DEVELOPMENT OF SOIL CLIMATE REGIMES OF KENYA USING SPATIAL JAVA NEWHALL SIMULATION MODEL

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A THESIS SUBMITTED TO THE SCHOOL OF AGRICULTURE AND BIOTECHNOLOGY IN THE PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF MASTER OF SCIENCE DEGREE IN SOIL SCIENCE, UNIVERSITY OF ELDORET, KENYA.

2015

DECLARATIONS

Declaration by student

This thesis is my original work and has not been presented in any other university for the award of a degree. To that effect no part of this work should be reproduced without the authority of the author and University of Eldoret.

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Sign…………………

Date……………….

Declaration by supervisors

This thesis has been submitted for examination with our approval as the university supervisors.

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DEDICATION

To my dad, Robert Ngunjiri; my mom, Margaret Ngunjiri; my brothers and sisters, Njeri, Charles, Mugane and Gladys; my nephews and nieces, Berti, Terry, Chichi, Robbie, Kim and Shiro; and my grandmother (RIP), Wangunju.

ABSTRACT

Climate change is a fundamental threat to food security, development and the fight against poverty. Identification of strategies to alleviate its impacts on agriculture is essential. One such strategy is making future climate predictions which help to develop ways to fight possible outcomes such as food shortages. Unfortunately, there is limited available information on biophysical data (especially up-to-date soil maps) required for multipurpose and specific land use planning. Soil maps production has for long relied on expert knowledge and manual delineation which has several limitations. This has led to low soil map production, a process that requires tremendous amounts of time and resources. Unlike paper maps, digital maps are accurate and can be updated easily with new information. However, use of current digital soil mapping techniques and models such as spatial Java Newhall simulation model and is not common in Kenya due to, among other factors, lack of expert knowledge and resources to undertake the soil survey procedures. The purpose of this study was to develop a digital soil climate map of Kenya illustrating the water and temperature constraints for agriculture, both for present and future conditions. Soil temperature and moisture regimes were estimated from the Newhall simulation model, using present (1971-2000) atmospheric climate records and future (2050) projected climate scenarios (precipitation and air temperature) from World Climate- Global Climate Data (Version 1.4). Records of temporal monthly patterns of the soil moisture and temperature regimes were then digitally mapped using ArcGIS for Desktop software. A relationship between the different soil temperature and moisture regimes and some of the current major crops was then explored. Spatial comparisons, in percent change units, was done to detect changes in soil climate between present and future conditions using subtraction method. The spatial comparison maps created were also used against crop spatial distributions, and a relationship derived. The output showed that Kenya is dominated by isohyperthermic, isothermic and isomesic soil temperature regimes both for current and future conditions. The aridic, ustic and udic soil moisture regimes also dominate the country in both conditions. Over 80% of the country will not experience changes in soil temperature in future global climate change scenarios expected in year 2050, but about half of it is expected to experience increases in soil moisture according to the model. Although the cryic temperature regime is present in both times, it covers less area in the future climate conditions where it is completely absent in the Aberdare Mountain Ranges of central Kenya. Thermic temperature is absent in current conditions but is expected to occur in the future while this is the reverse for pergelic temperature regime. Soil climate-crop relationships showed possible suitable soil moisture conditions for diversity in crop growth in the arid and semi-arid parts of Kenya. It was concluded that the variations in rainfall and temperatures due to climate change are likely to impact on Kenyan agriculture. To take advantage of the expected increases in soil moisture in the arid and semi-arid parts of Kenya, policies on land use need to be aligned to this. Overall, the techniques adopted for estimating the soil climate regimes in this study shows promising results, but field measurements and more expert knowledge are still needed for validation and fine tuning of the process.

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LIST OF ACRONYMNS

ArcGIS	Aeronautical Reconnaissance Coverage Geographical Information System
AWC	Available water content
DEM	Digital elevation model
DSM	Digital soil mapping
FC	Field capacity
GCM	Global circulation model
IPCC	Intergovernmental Panel on Climate Change
jNSM	java Newhall simulation model
MCS	Moisture control section
NRCS	National Resources Conservation Service
PET	Potential evapotranspiration
PWP	Permanent wilting point
RCP	Representative Concentration Pathway
USDA	United States Department of Agriculture

ACKNOWLEDGEMENTS

I would like to acknowledge the University of Eldoret and Purdue University for enrolling me as graduate student and for giving me the opportunity to attain knowledge. Many thanks to the United States Department of Agriculture-Natural Resources Conservation Service, Soil Survey for funding me throughout this study.

I would like to acknowledge the continuous support and invaluable guidance that my advisers, Dr. Phillip Owens (Purdue University) and Prof. Wilson Ng'etich (University of Eldoret) have given me since the onset of my interest to undertake my MSc project in the United States. I must say that their tremendous efforts especially in my U.S travel plans, have amazingly inspired me to work hard. Dr. Phillip Owens' contribution to the success of this research work was so bountiful that I at times ended up connecting with other soil scientists, outside Purdue University, looking for solutions. In this respect, I would like to acknowledge the integral contribution of Zamir Libohova and Sharon Waltman of USDA-Natural Resources Conservation Service. I also acknowledge Edwin Winzeler and Dr. Darrell Schulze (Purdue University). Your contributions throughout my research have not only earned me knowledge and experience in my field of study, but also enlightened me on other scopes of science. I am also highly indebted to the Owens' lab group (Bob Brown, Minerva Dorantes, Jenette Goodman, Shams Rahmani and Divya Virginin).

I am grateful to my family for their unceasing support and prayers during my study. It is with their love and support that I have come this far in life. This especially goes to my parents who have sacrificed so much for my success. God bless you all.

CHAPTER ONE

INTRODUCTION

1.1 Introduction

Kenya has a total land mass of about 569,140km^{2}and a population of about 43 million people (World Bank, 2012). It lies between latitudes 5^{0}N and 5^0 S and longitudes 34^0 and 42^{0}E. The climate in Kenya varies from tropical along the coast to temperate inland to arid in the north and northeastern parts of the country. Seventy percent of Kenya's merchandise exports are agricultural (Pearson, 1995) and dominates the country's economy (it accounts for about a third of gross domestic product), although only 15-17 percent of its land has sufficient fertility and rainfall to be farmed. Over 80% of Kenya is arid and semi-arid land (ASAL) with low agricultural potential. Out of the ASAL's 48 million ha, 24 million ha is only useful for nomadic pastoralism; the rest can support some commercial ranching and irrigated agriculture but with added technological input which is however limited due to high poverty levels (Orindi et al., 2007). The extent and depth of food insecurity in Kenya, being a developing country, remains unconscionable. National food security, as with other countries, is a key objective of the agricultural sector. The current food insecurity problems are attributed to, among other factors, climate variability, high costs of domestic food production due to high costs of farm inputs (especially fertilizer), high global food prices and low purchasing power due to high poverty levels (KARI, 2012).

In the past climate has been treated as static in soil classification and soil surveys. In soil climate studies, it is difficult to handle scale, resolution and time due to the mesoscale processes and microclimates involved. However, with the current climate change concerns, advances in precision farming and integrated crop management, there is need to improve the existing soil survey information and the evaluation of soil quality (Waltman et al., 1997).

Soil climate refers to the long-term record of seasonal and diurnal patterns of the most dynamic soil properties, mainly soil temperature and moisture. Soil temperature controls processes below ground for global and continental carbon budgets. The influence of soil temperature on soil decomposition and respiration is exponential and not linear (Raich and Schlesinger, 1992). Soil moisture forms a principal part of the plant as a whole and it drives many physical, chemical and biological processes of a soil. Soil moisture and soil temperature can be said to be dependent since they affect each other. Air temperature has a good correlation with soil temperature since both of them are determined by the energy balance at the ground surface. Also, precipitation and soil moisture are directly proportional. This relationship can be seen in the fact that the amount of precipitation determines the amount of soil water, assuming there is no any other external recharge system.

The Newhall Simulation Model (NSM), also known as Franklin Newhall’s model, for soil temperature and moisture regime determination, was originally written in COBOL (Newhall and Berdainer, 1994) then re-implemented in GW-BASIC (Wambeke et al., 1986 & 1992; Wambeke, 2000). This GW-BASIC version, also referred to as Van Wambeke 1.0, formed the computational basis for the new java NSM. The java NSM (jNSM) simulation acts in a similar manner to the original model given the same datasets and assumptions. It is an effective 1:1 port of the original model but goes further to incorporate additional features such as annual and summer water balances. jNSM is a desktop client application that employs Java 5 (Oracle Corporation) and Adobe Flex. The Flex and Java are integrated into an Adobe AIR executable application.

The jNSM simulates soil moisture and temperature data for calendar days through integration of monthly atmospheric climate data into information relevant to soil classification (Wambeke, 1982; Newhall and Bardanier, 1996). The jNSM has been used internationally in studies of soil taxonomy, responses of crops to weather and yield predictions (Bonfante et al., 2011, Jeutong et al., 2000, Waltman et al., 2011). For example, it has been used by the US Soil Survey for estimating soil climate from atmospheric climate records of weather stations since the 1970. In the US, the soil moisture regimes have been related to crops as: soils too dry to grow non irrigated crops (aridic), soils that grow crops without irrigation (udic) and soils that grow drought tolerant crops (ustic); wet soils (aquic) and soils found in the mediterranean climate (xeric) (Smith, 1982).

This mesoscale model assumes that excess precipitation is lost through runoff or deep percolation and hence its use is limited to well-drained soils. In the case of poorly drained soils, terrain attributes might be used as surrogates, though this process requires further refinement. The jNSM does not account for snowmelt nor antecedent moisture conditions and only functions on a calendar year rather than a hydrological year. Nevertheless, it provides useful monthly approximations for soil moisture (number of days dry, moist and partly dry or partly moist) and soil temperature (number of days <0°C, ≥0°C- < 8°C, ≥8°C- <15°C, ≥- 15°C<22°C and ≥22°C). Input for the jNSM is not intensive since it relies on monthly summary data of precipitation and air temperature rather than daily weather data. This monthly input data is available worldwide through datasets from various global circulation models. The mesoscale approximation of soil climate makes jNSM an important tool to soil survey, taxonomic classification and associated land-use (Smith, 1986).

The jNSM couples water balance more directly with available water-holding capacity as compared to other field scale models, which generate inferences of soil moisture and temperature parameters from climate records. Such models include EPIC and CENTURY (Constantini et al., 2000 and Williams et al., 1989). The jNSM also goes further to give output of the predicted soil temperature and moisture regimes. These outputs are used to assign taxonomic classes according to U.S Soil Taxonomy (1999) and FAO-UNESCO Soil Classification System (1974, 1988).

Digital soil mapping based on geographical information system data layers produce systematic digital maps by use of environmental covariates (McBratney et al., 2003). In the past, soil mapping was done manually by experts by use of interpolation and hand drawing climate boundaries leading to so many limitations which include: limitations to the size of the soil body that can be delineated, limited ability to update maps fast and efficiently, and the inevitability of errors since they are constructed using visual examination of the environmental covariates (Zhu et al., 2001). Knowledge regarding these traditional maps sometimes requires expert persons since they understand why certain delineations were made (Hudson, 1992). Lack of application of this expert knowledge at times leads to inconsistency since different experts may differ in interpretation. This calls for use of digital soil mapping (DSM) techniques which provides a standardized approach. In DSM, semi-automated techniques and technologies are used to acquire process and visualize information on soil types and properties and other auxiliary information. The end maps that are created are explicit, consistent and less expensive (Winzeler et.al. 2013). Also DSM products of the data-driven or statistical soil mapping tend to be more accurate and uncertainty can be more easily updated when new information is available.

This study aimed at providing information on soil moisture and temperature regimes of Kenya which in the past has never been executed using consistent data and statistical soil mapping techniques (Winzeler et al., 2013). Soil climate maps are useful harmonization to local soil surveys, corrects abrupt changes in soil maps at political boundaries (Scheffe et al., 2012) and offers versions of soil properties that can be analyzed without use of artifacts from local political boundaries.

1.2 Problem statement

Current climate change concerns, advances in precision farming and integrated crop management call for need to improve the existing soil survey information and the evaluation of soil quality in order to improve food security. Unfortunately, there is limited information available to the scientists and researchers to provide biophysical information required for multipurpose and specific land use planning. Production of soil maps in Kenya has in the past relied on expert knowledge and manual delineation (traditional method) which has several limitations such as inaccurate delineations, lack of useful information on soil properties and absence of flexibility for updating the maps when new information is available (Zhu et al., 2001). Hand-drawn maps are also inexplicit, inconsistent and very expensive (Winzeler et.al. 2013). This has led to low map production which requires tremendous amounts of time and financial resources. Use of simulation models such as java Newhall Simulation Model (jNSM) and current digital soil mapping techniques is not commonly used in Kenya due to unavailability of these technologies and lack of expert knowledge.

The hand-drawn map of calculated soil moisture and temperature regimes of Africa by Van Wambeke (1982) relied on heterogeneous sources of climatic data which led to many inconsistencies in his output. Also, the global soil climate regimes map developed by USDA-NRCS (2011) based on interpolation of over 20,000 climatic stations made overgeneralizations due to limited climatic data. From expert knowledge, this interpolated global soil climate map gave wrong delineations for Kenya's soil climate regimes especially to the eastern and northwestern Kenya, where xeric moisture regime (for Mediterranean climates) was demarcated. Also, the humid climates (expected to have a udic moisture regime) in the central and western parts of the country were delineated as having an ustic moisture. Such inaccurate soil climate information has led to lack of information to provide ecosystem services such as produce crops, store carbon and carbon deficits.

Many current and future world climate databases such as World Clim are open sources hence, available for public use. These databases have voluminous and up-to-date climatic data, for both current and future climatic conditions, with a pixel resolution of about 1 km, which is more accurate and precise compared to the latter. Although this is the case, these data sources are rarely used especially in developing countries like Kenya.

1.3 Justification

This study was carried out in order to avail information on the different soil temperature and moisture regimes in Kenya for both present and future climate and consequently, possible shifts in crops grown with climate change. It will offer a version that is more accurate and consistent as compared to the output maps by USDA (2011) and Wambeke (1982). The finer pixel resolution (approximately 1km) of the climatic data used in this study will be essential in making soil- crop- water relationships, which are very useful to crop modelers in determining the most suitable and capable crops in a region, in relation to the specific soil climate. Assessments of soil climate-crop relationships are essential in order to understand the implications for crop production due to climate change especially. Such assessments create awareness and provide useful information on impacts and adaptation to climate change which contributes to increase in potential land productivity and management of the different cropping systems, improves food security, improves the country's living standards and in general, increases the gross domestic product of a country like Kenya, whose major economic activity is farming. Also, making future soil climate predictions and assessing the relationships between crop productivity and climate change will help to develop ways to fight outcomes such as food shortages.

This study will avail information to the government of Kenya, which if implemented-in form of land use policies, will improve the soil productivity in the different regions of the country and help to solve land use issues. The soil climate map of Kenya developed can also act as a basis for further research on the soils of Kenya.

1.4 Main Objective

To produce a soil climate map of Kenya illustrating the water and temperature constraints for agriculture, both for present climatic conditions and future projected climate scenarios using the java Newhall simulation model

1.5 Specific Objectives

1) To identify the different soil moisture and temperature regimes in Kenya for both current and future climate conditions.
2) To draw a relationship between current and future soil climate regimes and some of the major suitable crops currently grown in Kenya
3) To draw spatial comparisons between the current and future soil climate regimes

1.6 Hypotheses (null)

H_0: There is no difference in current soil climate and future projected soil climate.

H_0: Soil climate has no effect on crops, land use practices and management.

CHAPTER TWO

LITERATURE REVIEW

2.1 Soil moisture

Soil moisture is the amount of water contained in the soil after precipitation seeps into the ground. It is the water held within soil pores. Soil moisture influences hydrological and agricultural processes, runoff generation, drought development and many other processes. It is also important in meteorological studies of climate system through atmospheric feedbacks. In agriculture, soil water is a principal constituent of the growing plant. It acts as a solvent and carrier of nutrients for plant growth (photosynthates to plant parts). Yield of crop is often determined more (or to a large extent) by the amount of moisture available rather than the deficiency of the essential nutrients. Soil moisture regulates soil temperature and the soil forming processes on it. For microbial activity to occur water is needed for their metabolic activities.

There are several factors that affect soil moisture. This includes:

Finer soil texture has more pore space and also surface area and hence there is greater water retention. Well- aggregated porous structure favors better porosity which in turn enhances water retention. Higher organic matter content increases water retention while a higher soil density decreases soil water retention. The salt content also affects the moisture content in that, the more the salt content in the soil, the less the water retention. Presence of 2:1 clays and greater soil depth also increases water retention in the soil.

2.1.1 Soil Moisture regimes

Soil moisture regimes refers to the level of ground water or to the seasonal presence or absence of water held at a tension of less than 1500 kPa in the soil or in specific horizons during periods of the year (USDA Soil Taxonomy, 2010). Water held at a tension of 1500kPa or more is not available to keep most mesophytic plants alive. This means that a horizon is considered dry when the moisture tension is 1500kPa or more and is considered moist if the tension is less than 1500kPa but more than zero. Dissolved salts affect the availability of water in that; if a soil is saturated with water that is too salty to be available to most plants, it is considered as salty rather than dry.

2.1.2 Normal year

Normal year refers to a year where the value for annual precipitation or air temperature is plus or minus one standard deviation of the long-term (30 years or more) mean annual precipitation; and where the value for the mean monthly precipitation is plus or minus one standard deviation of the long term monthly precipitation for 8 of the 12 months (USDA Soil Taxonomy, 2010). The term normal year replaces the terms “most years” and “6 out of 10 years” as used in the 1975 edition of Soil Taxonomy (USDA, SCS, 1975).

2.1.3 Soil moisture control section (SMCS)

The SMCS upper boundary is the depth to which a dry (tension of more than 1500kPa, but not air-dry) soil will be moistened by 2.5 cm of water within 24 hours. The lower boundary is the depth to which a dry soil will be moistened by 7.5 cm of water within 48 hours (USDA, NRCS, 2010). Any depths of moistening along any cracks or animal burrows that are open to the surface are not included in this depth.

