Evaluating Land Suitability to Increase Food Production in Kenya

by

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B.S., Mechanical Engineering and Renewable Energy Systems
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SUBMITTED TO THE DEPARTMENT OF CIVIL AND ENVIRONMENT ENGINEERING IN
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SUBMITTED TO THE DEPARTMENT OF CIVIL AND ENVIRONMENT ENGINEERING ON MAY 20, 2015 IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ENGINEERING IN ENVIRONMENTAL ENGINEERING

ABSTRACT

With increasing food deficits and growing population, Kenya is facing strong challenges to meet the food demand of the country, as the majority of the domestic consumption of some staple food sources, such as wheat and rice, is heavily relied on food relieve. This report aims to investigate the potential in increasing food production in Kenya by evaluating the availabilities of land and water resources. A land suitability analysis is carried out in this report to identify the arability of land of Kenya for the selected crops including maize, wheat and rice. The results of the report show that there is a huge potential for intensifying the food productions of the selected crops. And a discussion of the inefficiencies in the current crop production in Kenya is also included at the end of the report.

Thesis Supervisor: Dennis B. McLaughlin
Title: H.M. King Bhumibol Professor of Civil and Environmental Engineering
Acknowledgement

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1. Introduction

Kenya Vision 2030 (GoK, 2007) is the development plan for Kenya covering the period from 2008 to 2030, which aims at transforming Kenya into a “newly industrialising, middle-income country providing high quality life to all its citizens by the 2030”. Agriculture, which represents one of the pillars of Kenya’s economy, directly contributes to 24 percent of the country’s Gross Domestic Product (GDP), 45 percent of the Governmental revenue, 75 percent of industrial raw materials and more than 50 percent of the exportation earnings (KARI, n.d.). However, food deficits and food security issues still widely exist in the country. As of now, it is estimated that over 10 million people are in food insecure situations and currently live off food relief (KARI, n.d.). The Kenyan population has been growing at a steady rate of 2.7 percent for the past 10 years (World Bank, n.d.) and is projected to keep increasing, which would inevitably result in greater demand in food production and could pose more uncertainties on the food security in Kenya. Moreover, Kenya’s agriculture has been struck with recurring droughts, floods and other climatic adversities (Alila & Atieno, 2006), which have instant impacts on the crop production.

Motivated by the interests in learning Kenya’s potential to intensify food production to close the food deficits and feed the growing population, our study is set out to evaluate the availability of land and water resources in Kenya for maximizing the food production of three selected crops: maize, wheat and rice. The study is divided into two sub-projects: an evaluation of the land availability, which is documented in this report, and an evaluation of the water availability, which is elaborated in *Spatial and Temporal Allocation of Water and Land Resources for Optimal Cereal Production in Kenya* (Xydi, 2015). The deliverables of the land availability study include a land suitability analysis that generates a land grade map for each crop indicating the suitability for crop cultivation, and the maximum potential cultivation are for each crop that is calculated from the land grade map. This information is an important input for the study to
evaluate the crop production potential in Kenya.

2. Overview of Current Agricultural System and Kenyan Diet

2.1 Geography and climate

Kenya is bounded by Ethiopia and South Sudan to the north, Somalia and Indian Ocean to the east, Tanzania to the south, and Lake Victoria and Uganda to the west. Located on the East Coast of the African Continent and with the latitude stretching from 4 degrees north to 4 degrees south, Kenya has a variety of climates and ecological systems. The terrain of Kenya is composed of the tropical Coast Region to the south-east, the Eastern Plateau Region consisting of a belt of plains extending north- and southward to the cool, humid and agriculturally rich highlands located in Central Kenya, the arid Northern Plain stretching from the border with Uganda in the west to Somali in the east, which is home to Lake Turkana (also called Lake Rudolf) and the Chalbi Desert, the Great Rift Valley region stretching from Lake Turkana southward to Tanzania through the Highland, and the sub-humid Western Plateau Region that is part of the extensive basin around Lake Victoria (ASC, n.d.). The diverse landscape suggests great variability in the climate patterns of Kenya.

Kenya receives an average annual precipitation of 630mm, with a variation of less than 200mm in the north to over 1800mm along the slopes of Mount Kenya (FAO 2005), which is the highest mountain in central Kenya with an altitude of 5199m. Due to its close distance to the equator, the rainfall distribution in Kenya is largely dependent on the erratic movements of the Inter Tropical Convergence Zone (ITCZ), thus wide annual variation in rainfall amount and distribution exists in the rainfall pattern of Kenya. As the result, Kenya has less reliable rainfall than its neighbors, such as Uganda and Tanzania, and only 15 percent to 17 percent of Kenya’s land receives the amount of annual rainfall needed for medium potential cropped agriculture (Pereira, 1996). Furthermore, the annual rainfall is concentrated within two rain seasons, as long rains
occurring from April to June, and short rains occurring from October to December (Poff, 2007), which reduced the agricultural potential to a greater extent.

Figure 1. Map of Kenya with key physical features (MoW, n.d.)
The average monthly evapotranspiration in Kenya varies from 85 millimetres to 260 millimetres, and the months of high potential evapotranspiration also usually coincides with the months with the least precipitation (Woodhead, 1968), which aggravates the water stress in regions where there is no surplus from the rainfall to recharge the groundwater storage. Much area in East Africa remains unpopulous due to the waterless condition (Pereira, 1996). Consequently, about 80 percent of the country is identified as arid and semi-arid, and only 17 percent of the land is considered of high agricultural potential, which sustains 75 percent of the country's population (FAO 2005). However, the land with high agricultural potential is substantially advantageous, with frost-free condition and temperatures permitting crop growth all the year round. These lands also receive ample sunshine, with an average of 7 hours or more on a monthly basis (Pereira, 1996).
The soil types in Kenya vary with the geographic regions, as the result of different topographic features, the amount of precipitation and the parent materials. In the northern arid and semi-arid area, the soil type include vertisols, gleysols and phaeozems, which are usually identified with pockets of sodicity and salinity, low fertility and vulnerability to erosion. Coastal soils include arenosols, luvisols, and acrisols, which are coarse-textured and low in organic matter. The western part of the soil is consists of acrisols, cambisols, and the mixture of the two, which are highly weathered and leached with iron and aluminium oxides. The soils in central Kenya and the highlands are mostly nitosols and andosols, which are porous volcanic deposits with good water-storage-capacity and organic matter content (Infonet-Biovision, n.d.), making them more suitable for agricultural development (FAO 2005).

2.2 Agriculture Overview

As the single most important sector in the economy (Alila & Atieno, 2006), the agriculture in Kenya has experienced dramatic fluctuations throughout the decades, which is depicted in Figure 4. During the first two decades after Kenya’s independence from Britain in the 60s and 70s, the agricultural sector has experienced a rapid growth at
an average rate of 6 percent. The growth is largely due to the spurring and expansion of small-scaled farms on the amble unexploited land and the adoption of more efficient technologies. A number of governmental extensions and institutions were also formed during this period, providing the institutional support for the agricultural sector. During the 80s and 90s, the agricultural growth rate plummeted significantly from the peak rate of 8 percent to as low as 1.3 percent in 1990. During this time, the budgetary allocation for agriculture sector was cut down to less than 2 percent from the national budget under the Breton Woods project as the result of a series of structural adjustment programmes, causing significant loss in the agricultural investment. The slump was temporarily ceased in the early 20th century under the efforts of the National Alliance of Rainbow Coalition in prioritizing the agricultural sector, and the growth was again set back by the domestic violence ensuing the general election in 2007 and the following global financial crisis. However, the drop was soon arrested by the government and the growth was recovered again (GoK, 2010).

Currently, the agricultural sector in Kenya employs 75 percent of the national labour force and provides the main source of household income for over 80 percent of the population (Alila & Atieno, 2006). The agricultural sector consists of six subsectors: industrial crops, food crops, horticulture, livestock, fishery and forestry. The
horticulture (33 percent) is the biggest contributor to Agricultural Gross Domestic Products (AgGDP), closely followed by food crops (32 percent) and livestock (17 percent) (GoK, 2010). The agriculture accounts for 65 percent of Kenya’s exports, which is mainly comprised of industrial crops (55 percent) and horticulture (38 percent). The food crops only contribute to 0.5 percent of the exports, indicating that the food crops are mainly consumed domestically (GoK, 2010).

In 2013, the total agricultural production in Kenya reached about 29 million metric tons. The top five agricultural produces with the highest production are sugarcane (5.9 million metric tons), milk (4.9 million metric tons), maize (3.4 million metric tons), potatoes (2.2 million tons) and other types of vegetables (1.8 million tons)\(^1\), which are shown in Figure 5. While the majority of the sugarcane production is further directed into food manufacturing, the other agricultural produces are mainly consumed as food sources domestically. As of 2013, about 47 percent of the land is currently under cultivation in Kenya\(^2\). The majority of the agricultural activities are practiced in the unit of small-scaled farms, which often lack the ability to afford readily available modern farming technologies and equipment. As a result, the crop yield in Kenya performs poorly compared to regions with similar climatic characteristics (Alila & Atieno, 2006).

