables	7726	0	15453	9,784	-	19,568
	Vegetables	46358	30905	92716	58,704	39,136	117,409
	Fruits	30905	15453	46358	39,136	19,568	58,704
	Legumes	11589	0	15453	14,676	-	19,568

		SSP2			SSP5		
District	Food group	Intake (kg/day)	Intake min (kg/day)	Intake max (kg/day)	Intake (kg/day)	Intake min (kg/day)	Intake max (kg/day)
Ejisu	Whole grains	60,529	60,529	60,529	54418.77	54418.77	54418.77
	Tubers and starchy vegetables	13,045	-	26,090	11728.18	0	23456.37
	Vegetables	78,270	52,180	156,540	70369.1	46912.73	140738.2
	Fruits	52,180	26,090	78,270	46912.73	23456.37	70369.1
	Legumes	19,568	-	26,090	17592.27	0	23456.37
Feyiase	Whole grains	14,537	14,537	14,537	13069.38	13069.38	13069.38
	Tubers and starchy vegetables	3,133	-	6,266	2816.677	0	5633.354
	Vegetables	18,798	12,532	37,595	16900.06	11266.71	33800.13
	Fruits	12,532	6,266	18,798	11266.71	5633.354	16900.06
	Legumes	4,699	-	6,266	4225.016	0	5633.354
Kwadaso	Whole grains	51,755	51,755	51,755	46530.41	46530.41	46530.41
	Tubers and starchy vegetables	11,154	-	22,308	10028.11	0	20056.21
	Vegetables	66,924	44,616	133,849	60168.63	40112.42	120337.3
	Fruits	44,616	22,308	66,924	40112.42	20056.21	60168.63
	Legumes	16,731	-	22,308	42.16	0	0056.21

Available space per district, based on the GIS analysis.

	Land use class	Water	Forest	Vegetation (other)	Urban (High density)	Urban (Low density)	Marginal lands	Arable lands (Backyards, fields, etc.)	Clouds	**Total**
Ejisu	Area [10mx10m pixels]	25427	122411	43048	101927	149694	145862	305128	52622	**946119**
	Area [m²]	2542700	12241100	4304800	10192700	14969400	14586200	30512800	5262200	**94611900**
	Area [km²]	2.5427	12.2411	4.3048	10.1927	14.9694	14.5862	30.5128	5.2622	**94.6119**
Feyiase	Area [10mx10m pixels]	1111	38298	19080	23184	113895	65535	182154	370	**443627**
	Area [m²]	111100	3829800	1908000	2318400	11389500	6553500	18215400	37000	**44362700**
	Area [km²]	0.1111	3.8298	1.908	2.3184	11.3895	6.5535	18.2154	0.037	**44.3627**
Kwadaso	Area [10mx10m pixels]	203	3760	5091	183564	139927	52644	255625	280	**641094**
	Area [m²]	20300	376000	509100	18356400	13992700	5264400	25562500	28000	**64109400**
	Area [km²]	0.0203	0.376	0.5091	18.3564	13.9927	5.2644	25.5625	0.028	**64.1094**

Necessary space to meet demand in the season, divided by scenario, neighbourhood, crop group and adaptation

Current (2017-2021)							
District	**Crop group**	**Total demand in season (kg)**	**Fields (km²)**	**Backyards (km²)**	**Marginal lands (km²)**	**Sacks (km²)**	**Season duration (days)**
Feyiase	Whole grains (Maize)	1,329,173	0.91	0.90	0.90	-	132
	Tubers and starchy vegetables (Cassava)	781,254	0.34	0.33	0.35	-	360
	Leafy vegetables (Cabbage)	1,132,818	-	1.84	1.84	1.67	87
	Fruiting vegetables (Tomato)	1,705,738	2.83	2.83	2.83	2.71	131
	Legumes (Dry Bean)	374,351	0.92	0.92	0.92	0.89	115
Kwadaso	Whole grains (Maize)	4,732,204	3.89	3.83	3.89	-	132
	Tubers and starchy vegetables (Cassava)	2,781,468	1.30	1.56	-	-	360
	Leafy vegetables (Cabbage)	4,033,129	7.87	7.90	-	7.11	87
	Fruiting vegetables (Tomato)	6,072,872	12.71	11.49	-	10.95	131
	Legumes (Dry Bean)	1,332,787	3.75	3.75	3.75	3.58	115
Ejisu	Whole grains (Maize)	5,534,461	6.02	6.03	6.02	-	132
	Tubers and starchy vegetables (Cassava)	3,253,014	1.96	2.24	-	-	360
	Leafy vegetables (Cabbage)	4,716,870	12.19	12.19	10.61	11.06	87
	Fruiting vegetables (Tomato)	7,102,414	16.84	16.30	21.75	15.60	131
	Legumes (Dry Bean)	1,558,736	6.06	6.06	5.51	5.79	115

SSP1 (2040-2045)