2.1.4 Classes of Soil Moisture Regimes

The following soil moisture regimes are defined according to the USDA Soil Taxonomy, 2010. The classes of the soil moisture regimes are basically defined in reference to the level of ground water and to the seasonal presence or absence of water held at a tension of less than 1500kPa in the SMCS. Assumptions are made that the soil supports vegetation and the amount of stored moisture is not being increased by irrigation or fallowing. These cultural practices affect the soil moisture conditions if continued.

2.1.5 Soil moisture regime subgroups (subgroup modifiers)

The definitions of soil moisture subgroup modifiers (tentative subdivisions of moisture regimes) are defined as proposed in the Newhall source code (Wambeke, et al., 2000; and Wambeke, 1982) and not the moisture subgroups used in Keys to Soil Taxonomy (2010). In this key, all climatic requirements are assumed to occur in most years (6 out of 10).

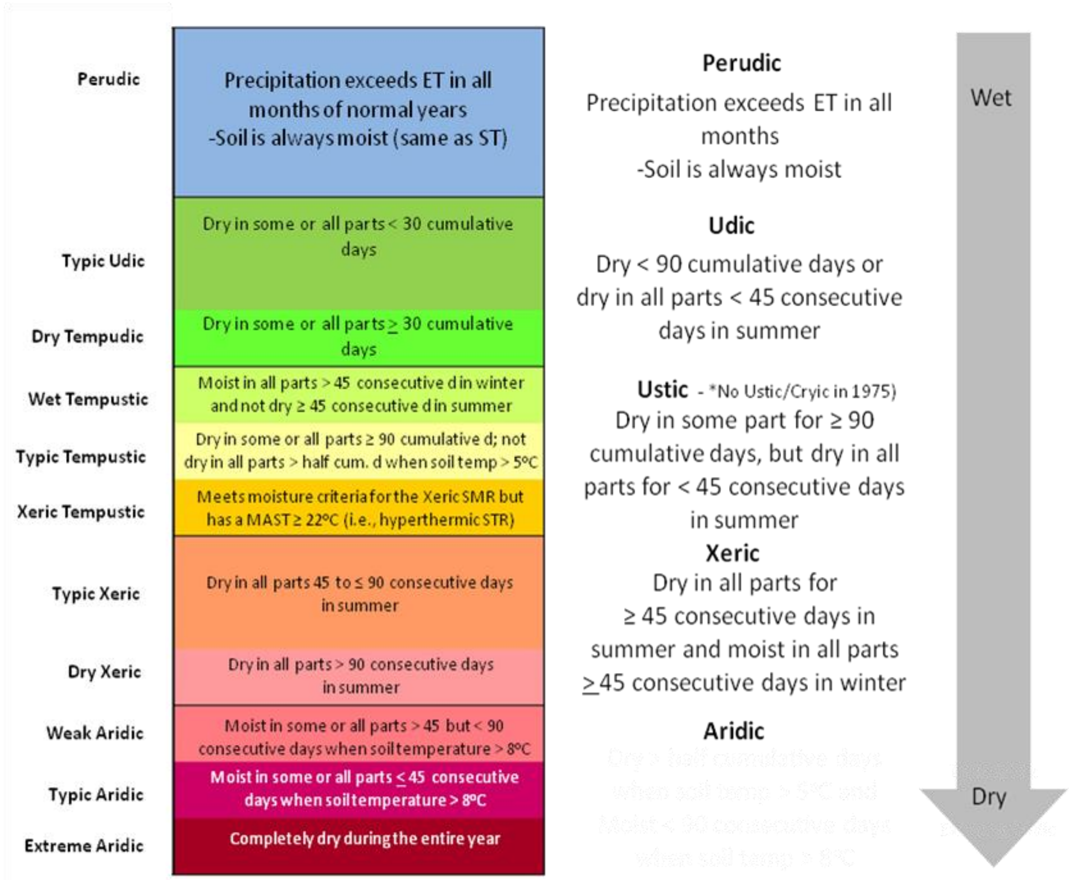


Fig 2.1: Soil moisture regimes and their subdivisions

(Wambeke et al., 1982 and 2000; USDA Soil Taxonomy, 2010)

2.2 Soil temperature

Soil temperature affects plant growth directly, almost all crops practically slow down their growth below the soil temperature of about 9^0C and above the soil temperature of above 50^0C (AgriInfo, 2011). Seeds require different ranges of soil temperature for germination. For example maize begins to germinate at soil temp of 7 to 10^0C. Photosynthesis slows down at low temperatures. Most of the soil organisms function best at an optimum soil temperature of 25 to 35^0C and the optimum soil temperature for nitrification is about 32^0C. Soil temperature also influences soil moisture content, aeration and availability of plant nutrients (Nutrient release and N fixation). Excessive high temperature is harmful to the functionality of plant roots and also causes stem lesions. Extreme low and high temperature influences the soil microbial population and rate of organic matter decomposition whereby the rate of decomposition is high under high soil temperatures.

2.2.1 Factors affecting soil temperature

Slope aspect is an important factor in temperate regions. In the northern hemisphere a south facing slope is always warmer than a north facing slope. Shallow tillage reduces the heat flow between the surface and sub soil. A cultivated soil has greater temperature amplitude compared to uncultivated soil. Availability of soil moisture maintains the soil temperature at a certain required level. Sandy soil warm up more rapidly than clay soils, because of the high heat capacity of clay soils. Organic matter reduces the heat capacity and thermal conductivity of soil, but increases absorptivity due to dark color.

2.2.2 Classes of Soil Temperature Regimes

The following are classifications according to the USDA Soil Taxonomy, 2010.

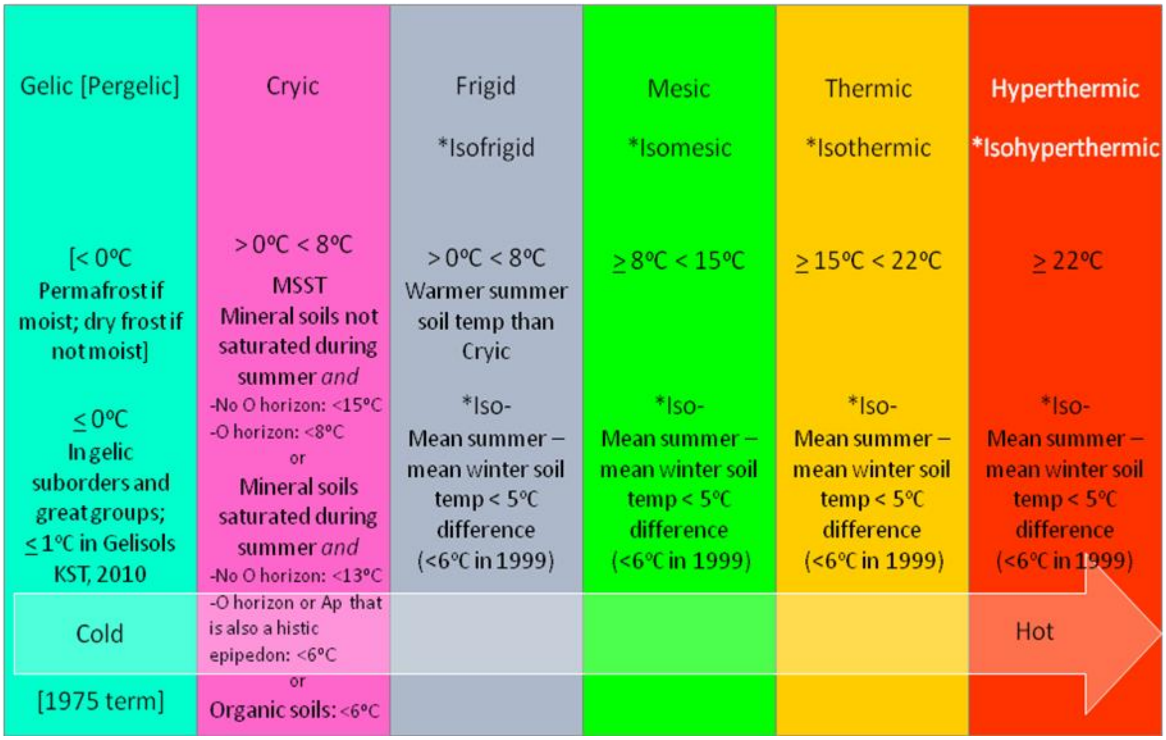


Fig 2.2: Soil temperature regimes (USDA Soil Taxonomy, 2010)

2.3 Significance of use of soil temperature and moisture regimes in soil classification

- Climate is one of the major pedogenic factors. It is one of the soil forming factors.
- Use of soil climate data makes taxa more meaningful for interpretation purposes by defining units in such a way that major soil limitations for plant growth are implied in the system.
- Uniform and extensive geographical area may be recognized on small scale maps which facilitate preparation of generalized soil maps that can easily be interpreted, particularly for crops adapted to certain climatic conditions.

2.4 The Java Newhall simulation model (jNSM)

The Java Newhall Simulation Model, or jNSM, is a desktop client application that employs Java 5 (Oracle Corporation) and Adobe Flex to manage the model input and the formatting of the output products of the application. It reflects Soil Taxonomy rules and at the same time reflects proposed moisture regime subdivision terms (Wambeke, 1982). The jNSM simulation behaves identically as the GW-BASIC version, also known as Van Wambeke 1.0, given the same dataset and assumptions. However, the jNSM further incorporates additional features such as annual and summer water balances; summer is considered June through August in northern hemisphere and, December through February in the southern hemisphere. jNSM provides a systematic and quantitative approach to characterizing soil climate regime. It can provide clues about more variable soil landscapes and trends through time and can help recognize rainshadows and defining climate criteria in ecological site descriptions. It was deployed to USDA-NRCS deskstops in 2012. This java implementation comprises the main computational engine of the current jNSM application.

2.4.1 The model input

The application takes batch input in the form of CSV (comma separated by value) batch file and also allows interactive input of data comprising a single model run. When the jNSM application is run, the interface opens in input mode whereby the user is expected to supply input data either interactively or in batch mode or review an existing output XML (Extensible Markup Language) file from previous model run.

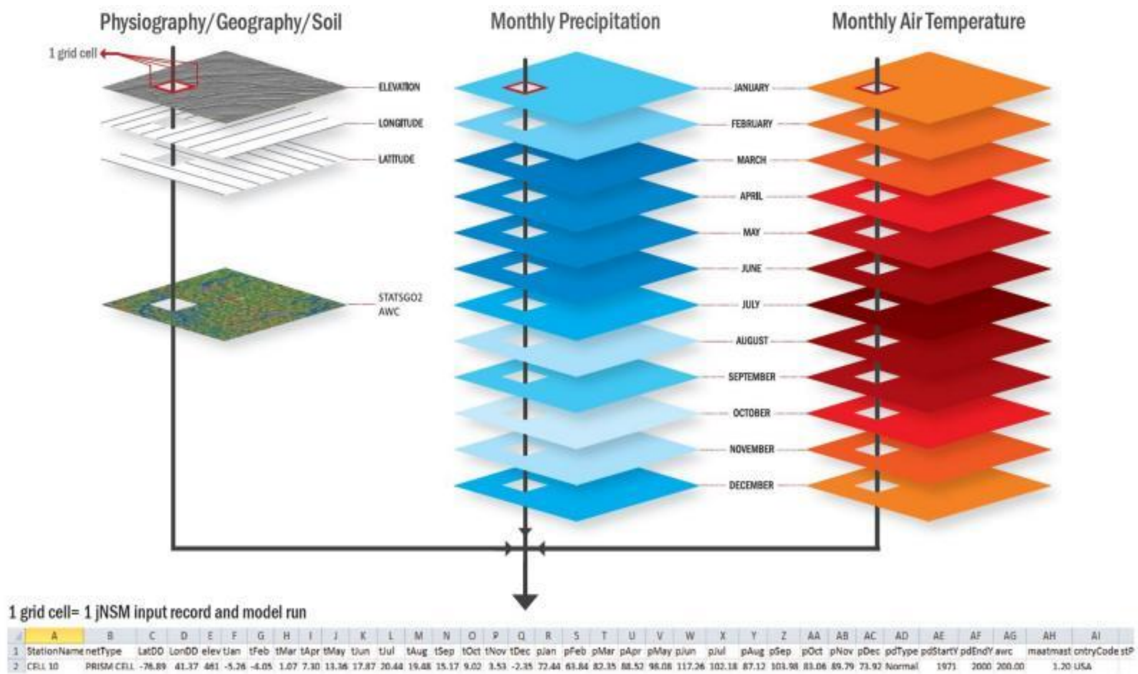


Fig 2.3: An illustration of the Java Newhall simulation model input records (above) and model run output (below) used to produce the soil climate regimes (Winzeler et al., 2013)

2.4.2 The model output

The jNSM application produces three output information products and a machine-readable model run output file in XML format. The output products are a report page, a climograph page and a model run summary page. These are displayed on the user's monitor. Model run results are stored in XML format. In case of multiple XML files, conversion to a single CSV file can be done by using the XML2CSV tool (Wambeke, 2000). The tool consolidates the XML files output from a jNSM batch run into a single spreadsheet file for the sake of further analysis.

2.4.3 The model soil moisture profile

The jNSM soil moisture profile extends from the surface downwards to a depth of 200mm (about 8 inches) which is the available water holding capacity (AWC). This soil depth is dependent on the geometry of pore spaces, that is, 80cm for well-structured clay to 200cm for a light sandy loam and for medium textured it is normally between 100 and 135cm. The soil moisture profile has eight layers (see fig 2.2) each of which retains 25mm of available water whereby the second and third layer form the moisture control section (MCS). Assumptions are made that the soil supports vegetation and the amount of stored moisture is not being increased by irrigation or fallowing. These cultural practices affect the soil moisture conditions if continued. The vertical axis shows the depth of the eight layers while the amount of available water contents is shown on the horizontal axis. The water in the profile is held at a tension and this decreases from left at permanent wilting point (PWP) to right at field capacity (FC). Each of the eight layers is divided into eight units to form an 8 x 8 square matrix having a total of 64 units (slots). Each unit can be filled with an amount of water varying from zero and 1/ 64^{th} part of the total available water content (AWC), that is, 3.125mm for the value of 200mm (AWC).

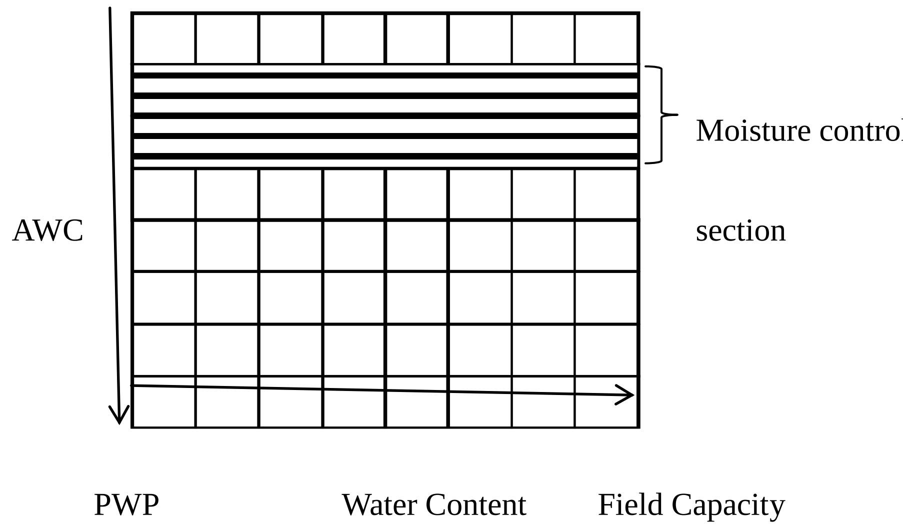


Fig 2.4: A general diagram showing the model soil moisture profile with the available soil water content ranging from permanent wilting point to field capacity (Wambeke, 2000)

2.4.4 How the model works (Changes in water content)

The changes in water content are explained according to the Java Newhall simulation model version 1.6 manual (USDA- NRCS, 2012) and a review- The Newhall simulation Model for estimating soil moisture and temperature regimes (Wambeke, 2000). A stepwise summary with screen captions is given in the appendices (Appendix 1 to 10), but below is the explanation of the concept used.

The NSM uses the concept of downward movement of moisture as in a wetting front progression. The amount of water needed to bring all the soil above the wetting front to field capacity determines how far it moves. When the complete soil moisture profile is at field capacity, the wetting front is at the profile bottom and the excess water is lost either through percolation or runoff. The rate of depletion depends on the amount of energy available for extraction of the moisture. This is expressed in terms of potential evapotranspiration (PET). This energy depends on the amount of water (AW) present and the extent of the forces exerted by the soil to retain it within the profile. Water is removed more readily when the water content in the profile is at maximum (low tension) than when at high tension.