\(^2\) http://data.worldbank.org/indicator/AG.LND.AGRI.K2
The average calorie intake of a Kenyan in 2013 is 2206 kcal per day per capita, similar to its neighbor Tanzania’s 2208 kcal per day per capita, and Ethiopia’s 2131 kcal per day per capita (FAOSTAT, n.d.). The Kenyan diet is largely composed of cereals consumption, and complemented with a small amount of meat consumption and other fruits and vegetables. The protein is mostly consisted of vegetarian sources intake (74 percent), such as pulses and cereals including maize and wheat, and the rest one third of protein intake is from animal sources, which could be evenly divided between milk and meat (FAOSTAT, n.d.).
Total Calorie Intake in 2013: 2206 kcal/day per capita

Figure 6. Total caloric intake breakdown of Kenyan diet (FAOSTAT, n.d.)
3. Scope

The purpose of our project is to investigate the potential of the food production increase in Kenya, so that more Kenyan people could be fed when the country’s population is growing steadily. We limit the project scope to only include three crops for the sake of modelling simplicity, whereas a more accurate and comprehensive model would include most if not all crops that are currently cultivated as food crops in Kenya. The current Kenyan diet is used as the guideline for selecting the crops for this study, and three kinds of cereals including maize, wheat and rice were selected. These three crops are the top three most consumed cereals in the Kenyan diet, and the consumption of these crops consists of about 50 percent of the overall daily calorie intake of a Kenyan on average. As for the production of these three crops, maize is the third most productive food source in Kenya, ranking just next to sugarcane and milk. Together with a small amount of import, maize is primarily consumed domestically as an important food source for calorie and protein. Wheat is the second most important calorie source and the third most important protein source, but the wheat production is very limited, and about 70 percent of the consumption of wheat is relied on intensive import. Rice shares a similar situation with wheat, with a limited quantity of production and a heavy import to sustain about 74 percent of the consumption.

Table 1. Production and consumption of maize, wheat and rice in Kenya in 2013 (FAOSTAT, n.d.)

<table>
<thead>
<tr>
<th></th>
<th>Production</th>
<th>Import</th>
<th>Total supply</th>
<th>Food utilization rate</th>
<th>Total calorie</th>
<th>Protein</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>1000 metric tons</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2206</td>
<td>61.84</td>
</tr>
<tr>
<td>Maize</td>
<td>3391</td>
<td>112</td>
<td>3697</td>
<td>91%</td>
<td>663</td>
<td>17.47</td>
</tr>
<tr>
<td>Wheat</td>
<td>486</td>
<td>1092</td>
<td>1612</td>
<td>95%</td>
<td>258</td>
<td>7.73</td>
</tr>
</tbody>
</table>
Although multi-cropping and crop rotation are both effective agricultural practices that could potentially increase crop production (Wokabi, n.d.), for the simplicity of modelling, we assume that there is no overlap between croplands. Also, in this study we only consider one growing season annually for each crop, while multiple growing seasons are practically feasible with Kenyan climate. The crop growth could be divided into four stages: initial ($L_{ini}$), development ($L_{dev}$), midseason ($L_{mid}$) and late season periods ($L_{late}$) (Allen et al., 1998a). For each stage, the crop water requirement is different in terms of evapotranspiration intensity, which will be further elaborated in the following section. The plant date and growing season with four growth stages for each crop throughout the year are specified in Table 2.

Table 2. Plant dates and growing periods for maize, wheat and rice in East Africa (Allen et al., 1998a)

<table>
<thead>
<tr>
<th>Plant Date</th>
<th>$L_{ini}$/days</th>
<th>$L_{dev}$/days</th>
<th>$L_{mid}$/days</th>
<th>$L_{late}$/days</th>
<th>Total /days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td>April</td>
<td>30</td>
<td>50</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>Wheat</td>
<td>July</td>
<td>15</td>
<td>30</td>
<td>65</td>
<td>40</td>
</tr>
<tr>
<td>Rice</td>
<td>May</td>
<td>30</td>
<td>30</td>
<td>80</td>
<td>40</td>
</tr>
</tbody>
</table>

The crop production could be determined by the total cultivation area and the crop yield on unit land. To increase the crop production, we could either expand the cultivation land by planting more crops on the land that is deemed arable, or increase the yield on unit land by improving the soil properties with fertilizers or other soil modification methods. For the base case scenario, we assume no fertilizer or any soil modification method is applied, and only the natural soil properties are considered. In this case, prioritizing the crop cultivation on the land with higher grade as opposed to lower grade
could improve the unit area yield, so that the overall total crop production is increased. A sensitivity analysis is presented later in Section 5.3 to discuss the crop production increase potential with application of fertilizers and soil modification methodologies.

The arability of land is crop-dependent, and it could be evaluated by comparing the land properties with crop requirements in respect to climate, topography, soil properties and water availability, and any limiting condition within the four requirements could result in lower crop productivity or even inarability of the land. Sys, C. et al. (1991) has established a land evaluation framework with a parametric method, where the land is rated on a numerical scale from 0 to 100 based on the limitation levels of the land characteristics, and the land could be divided into six sub-classes with six rating ranges: 100 – 95; 95 – 85; 85 – 60; 40 – 25 and 20 – 0. In this study, we specify five land grades from 1 to 5, where grade 1 represents Sys, C. et al (1991)’s parametric rating range 100 – 95, and 5 represents 40 – 0, as shown in Table 3. For this study, we define land with grade 1 to grade 3 as arable, whereas the land with grade 4 and grade 5 are excluded for crop cultivation due to the marginal crop yields.


<table>
<thead>
<tr>
<th>Sys. C</th>
<th>100 – 95</th>
<th>95 – 85</th>
<th>85 – 60</th>
<th>60 – 40</th>
<th>40 – 25</th>
<th>25 – 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land Grade</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

Muller, N. et al (2012) has conducted a global assessment on the yield gaps of major crops worldwide to investigate the prospect of intensifying the global food production by closing the yield gap, and the most attainable yields for the major crops in Kenya are determined by identifying the crop yields in the high-yielding zones that share similar climatic conditions with Kenya. The highest attainable yield are shown in Table 4. As different land grades can result in varying crop yields, we assume that Sys, C. et al (1991)’s numerical rating of the land could be directly translated into the percentage of the most attainable yield for each crop that is achievable for each land grade, and the
lower bound of the rating range is chosen to represent the achievable yield for each land grade.

Table 4. Maximum attainable yield and achievable yield for each land grade

<table>
<thead>
<tr>
<th></th>
<th>Max. yield</th>
<th>Achievable yield</th>
<th>Grade 1</th>
<th>Grade 2</th>
<th>Grade 3</th>
<th>Grade 4</th>
<th>Grade 5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>t/ha</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maize</td>
<td>4.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wheat</td>
<td>4.46</td>
<td>95%</td>
<td>85%</td>
<td>60%</td>
<td>40%</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Rice</td>
<td>6.52</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

The water requirement for each is assumed to be proportional to the crop evapotranspiration, which is represented in the equation below:

$$ET_{crop} = ET_o K_c$$

Where $ET_o$ is the reference evapotranspiration, and $K_c$ is the crop coefficient, which is a crop characteristic that takes into account the difference in evapotranspiration between field crops and reference grass surface. Throughout the growing cycle, crops have different evapotranspiration in each growing stage, thus $K_c$ is also different in each crop growth stage (Allen et al., 1998a). Table 5 summarizes the monthly $K_c$ for each crop during the growing season.

Table 5. Crop coefficient during the growing season (Allen et al., 1998a)

<table>
<thead>
<tr>
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<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td></td>
<td></td>
<td></td>
<td>0.3</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>0.48</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wheat</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.3</td>
<td>1.15</td>
<td>1.15</td>
<td>1.15</td>
<td>0.33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rice</td>
<td></td>
<td>1.05</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td></td>
<td>0.75</td>
<td></td>
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</table>

$ET_o$ is defined as the evapotranspiration from a reference surface, which is a
hypothetical grass reference crop with an assumed crop height of 0.12m, a fixed surface resistance of 70 m s\(^{-1}\) and an albedo of 0.23 (Allen et al., 1998b). \(ET_\theta\) can be calculated from meteorological data, and many models have been developed for computing \(ET_\theta\), as summarised in Table 6.

Table 6. Comparison of five ETo computation models (Zomer et al., 2006)

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<thead>
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<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Africa</td>
<td>Jan</td>
<td>71.8</td>
<td>40.2</td>
<td>41.6</td>
<td>33.3</td>
<td>22.3</td>
<td>16.1</td>
<td>24.8</td>
<td>20.1</td>
<td>11.1</td>
<td>12.6</td>
</tr>
<tr>
<td></td>
<td>July</td>
<td>84.4</td>
<td>41.7</td>
<td>32.1</td>
<td>23.7</td>
<td>20.0</td>
<td>19.3</td>
<td>21.1</td>
<td>19.3</td>
<td>12.7</td>
<td>16.0</td>
</tr>
</tbody>
</table>

The Penman-Monteith model developed by FAO is the most extensively adopted methodology, because this model has the least difference between the \(ET_\theta\) predicted and the \(ET_\theta\) observed, as the mean difference in Table 6 suggests. However, the Penman-Monteith model requires a significant amount of meteorological data input, including radiation, air temperature, air humidity and wind speed data, which creates great complexity in data collection and computation. Instead, the Hargreaves model was used to calculate \(ET_\theta\), because the mean difference between the predicted \(ET_\theta\) and the observed \(ET_\theta\) is also relatively small, so is the standard deviation. Hargreaves model requires much less meteorological data input, as only monthly average mean temperature, daily temperature range and extra-terrestrial radiation are required, as shown in equation below (Zomer et al., 2006).

\[
ET_{\theta,\text{Hargreaves}} = 0.0023 \times RA \times (T_{\text{mean}} + 17.8) \times TD^{0.5},
\]

where RA is the monthly extra-terrestrial radiation expressed in the unit of mm/month as equivalent of water evaporation, \(T_{\text{mean}}\) is the monthly mean temperature in degree Celsius, and \(TD\) is the monthly average daily temperature range in degree Celsius. The
monthly averaged extra-terrestrial radiation data is obtained from CGIAR-CRI (n.d.) at 30 arc-second resolution, and the monthly mean temperature and the average daily temperature range data is obtained from WorldClim (n.d.) at 30-second resolution, and it is averaged during the 1950 – 2000 period.