District	Crop group	Total demand in season (kg)	Fields (km²)	Backyards (km²)	Marginal lands (km²)	Sacks (km²)	Season duration (days)
Feyiase	Whole grains (Maize)	1,683,174	1.30	1.14	1.13	-	132
	Tubers and starchy vegetables (Cassava)	989,327	0.44	0.43	0.45	-	360
	Leafy vegetables (Cabbage)	1,434,524	-	2.23	2.2	2.03	87
	Fruiting vegetables (Tomato)	2,160,030	3.42	3.43	3.43	3.28	131
	Legumes (Dry Bean)	474,052	1.15	1.15	1.15	1.12	115
Kwadaso	Whole grains (Maize)	5,992,540	4.55	4.48	4.54	-	132
	Tubers and starchy vegetables (Cassava)	3,522,261	1.70	2.03	-	-	360
	Leafy vegetables (Cabbage)	5,107,278	8.90	8.46	-	7.75	87
	Fruiting vegetables (Tomato)	7,690,270	14.53	13.29	-	12.64	131
	Legumes (Dry Bean)	1,687,750	4.00	4.00	4.00	4.00	115
Ejisu	Whole grains (Maize)	7,008,463	4.74	4.72	4.71	#DIV/0!	132
	Tubers and starchy vegetables (Cassava)	4,119,395	1.65	1.89	#DIV/0!	#DIV/0!	360
	Leafy vegetables (Cabbage)	5,973,122	9.20	9.20	8.01	8.35	87
	Fruiting vegetables (Tomato)	8,994,012	12.71	12.29	16.41	11.77	131
	Legumes (Dry Bean)	1,973,877	4.60	4.60	5.10	4.28	115

		SSP2 (2040-2045)					
District	Crop group	Total demand in season (kg)	Fields (km²)	Backyards (km²)	Marginal lands (km²)	Sacks (km²)	Season duration (days)
Feyiase	Whole grains (Maize)	1,918,857	1.42	1.29	1.28	-	132
	Tubers and starchy vegetables (Cassava)	1,127,855	0.49	0.48	0.49	-	360
	Leafy vegetables (Cabbage)	1,635,390	-	2.46	2.46	2.23	87
	Fruiting vegetables (Tomato)	2,462,483	3.78	3.78	3.78	3.61	131
	Legumes (Dry Bean)	540,430	1.30	1.30	1.30	1.27	115
Kwadaso	Whole grains (Maize)	6,831,632	5.01	4.93	5.01	-	132
	Tubers and starchy vegetables (Cassava)	4,015,457	1.84	2.22	-	-	360
	Leafy vegetables (Cabbage)	5,822,413	10.09	9.77	-	9.16	87
	Fruiting vegetables (Tomato)	8,767,082	15.71	14.53	-	13.97	131
	Legumes (Dry Bean)	1,924,073	4.39	4.39	4.39	4.20	115
Ejisu	Whole grains (Maize)	7,989,807	6.01	5.94	5.93	-	132
	Tubers and starchy vegetables (Cassava)	4,696,203	2.02	2.32	-	-	360
	Leafy vegetables (Cabbage)	6,809,495	11.27	11.28	9.82	10.23	87
	Fruiting vegetables (Tomato)	8,767,082	13.31	12.88	17.20	12.33	131
	Legumes (Dry Bean)	2,250,264	5.67	5.67	6.06	5.43	115

SSP5 (2040-2045)

District	Crop group	Total demand in season (kg)	Fields (km²)	Backyards (km²)	Marginal lands (km²)	Sacks (km²)	Season duration (days)
Feyiase	Whole grains (Maize)	1,725,158	1.38	1.15	1.15	-	132
	Tubers and starchy vegetables (Cassava)	1,014,004	0.42	0.41	0.43	-	360
	Leafy vegetables (Cabbage)	1,470,305	-	2.14	2.14	1.94	87
	Fruiting vegetables (Tomato)	2,213,908	3.28	3.28	3.28	3.14	131
	Legumes (Dry Bean)	485,877	1.14	1.14	1.14	1.12	115
Kwadaso	Whole grains (Maize)	6,142,014	4.50	4.44	4.50	-	132
	Tubers and starchy vegetables (Cassava)	3,610,118	1.59	1.90	-	-	360
	Leafy vegetables (Cabbage)	5,234,671	8.44	8.37	-	7.73	87
	Fruiting vegetables (Tomato)	7,882,091	13.67	12.62	-	12.17	131
	Legumes (Dry Bean)	1,729,848	3.81	3.81	3.81	3.65	115
Ejisu	Whole grains (Maize)	7,183,278	6.68	6.57	6.56	-	132
	Tubers and starchy vegetables (Cassava)	4,222,146	2.15	2.48	-	-	360
	Leafy vegetables (Cabbage)	6,122,112	12.12	12.13	10.56	11.00	87
	Fruiting vegetables (Tomato)	9,218,352	14.31	13.85	18.49	13.26	131
	Legumes (Dry Bean)	2,023,112	6.12	6.12	6.37	5.86	115