In this model more energy is needed to extract water from the lower layers than from the upper layers; hence, the time needed for water extraction depends on the depth at which a layer is located. In this respect the roots of plants are more abundant at near the surface than in deeper horizons- the model applies this principle. Water depletion occurs until the soil reaches PWP (tension= 1500kPa).

a) Accretion

Water enters the soil in each non-full slot following a specific order (see fig 2.3). This simulates the additions of water to the profile. The sequence starts with the left slot in the top row and progresses to the underlying row when the current row is completely filled with water. This continues downward until all the rows are completely filled with water. This accretion process follows that of the downward movement of a wetting fron

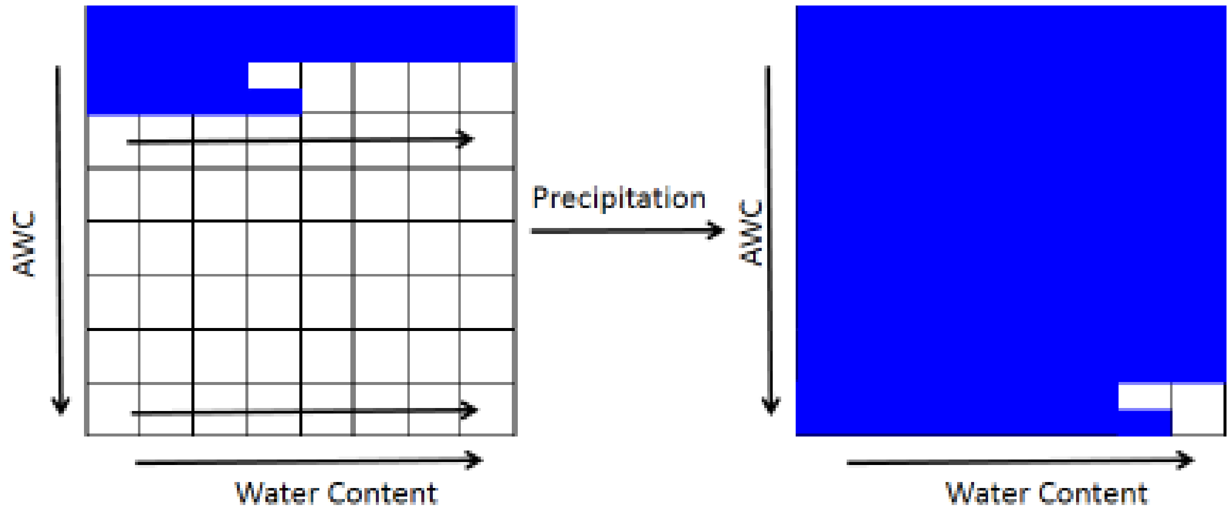


Fig 2.5: An illustration showing the water addition sequence of the model which starts with the left slot in the top row (left), and progresses to the underlying row until all the rows are completely filled with water (right) (Wambeke, 2000)

b) Depletion

Water extraction from the profile starts with the top right-hand slot and scans the slots in successive right-downward diagonals (see fig. 2.4 and 2.5). Each slot is examined and if water is present, it is removed from it. Water depletion stops when the potential evapotranspiration is exhausted. Any remaining depletion amount is not carried forward but is discarded.

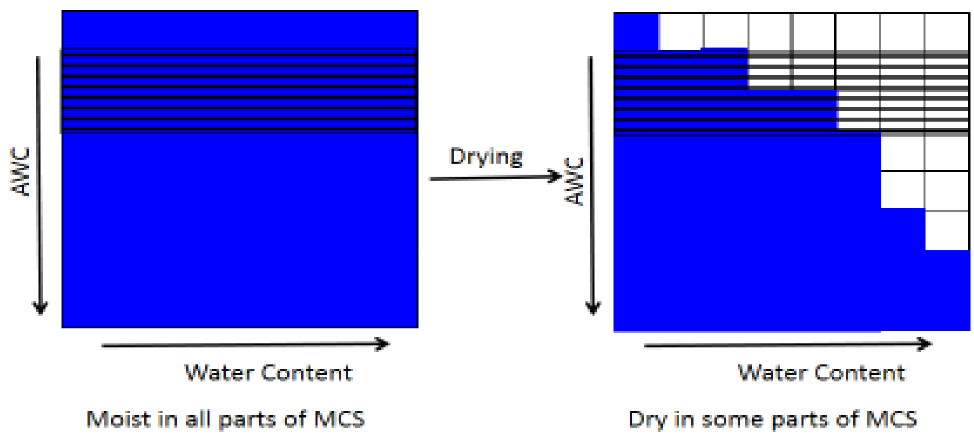


Fig 2.6: An illustration showing the water extraction sequence of the model (right) which starts with the top right-hand slot and scans the slots in successive right-downward diagonals (Wambeke, 2000)

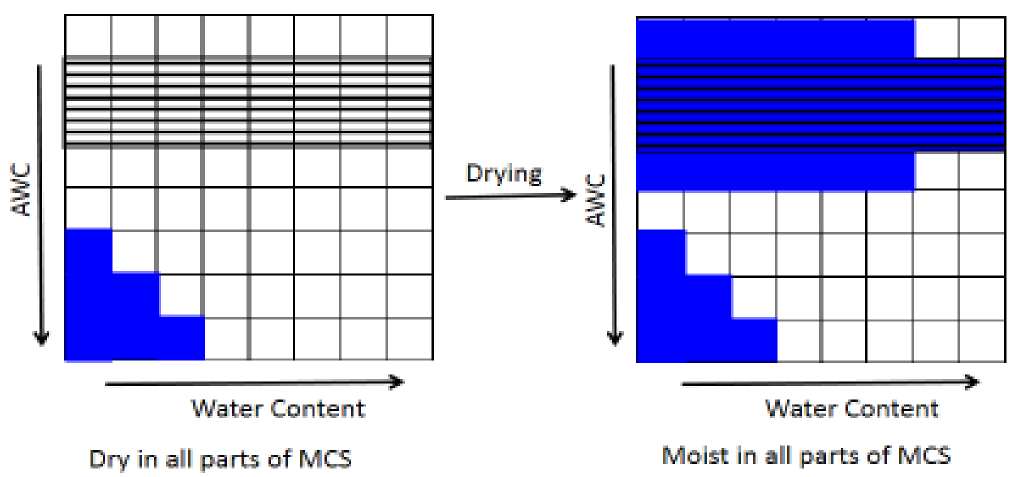


Fig 2.7: An example of the soil moisture control section (MCS) description for the model showing conditions when the MCS is dry in all parts (left) and moist in all parts (right) (Wambeke, 2000)

The rate of water depletion is inversely proportional to the tension under which the water is held and also varies with the depth of the layer. These two factors are accounted for by means of the depletion requirement diagram which indicates the value by which a unit of energy (expressed as evapotranspiration) has to be multiplied with to extract one unit of water from the soil. This process proceeds until all the evapotranspiration has been used or until all slots have been set to zero.

c) Soil moisture conditions

Soil Taxonomy differentiates three soil moisture conditions which are diagnostic for the determination of moisture regime of a pedon. These are evaluated in the soil moisture control (MCS) section. When the leftmost slots numbered 09, 17 and 25 are empty the MCS is dry in all parts or completely dry. When none of the leftmost slots numbered 09, 17 and 25 are empty the MCS is moist in all parts or completely moist. When the MCS does not fulfil the requirement for the above two conditions then the MCS is dry or moist in some parts or partly dry or moist. Slot 25 is located outside the MCS to determine the soil moisture condition.

d) Precipitation

Monthly precipitation is distributed into two. Half of the monthly precipitation (heavy precipitation, HP) during a storm falls in the middle of the month. It is assumed that the water enters the soil without any losses unless the soil AWC is exceeded. The other half of the monthly precipitation (light precipitation, LP) occurs during light falls and part of it is lost through evapotranspiration (ET) before entering the soil unless LP>ET.

2.4.5 Potential evapotranspiration (PET)

Potential evapotranspiration is the amount of water that could be evaporated from land, water and plant surfaces if soil water were in unlimited supply (White and Host, 2002). In the Newhall model, PET is assumed to be uniform throughout the month and that not all its energy is used for water extraction. Part of the PET is used to dissipate as much light precipitation as possible before reaching the soil. Calculation of PET is done according to Thornthwaite (1948).

2.5 Assumptions/ Limitations of the Newhall model

The model is not a sophisticated simulation of water movement through a soil. By default, soil is regarded as a reservoir with fixed capacity of 200 mm available water capacity (AWC), but can be changed depending on the input data. Water is added to soil by precipitation; removed by evapotranspiration. When the bucket is full, no more water can be added. All rainfall is considered to be effective and that percolation of water through the profile is unrestricted by pans or contacts at shallow depth. It is assumed that the model uses a profile deep enough to store 200mm of water between permanent wilting point and field capacity. Excess precipitation is lost through runoff or deep percolation and hence its use is limited to well-drained soils. Runoff may considerably change the moisture conditions in the soils in semi-arid environments with open vegetation, making them drier than the model calculations would indicate. Potential evapotranspiration is calculated from Thornthwaite model (1948). Mean annual soil temperature is got from mean annual air temperature plus offset (2.5 ^{o}C is default; but can be changed).The moisture control section (located below the surface horizons in the profile) conditions are used to define the moisture regimes and their subdivisions. This means that the topsoil is not considered. With respect to this, immediate interpretation on water availability for plant growth at a certain time of the year cannot be given without additional information on the moisture conditions prevailing in the topsoil. Also, consideration of deep horizons from which plants may exact water is not considered in this model although essential especially in determination of water supplying power of the soils. The jNSM does not also account for snowmelt nor antecedent moisture conditions.

The monthly climate data used is usually averages over many years, usually 30 years, and hence, this type of input tends to reduce the intensity of the extremes which occur when data for each year is used. Also, the model functions on a calendar year rather than a hydrological year.

2.6 Digital soil mapping (DSM)

This is also called predictive soil mapping or pedometric mapping whereby production of soils and soil properties is computerized. It makes use of computational advances which includes GIS, digital elevation model, geostatistical interpolation and inference algorithms and data mining. It also entails technological advances such as GPS receivers, field scanners and remote sensing. It is “the creation and population of spatial soil information models by numerical models inferring the spatial and temporal variations of soil types and soil properties from observation and knowledge from related environmental variables” (Lagacherie and McBratney, 2006) and "the creation and the population of a geographically referenced soil databases generated at a given resolution by using field and laboratory observation methods coupled with environmental data through quantitative relationships.” (Working Group on Digital Soil Mapping (WG-

DSM), 2006). Pedometric or statistical soil mapping main objective is to predict some soil variable at unobserved locations and access certainty of that estimate using statistical optimal approaches (statistical inference). It generates maps of soil properties and soil classes that can be used to feed other environmental models or be used for decision making. It is largely based on applying geostatistics in soil science and other statistical methods used in pedometrics (McBratney et al., 2003).

A digital soil map provides:

I. Information on soil's capacity to provide ecosystem services such as produce crops and store carbon.
II. A geographical representation of soil constraints with known confidence such as carbon deficits
III. Spatial targeting of management recommendations such as land use management, and
IV. A baseline for change detection and impact assessment (McBratney et al., 2003).

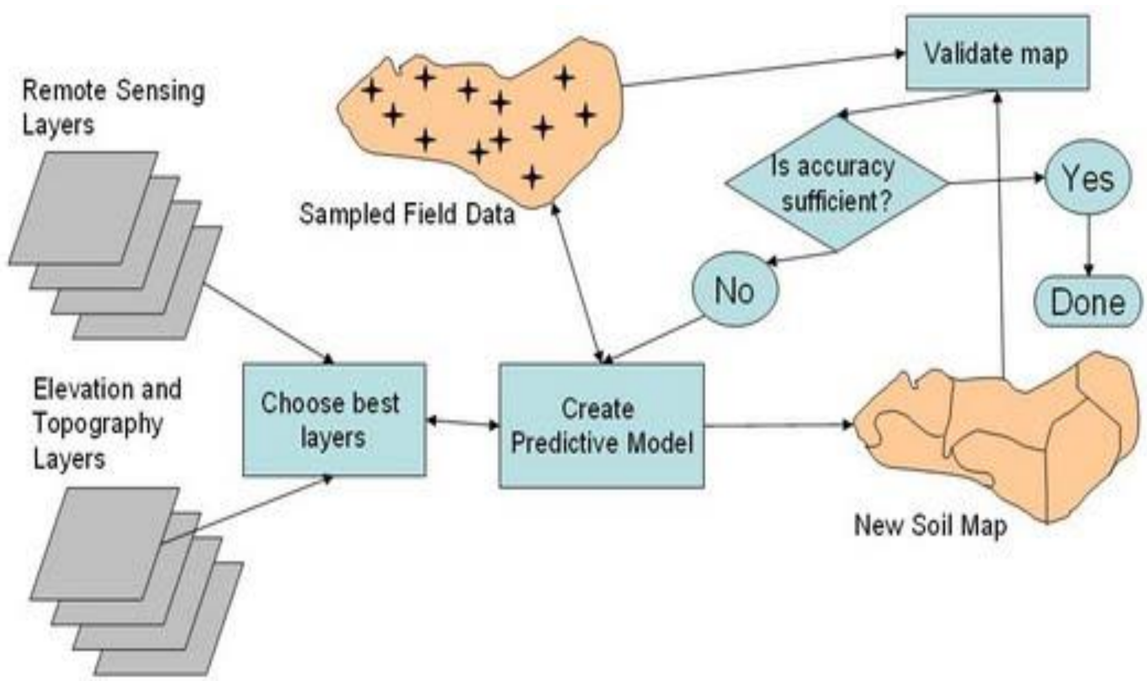


Fig 2.8: Example of a digital soil mapping (after Nauman Geospatial, 2012)

2.7 Global circulation models (GCMS)

A general circulation model, also known as general climate model, is a type of climate model that uses mathematical modeling techniques of the general circulation of a planetary or ocean. It is based on Navier- Stokes equations on a rotating sphere with thermodynamic terms of various energy sources such as radiation and latent heat. GCMs are widely used in studying climate, projecting climate change and weather forecasting. The most recent GCMs were used in the Fifth Assessment IPCC report (IPCC, 2012). The GCM output was downscaled and calibrated using WorldClim 1.4 (release 3) as baseline current climate.

2.7.1 Goddard Institute for Space Studies (GISS) GCM ModelE

This is the current incarnation of the GISS series of coupled atmosphere-ocean models. It is one of the most recent GCM climate models that are used in the Fifth Assessment IPCC report (Coupled Model Intercomparison Project Phase 5 (CMIP5)). It provides the ability to simulate many different configurations of Earth System Models which includes standard atmosphere, ocean and sea ice, land surface components, interactive atmospheric chemistry, aerosols, carbon cycle and other tracers (Schmidt et al., 2013).

2.7.2 Representative concentration pathways (RCPs)

RCPs are four greenhouse concentration pathways or trajectories adopted by the Intergovernmental Panel on Climate Change (IPCC) for its fifth Assessment Report (AR5). These trajectories are used for climate modeling and research. The four RCPs are RCP2.6, RCP4.5, RCP6, and RCP8.5 (+2.6, +4.5, +6.0, and +8.5 W/ m^2 respectively). These are named after a possible range of radiative forcing and concentrations of greenhouse gases up to the year 2100. These four RCPs describe four possible climate futures depending on how much greenhouse gases are emitted in the years to come. (Moss et al., 2010

2.7.3 Information on individual RCPs

RCP2.6

This is developed by the IMAGE modeling team of the Netherlands Environmental Assessment Agency. Its emission pathway is representative for scenarios in the literature leading to very low greenhouse gas concentration levels. Its radiative forcing level first reaches 3.1 W/ m^2 mid-century, then returning to 2.6 W/ m^2 by 2100 (Van Vuuren et al., 2007)

RCP 4.5

This is developed by the MiniCAM at the Pacific Northwest National Laboratory's Joint Global change Research Institute (JGCRI). It is a stabilization scenario. A range of technologies and strategies for reducing greenhouse gas emissions are employed to stabilize the radiative forcing before 2100. (Clarke et al., 2007 and Wise at al., 2009)

RCP 6.0

This is developed by the AIM modeling team at the National Institute FOR Environmental Studies (NIES). It is also a stabilization scenario. A range of technologies and strategies for reducing greenhouse gas emissions are employed to stabilize the radiative forcing after 2100. (Fujino et al., 2006 and Hijioka et al., 2008)

RCP 8.5

This is developed by the MESSAGE modeling team and the Integrated Assessment Framework at the International Institute for Applied Systems Analysis (IIASA). Its emission pathway is representative for scenarios in the literature leading to high greenhouse gas concentration levels. The underlying scenario drivers and the development path are based on A2r scenario. (Riahi et al., 2007)

2.8 Change detection

This is a technology ascertaining the changes of specific features within a certain time interval. Change detection tries to identify changes in the probability distribution of a stochastic process or time series. It not only provides the spatial distribution of features but also qualitative and quantitative information of feature changes.

The main change detection methods can be classified in three categories: characteristic analysis of spectral type, vector analysis of spectral changes and time series analysis. Time series analysis method analyzes the process and trend of changes by monitoring ground objects based on remote sensing continuous observation data. Three methods are involved:

2.8.1 Image subtraction method

This is the most extensive application that can be applied to a wide variety of types of images and geographical environments. It is based on gray values and the changed region and unchanged region is determined by selecting the appropriate threshold values of gray levels in the subtraction image. The gray value shows the differences of corresponding pixels of two images (Zhang and Lu, 2008)

2.8.2 Image ratio method

In this method, a pixel value of a time series image divides the corresponding pixel of another time series image. The ratio of the corresponding pixels in each band from two images of different periods after image co-registration is calculated. The histogram of the ratio image is used to choose the threshold value of “change” or “no change” pixels. This threshold values selects significant changes in the ratio image and varies in different regions, different times and different images. This method is useful for vegetation and texture extraction (Zhang and Lu, 2008).

2.8.3 Method of change detection after classification

In this method, each image of multi-temporal images is classified separately and comparisons of the classification result images are made. The pixel is known not to have changed if the corresponding pixels have the same category label; otherwise, the pixel has changed. Two types of classification methods exist: supervised and non-supervised (cluster analysis or point cluster analysis). The cluster analysis method involves the process of searching and defining the natural spectrum cluster group in the multi-spectral image where the computer automatically composes cluster groups according to pixel spectral values or space position (Zhang and Lu, 2008).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study area

Kenya is a country located in Eastern Africa and is bordered by five countries: Ethiopia, Somalia, South Sudan, Tanzania and Uganda. It lies between latitudes 5^0N and 5^0 S and longitudes 34^0 and 42^0E. Kenya occupies a total area of 580,367 km^2 (569,140 km^2 land area and 11,227 km^2 water area)**.** The climate in Kenya varies from tropical along the coast to temperate inland to arid in the north and northeastern parts of the country. The lowest point on Kenya is at sea level on the Indian Ocean and the highest point on Kenya is 5,199 meters. Elevation is the major factor in temperature levels, with the higher areas, on average, as 11 °C cooler, day or night, with the hottest period being from December to February and coldest in July to August. The daytime temperatures average between 20 ^{0}C and 28 ^{0}C, but are warmer along the coast. The long rains occur from April to June and short rains from October to December.