To study the spatial land properties, we put Kenya in ArcGIS on a fishnet with 0.25-degree (~110 km) size pixels with the GCS_WGS_1984 coordinate system. The data sets of the land characteristics that are of interest to the crop production are imported into ArcGIS and overlaid on the Kenya fishnet. The land grade is calculated based on the land characteristics inputs with respect to the crop requirements. Each pixel is then studied in terms of the percentage of area for each land grade, which will eventually translate into percentage of arable land that are of grade 1 to grade 3 in each pixel for each crop.

The information on the current cultivated land for rainfed and irrigated maize, wheat and rice in the year 2000 is obtained from GAEZ (n.d.), and this cultivated land data is further processed to produce the Figure 7 below showing the cultivated percentage of the land in each pixel. As can be seen from the figures, for all the three crops, on average less than 10 percent of the pixels are currently cultivated.
Figure 7. Current harvested land fraction for maize, wheat and rice
4. Methodology

A model is used to investigate the prospect in crop production intensification in Kenya. The model is characterized with climatic data and the information on land properties of Kenya, and two optimization problems are proposed to firstly calibrate the model with respect to the climatic characteristics, and then utilize the model to maximize crop productions of the three crops. Each optimization problem is set up with GAMS with the non-negative decision variables (in bold fonts) and the input data specified, and the optimization results are obtained on the premise of satisfying the constraints.

4.1 Optimization 1 – current situation

The objective of the first optimization problem is to calibrate the model with historic climatic data and current cultivated land information so that the model could be an accurate representation of the current agricultural condition in Kenya. The decision variables include are estimated monthly precipitation and evapotranspiration in each pixel, and the data inputs are the recorded monthly precipitation and evapotranspiration data, the amount of water inflow and outflow in each pixel, and the current cultivated land fraction in each pixel for each crop.

The recorded evapotranspiration data includes several components: the evapotranspiration from maize, wheat and rice that are currently grown in Kenya, the evapotranspiration of other crops that are currently grown in Kenya, the evapotranspiration of the natural vegetation, and the evaporation from the urban and rural human inhabitants. In our model, we simplify the evapotranspiration term by dividing it to only two components: the crop evapotranspiration of maize, wheat and rice, and the non-crop evapotranspiration that encompasses all the rest of the evapotranspiration sources. Thus a discrepancy is created between the evapotranspiration data in our model and that in the actual situation. Similarly, there is also a discrepancy between the precipitation component in the model and that in the
actual situation due to the simple nature of the model. By minimizing the difference between the estimated data and the actual data, the discrepancy could be minimized and the accuracy of the model could be greatly improved.

The mean least-square-error methodology is adopted for this optimization problem, and the objective function is defined as to minimize the sum of the misfit terms, which is the difference between the estimated data and actual measurements of precipitation data and evapotranspiration. The first optimization problem is formulated as below.

Objective function:

$$
\text{Minimize } F_{\text{current}} = \sum_{t \in \Omega_{\text{ann}}(t)} \sum_{p \in \Omega(p)} \frac{1}{n_p} (\delta^2 E_{p,t} + \delta^2 P_{p,t})
$$

where:

$$
\delta E_{p,t} = \frac{1}{E_{p,t}} (\bar{E}_{p,t} - E_{p,t}) = \text{Evapotranspiration misfit in month } t \text{ in pixel } p
$$

$$
\delta P_{p,t} = \frac{1}{P_{p,t}} (\bar{P}_{p,t} - P_{p,t}) = \text{Precipitation misfit in month } t \text{ in pixel } p
$$

$$
P_{p,t} = \text{Estimated precipitation in month } t \text{ in pixel } p
$$

$$
E_{p,t} = E_{p,t}^{\text{non}} + \sum_{c \in \Omega(c)} E_{p,c,t}^{\text{crop}} = \text{Estimated total evapotranspiration in month } t \text{ in pixel } p
$$

$$
E_{p,t}^{\text{non}} = \text{Estimated non-crop evapotranspiration in month } t \text{ in pixel } p
$$

$$
E_{p,c,t}^{\text{crop}} = K_{c,t} ET_{o,p,t} f_{p,c,t} = \text{Current non-crop evapotranspiration in month } t \text{ in pixel } p
$$

$$
K_{c,t} = \text{Crop coefficient of crop } c \text{ in month } t
$$

$$
ET_{o,p,t} = \text{Reference evapotranspiration in month } t \text{ in pixel } p
$$

$$
f_{p,c,t} = \text{Current cultivated land fraction for crop } c \text{ in month } t \text{ in pixel } p
$$

$$
\bar{E}_{p,t} = \text{Historic total evapotranspiration in month } t \text{ in pixel } p
$$
\( \overline{P}_{p,t} \) = Historic precipitation in month \( t \) in pixel \( p \)

\( n_p \) = Number of pixels in the grid

\( p \in \Omega(p) \) = Set of pixels in the grid

\( c \in \Omega(c) \) = Set of crops (maize, wheat, rice)

\( t \in \Omega_{ann}(t) \) = Set of months in a year

\( t \in \Omega_{fallow}(t) \) = Set of fallow months in a year

\( t \in \Omega_{GS}(t) \) = Set of growing season months in a year

It should be noticed that when the month is out of the growing season of each crop, which is specified in Table 5, we assume no crops are grown, thus \( f_{p,c,t} = 0 \) for

\( t \in \Omega_{fallow}(t) \); when the month is within the crop growing season \( t \in \Omega_{GS}(t) \), \( f_{p,c,t} \) is constant throughout the whole growing season, and it is input into the optimization as known.

The historical monthly precipitation and evapotranspiration data is obtained from Wilmott and Matsura's Climate Data Archives (University of Delaware, n.d.) and averaged through the 1950 – 2000 period. The current cultivated land fraction for each crop in each pixel is calculated in Section 3.

As for the water resources constraints for the optimization, a water mass balance is imposed in each pixel. A groundwater storage change term is specified in each pixel on the right hand side of the water mass balance equation. Assuming sustainable irrigation practices, the change in groundwater storage each month is assumed be less than 15 percent of the annual precipitation, and the net change of the groundwater storage in one pixel throughout the whole year should add up to zero. Also, the non-crop evapotranspiration should be theoretically less than total precipitation in each pixel. The land constraint of the optimization is the conservation of land area, which means that the total cropped fraction and the non-crop fraction should be added up to 1 for each pixel.
The constraints of the first optimization problem are formulated as below:

\[
\text{Mass balance in each pixel: } Q_{\text{in},p,t} + P_{p,t} - E_{p,t} - Q_{\text{out},p,t} = \Delta S_{p,t}
\]

\[
\text{Groundwater storage change limit: } \Delta S_{p,t} \in [-0.15P_{\text{ann},p}, 0.15P_{\text{ann},p}]
\]

\[
\text{Sustainable irrigation practices: } \sum_{t \in \Omega_{\text{ann}}(t)} \Delta S_{p,t} = 0
\]

\[
\text{Non-crop evapotranspiration limit: } E_{p,t}^{\text{non}} \leq P_{p,t}
\]

\[
\text{Land conservation: } \sum_{c \in \Omega(c)} f_{p,c,t} + f_{p,t}^{\text{non}} = 1
\]

Where:

\[
Q_{\text{in},p,t} = \text{Water inflow in month } t \text{ in pixel } p
\]

\[
Q_{\text{out},p,t} = \text{Water outflow in month } t \text{ in pixel } p
\]

\[
\Delta S_{p,t} = \text{Groundwater storage change in month } t \text{ in pixel } p
\]

\[
P_{\text{ann},p} = \sum_{t \in \Omega_{\text{ann}}(t)} P_{p,t} = \text{Annual precipitation in pixel } p
\]

\[
f_{p,t}^{\text{non}} = 1 - \sum_{c \in \Omega(c)} f_{p,c,t} = \text{Non-crop land fraction in month } t \text{ in pixel } p
\]

The historic water inflow and outflow inputs in each pixel are calculated based on the water mass balance equation from the historical precipitation and evapotranspiration data from Willmott and Matsuura mentioned above, and the flowing routing map obtained from NTSG (n.d.) showing the direction of the outflow in each pixel. For a more detailed description on the calculation of this information, please refer to in Spatial and Temporal Allocation of Water and Land Resources for Optimal Cereal Production in Kenya.

As part of the results of the first optimization problem, the calibrated monthly precipitation and evapotranspiration data are used as the climatic characteristics of the model, which could be treated as an input in the second optimization problem. Also, the non-crop evapotranspiration rate in each pixel for each month could be calculated as below and input into the second optimization problem as a climatic characteristic of the model:
4.2 Optimization 2 – optimizing the crop production

In the second optimization problem, the objective is to maximize the total calorie production of the three crops in order to feed more Kenyan population. The calorie production increase, which is the result of the crop production increase, could be achieved by expanding the cultivation of crops onto lands that are deemed arable, and prioritizing the planting of the crops on land with better grade. For the base case scenario, we assume no application of fertilizer and the natural condition of the soil is evaluated in the determination of the land grade. The second optimization problem can be formulated as below:

The objective function is:

$$\text{Maximize } F_{\text{potential}} = \sum_{p \in \Omega(p), c \in \Omega(c)} \phi_c \times M_{p,c}$$

Where:

$$\phi_c = \text{caloric content of crop } c$$

$$M_{p,c} = \sum_{t \in \Omega_G(t)} \sum_{g,c \in \Omega_{\text{arable},c}(g)} (f_{p,g,c,t} y_{g,c}) L_p = \text{weight of crop production for crop } c \text{ on arable land throughout growing season in pixel } p$$

$$f_{p,g,c,t} = \text{Optimized cultivated land fraction for crop } c \text{ of grade } g \text{ in month } t \text{ in pixel } p$$

$$y_{g,c} = \text{Yield for crop } c \text{ of grade } g$$
\( g \in \Omega_{\text{arable}}(g) = \text{set of arable soil grades for crop } c \)

Similarly, when the month is out of the growing season of each crop, we assume \( f_{p,g,c,t} = 0 \) for \( t \in \Omega_{\text{fallow}}(t) \); when the month is within the crop growing season \( (t \in \Omega_{\text{GS}}(t)) \), \( f_{p,g,c,t} \) is constant throughout the whole growing season, and it is treated as a decision variable and an output from optimization two.