3.2 Climate data

3.2.1 Source of climate data

The climatic data used was freely accessed from WorldClim-Global climate data (http://www.worldclim.org). WorldClim is an open source set of global climate layers or grids generated through interpolation from weather stations on a 30 arc-second resolution grid (often referred to as “1km” resolution). The current version is Version 1.4 (release 3)

(Hijmans et al., 2005). In the WorldClim database, climate layers were interpolated using:

1. Major climate databases compiled by the Global Historical Climatology Network (GHCN), the FAO, the WMO, the International Center for Tropical Agriculture (CIAT), R-HYdronet, and a number of additional minor databases for Australia, New Zealand, the Nordic European Countries, Ecuador, Peru, Bolivia, amongst others.
2. The SRTM elevation database (aggregated to 30 arc-seconds, "approximately 1 km")
3. The ANUSPLIN software. ANUSPLIN is a program for interpolating noisy multi-variate data using thin plate smoothing splines. We used latitude, longitude, and elevation as independent variables.

3.2.2 Current climate data input

Monthly precipitation and mean air temperature data for current conditions which is obtained through interpolations of observed data, representative of years 1950-2000 was used. The data, from ESRI grids, on the current conditions (baseline) of 30-year normals (1971- 2000) with a spatial resolution of 30-arc seconds was used. Tiles 27 and 37 were used as this is where Kenya lies on the ESRI grids.

3.2.3 Future climate data input

Future monthly precipitation and mean air temperature downscaled GCM data from $CMIP_5$ (IPCC fifth assessment) was used. The GCM used was Goddard Institute for Space Studies (GISS-E2-R), with a spatial resolution of 30-arc seconds and a representative concentration pathway (RCP) of 2.6W/m^2. The time period for the data used was 2050 (average for 2041-2060).

3.3 Other model inputs

Elevation data from the shuttle radar topographic mission (SRTM) data set (CGIAR-CSI, 2011) was used by extracting the specific tiles for Kenya. The elevation data (3-arc seconds, 90m resolution) was re-sampled from the native SRTM resolution to match the resolution of the climate data (30-arc seconds, 900m resolution) inputs using bilinear convolution for the full extent of Kenya. This means that one elevation estimate was available for each climate data raster cell.

3.4 Digital soil mapping assessments

Mapping tasks were performed using Aeronautical Reconnaissance Coverage Geographical Information System (ArcGIS) Software version 10.1 (ESRI, 2012).

3.4.1 Preparation of the climate data for jNSM input

This involved several ArcMap procedures:

1. Mosaic weather data: This involved putting multiple raster datasets into a new raster dataset. Monthly mean air temperatures and precipitation datasets were separately mosaicked into 12 months (January through December) by putting the tiles for the same months together using the “mosaic to new raster” tool. Elevation data for the full extent of Kenya was also mosaicked.

2. Raster projection: All areal estimates were projected using Africa Albers equal area conic projection using "project raster" tool and rasterized to 900m pixel resolution.
3. Hillshade: For more DEM visualization, a hillshade was created using the "hillshade" tool.
4. Resampling: The elevation data (3-arc seconds, 90m resolution) was re-sampled to match the resolution of the climate data (30-arc seconds, 900m resolution) inputs using bilinear convolution for the full extent of Kenya.
5. Divide: The WorldClim data provides the mean air temperature in multiples of 10. That is, ^{0}C ×10. For actual measurements, all monthly mean air temperatures were divided by 10 using the "divide" tool.
6. Extraction by mask: Extraction of cells of rasters corresponding to the full extent of Kenya was done using "extract by mask" tool. In this case, the feature mask data was the shapefile of Kenya showing county level boundaries (1998) (ILRI, 2007)
7. Conversion from raster datasets to point features: This involved converting all the monthly mean air temperatures and precipitation rasters to point features using "raster to point" tool, and then using the point shapefile for mean air temperatures for the month of January to convert the elevation raster datasets to point features. Here, "extract values to points" tool was used.

3.4.2 Making table for the jNSM

The table was made according to the input batch file format for jNSM (USDA-NRCS, 2012). This involved the following steps:

1. Addition of the XY coordinates: XY coordinates were added to each of the points in the shape file. This was done by using "add XY coordinates" tool to the elevation shapefile and then extracting these coordinates to the rest of the shapefiles. On opening the elevation attribute table, the *POINT_X* and *POINT_Y* columns were in meters because the projection was in Africa Albers Equal_Area Conic projection.
2. Re-projection of the elevation shapefile to world geographic coordinate system (GCS_WGS_1984): This was done in order to have the coordinate system in decimal degrees (DD) as the jNSM input table requires. The "project" tool was used.
3. Addition of the XY coordinates in DD: This was done to the re-projected elevation shapefile using the "add XY coordinates" tool.
4. Ordering the columns in the elevation attribute table as in the jNSM input table was done in the field table of the elevation attribute table, whereby POINTIDserved as *stationName*, POINT_X and POINT_Y as*lonDD* and *latDD* respectively, RASTERVALU as *elevation (elev)* and GRID_CODE as *temperature for January (tJan)*.The netType was *SRTM*.
5. Recalculating the columns and giving them names as in the jNSM input table: This was done using the "add field" option in the attribute table. The data type was specified as in the jNSM input table format. Addition of values to the created

fields was done using "field calculator". This created columns the following columns: stationName, netType, elevation, latDD, lonDD and tJan.

6. Adding columns for the other months as they appear in the jNSM: This was done using the "extract multi values to points" tool. The names were then changed as in the jNSM input table.
7. Exporting the table to excel: This was done using the "export" option of the attribute table. The table was saved as a text file with a "csv" extension.

3.5 Running the jNSM (refer to appendices 1 to 10 for a more detailed stepwise procedure)

1. Entering the user information: This was done by filling all the fields in the "user info" tab.
2. Adding the CSV file to the jNSM for a run: This was done in the "data" tab. Batch model run was used. The batch input units were in metric (^{0}C, mm,m) for temperature, precipitation and elevation respectively. A location for the output file was chosen and the model was run by hitting the "run batch" button. The output files were in XML file format. The jNSM XML files were 728,509 for the present conditions and 729, 569 for the future conditions.
3. Converting XML file to CSV: This was done using the Newhall XML2CSV tool 1.2.1. (USDA-NRCS, 2012). The output excel table had additional columns showing the different soil temperature and moisture regimes and the subgroup modifiers as shown:

3.5.1 Coding the soil temperature and moisture regimes

The coding of the regimes was done in the excel tables according to the following codes:

Table 3.1: Soil moisture and temperature regime codes

3.6 Digital mapping of the soil moisture and temperature regimes using Arcmap

	SubgroupModifiers		Temperature Regimes		Moisture Regimes
1	Aridic Tropustic	1	Isothermic	1	Ustic
2	Dry Tempudic	2	Thermic	2	Udic
3	Dry Tropudic	3	Isohyperthermic	3	Xeric
4	Dry Xeric	4	Mesic	4	Aridic
5	Extreme Aridic	5	Cryic	5	Undefined
6	Typic Aridic	6	Frigid	6	Perudic
7	Typic Tempustic	7	Hyperthermic		
8	Typic Tropustic	8	Isofrigid		
9	Typic Udic	9	Isomesic		
10	Typic Xeric	10	Pergelic		
11	Udic Tropustic				
12	Undefined				
13	Weak Aridic				
14	Wet Tempustic				
15	Xeric Tempustic				

1. Addition of the new map layers based on XY events from the CSV table: This was done by specifying the X, Y and Z fields and the coordinate system of input coordinates (WGS-1984) using the “display XY data” option, then exporting this data to make a shapefile.
2. Conversion of the point shapefiles to raster: The “point to raster” tool was used.
3. In the layer properties, unique values were assigned (as per the codes) and the output was different maps showing the different soil temperature and moisture regimes both for present and future conditions.

3.6.1 Creating a relationship between soil climate regimes and major crops grown in Kenya

The crop shapefile used was from ILRI (2007) databases on agroecological zones (AEZs) of Kenya based on temperature and crop suitability. The Farm Management Handbook of Kenya (2006), volume II, was used to relate the AEZs to the crops. The database was only available for the arable land of Kenya which covered the central and western regions of the country.

1. Adding crop field to the AEZ table: Various major crop names were added to the AEZ attribute table in correspondence to the AEZ allocated in the Kenya Farm Management Handbook.
2. Finding the centroid of the crop thematic map: New fields (latitude and longitude) were added to the attribute table and their coordinate values was calculated using “calculate geometry” option. This was then exported to a table.

3. The crop map and the soil climate regimes maps were spatially aligned using georeferencing tool. In order to join the input crop point feature with the input soil climate regimes rasters, “extract multiple values to points” tool was used.

3.6.2 Change detection as a tool for creating spatial comparisons

Spatial comparisons, in percent change units, was done to detect changes in soil climate between present and future conditions. This was done using subtraction method. The present and future soil climate maps were first snapped together to ensure that the grids were of the same resolution and projection. Using raster calculator, the current soil climate was subtracted from the future soil climate in order to identify the tension zones. The output raster map consisted of 0, + and - values or numbers. The spatial comparison maps created were also used against crop spatial distributions, and a relationship driven.

3.6.3 Graph comparisons

Graphs showing the magnitude and area of the soil temperature and moisture regime changes were also computed. This involved:

1. Building an attribute table for the rasters as this was missing because the pixel type was float with 32-bit floating point: Before converting the dataset to integer, the grids were multiplied by 100 in order to preserve the decimal value (temperature values were to 2 decimal places). This was later compensated for by multiplying the grids with the same value (100) after running the statistics. The “build raster attribute table” tool was then used to build the raster table showing

the total number of pixels (counts) for each zone (value column containing -1, 0, +1 etc)

2. Calculation of the total area of the zones: This was done by multiplying the total number of pixels for each zone with the individual pixel area (900m×900m= 810,000m^2= 0.81km^2).
3. Plotting graphs: To show the overall trend for the zones, a bar graph of total area against each zone was plotted for both soil temperature and moisture regimes.

Connecting the soil temperature and moisture regime changes to how crops will be affected was also done. This involved conversion of crop maps into rasters and snapping them together with the soil temperature and moisture regime, to ensure they are of the same resolution and projection. The maps were then overlaid together and crops that fell in each of the zones were identified.

CHAPTER FOUR

RESULTS

4.1 Current (1971-2000) soil temperature regimes of Kenya according to the spatial Java Newhall simulation model

The current soil temperature regimes of Kenya were found to be of five types: Isohyperthermic, isothermic, isomesic, pergelic and cryic as shown in fig 4.1 and 4.2. The isohyperthermic temperature regime dominates the country with approximately over 80% of Kenya's total area. This is mainly to the northern, eastern and coastal regions of the country. The second is isothermic, covering about 17% of Kenya to the western and central parts, and the third is isomesic, covering about 1.5% of the central and western parts of the country. Pergelic and cryic had the least coverage of 0.03% and 0.06% respectively, occurring in L. Turkana and on Mt. Kenya and Aberdare Mountain Ranges respectively.

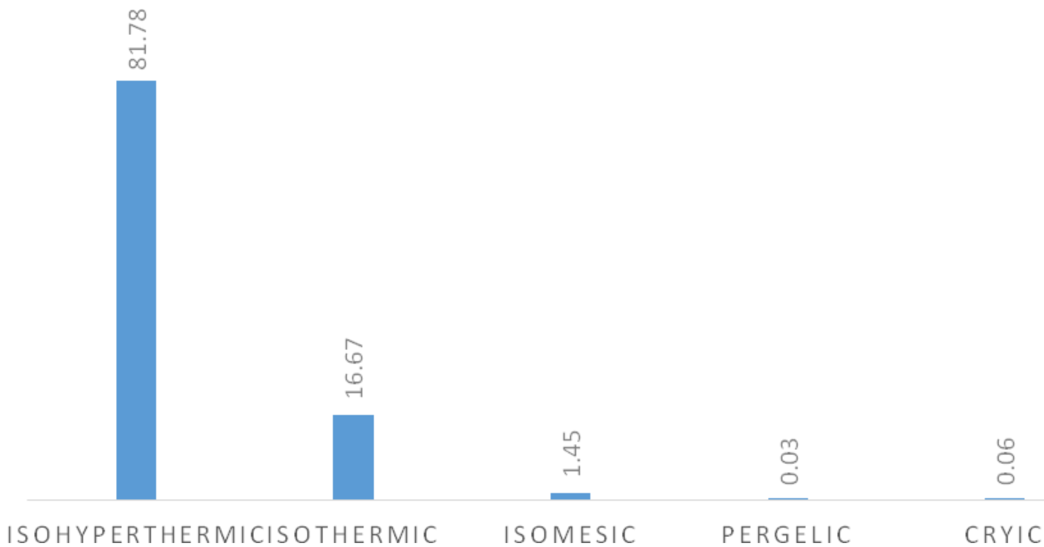
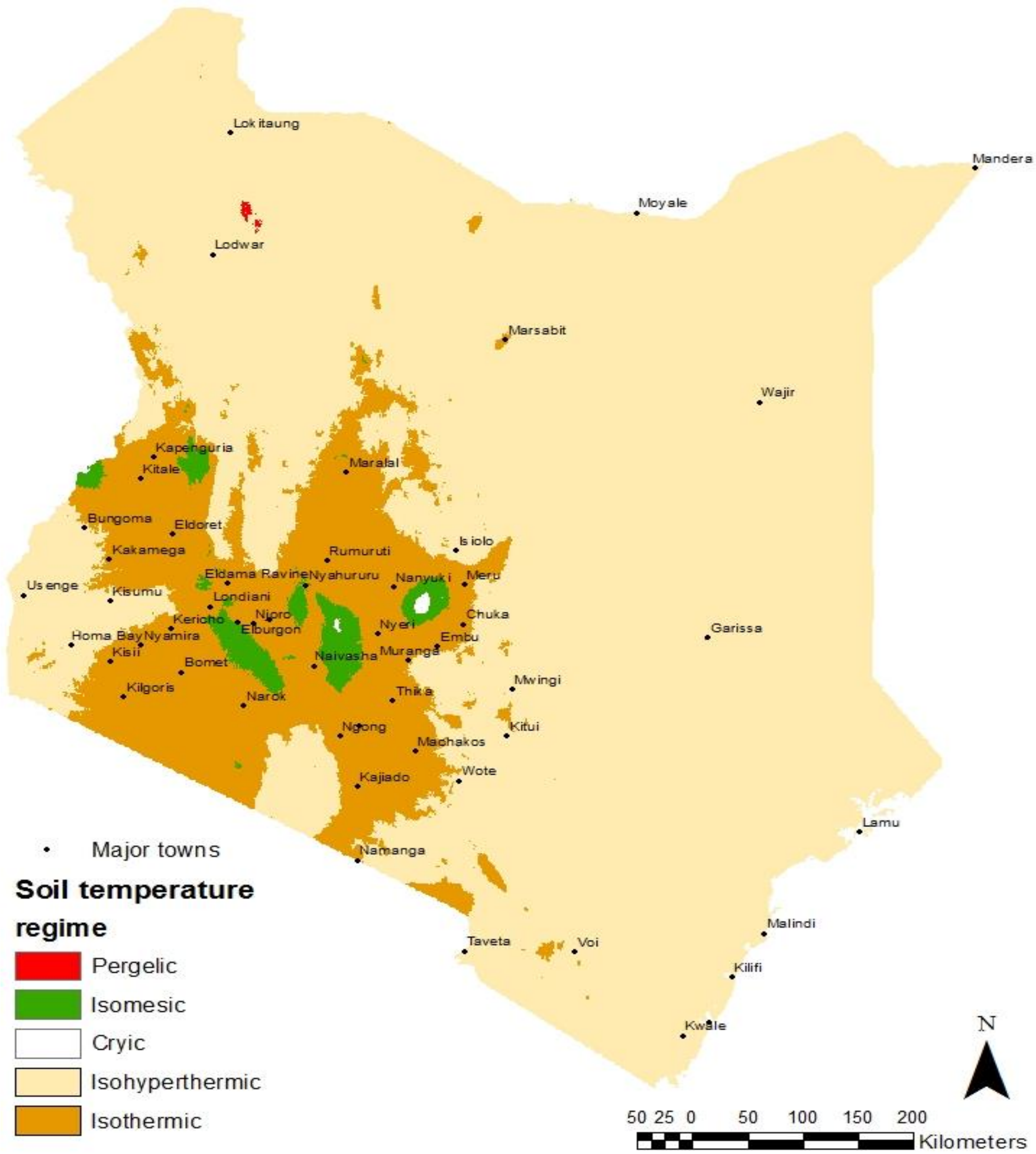


Fig 4.1: A bar graph showing the percentage area coverage (value above bars) of the current soil temperature regimes of Kenya according to the Java Newhall model



(Source: Author, 2014)

Fig 4.2: A map showing the current (1971-2000) soil temperature regimes of Kenya according to the spatial Java Newhall simulation model

4.2 Future (2050) soil temperature regimes of Kenya according to the spatial Java Newhall simulation model

The future soil temperature regimes of Kenya were found to be of five types: Isohyperthermic, isothermic, isomesic, thermic and cryic as shown in fig 4.3 and 4.4. It was noted that the isohyperthermic temperature regime will still dominate the country with an approximate coverage of 73% of Kenya's total area to the northern, eastern and coastal regions. The second highest soil temperature regime coverage will still be isothermic, covering about 26% of Kenya mainly to the western and central parts. The third willstill be isomesic, covering about 1.3% of Kenya's central and western region. Thermic and cryic will cover the least area of about 0.03% and 0.02% respectively. The cryic temperature regime will only be on Mt. Kenya in 2050.