The water resources constraints for the second optimization problem are similar to those of the first optimization, except that the crop evapotranspiration terms are now considered as decision variables rather than known values. As for the land resources constraints, the optimized cultivated land fraction for each crop should be smaller than the maximum arable land fraction identified in each pixel.

The constraints for the second optimization problem are:

- **Mass balance:**  
  \[ Q_{in,p,t} + P_{p,t} - E_{p,t} - Q_{out,p,t} = \Delta S_{p,t} \]

- **Groundwater storage change range:**  
  \[ \Delta S_{p,t} \in [0.15 P_{p,ann}, 0.15 P_{p,ann}] \]

- **Sustainable irrigation strategy:**  
  \[ \sum_{t \in \Omega_{ann}(t)} \Delta S_{p,t} = 0 \]

- **The optimized cultivated land fraction limit:**  
  \[ f_{p,g,c,t} \leq f_{p,g,c}^{\text{arable}} \]

Where:

- \( P_{p,t} \) = Precipitation in month \( t \) in pixel \( p \) (input from optimization one)

- \( E_{p,t} = E_{p,t}^{\text{crop}} + E_{p,t}^{\text{non}} \) = Total evapotranspiration in month \( t \) in pixel \( p \)

- \( E_{p,t}^{\text{crop}} = \sum_{c \in \Omega(c)} \sum_{g \in \Omega_{\text{arable}}(g)} ET_{p,t} \times K_{c} \times f_{p,g,c,t} \) = Optimized crop evapotranspiration in month \( t \) in pixel \( p \)

- \( E_{p,t}^{\text{non}} = e_{p,t}^{\text{non}} \times f_{p,t}^{\text{non}} \) = Optimized non-crop evapotranspiration in month \( t \) in pixel \( p \)

- \( f_{p,t}^{\text{non}} = 1 - \sum_{c \in \Omega(c)} \sum_{g \in \Omega_{\text{arable}}(g)} f_{p,g,c,t} \) = Optimized non-crop land fraction in pixel \( p \)
\[ p_{p}^{\text{ann}} = \sum_{t \in \Omega_{\text{ann}}(t)} p_{p,t} \]  
Annual precipitation in pixel p (input from optimization one)

\[ f_{p.g,c}^{\text{arable}} = \text{Land fraction for arable land grade } g \text{ for crop } c \text{ in pixel } p \text{ (identified in the land suitability analysis)} \]

\[ g \in \Omega_{\text{arable}}(g) = \text{Set of arable grades of land (grade 1 to 3)} \]

As one land pixel might be identified arable for multiple crops, to prevent overlapping between optimized cultivated lands of the three crops, the following constraints are imposed.

\[ f_{p,t}^{\text{maize}} + f_{p,t}^{\text{wheat}} \leq f_{p}^{\text{ara,maize}} + f_{p}^{\text{ara,wheat}} - f_{p}^{\text{overlap,m+w}} \]
\[ f_{p,t}^{\text{maize}} + f_{p,t}^{\text{rice}} \leq f_{p}^{\text{ara,maize}} + f_{p}^{\text{ara,rice}} - f_{p}^{\text{overlap,m+r}} \]
\[ f_{p,t}^{\text{wheat}} + f_{p,t}^{\text{rice}} \leq f_{p}^{\text{ara,wheat}} + f_{p}^{\text{ara,rice}} - f_{p}^{\text{overlap,w+r}} \]
\[ f_{p,t}^{\text{maize}} + f_{p,t}^{\text{wheat}} + f_{p,t}^{\text{rice}} \leq f_{p}^{\text{ara,maize}} + f_{p}^{\text{ara,wheat}} + f_{p}^{\text{ara,rice}} - f_{p}^{\text{overlap,m+w}} - f_{p}^{\text{overlap,m+r}} - f_{p}^{\text{overlap,w+r}} + f_{p}^{\text{overlap,m+w+r}} \]

Where:

\[ f_{p,t}^{\text{maize}} = \text{Potential cultivated land fraction for maize in pixel } p \]
\[ f_{p,t}^{\text{wheat}} = \text{Potential cultivated land fraction for wheat in pixel } p \]
\[ f_{p,t}^{\text{rice}} = \text{Potential cultivated land fraction for rice in pixel } p \]
\[ f_{p}^{\text{ara,maize}} = \text{Arable land fraction for maize in pixel } p \]
\[ f_{p}^{\text{ara,wheat}} = \text{Arable land fraction for wheat in pixel } p \]
\[ f_{p}^{\text{ara,rice}} = \text{Arable land fraction for rice in pixel } p \]
\( f_{p \text{ overlap,} m+w} \) = Overlapped arable land fraction for maize and wheat in pixel \( p \)

\( f_{p \text{ overlap,} m+r} \) = Overlapped arable land fraction for maize and rice in pixel \( p \)

\( f_{p \text{ overlap,} w+r} \) = Overlapped arable land fraction for wheat and rice in pixel \( p \)

\( f_{p \text{ overlap,} m+w+r} \) = Overlapped arable land fraction for maize, wheat and rice in pixel \( p \)

In the above equations, the maximum arable land fraction for each crop in each pixel is identified through a Land Suitability Analysis, which is presented in the following section.

**4.3 Land suitability analysis**

A land suitability analysis is conducted to identify the arable fraction for each crop in each fishnet pixel. The land arability is dependent on the climatic, topographic and the soil characteristics of the land, and the data inputs of these three characteristics are resampled at 0.025-degree resolution, which is of one-tenth of the resolution of the Kenya fishnet with 0.25-degree pixels, meaning in each Kenya fishnet pixel the land is of varying characteristics. As mentioned in Section 3, five grades are specified for topographic, climatic and soil characteristics respectively after comparing the characteristic data with the crop requirement. Based on the climatic, topographic and soil grades of the land, an overall land grade ranging from 1 to 5 is determined for each crop on the Kenya fishnet. As the arable land grades are determined to be from grade 1 to grade 3, by counting the number of data pixels with arable overall land grade in each fishnet pixel, we can determine the arable land fraction in each fishnet pixel for each crop.

**4.3.1 Crop requirement**

Sys, C. et al (1993) has conducted a detailed evaluation on the crop requirements with
respect to climate, topography, and soil conditions, which serves as the guidance for determining the land arability of Kenya for each crop in the land suitability analysis.

4.3.1.1 Climate

Temperature affects the growth and development rate of crops, as low temperature may result in poor seed set and delay the flowering and maturation stages, while high temperature could shorten the crop growth duration and reduce the productivity of the crops (FAO 1996). In addition, the optimal photosynthesis rate of C3 (wheat and rice) and C4 (maize) crops can only be achieved within a certain temperature range, implying that the temperature could directly influence crop yield. In the evaluation framework, the characteristic that is taken into account is the mean daily temperature during the growing cycle of the crops (Sys et al., 1991).

The climatic requirements of crops are summarized in Table 7.

Table 7. Climatic requirement for maize, wheat and rice (Sys et al., 1991)

<table>
<thead>
<tr>
<th>Climatic Characteristics</th>
<th>Crop</th>
<th>Grade 1</th>
<th>Grade 2</th>
<th>Grade 3</th>
<th>Grade 4</th>
<th>Grade 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean temp. of the growing cycle (°C)</td>
<td>Maize</td>
<td>22 – 26</td>
<td>18 – 22;</td>
<td>16 – 18;</td>
<td>14 – 16;</td>
<td>&lt; 14;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>26 – 32</td>
<td>32 – 35</td>
<td>35 – 40</td>
<td>&gt; 40</td>
<td></td>
</tr>
<tr>
<td>Mean temp. of the growing cycle (°C)</td>
<td>Wheat</td>
<td>15 – 20</td>
<td>12 – 15;</td>
<td>10 – 12;</td>
<td>8 – 10;</td>
<td>&lt; 8;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20 – 23</td>
<td>23 – 25</td>
<td>25 – 30</td>
<td>&gt; 30</td>
<td></td>
</tr>
<tr>
<td>Mean temp. of the growing cycle (°C)</td>
<td>Rice</td>
<td>30 – 32</td>
<td>24 – 30;</td>
<td>18 – 24;</td>
<td>10 – 18</td>
<td>&lt; 18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>32 – 36</td>
<td>&gt; 36</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The climatic characteristic data inputs are the monthly maximum, minimum and mean temperatures averaged during the 1950 – 2000 period, which are obtained from WorldClim (n.d.) at 30-second resolution.

After comparing the climatic characteristic with the crop requirements, the climatic
grades for each crop are shown in Figure 8 below.

![Maps of maize, wheat, and rice grades](image)

**Figure 8. Temperature grade for maize, wheat and rice**

### 4.3.1.2 Topography

Land slope could affect the amount of runoff, which affects the water availability for both rain-fed and irrigated crop production. In low-lying region with depression landscape, even small amount of precipitation could be accumulated and cause water-logging for the crops, whereas greater slope would result in large amount of water runoff, which could limit the amount of water that is available for the crops. Irrigated agriculture has a more stringent land slope limitation than rain-fed crops, and different land utilizations types and irrigation methods also have varying slope requirements (Sys et al., 1991). Sys, C. et al. (1993) specified three land utilizations types for the crop
slope requirements: (1) Irrigated agriculture, basin furrow irrigation; (2) High level of management with full mechanization; (3) Low level of management animal traction or handwork. For the base case scenario, land utilization type (3) is chosen based on the current low management level in Kenyan agriculture system.