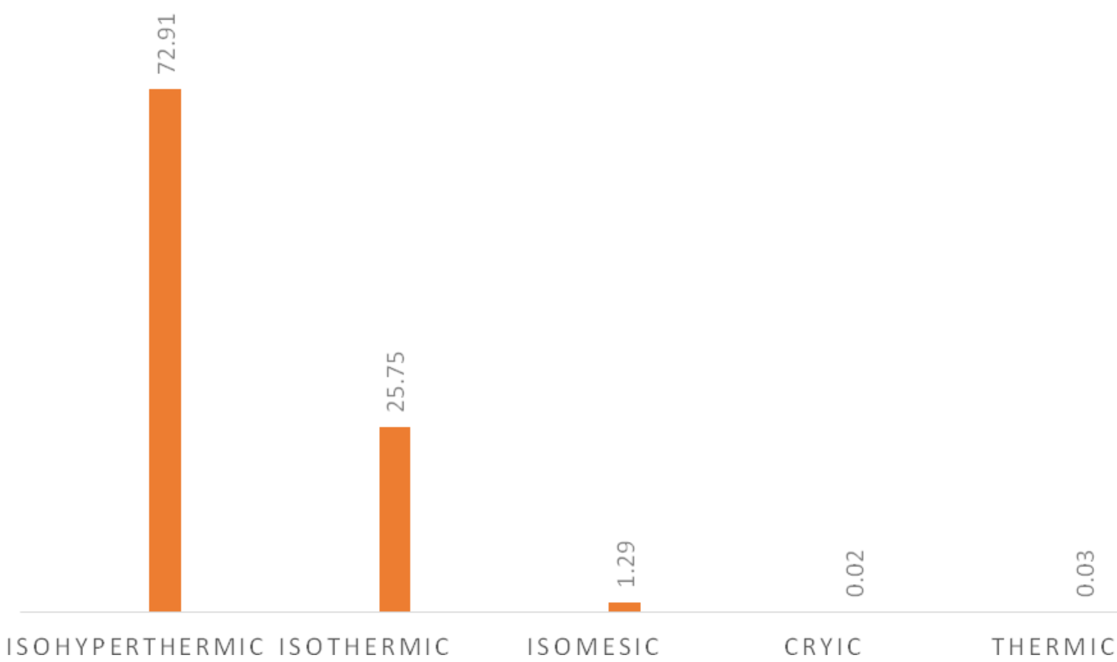
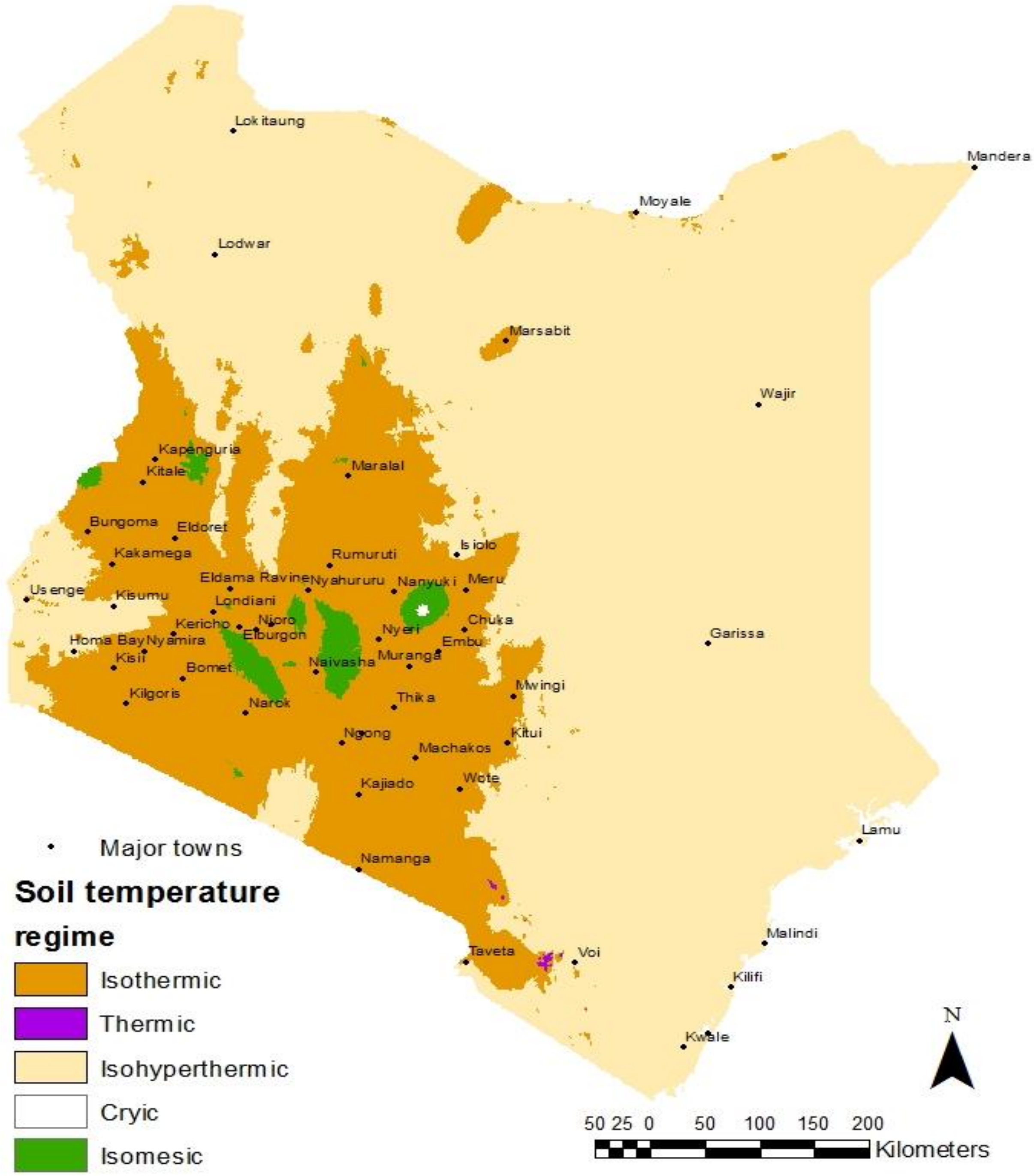


Fig 4.3: A bar graph showing the percentage area coverage (value above bars) of the future soil temperature regimes of Kenya according to the Java Newhall model



(Source: Author, 2014)

Fig 4.4: A map showing the future (2050) soil temperature regimes of Kenya according to the spatial Java Newhall simulation model

4.3 Percentage coverage comparisons between current and future soil temperature regimes

The isohyperthermic temperature regime dominates the country both for current and future conditions as shown in fig 4.5. However, the current isohyperthermic temperature regime covers more area than the future, with a percentage difference of about 10 %. The isothermic temperature regime occupies the second highest portion of the country in both current and future conditions. However, the current isomesic temperature regime covers less area compared to the future, with a percentage difference of about 10%. The isomesic temperature regime seems to be relatively the same for both current and future conditions. Cryic temperature regime also seems to be relatively the same, but it is worth noting that the future conditions will have a less coverage than the present. This will be the case for Mt. Kenya; however, the cryic moisture regime completely misses out in the Aberdare Mountain Ranges. Thermic temperature regime is absent in current conditions but present in the future while pergelic temperature regime is present in current conditions but absent in the future conditions.

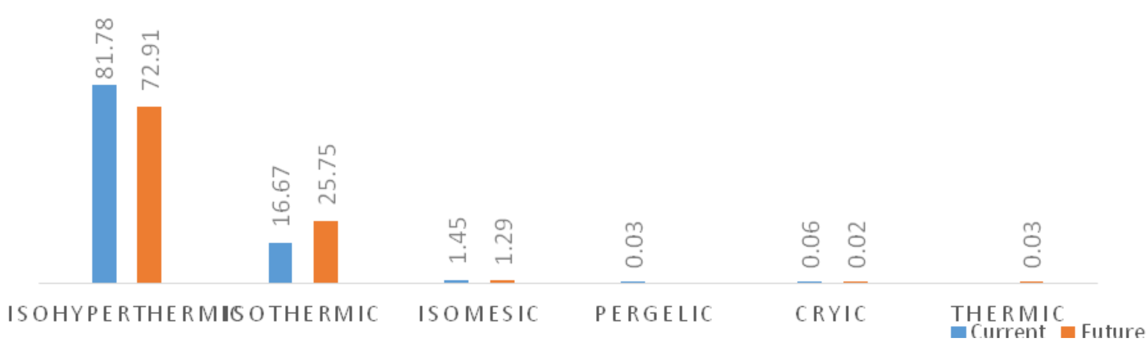


Fig 4.5: A bar graph showing comparisons between the current and future soil temperature regimes of Kenya in percentage area coverage (value above bars) according to the Java Newhall model

4.4 Current (1971-2000) soil moisture regimes of Kenya according to the spatial Newhall simulation model

The current soil moisture regimes of Kenya were found to be of four types: aridic, ustic, udic and perudic as shown in fig 4.6 and 4.7. The aridic moisture regime dominates the country with an approximate coverage of 47 % of Kenya's total area to the northern and eastern parts. The second is ustic, covering about 27% of Kenya. The ustic moisture regime acts as a boundary between the aridic and udic moisture regime and is mainly to the coastal regions. Udic moisture regime follows closely with percentage area coverage of about 24%, mainly to the central and western regions. Perudic moisture regime covers the least area of about 1.5 %, to the central and western parts of the country.

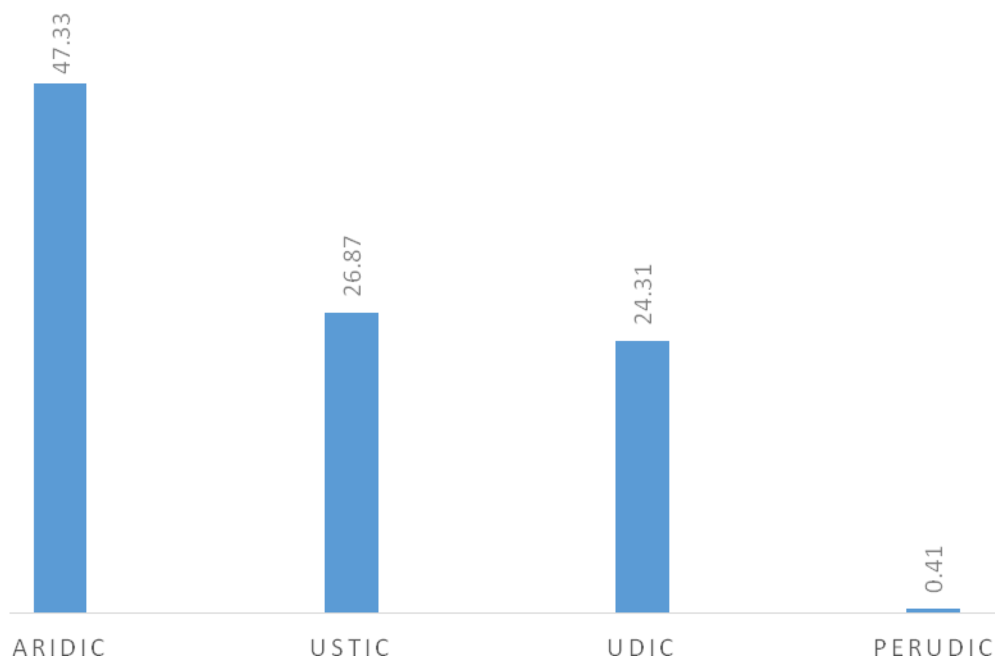
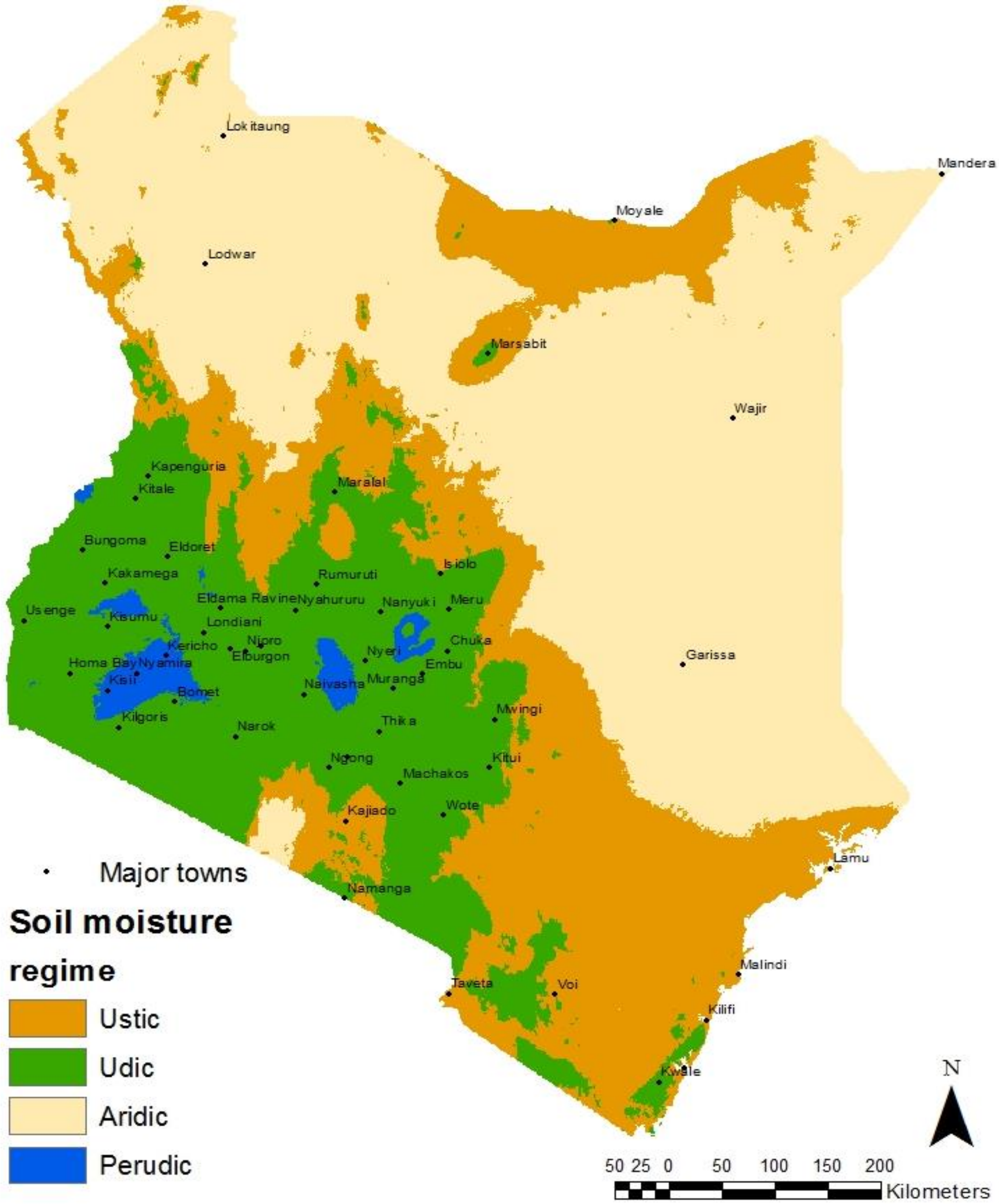


Fig 4.6: A bar graph showing the percentage area coverage (value above bars) of the current soil moisture regimes of Kenya according to the Java Newhall model



(Source: Author, 2014)

Fig 4.7: A map showing the current (1971-2000) soil moisture regimes of Kenya according to the spatial Java Newhall simulation model.

4.5 Future (2050) soil moisture regimes of Kenya according to the spatial Newhall simulation model

The future soil moisture regimes of Kenya were found to be the same as those of current conditions. These are: aridic, ustic, udic and perudic as shown in fig 4.8 and 4.9. The ustic moisture regime, however, will dominate the country with a coverage of about 72% of Kenya's total area, mainly to the northern, eastern, coastal and parts of central parts. The udic moisture regime will be second, with an approximate coverage of 17%, mainly to the western parts of central Kenya. The aridic moisture regime will be third, covering about 11% of Kenya's total area, mainly to the northeastern and southeastern parts. Perudic will cover the least area of approximately 0.4%.