The topographic requirements for each crop are summarized in Table 8.

<table>
<thead>
<tr>
<th>Topographic Characteristic</th>
<th>Crop</th>
<th>Grade 1</th>
<th>Grade 2</th>
<th>Grade 3</th>
<th>Grade 4</th>
<th>Grade 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope (%)</td>
<td>Maize, Wheat</td>
<td>0-4</td>
<td>4-8</td>
<td>8-16</td>
<td>16-30</td>
<td>&gt;30</td>
</tr>
<tr>
<td></td>
<td>Rice</td>
<td>0</td>
<td>&lt;1</td>
<td>1-2</td>
<td>2-4</td>
<td>&gt;4</td>
</tr>
</tbody>
</table>

The slope input data is generated with the Slope tool in ArcGIS from the digital elevation model (DEM) at 250-meter resolution obtained from the World Resource Institute (WRI, 2007b).

After comparing the topographic characteristic with the crop requirements, the topographic grades for each crop are shown in Figure 9 below.
4.3.1.3 Soil characteristics

The soil characteristics could be divided into three categories: physical characteristics, fertility characteristics and salinity and alkalinity. The physical soil characteristics, such as texture, calcium carbonate and gypsum contents, could affect the availability of the moisture, the oxygen and the foothold for root development of the soil; the fertility soil characteristics including apparent cations exchange capacity (CEC), soil acidity and organic carbon could determine the available nutrients necessary for the crop growths; and the salinity and alkalinity of the soil are important limitations for the agricultural development (Sys et al., 1991).
Texture

Texture is considered as one of the most important physical soil characteristics, as it influences important soil properties such as water availability, infiltration rate, drainage, tillage condition and nutrient retaining capability. Texture is also an important consideration in choosing the irrigation method, as the soil texture could affect the infiltration rate of the irrigated water (Sys et al., 1991). According to USDA (1951), the textural class of the soil is calculated with respect to the clay, silt and sand content in the soil, and the calculation scheme is shown as the soil texture triangle in Figure 10. Coarse textured soil indicates high sand fraction, while fine textured soil indicates high clay fraction. For medium textured soil, the silt is dominant constituent (HWSD 2012).

![Figure 10. Soil texture triangle (USDA, 1951)](image)

Maize could adapt to a variety of soil textures that are well drained and well aerated, such as deep loam and silt loam soils; wheat can also grow on a broad range of soil textures from sandy loam to clay loam texture; rice growth prefers heavier soil textures with a higher clay texture (Sys et al., 1993).

CaCO₃

Studies have shown that moderate application of calcium carbonate to the cropland
could increase the weight of the dry matter in the plants (Babalar 2010), as calcium is required by plants as a type of nutrient to make up the constituent of the plant cell walls. However, high concentration of calcium carbonate could prevent the root penetration of the plants and might bring risks of lime-induced chlorosis for many crops, which could be detrimental for the crop yields (Sys et al., 1991).

**Gypsum**

Small content of gypsum is favorable for crop growth, as it improves the permeability and infiltration rate of the soil, and it serves as a soluble source of calcium as plant nutrients. A small amount of gypsum in the soil could also preserve the chemical and physical soil degradation by replacing sodium in exchange complex (Sys et al., 1991). However, high gypsum content would cause ion imbalance in the soil and substantially reduce the crop yields (FAO 1990).

It is found out in a study that 2 percent gypsum in soil is beneficial to crop growth, between 2 and 25 percent has little or no negative impacts, but more than 25 percent would cause reduction in crop yields (FAO 1990).

**Apparent cation exchange capacity (CEC)**

Apparent CEC is an indicator for the fertility of the soil, which reflects the relative ability of soils to store the group of nutrients in the form of cations. The most common soil cations include calcium ($\text{Ca}^{2+}$), magnesium ($\text{Mg}^{2+}$), potassium ($\text{K}^+$), ammonium ($\text{NH}_4^+$), hydrogen ($\text{H}^+$) and sodium ($\text{Na}^+$), while clay and organic matter particles are normally of net negative charge and are attractive to the cations. So CEC is measure of the total number of cations that could hold on the clay and organic matter particles (Mengel, n.d.).

**Base saturation**

Base saturation also reflects the fertility characteristics of the soil, and it is defined as the percentage of the basic cations ($\text{Ca}^{2+}$, $\text{Mg}^{2+}$ and $\text{K}^+$) presented in total CEC to distinguish from other acid cations, such as $\text{H}^+$ and $\text{Al}^{3+}$. High percentage of $\text{Al}^{3+}$ is
presented in low pH environment, which would hinder the growth of most plant species. Thus base saturation can be regarded as a fertility index for the soil (Sonon et al., n.d.). The higher the base saturation is, the more fertile the soil is.

\textbf{pH-H}_2\text{O}

pH-H\textsubscript{2}O is measured from the soil-water solution (as opposed to soil-KCL solution), as the pH-H\textsubscript{2}O value is an indicator of the acidity of the soil. Similar to base saturation, pH-H\textsubscript{2}O could also be correlated with the sum of exchangeable cations in the soil. Moreover, pH-H\textsubscript{2}O value could also imply probable soil toxicities. As mentioned in base saturation section, low pH value would introduce higher content of Al\textsuperscript{3+} in the soil, which could cause aluminium toxicity to the crops (Sys et al., 1991). Also, as soil gets more and more acidic, less phosphorus will become available to crops (Cornell University, n.d.). Acidic soil could be corrected with lime application, and alkaline soil could be corrected with sulfur application.

\textbf{Organic carbon}

The organic carbon is an important soil characteristic, as under natural vegetation the organic carbon content could often be used as a good expression of the natural fertility of the soil. Sys, C. et al. (1991) characterized three types of organic carbon: (1) Kaolinitic materials; (2) Non kaolinitic, non-calcareous materials; (3) Calcareous materials. The sum of the three types of organic carbon is used for land evaluation.

\textbf{Electrical conductivity (ECe)}

Salinity (ECe) is seen as one of the most common limiting factors in agricultural development (Sys et al., 1991). High salinity content could cause difficulty for plants to extract water from the soil, nutrients imbalances which would lead to plant toxication, and reduce water infiltration rate in the soil (Kotuby-Amacher et al., 2000). Maize, wheat and rice are of medium salt tolerance, meaning the crop yield is moderately sensitive to the increasing level of conductivity in the soil. Salinity will also affect the suitability for irrigation, because the amount of water to be applied will depend on the
salt content of the soil due to necessity for leaching practices (Sys et al., 1991).

**Exchange sodium percentage (ESP)**

ESP is an important soil characteristic, and it significantly influences the soil structure and permeability (Sys et al., 1991). As ESP increases, the soil tends to become more dispersed, which could break down the soil aggregates and lower the permeability of the soil to air and water. High ESP will also affect the nutrient availability to the crops, and may cause plant toxication with sodium, molybdenum and boron (Abrol et al., 1988). The salt tolerance is very crop-dependent, as the salt tolerance is extremely variable with different crops (Sys et al., 1991).

The soil requirements for each crop are summarized in Table 9 to 11 below.

Table 9. Soil requirement for maize (Sys et al., 1993)

<table>
<thead>
<tr>
<th>Maize</th>
<th>Grade 1</th>
<th>Grade 2</th>
<th>Grade 3</th>
<th>Grade 4</th>
<th>Grade 5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Texture</strong></td>
<td>C&lt;60s, Co, SiC, SiL, CL</td>
<td>C&lt;60v, SC, C&gt;60s, L, SCL</td>
<td>C&gt;60v, SL, LfS, LS</td>
<td>fS, S, LcS</td>
<td>Cm, SiCm, cS</td>
</tr>
<tr>
<td>CaCO3 (%)</td>
<td>0 – 6</td>
<td>6 – 15</td>
<td>15 – 25</td>
<td>25 – 35</td>
<td>&gt; 35</td>
</tr>
<tr>
<td>Gypsum (%)</td>
<td>0 – 2</td>
<td>2 – 4</td>
<td>4 – 10</td>
<td>10 – 20</td>
<td>&gt; 20</td>
</tr>
<tr>
<td>Apparent CEC (cmol (+)/kg clay)</td>
<td>&gt; 24</td>
<td>16 – 24</td>
<td>&lt; 16 (-)</td>
<td>&lt; 16 (+)</td>
<td>-</td>
</tr>
<tr>
<td>Base Saturation</td>
<td>&gt; 80</td>
<td>50 – 80</td>
<td>35 – 50</td>
<td>20 – 35</td>
<td>&lt; 20</td>
</tr>
<tr>
<td>pH H2O</td>
<td>6.2 – 7.0</td>
<td>5.8 – 6.2; 7.0 – 7.8</td>
<td>5.5 – 5.8; 7.8 – 8.2</td>
<td>5.2 – 5.5; 8.2 – 8.5</td>
<td>&lt; 5.2; &gt; 8.5</td>
</tr>
<tr>
<td>Organic Carbon (%)</td>
<td>&gt; 4</td>
<td>2.4 – 4</td>
<td>1.3 – 2.4</td>
<td>&lt; 1.3</td>
<td>-</td>
</tr>
<tr>
<td>ECe (dS/m)</td>
<td>0 – 2</td>
<td>2 – 4</td>
<td>4 – 6</td>
<td>6 – 8</td>
<td>&gt; 8</td>
</tr>
<tr>
<td>ESP (%)</td>
<td>0 – 8</td>
<td>8 – 15</td>
<td>15 – 20</td>
<td>20 – 25</td>
<td>&gt; 25</td>
</tr>
</tbody>
</table>
Table 10. Soil requirement for wheat (Sys et al., 1993)