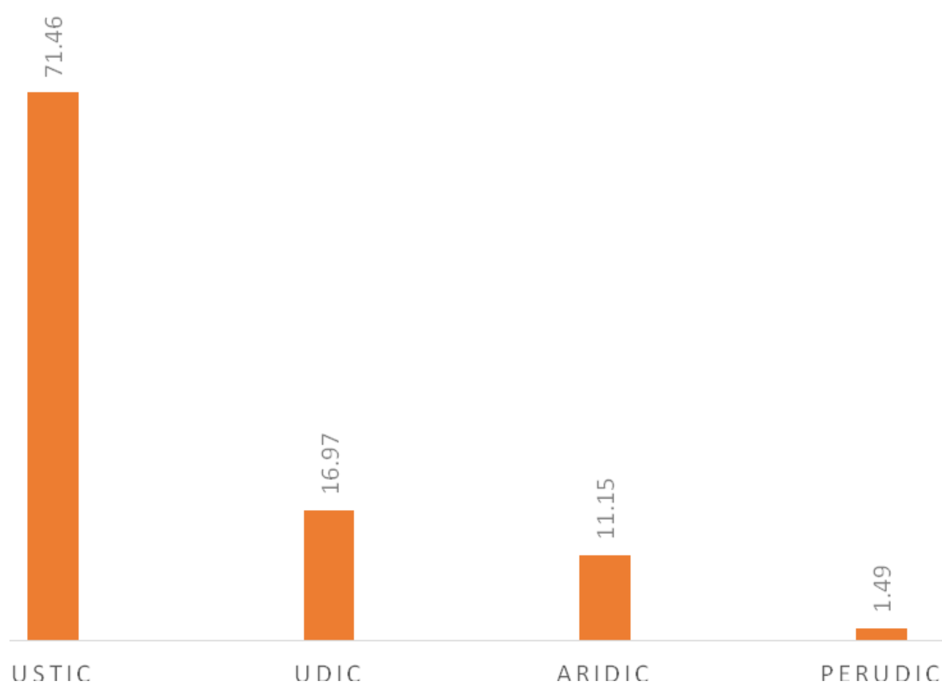
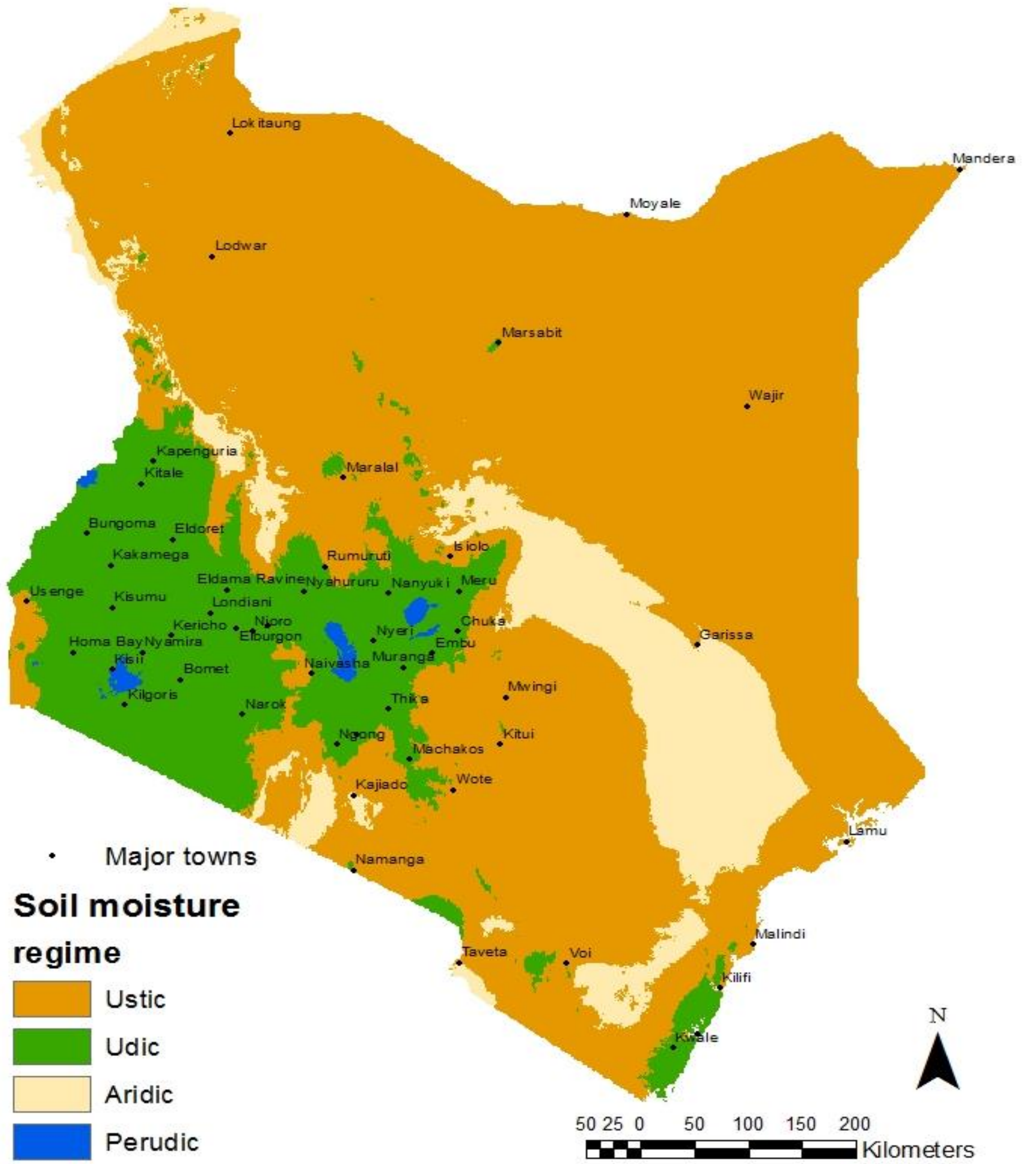


Fig 4.8: A bar graph showing the percentage area coverage (value above bars) of the future soil moisture regimes of Kenya according to the Java Newhall model



(Source: Author, 2014)

Fig 4.9: A map showing the future (2050) soil moisture regimes of Kenya according to the spatial Java Newhall simulation model

4.6 Percentage coverage comparisons between current and future soil moisture regimes

According to the model, the aridic moisture regime dominates the country in the current conditions while the ustic moisture regime dominates in the future conditions as shown in fig 4.10. It is worth noting that the area coverage of the aridic moisture of the future conditions is far much less as compared to the current conditions, with a percentage difference of about 36%. Also, the area coverage of the ustic moisture regime for the current conditions is far much less than that of the future conditions, with a percentage difference of about 45%. The area coverage for the current udic moisture is higher than that of the future conditions, with a percentage difference of about 8%. The perudic moisture regime has the least area coverage in both, but the future conditions show that it will cover a larger area (1% more).

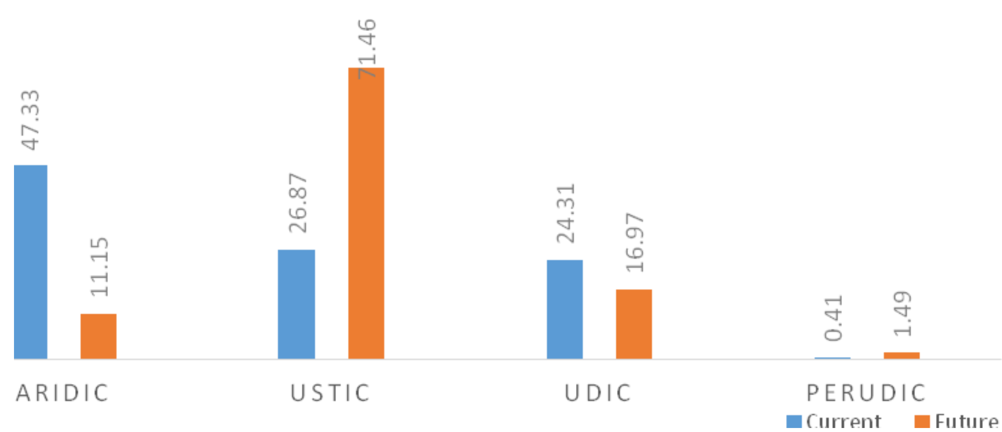


Fig 4.10: A bar graph showing comparisons between the current and future soil moisture regimes of Kenya in percentage area coverage (value above bars) according to the Java Newhall model

4.7 Current (1971-2000) soil moisture regime subdivisions (subgroup modifiers) of Kenya according to the spatial Newhall simulation model as described by Van Wambeke, 2000)

The current soil moisture regime subdivisions can be classified under each soil moisture regime as: (i) Aridic moisture regime: Extreme Aridic and Weak Aridic (ii) Ustic moisture regime: Aridic Tropustic, Typic Tropustic and Udic Tropustic and (iii) Udic moisture regime: Typic Udic and Dry Tropudic. This is as shown in fig 4.11 and 4.12

From the model results, the weak aridic subgroup modifier covers the largest area of the country, occupying about 47 % of Kenya's area. This is mainly to the northern and northeastern parts of the country. Typic udic comes second, covering about 19% of the central and western parts. Aridic tropustic covers about 14% of some parts to the north, and forms a boundary between the weak aridic and the rest of the subgroup modifiers. Typic tropustic, dry tropudic and udic tropustic cover about 8%, 6% and 5% of the country respectively. A small portion of extreme aridic, 0.03%, falls in the northwestern parts. About 1.5% of the western and central parts of the country seem to have lacked a name code according to the descriptions given by Wambeke (2000), hence undefined.

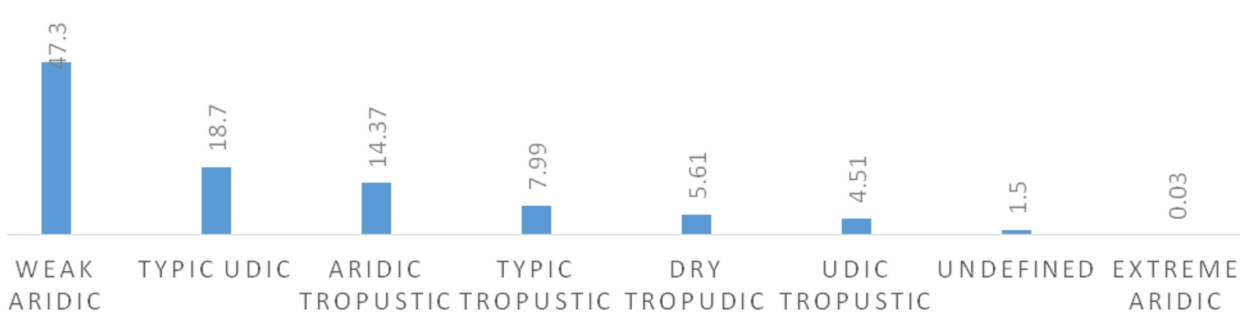
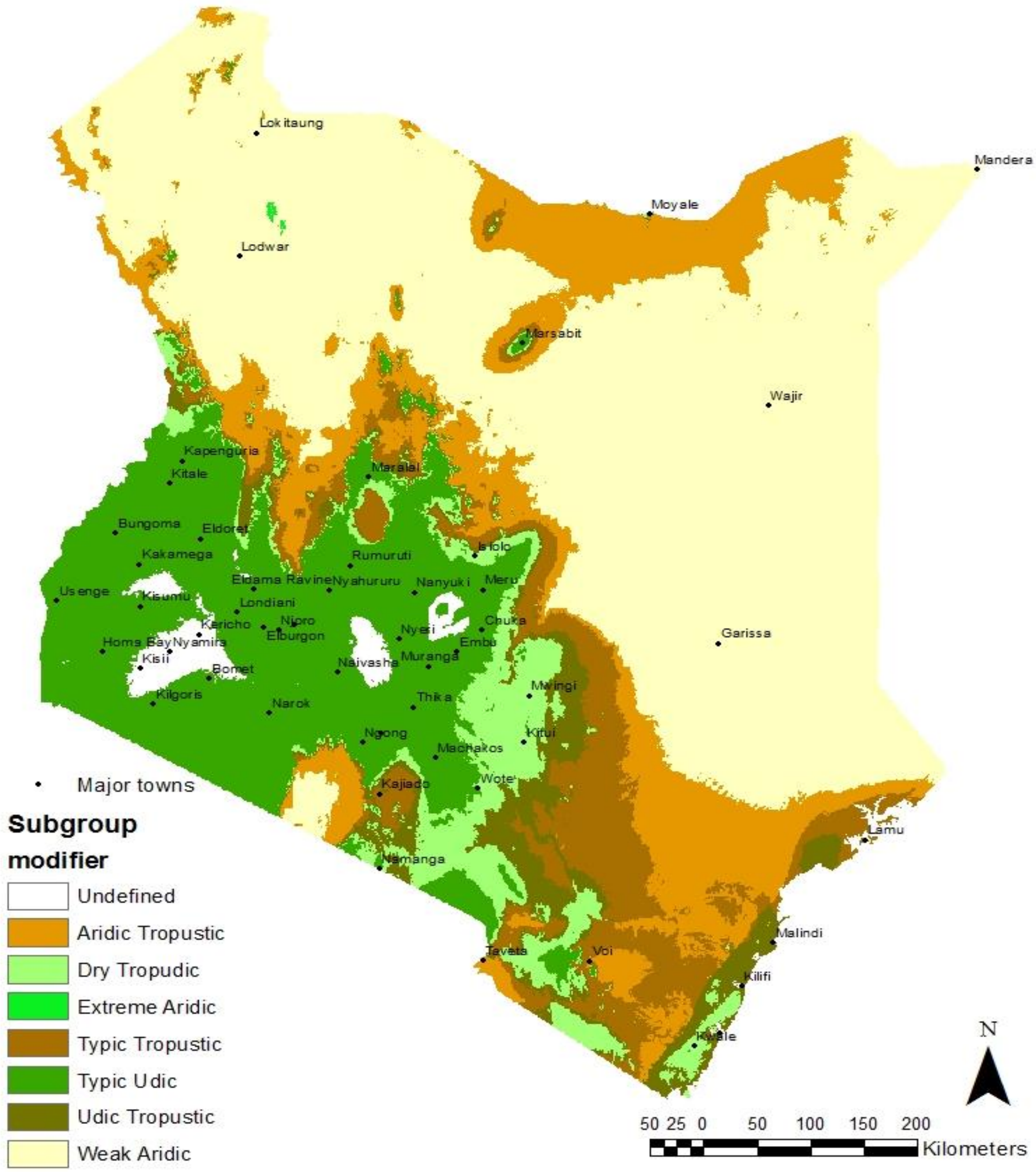


Fig 4.11: A bar graph showing the percentage area coverage (value above bars) of the current subgroup modifiers of Kenya according to the Java Newhall model.



(Source: Author, 2014)

Fig 4.12: A map showing the current (1971-2000) subgroup modifiers of Kenya according to the spatial Java Newhall simulation model as described by Wambeke (2000).

4.8 Future (2050) soil moisture regime subdivisions (subgroup modifiers) of Kenya according to the spatial Newhall simulation model as described by Van Wambeke (2000)

The future soil moisture regime subdivisions can be classified under each soil moisture regime as:

i. Aridic moisture regime: Typic aridic and weak aridic
ii. Ustic moisture regime: Aridic tropustic, typic tropustic, udic tropustic and typic tempustic
iii. Udic moisture regime: Typic udic, dry tropudic and dry tempudic

From the model results, the aridic tropustic subgroup modifier will dominate the country, covering about 65 % as shown in fig 4.13 and 4.14. Typic udic falls second, mainly covering the western parts. Typic aridic, typic tropustic, weak aridic, dry tropudic and udic tropustic cover approximately 7%, 5%, 4%, 3% and 2% respectively and the coverage of the latter is mainly towards the south. Dry tempudic and typic tempustic subgroup modifiers are negligible. The undefined areas lay under the perudic moisture regime and covered 0.41 % of the country.

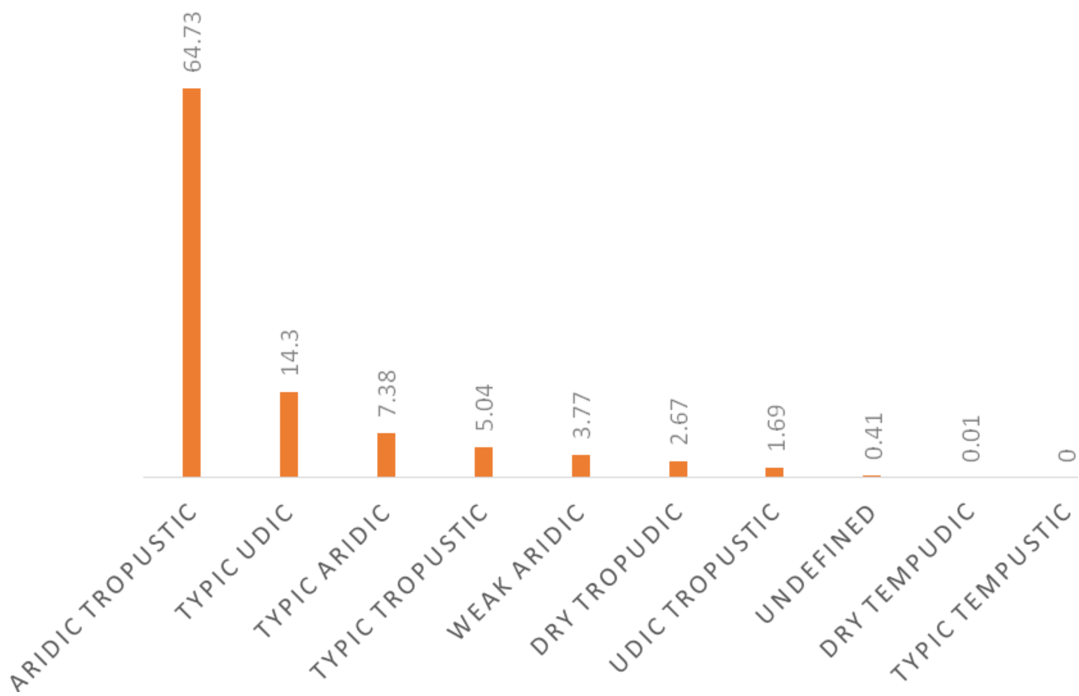
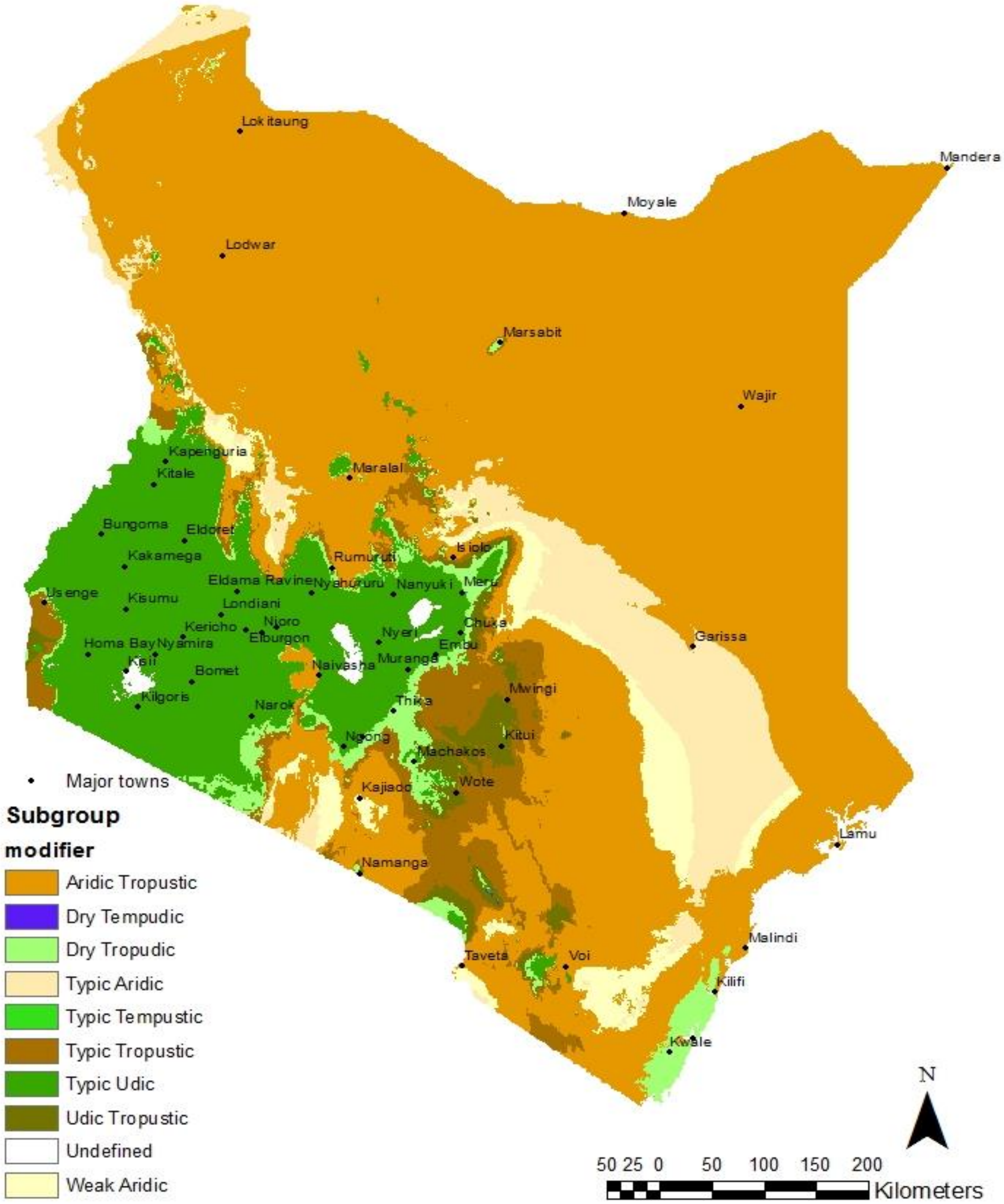


Fig 4.13: A bar graph showing the percentage area coverage (value above bars) of the future subgroup modifiers of Kenya according to the Java Newhall model



(Source: Author, 2014)

Fig 4.14: A map showing the future (2050) subgroup modifiers of Kenya according to the spatial Java Newhall simulation model as described by Wambeke (2000)

4.9 Percentage coverage comparisons between current and future subgroup Modifiers

The weak aridic subgroup modifier, about 47%, dominates the country in the current conditions while the aridic tropustic, 65%, dominates the country in the future conditions as shown in fig 4.15. It is worth noting that typic aridic is absent in the current conditions but present for the future conditions, covering about 7% of the country.

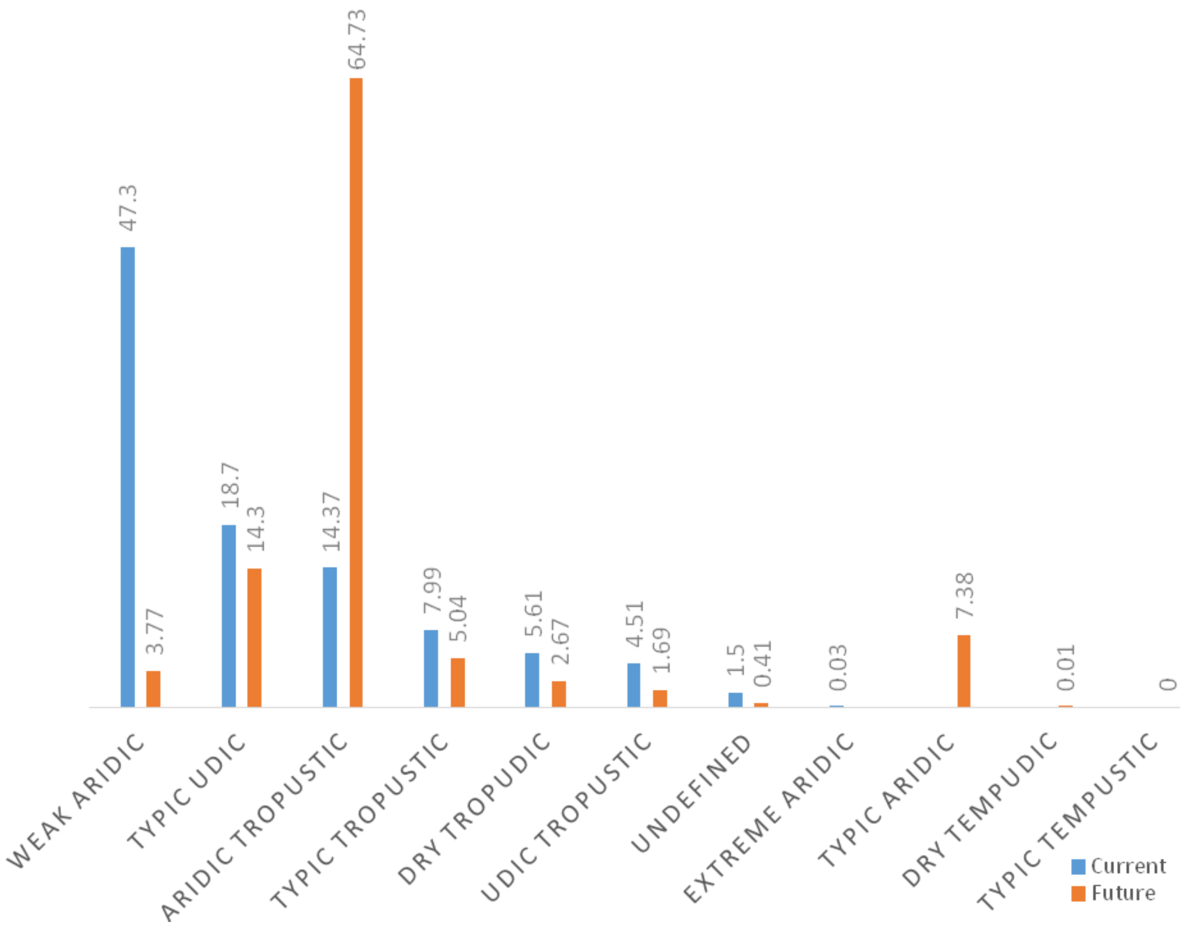


Fig 4.15: A bar graph showing comparisons between the current and future subgroup modifiers of Kenya in percentage area coverage (value above bars) according to the Java Newhall model

4.10 Spatial comparisons between current (1971-2000) and future (2050) soil moisture regimes of Kenya according to the spatial Java Newhall model

This model output raster map illustrated a series of negative and positive numbers and zero change. About half of the country will have no change (0 value) in soil moisture in the year 2050 which occurs mainly in the western, southern and central regions. Major shifts in soil moisture were found in the northern and eastern parts of the country, having the ustic (Aridic tropustic) moisture regime (-3 value) dominating whereas, the current conditions were dominated by the aridic (weak aridic) moisture regime as shown in fig 4.16 and appendices 13, 14, 15 and 16. According to the model predictions, the central and southwestern parts will experience reduction in area coverage by the udic moisture regime, having the ustic moisture regime (-1 value) dominating. Also, the aridic (Typic aridic) moisture regime (value 3) seems to draw a boundary between the ustic and udic moisture regime, unlike in the current conditions where the aridic moisture regime clearly separates the ustic and udic moisture regimes.

It is worth noting that the lake regions seem to experience drastic changes too. For example, parts of the L.Victoria will change from udic (Typic udic) to ustic (Typic tropustic and udic tropustic) moisture regime. L. Baringo will fall in an aridic (Typic aridic) moisture regime unlike at present, where it falls under an ustic (Aridic tropustic) moisture regime. L. Elementaita and L. Naivasha will also closely fall under an ustic (Aridic tropustic) moisture regime, unlike at present where each of them falls under an udic (Typic udic) moisture regime. Although the perudic moisture regime does not shift to new areas, it reduces in its coverage, having smaller portions in 2050.

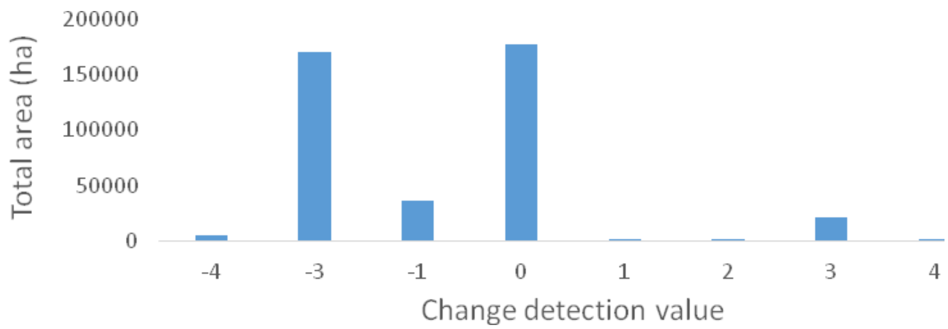


Fig 4.16: A bar graph showing the spatial comparisons between present (1971-2000) and future (2050) soil moisture regimes of Kenya in percent change units according to the spatial Java Newhall model

4.11 Spatial comparisons between current (1971-2000) and future (2050) soil temperature regimes of Kenya according to the spatial Java Newhall model

Spatial comparisons for soil temperature regimes showed no change (0 value) in over 70% of the country, having an isohyperthermic temperature regime dominating for both current and future conditions as shown in fig 4.17 and appendices 11 and 12. Parts of the isothermic temperature regime (-2 value) however, shifts to isohyperthermic, making the latter more vast in the future conditions. Pergelic temperature regime (-7 value) is completely absent in the future conditions while cryic temperature regime (+4 value) greatly reduces in area coverage around Mt. Kenya in the projected scenarios and is absent in the Aberdare Mountain Ranges. Thermic soil temperature regime (+2 value) was found to be present in the future climate conditions.

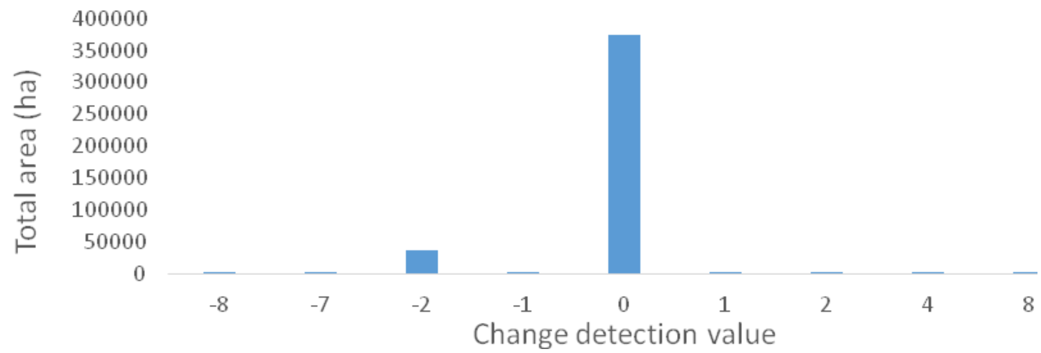
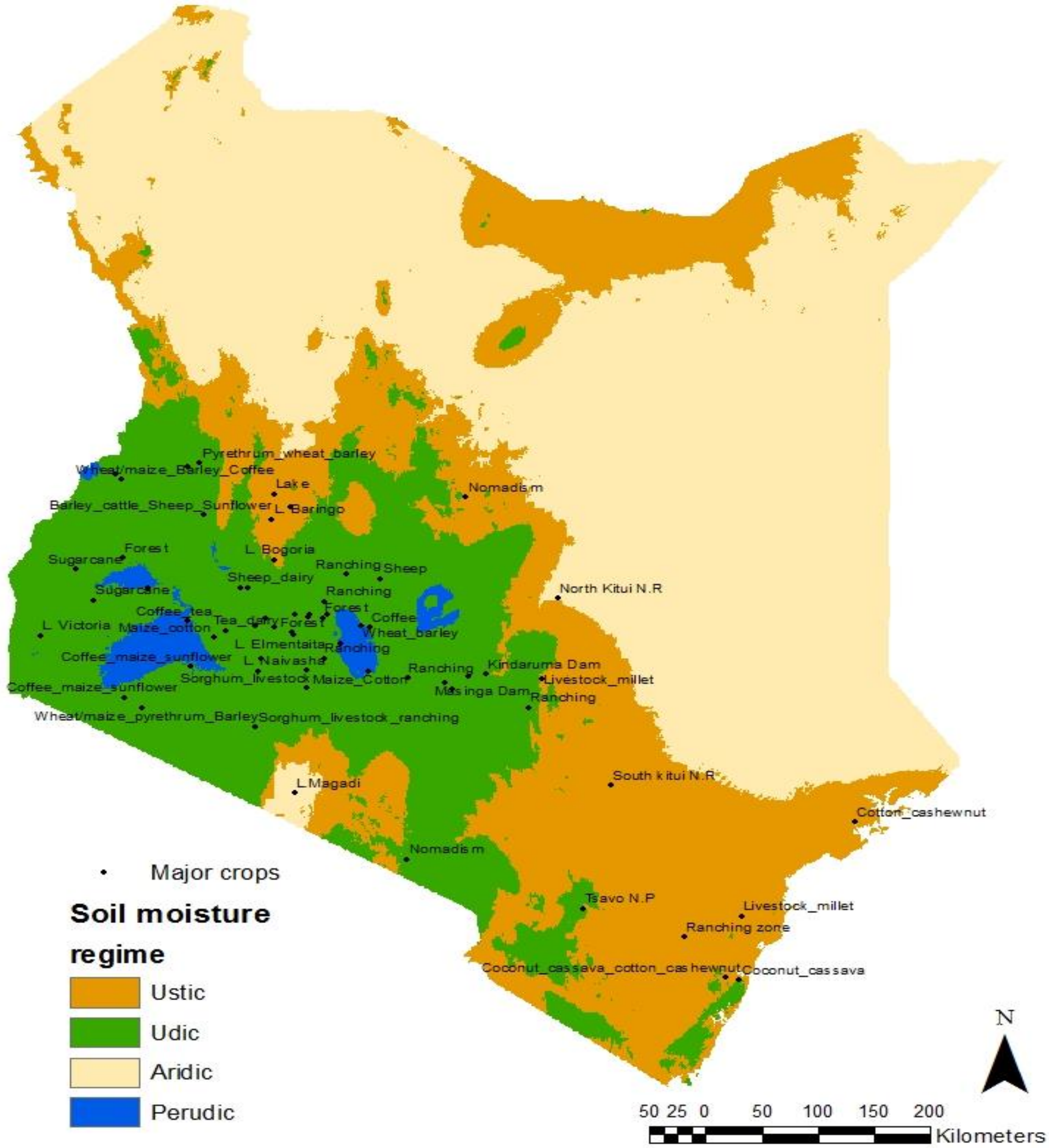


Fig 4.17: A bar graph showing the spatial comparisons between present (1971-2000) and future (2050) soil temperature regimes of Kenya in percent change units according to the spatial Java Newhall model

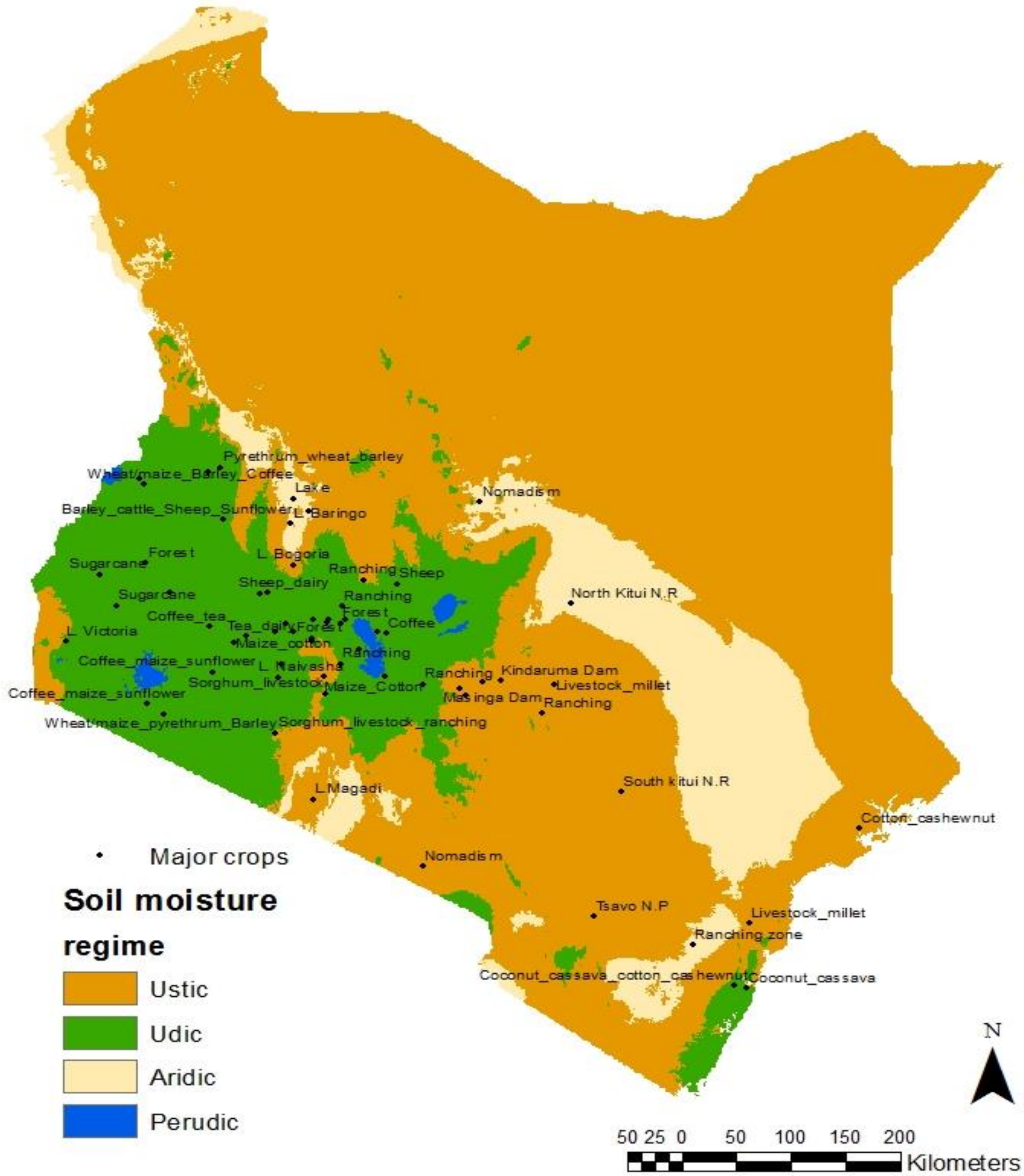
4.12 Spatial comparisons between current and future soil climate and some of the major crops

An overlay of the soil temperature and moisture regimes with some of the major crops was done as shown in fig 4.18 and 4.19. The spatial comparison maps created were also used against crop spatial distributions. Since the crop thematic map(Ministry of Agriculture, 2006 and ILRI, 2007) used represented only the arable parts of Kenya (majorly central and western Kenya) with only a few major crops represented, there were no major shifts found and therefore, are negligible. The arid and semi-arid regions of the country (northern and eastern Kenya) were not represented in the crop spatial distribution map. However, from the model output, it was noted that the northern and eastern parts of the country will have an ustic (Aridic tropustic) moisture regime dominating in the future, unlike in the current conditions where the aridic (weak aridic) moisture regime dominates. Such shifts in soil moisture regimes could mean shifts and diversity in potential crops grown, different land management options and potential for land degradation. Also, it was noted that there will be a reduction in the udic soil moisture regime in the central and western parts of the country in the year 2050. Crops acclimated to humid climatic conditions such as tea and coffee will no longer be suitable for growth in the affected areas. This will lead to decrease in agricultural productivity of these crops and this will call for growth of alternative crops. There is an increase in the perudic soil moisture regime in these parts (central and western) of the country which might imply shifts to growth of crops acclimated to waterlogged conditions such as rice.