<table>
<thead>
<tr>
<th>Texture</th>
<th>Grade 1</th>
<th>Grade 2</th>
<th>Grade 3</th>
<th>Grade 4</th>
<th>Grade 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Texture</td>
<td>C&lt;60s, SiC, Co, Si, SiL, CL</td>
<td>C&lt;60s, SC, C&gt;60s, L</td>
<td>C&gt;60s, SCL</td>
<td>SL, LfS</td>
<td>Cm, SiCm, LcS, fS, cS</td>
</tr>
<tr>
<td>CaCO3 (%)</td>
<td>3 – 20</td>
<td>0 – 3; 20 – 30</td>
<td>30 – 40</td>
<td>40 – 60</td>
<td>&gt; 60</td>
</tr>
<tr>
<td>Gypsum (%)</td>
<td>0 – 3</td>
<td>3 – 5</td>
<td>5 – 10</td>
<td>10 – 20</td>
<td>&gt; 20</td>
</tr>
<tr>
<td>Apparent CEC (cmol (+)/kg clay)</td>
<td>&gt; 24</td>
<td>16 – 24</td>
<td>&lt; 16 (-)</td>
<td>&lt; 16 (+)</td>
<td>-</td>
</tr>
<tr>
<td>Base Saturation</td>
<td>&gt; 80</td>
<td>50 – 80</td>
<td>35 – 50</td>
<td>&lt; 35</td>
<td>-</td>
</tr>
<tr>
<td>pH H2O</td>
<td>6.5 – 7.5</td>
<td>6.0 – 6.5; 7.5 – 8.2</td>
<td>5.6 – 6.0; 8.2 – 8.3</td>
<td>5.2 – 5.6; 8.3 – 8.5</td>
<td>&lt; 5.2; &gt; 8.5</td>
</tr>
<tr>
<td>Organic Carbon (%)</td>
<td>&gt; 6.1</td>
<td>3.7 – 6.1</td>
<td>1.5 – 3.7</td>
<td>&lt; 1.5</td>
<td>-</td>
</tr>
<tr>
<td>ECe (dS/m)</td>
<td>0 – 1</td>
<td>1 – 3</td>
<td>3 – 5</td>
<td>5 – 6</td>
<td>&gt; 6</td>
</tr>
<tr>
<td>ESP (%)</td>
<td>0 – 15</td>
<td>15 – 20</td>
<td>20 – 35</td>
<td>35 – 45</td>
<td>&gt; 45</td>
</tr>
</tbody>
</table>

Table 11. Soil requirement for rice (Sys et al., 1993)

<table>
<thead>
<tr>
<th>Rice</th>
<th>Grade 1</th>
<th>Grade 2</th>
<th>Grade 3</th>
<th>Grade 4</th>
<th>Grade 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Texture</td>
<td>Cm, SiCm, C+60v, C+60s, SiC</td>
<td>C-60v, C-60s, SiCs</td>
<td>Co, SiCL, CL, Si</td>
<td>SiL, SC</td>
<td>L and Lighter</td>
</tr>
<tr>
<td>CaCO3 (%)</td>
<td>&lt; 3</td>
<td>3 – 6</td>
<td>6 – 15</td>
<td>15 – 25</td>
<td>&gt; 25</td>
</tr>
<tr>
<td>Gypsum (%)</td>
<td>&lt; 1</td>
<td>1 – 3</td>
<td>3 – 10</td>
<td>10 – 15</td>
<td>&gt; 15</td>
</tr>
<tr>
<td>Apparent CEC (cmol (+)/kg clay)</td>
<td>&gt; 24</td>
<td>16 – 24</td>
<td>&lt; 16 (-)</td>
<td>&lt; 16 (+)</td>
<td>-</td>
</tr>
<tr>
<td>Base Saturation</td>
<td>&gt; 80</td>
<td>50 – 80</td>
<td>35 – 50</td>
<td>20 – 35</td>
<td>&lt; 20</td>
</tr>
<tr>
<td>pH H2O</td>
<td>6.0 – 7.0</td>
<td>5.5 – 6.0; 7.0 – 8.2</td>
<td>5.0 – 5.5; 8.2 – 8.5</td>
<td>4.5 – 5.0; 8.5 – 9.0</td>
<td>&lt; 4.5; &gt; 9.0</td>
</tr>
<tr>
<td>Organic Carbon (%)</td>
<td>&gt; 2</td>
<td>1 – 2</td>
<td>2 – 4</td>
<td>4 – 6</td>
<td>&gt; 6</td>
</tr>
<tr>
<td>ECe (dS/m)</td>
<td>0 – 1</td>
<td>1 – 2</td>
<td>2 – 4</td>
<td>4 – 6</td>
<td>&gt; 6</td>
</tr>
<tr>
<td>ESP (%)</td>
<td>0 – 10</td>
<td>10 – 20</td>
<td>20 – 30</td>
<td>30 – 40</td>
<td>&gt; 40</td>
</tr>
</tbody>
</table>
The pH-H$_2$O and organic carbon data of the 25cm topsoil are obtained from ISRIC World Soil Information (n.d.) at 1km resolution, and all the rest of soil characteristics data are obtained from the Harmonized World Database (IIASA, 2012) with spatially varying resolution, because the data was compiled from multiple sources with different resolution.

After comparing the soil characteristics with the crop requirements, the climatic grades for each crop are shown in Figure 11 below.

![Soil grade for maize, wheat and rice](image)

Figure 11. Soil grade for maize, wheat and rice
4.3.2 Land grade

After classifying the land into five grades with respect to climatic, topographic and soil characteristics, the overall land grade is obtained by superposing the three groups of characteristic grades. The worst grade of the three characteristics, that is the highest grade number, is chosen to be the overall land grade. The overall land grades for the three crops are shown in Figure 12.

\[\text{Legend}\]

Maize

Wheat

Rice

Figure 12. Overall land grade for maize, wheat and rice

4.3.3 Arable land fraction

The fraction of arable land in each Kenya fishnet pixel for each crop is calculated by
summing the number of data pixels that are shown to be arable after the land suitability analysis, and divided by the total number of data pixel within one fishnet pixel. As the result, the arable land fractions for each crop in each fishnet pixel are shown in Figure 13.

Figure 13. Arable land fraction in each fishnet pixel for maize, wheat and rice

As the figure suggest, the Central Highland and the Western Lake Basin regions show greatly potential for maize and wheat production, whereas the regions with high rice cultivation potential are scattered around the Coastal Region, the Western Lake Basin region, and the regions around the Central Highland and the elevated north end.
5. Results

5.1 Optimization 1

The results from the first optimization problem include the adjusted monthly precipitation, evapotranspiration, and the non-crop evapotranspiration rate for each pixel. After minimising the precipitation and evapotranspiration misfits between the estimated and the historic data, the estimated precipitation and evapotranspiration data is used to characterize the climatic characteristics of the model. The non-crop evapotranspiration rate on unit land area is calculated by dividing the non-crop evapotranspiration (in mm) by the non-crop land fraction (in percentage) in each pixel, as described in Section 4.1.

Table 12 shows the average absolute difference ($P_{\text{estimated}} - P_{\text{measurements}}$) and average relative change ($\left(\frac{P_{\text{estimated}} - P_{\text{measurements}}}{P_{\text{measurements}}}\right)$) and its standard deviation between the estimated and the measurement of the monthly precipitation and evapotranspiration data, which is averaged from 759 pixels (the number of pixels in the fishnet) in each month and the whole year. From the table, we could see that the estimated monthly precipitation is adjusted to be higher than the measurements, and the adjustment is significant in months including January, February, June and July. The estimated monthly evapotranspiration is adjusted to be lower than the measurements, and the adjustment is the greatest in the same months: January, February, June and July. The estimated evapotranspiration and the precipitation in April remain the same with no adjustment from the measurements.
Table 12. Statistics of the optimization one result

<table>
<thead>
<tr>
<th></th>
<th>$P_{\text{Est}} - P_{\text{Mea}}$ (mm)</th>
<th>Relative change</th>
<th>Standard Deviation</th>
<th>$E_{\text{Est}} - E_{\text{Mea}}$ (mm)</th>
<th>Relative change</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan.</td>
<td>3.1</td>
<td>10.70%</td>
<td>0.06</td>
<td>-7.45</td>
<td>-16.20%</td>
<td>0.12</td>
</tr>
<tr>
<td>Feb.</td>
<td>1.82</td>
<td>9.20%</td>
<td>0.06</td>
<td>-3.83</td>
<td>-13.30%</td>
<td>0.11</td>
</tr>
<tr>
<td>Mar.</td>
<td>0.27</td>
<td>0.70%</td>
<td>0.01</td>
<td>-0.3</td>
<td>-0.70%</td>
<td>0.01</td>
</tr>
<tr>
<td>Apr.</td>
<td>0</td>
<td>0.00%</td>
<td>0</td>
<td>0</td>
<td>0.00%</td>
<td>0</td>
</tr>
<tr>
<td>May</td>
<td>1.45</td>
<td>3.60%</td>
<td>0.05</td>
<td>-2.38</td>
<td>-4.70%</td>
<td>0.07</td>
</tr>
<tr>
<td>Jun.</td>
<td>1.03</td>
<td>8.40%</td>
<td>0.08</td>
<td>-6.44</td>
<td>-21.00%</td>
<td>0.24</td>
</tr>
<tr>
<td>Jul.</td>
<td>0.91</td>
<td>5.20%</td>
<td>0.07</td>
<td>-3.11</td>
<td>-8.80%</td>
<td>0.23</td>
</tr>
<tr>
<td>Aug.</td>
<td>0.91</td>
<td>3.70%</td>
<td>0.06</td>
<td>-2.47</td>
<td>-1.10%</td>
<td>0.38</td>
</tr>
<tr>
<td>Sep.</td>
<td>0.91</td>
<td>3.00%</td>
<td>0.05</td>
<td>-1.92</td>
<td>-3.30%</td>
<td>0.14</td>
</tr>
<tr>
<td>Oct.</td>
<td>0.24</td>
<td>0.60%</td>
<td>0.02</td>
<td>-0.34</td>
<td>-0.70%</td>
<td>0.02</td>
</tr>
<tr>
<td>Nov.</td>
<td>0.05</td>
<td>0.10%</td>
<td>0.01</td>
<td>-0.07</td>
<td>-0.10%</td>
<td>0.01</td>
</tr>
<tr>
<td>Dec.</td>
<td>1.53</td>
<td>4.10%</td>
<td>0.05</td>
<td>-2.46</td>
<td>-5.30%</td>
<td>0.07</td>
</tr>
<tr>
<td>Annual</td>
<td>1.02</td>
<td>4.11%</td>
<td>0.06</td>
<td>-2.57</td>
<td>-6.3%</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Figure 14 below summarizes the number of data points out of total 9,108 data points (759 pixels of the fishnet multiplied by 12 months) that are adjusted within certain ranges. It could be observed that for the estimated precipitation, most of the adjustment happens within the less than 5 percent range, and the highest adjust is 25 percent of increase from the historical precipitation data. No decrease adjustment is made for the estimated precipitation data. In comparison, for the estimated evapotranspiration, the majority of the data points remains unchanged or of really small adjustment, and the rest of the data is either increased by up to 5 percent, or decreased by up to 50 percent.
Figure 14. The count of data points in each adjustment range (Xydi, 2015)

Figure 15 shows the spatial distribution of the relative change \( \frac{(X_{\text{estimated}} - X_{\text{measurements}})}{X_{\text{measurements}}} \) between the estimated annual evapotranspiration and precipitation and the historical ones. As for the precipitation, the estimated precipitation in the Chalbi Desert and the coastal regions is adjusted to be higher than the historical data, and the estimated precipitation along the Great Rift Valley is of minor or no adjustment. As for the evapotranspiration, the estimated evapotranspiration is slightly smaller than the historical evapotranspiration in the Great Rift Valley and the Eastern Plateau region, and the estimated evapotranspiration are significantly reduced compared with the historical evapotranspiration over the Central Highland region and the elevated region along the border with Ethiopia in the north end.
With the estimated evapotranspiration data and the known current cultivated land fraction in each pixel, we can calculate the non-crop evapotranspiration rate in each pixel for each month, which is shown in Figure 16. The non-crop evapotranspiration rate in each pixel is used as an input data for the second optimization problem.
Figure 16. Non-crop evapotranspiration rate in each month
5.2 Optimization 2

The result of the second optimization problem shows the optimized cultivation land fractions in each pixel for maize, wheat and rice, which are shown in Figure 17.

Figure 17. Optimized cultivation land fraction for maize, wheat and rice

Figure 18 shows the absolute difference between the optimized and current cultivated land fraction. It can be observed that there is both expansion and elimination of the current land cultivation as the result of the optimization. As for maize, the optimized cultivation land fraction eliminates the current cultivation area along the coastal area and intensifies the cultivation around the highland area around Mount Kenya and the Lake Victoria basin in the west. The optimized wheat and rice cultivation lands have far
more expansion than elimination, which suggests huge potential for production increase of these two crops. In general, as for the total cultivated land of the three crops, the Central Highland region and the Lake Victoria basin region in the west show strong potential for cultivation intensification.

Figure 18. Absolute difference between the optimized and current cultivated land fraction for maize, wheat and rice in the base case scenario.

Table 13 shows the current and optimized total cultivation area and caloric production for each crop, as well as the percentage of increase of the optimized results from the current scenario \((X_{optimized} - X_{current}/X_{current})\). As the results suggest, in the base case scenario with the natural soil condition and the low management level input, the total cultivation land for maize could be doubled, and for wheat and rice the cultivation land could be potentially further expanded by about 20 and 200 times. With the expansion in cultivation area, maize can see a triple increase in the caloric production, whereas the
caloric production of wheat and rice could be increased by more than 25 and 500 times. As the result, the total cultivation area for the three crops has the potential to be increased by 4 times, and the total caloric production of the three crops could be potentially increased by 8 times.

Table 13. Summary of optimization two results in base case scenario

<table>
<thead>
<tr>
<th>Unit</th>
<th>Cultivate land fraction</th>
<th>Caloric Production</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Percentage</td>
<td>Kcal</td>
</tr>
<tr>
<td></td>
<td>Current</td>
<td>Optimized</td>
</tr>
<tr>
<td>Maize</td>
<td>2.59%</td>
<td>5.07%</td>
</tr>
<tr>
<td>Wheat</td>
<td>0.22%</td>
<td>4.53%</td>
</tr>
<tr>
<td>Rice</td>
<td>0.025%</td>
<td>4.81%</td>
</tr>
<tr>
<td>Total</td>
<td>2.84%</td>
<td>14.41%</td>
</tr>
</tbody>
</table>

5.3 Sensitivity Analysis

So far only the natural condition of the soil is taken into account in the land suitability analysis. However, with the soil modification practices, a few soil limitations could be excluded from the evaluation, enabling more land to be arable for cultivation. Also, with more investment in the agricultural sector, the management level of the farms could be improved in terms of the level of mechanization, which could further increase the production efficiency in the agricultural sector.

With an optimistic outlook, for the sensitivity analysis, a scenario with improved management level is proposed, where full mechanization is applied and the optimum level of fertilizer, pesticide and other soil modification methodologies are utilized. As the result of the full mechanization level, the topographic grade on Kenya for each crop needs to be updated according to the crop requirements, and the pH-H\textsubscript{2}O and organic carbon characteristics of the soil are excluded from the land suitability analysis, as the limiting pH-H\textsubscript{2}O of soil could be corrected with lime (low pH) or sulfer (high pH), and the organic carbon deficiency could be overcome with fertilizer application.

For the sensitivity analysis, slope requirement for the land utilization type (2) High level
of management with full mechanization is used, which is shown in Table 14.

Table 14. Slope requirement for maize, wheat and rice in high level of management scenario

<table>
<thead>
<tr>
<th>Topographic Characteristic</th>
<th>Crop</th>
<th>Grade 1</th>
<th>Grade 2</th>
<th>Grade 3</th>
<th>Grade 4</th>
<th>Grade 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope (%)</td>
<td>Maize, Wheat</td>
<td>0-2</td>
<td>2-4</td>
<td>4-8</td>
<td>8-16</td>
<td>&gt;16</td>
</tr>
<tr>
<td></td>
<td>Rice</td>
<td>0</td>
<td>&lt;1</td>
<td>1-2</td>
<td>2-4</td>
<td>&gt;4</td>
</tr>
</tbody>
</table>

With the new slope requirement and the exclusion of pH-H₂O and organic carbon content limitations, the arable land fraction under the high management level scenario is shown in Figure 19.

Figure 19. The updated overall grade on Kenyan land for maize, wheat and rice

The new arable land fraction in each fishnet pixel for each crop is also calculated, which
is shown in Figure 20. As the figures suggest, in the high management level scenario, almost the whole country is identified as arable for maize cultivation, and the arable regions for wheat and rice cultivation are also significantly expanded.

Figure 20. Updated land grades for maize, wheat and rice in high management input scenario

Figure 21 shows the optimized cultivated land fraction for the three crops under the high management level scenario. Compared with the Figure 17 of the base case scenario, the cultivation intensification for the three crops is of great extent, but around the same region. As for maize, compared with the base case scenario, the north-western region is added to the cultivation land; for wheat, cultivation is further intensified in the Central Highland region, and more rice is shown to be grown in the coastal region and the Eastern Plateau region, where more available grade 2 and grade 3 lands have emerged.
Figure 21. Optimized land cultivation fraction for maize, wheat and rice in high management level scenario.

Figure 22 shows the absolute difference between the optimized cultivation area and the current cultivation area for the three crops. It can be observed that the total cultivation areas for the three crops are shown to be significantly increased in Central Highland region, the coastal region and the Lake Victoria basin region.
Figure 22. Absolute difference between the optimized and current cultivated land fraction for maize, wheat and rice in high management input scenario.

The optimization results in the high management input scenario are summarized in Table 15. As the result of high management level with full mechanization and application of soil modification, the total cultivation area of the three crops could be increased by more than 10 times, and the caloric production of the three crops can be increased by more than 20 times.
Table 15. Summary of optimization results in high management level scenario

<table>
<thead>
<tr>
<th>Unit</th>
<th>Cultivate land fraction</th>
<th>Caloric Production</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Percentage</td>
<td>Kcal</td>
</tr>
<tr>
<td></td>
<td>Current</td>
<td>Optimized</td>
</tr>
<tr>
<td>Maize</td>
<td>2.59%</td>
<td>15.89%</td>
</tr>
<tr>
<td>Wheat</td>
<td>0.22%</td>
<td>10.78%</td>
</tr>
<tr>
<td>Rice</td>
<td>0.025%</td>
<td>6.47%</td>
</tr>
<tr>
<td>Total</td>
<td>2.84%</td>
<td>33.14%</td>
</tr>
</tbody>
</table>
6. Discussion

6.1 Model limitation

The optimized results of the cultivation area and caloric production for maize, wheat and rice from the base case and high management level scenarios both suggest huge potential for production increase for maize, wheat and rice in Kenya. However, it is necessary to discuss the limitations of the model and the implications on the optimization results. The model completely excludes the land demand for other uses, such as the cultivation of other crops, pastoral area for grazing livestock, the rural and urban settlements and the protected area, which could pose uncertainty on the optimization results.

As for the land demand of other crops, the agricultural cultivation area takes up 20 percent of the total area of Kenya in 2000, and only 2.84 percent of the total land area of Kenya is dedicated to maize, wheat and rice. Table 16 shows the top eleven crops with the highest cultivation acreage in 2000. From Table 16, it can be seen that beans and pulses also constitute a significant portion of the cultivation land, as they are important food sources for protein in Kenyan diet. Coffee and horticulture including vegetables and fruits are also among the list of the crops with highest cultivation area, since they are important cash crops which combined account for more than 40 percent of the total agricultural exports (Embassy of Kenya, n.d.). Thus, with these crops that demand guaranteed land resources in mind, the results from our model should be viewed as a general estimation of the maximum production potential of the three most consumed cereals in Kenya, whereas in reality the production growth of the three crops should be proportional to the overall production growth of the agricultural sector.
Table 16. Top 11 crops with the highest cultivation acreage in year 2000 (FAOSTAT, n.d.)

<table>
<thead>
<tr>
<th>Crop</th>
<th>Acreage (1000 ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td>1500</td>
</tr>
<tr>
<td>Pulses</td>
<td>1151</td>
</tr>
<tr>
<td>Beans</td>
<td>771</td>
</tr>
<tr>
<td>Roots and Tubers</td>
<td>232</td>
</tr>
<tr>
<td>Oil crops Primary</td>
<td>214</td>
</tr>
<tr>
<td>Oil cakes Equivalent</td>
<td>198</td>
</tr>
<tr>
<td>Pigeon peas</td>
<td>172</td>
</tr>
<tr>
<td>Coffee</td>
<td>170</td>
</tr>
<tr>
<td>Vegetables</td>
<td>150</td>
</tr>
<tr>
<td>Fruit</td>
<td>150</td>
</tr>
<tr>
<td>Wheat</td>
<td>132</td>
</tr>
</tbody>
</table>

As for the possible overlapping between crop cultivation area and pastoral area, the arid and semi-arid lands are identified as suitable for grazing, whereas the land with better precipitation condition is deemed arable for crop cultivation (Suttie et al., 2005). Thus, it is safe to assume that the potential pastoral land has been excluded during the land suitability analysis and poses insignificant impacts on the optimization results. In fact, the expansion of crop farming could be a threat to the pastoral area for grazing. One of the examples is Massai people who have progressively lost some of their grazing land to crop farming (Kioko et al., 2012). Thus the tension between the agricultural and livestock sectors in terms of land use should be further studied, and an incorporative development plan for both farming and livestock sectors should be established.
Figure 23 shows the distribution of several land cover types in Kenya. As the figure suggests, about 11.6 percent of the land in Kenya is under protection (World Bank, n.d.), where agricultural development activities are strictly forbidden. Therefore, the optimization results of the cultivation land for the three crops should be excluded within the protected area. As for the area used for major settlements, since Kenya has a very low urbanization rate with only 25 percent of the population live in urbanized environment in 2013 (World Bank, n.d.), the major settlement areas are decided to be neglected, and it should be safe to assume that the impacts of the human settlements on crop cultivations are insignificant. The bare area and wetland are both excluded from the land suitability analysis, thus their impacts on crop cultivation land results are very small as well.

6.2 Inefficiencies in crop productions

Despite the limitations of the model, the optimization results show consistent optimistic projections with the findings of governmental and research organizations. For example, a study estimated that the irrigated rice cultivation could increase by 2.3 million
hectares (FAO 2012), which is close to the 2.8 million hectares of increase calculated in our model. So the question remains: why is Kenya not producing as much food as its capacities suggest? To answer this question, the current agricultural practices for the production of maize, wheat and rice are examined, and the limiting factors of the practices and the policy are identified.

Maize Production and Consumption from 2003 to 2013

![Maize Production and Consumption from 2003 to 2013](image)

Figure 24. Maize production and consumption from 2003 to 2013 (FAOSTAT, n.d.)

70 percent of the maize production comes from small-scale producers, and the rest 30 percent comes from large-scale farms. The small-scale farmers mainly grow maize for subsistence, retaining up to 58 percent of their total output for household consumption (Onono et al., 2013). The average maize yield in Kenya is 2 tonnes per hectare, which is far below the highest attainable yield of 4.2 tonnes per hectare suggested by Muller et al. (2012). The underperforming yield is blamed on the high input cost, lack of funding and inadequate governmental extension services for the small-scale farmers, which results in low-level applications of modern production technologies such as high yielding maize varieties and fertiliser (Onono et al., 2013). Onono et al. (2013)'s results suggest that 1 percent increase in the ratio of fertiliser to maize prices reduced maize production by 0.18 percent, which is largely due to the small-scale farms that dominate the maize production, and they tend to retain maize for household consumption when fertiliser price goes up. So in order to increase maize production, Kenyan government should
provide the small-scale farmers with subsidies for higher level of input, as well as more accessible extension services.

Compared with maize, wheat production in Kenya is dominated by medium- and large-scale farms that output 83 percent of the tonnage production and take up 75 percent of the acreage. These wheat farms are equipped with capital-intensive technologies that are competitive with that in the Western Europe. The rest of the wheat production is undertaken by the small-scale wheat farmers who receive effective tariff protection from imports (FAO 2013). As shown in figure, the production of wheat remained constant until 2009, when a drought hit Kenya and the wheat production plummeted.

Wheat farming is input-intensive in terms of mechanization level and the application of fertilizer and chemicals, which account for about 60 percent of the total cost for wheat production. Thus, the inefficiency in wheat production can be attributed to the high cost of these inputs. Furthermore, the majority of the currently cultivated wheat varieties are the older generations and of low yield (Gitau et al., 2011). And the wheat varieties cultivated in Kenya tend to carry the wheat stem rust (Ug99), and with farmers recycling the seeds, the disease keeps prevailing in the wheat farms, which contributes
to the low yield.

![Graph of Rice Production and Consumption from 2003 to 2013](image)

Figure 26. Rice production and consumption from 2003 to 2013 (FAOSTAT, n.d.)

The majority of rice production in Kenya is undertaken by small-scale farmers. About 95 percent of the rice grown in Kenya is from irrigation schemes while the remaining 5 percent is produced under rain-fed condition. To fully unlock the potential of rice production, the inefficiencies in the current cultivation scheme could possibly hinder the process. First of all, rice production is labor intensive, as the labor cost takes up 56 percent of the total cost. Appropriation of machinery is a feasible way to reduce the labor cost. However, the capital cost of the mechanization could also be significant for the small-scale farmers. Secondly, as the rice production is divided among small units, the water rationing emerged under this cultivation scheme greatly affects the intensity in rice production, causing some farmers to completely abandon rice production. Last but not the least, the poor irrigation infrastructure and uneven distribution of the rice mills are identified as one inefficiency in rice production, as the value chain does not efficiently connect the production to the market, which could hinder the farmers’ interest in intensifying the rice production (Gitau et al., 2011).
7. Conclusion & Further work

In order to study the potential increase in the productions of maize, wheat and rice in Kenya, a model was proposed firstly as the representation of the current agriculture conditions for the three crops, then the model was used to optimize the cultivation area for each crop with specified land and water constraints. Two optimization problems were set up in GAMS: the first optimization problem adjusted the estimated evapotranspiration and precipitation data with the mean least-square-error methodology, and the second optimization problem optimized the cultivation land for each crop based on land and water constraints.

As for the second optimization problem, a land suitability analysis was carried out to determine the arability of Kenyan land for maize, wheat and rice respectively according to the crop requirements summarised by Sys, C. et al. (1993). Climatic, topographic and soil characteristics of the Kenyan land were evaluated, and the data sets for the three characteristics were collected and imported into ArcGIS. As the result, Kenyan land was categorized into five grades, and the percentage of the arable land in each fishnet pixel was calculated for each crop. This information was then input into the second optimization as land constraints for the optimization problem. The water constraint for crop cultivation optimization is further discussed in Spatial and Temporal Allocation of Water and Land Resources for Optimal Cereal Production in Kenya (Xydi, 2015).

As the result of the first optimization, the estimated precipitation was adjusted to be up to 5 percent higher than the historical precipitation data, while the estimated evapotranspiration was adjusted from increasing by 5 percent to decreasing by 50 percent. The results from the second optimization showed that the cultivation land for maize could be doubled, and for wheat and rice the cultivation land could be increased by about 20 times and 200 times respectively. The optimized total caloric production of maize, wheat and rice showed a potential to be increased by about 2 times, 25 times, and 500 times respectively. The high management input scenario proposed in the
sensitivity analysis showed an even greater potential for the cultivation land the caloric production.

The limitations of the model were also discussed in terms of the land resources demanded by other types of use. The discussion indicated that the results in this only served as a general estimation for the maximum production of these three crops, since the land use for other crops and the protected area in Kenya were not excluded from the scope of optimization. The inefficiency in current production of the three crops were also presented. The high input cost and lack of funding and extension services support were identified as the biggest obstacles for expanding the agricultural sector in Kenya, together with other limitations in terms of old crop varieties, crop diseases, and inadequate development of supportive infrastructures.

As this project is only a preliminary study on the production increase potential of three selected crops, a feasible focus of the future work could be integrating more crops of the Kenyan diet into the optimization problem, which will greatly increase the computational complexity in terms of the crop cultivation combinatorial problem with spatially and temporally varying crop data inputs. Also, a more detailed land suitability study could be established to incorporate more land characteristics, such as the relative humidity and coarse fragmentation in the soil, in order to investigate the impacts of these additional characteristics on crop production. Last but not the least, an in-depth study of the social-economic and social-political environment of Kenya should be conducted, as a better knowledge of these social factors in Kenya could be very useful in terms of understanding the potential opportunities and obstacles in intensifying the crop production in Kenya.
Bibliography


Arid Zone Studies, University of Wales, Bangor.


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