(Source: Author, 2014)

Fig 4.18: A map showing spatial comparisons between current soil moisture regimes and some of the major crops currently grown in Kenya according to the spatial Java Newhall simulation model



(Source: Author, 2014)

Fig 4.19: A map showing spatial comparisons between future soil moisture regimes and some of the major crops currently grown in Kenya according to the spatial Java Newhall simulation model

CHAPTER FIVE

DISCUSSION

5.1 Soil temperature regimes of Kenya

According to the Newhall model, the isohyperthermic, isothermic and isomesic soil temperature regimes dominate the country in both present and future climate conditions (see figs 4.2 and 4.3). This is expected since Kenya has a tropical climate. The country is hot and humid at the coast, temperate inland and arid and semi-arid in the north and northeastern parts. The reduction in area coverage by the isohyperthermic temperature regime, the increment of the isothermic temperature regime and the presence of thermic temperature regime for the future conditions, can be attributed to increase in precipitation in the year 2050 due to climate change. Global warming due to causes such as greenhouse gases is likely to cause more water evaporation from natural water bodies such as lakes and seas, which condenses in the higher atmosphere levels then falls as precipitation. Increase in precipitation can lower the soil and air temperature leading to the prevalence of cooler soil climates. According to Christensen (2007), the amount and intensity of precipitation is likely to increase in a more pronounced way by 2100 in the tropical and high-latitude regions. In the drylands, water may become a critical issue. Soaring temperatures and erratic rainfall may dry up surface water (IPCC, 2007). This could mean that hot and humid climate will be more prevalent in the year 2050 as compared to the current climate conditions.

The pergelic temperature regime present in current conditions occupies a small portion of the L.Turkana (see fig. 4.2). The mean annual temperature in this small portion of the lake could be lower than 0^0C leading to formation of dry frost. This could be due to the lake effect mechanism where cold winds move across long expanses of warmer lake water providing enough energy to pick up water vapor, which freezes and is deposited on the leeward shores of the lake. This majorly happens during the night when the air temperatures are cool, which could imply that the climatic data was collected during the night. The cryic moisture regime, present in both current and future condition, falls on Mt. Kenya and Aberdare Ranges. Here, the mean annual temperatures could be higher than 0^0C but lower than 8^0C leading to very cold soils. The absence of the pergelic temperature regime and the reduction in area coverage by the cryic temperature regime (misses out on the Aberdare Ranges) in the future conditions can be attributed to climate change. With an expected rise in global land and water surface temperatures, melting of ice and permafrost and reduction of snow cover is inevitable. IPCC (2007) predicts that the glaciers of Kenya's eponymous mountain may disappear, leaving only seven of the eighteen glaciers recorded on Mount Kenya in 1900.

A report from the United Nations' Intergovernmental Panel on Climate Change (2007) concluded that, if no specific actions were taken to reduce greenhouse gas emissions, global soil temperatures would be likely to rise between 1.4 and 5.8^0 C from 1990 to 2100. Kenya would be one of the countries at most risk from climate change. According to the Farm Management Handbook (2009) and the Atlas of Kenya's changing environment (2009), observations show that Kenya's average annual temperatures increased by 1^0 C between 1960 and 2003. In specific, the Western Kenya temperatures rose by 0.5^0 C between 1981 and 2004. In the north and northeastern parts of Kenya, temperatures rose by 1.5^0 C over the same period. It is projected that Kenya's temperatures will increase by about 4^0C by the year 2100 (ACCI, 2014). The Intergovernmental Panel on Climate Change (IPCC, 2007) predict an 18 to 59 cm rise in sea- level globally by 2100. One study suggests that 17% of Mombasa's area could be submerged by a sea-level rise of 30 cm (Orindi and Adwera, 2008). It is expected that the natural and artificial water bodies will become drier and more contaminated due to soil erosion. This will mean that people, especially the poor, will have to walk even greater distances to fetch water (UCSB, 2010).

5.2 Soil moisture regimes of Kenya

In general, aridic, ustic and udic soil moisture regimes dominate the country in the current and future climate conditions according to the model. In the current conditions, the aridic (weak aridic) moisture regime dominates the country in the north and northeastern parts while in the future, the ustic (aridic tropustic) moisture regime replaces the latter. Wetter conditions in Kenya, especially in the short rains and especially in northern Kenya (where rainfall increases by 40% by the end of the 20th century) are likely to be experienced as shown in fig 5.2. Analysis of the northern Kenya region show that the increase in seasonal total rainfall in the short rains occurs by means of a trend of increasing rainfall extremes which, in models like MPI, are evident from the outset of the 21st Century (IPCC, 2007). The percentage difference between the present aridic soil moisture regime and the future is about 36%.

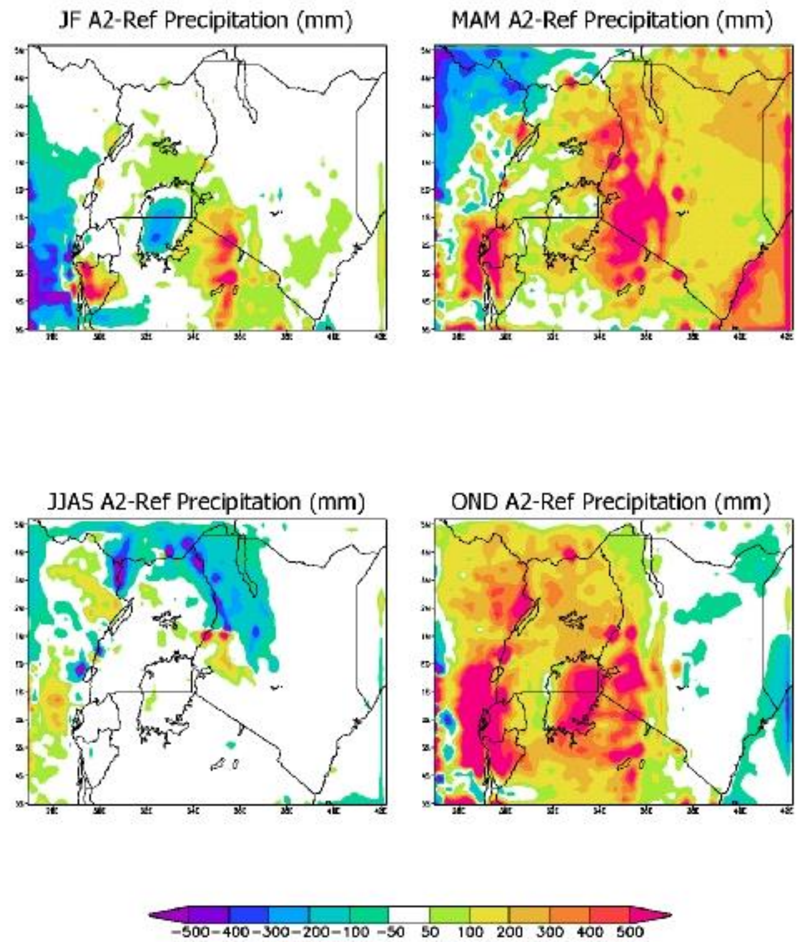


Fig 5.1: REGCM3 projection results for 2071 to 2100 (A2 RF, 20km resolution) for four rainfall seasons in Kenya (IPCC, 2007)

The area coverage by the udic (typic udic) moisture regime in the future is about 8% less than the present. However, the perudic moisture regime in the future, although still covering a small portion of the country, is about 1% higher than the current conditions. Kenya, like the rest of the world, is expected to experience climate change and variability and the associated adverse impacts. The climate change impacts include increased flooding, storms, excessive and erratic rainfall and drought (IPCC, 2007). These impacts could mean deterioration of soil degradation and hence, implementation of new soil management practices.

According to the pilot project commissioned by Adaption to Climate Change and Insurance (2014), seasonal trends in rainfall were found to give mixed results in Kenya, with some locations indicating increasing trends while others show no significant differences. However, there was a general decline in the main long rains season although annual rainfall totals were either neutral or slightly decreasing trends. The excessive and erratic rainfall can lead to an increase in perudic moisture regime in the year 2050 and to some extent, the aquic moisture regime. Global temperatures are generally expected to increase as global precipitation increases. This could be used to explain the decline in the udic moisture regime as increase in temperatures could lead to increase in evapotranspiration leading to less soil moisture. It is also possible that these areas will receive less rainfall compared to other parts of the country due to variations in seasonal trends in rainfall.

5.3 Spatial comparisons between current and future soil climate and some of the major crops

Although no major soil climate-crop assessments were done in this study, it was noted that shifts in soil moisture regimes could mean shifts and diversity in crops grown. A National Climate Change Action Plan (NCCAP 2013-2017) developed by ACCI (2014) show crop diversification and mixed cropping as some of the strategies for adapting agriculture to climate change. The ustic soil moisture regime is a characteristic of soils that can support drought tolerant crops (Smith, 1986). The northern and eastern parts of the country, having an ustic (Aridic tropustic) moisture regime dominating in the future, unlike in the current conditions where the aridic (weak aridic) moisture regime dominates, could lead to more suitable climatic conditions for crop growth due to increase in rainfall. This means that these regions would support drought tolerant crops like sorghum and millet.

Livestock production and/or pastoralism is the major economic activity of the North Rift and Northeastern regions of the country. These regions have had complex patterns of conflicts due to, among other factors, competition over and access to natural resources such as pasture and water, raiding and cattle rustling (CDC, IISD and Saferworld, 2009). Conflict resolution and cross border harmonization among the pastoralists from different cultures in these regions has formed an integral part of the government of Kenya aim of reducing such conflicts (Oyugi, 2002). With an ustic moisture regime, more drought tolerant pasture grasses will thrive and with an expected increase in rainfall, more water will be available for the livestock. This will lead to reduction in competition for these natural resources (UNEP, 2009). Also, introduction of food crop production and land management practices might help solve some of these conflicts; although this might mean in-depth education and extension services for the staunch pastoralists, who have developed a tradition of keeping livestock.

Increasing temperatures are also likely to affect the growing of major crops in the country and threaten the livelihoods of farmers. Rain-fed agriculture, which accounts for 98% of the agricultural activities in the country, is the backbone of Kenya’s economy and is very vulnerable to increasing temperatures, droughts and floods in the future conditions. This is especially seen in the reduction of the udic moisture regime in the central parts of the country in the year 2050. Crops acclimated to humid climatic conditions such as tea and coffee will no longer be suitable for growth in the affected areas. This will lead to a decrease in agricultural productivity of these crops. Research conducted by CIAT (2011) on future climate scenarios for Kenya's tea growing areas shows a decline in suitability for tea growth in the western and central parts of the country in the year 2050. The CIAT research group went further and identified potential diversification strategies for the tea farms. This group identified six crops: maize, pea (pigeon variety), cabbage, banana, passion fruit and coffee (Arabica and Robusta).

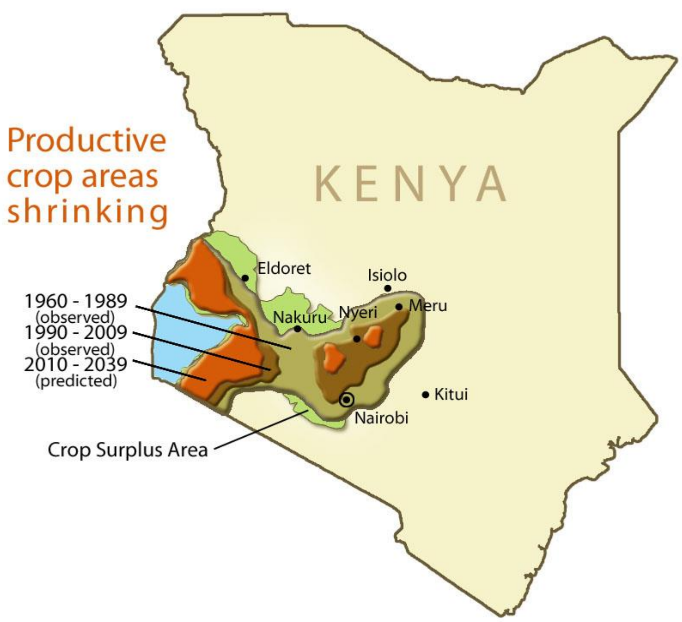


Fig 5.2: A map of Kenya showing the shrinkage of the productive crop areas (arable land of Kenya) (UCSB, 2010)

5.4 Undefined portions of the subgroup modifiers of Kenya produced by the Java Newhall model for in current and future climatic conditions

The undefined parts of the soil moisture subdivisions might not have met any of the soil moisture conditions as described by Wambeke et al., (1982) and Wambeke (2000). This case would apply to soils high in clay content such as smectites. In such soils the moisture penetrates through the soil slowly but is held tightly within the soil pores due to high matric potential (Tolk, 2003). Here, soil water content boundaries such as field capacity and permanent wilting point which determine the plant available water are negligible or even absent. This means that the plant roots are not able to extract this water as required for plant growth and development. The undefined subgroup modifiers fall in areas expected to have soils with vertic properties such as Kano plains in western Kenya and in the central Kenyan plateau areas of Mwea, Masinga, Matuu and Athi River. Soils of these areas (vertisols) are successfully used for growth of irrigated crop production of rice, cotton, maize and horticultural crops (Ikitoo et al., 2011). Such soil moisture conditions could have been missing or even negligible when Wambeke and his co-authors developed the key to the subgroup modifiers. In this key, all climatic requirements are assumed to occur in most years (6 out of 10) which could attribute to lack of capture of soil water conditions that occurred for short periods. These undefined parts, however, fall under the perudic moisture regime.

The definitions of soil moisture subgroup modifiers by Wambeke (1982) were tentative subdivisions of moisture regimes. This means that they can be adjusted after a careful study on soil moisture properties in relation to soil physical, chemical and biological attributes. New soil moisture subdivisions can also be developed especially with the changing soil climate due to climate change.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The Newhall model output produced isohyperthermic, isothermic pergelic, isomesic and cryic soil temperature regimes for the current climate conditions. The pergelic moisture regime is absent in the projected climate scenarios but the thermic temperature is present. Aridic, ustic, udic and perudic soil moisture regimes are present in both current and future climatic conditions.

According to the Newhall model, the isohyperthermic temperature regime dominates the country both for current and future conditions, occupying over 70 % of the country's total area, and the isothermic and isomesic soil temperature regimes fall second and third, respectively. Although the cryic temperature regime is present in both times, it covers less area in the future climate conditions where it is completely absent in the Aberdare Mountain Ranges. Thermic temperature is absent in current conditions but present in the future while pergelic temperature regime is present in current conditions but absent in the future conditions.

According to the model, the aridic moisture regime dominates the country in the current conditions while the ustic moisture regime dominates in the future conditions. The area coverage for the current udic moisture is higher (about 8%) than that of the future conditions. The perudic moisture regime has the least area coverage in both, but the future conditions show that it will cover a larger area (1%)

According to the model, the northern and eastern parts of the country will be dominated by the ustic moisture regime in the future, unlike in the current conditions where the aridic moisture regime dominates. Such shifts in soil moisture regimes could mean shifts and diversity in crops grown. Drought tolerant crops such as millet and sorghum could be highly recommended. This would mean adoption of mixed farming by the people of North Rift and Northeastern regions of Kenya, whose current major economic activity is pastoralism. Implications are that the distribution of crop suitability within the current udic and perudic soil moisture regimes in general will decrease quite seriously by 2050; for example, the tea and coffee growing areas.

6.2 Recommendations

From this study, growing of drought tolerant crops such as sorghum and millet along with crop diversification in the north and northeastern parts of the country, where rainfall is expected to increase by the year 2050, are some of the innovative methodologies that can be adopted in these areas. Such improved soil moisture conditions can also support growth of improved pasture grasses. Creation of new land use policies and mainstreaming of climate change into agricultural extension services is highly recommended for fast and efficient adoption by the farmers (currently pastoralists) in these areas.

With an expected increase in rainfall, there is a danger of soil loss and land degradation in the current bare lands of north and northeastern Kenya; therefore, soil erosion and soil degradation control measures. This will include building of gabions, contour farming and integrated soil fertility management to enrich the soils which are highly prone to soil degradation due to their weak aggregate stability (mainly sandy soils).

Relationships of length of growing period of crops to soil moisture availability and suitable soil temperatures will be essential in central and western parts of the country (arable lands of Kenya) where a reduction in the humid climates is expected by the year 2050. This will call for intervention from agronomists (soil scientists, crop scientists and modelers) in order to identify alternative crops suitable for growth in the affected areas.

6. 3 Limitations of the study

- This reflects back to the model's assumptions and limitations. The model is only valid for well drained soils. No aquic moisture regimes are indicated on the map and hence this research does not provide information on poor drainage conditions.
- Ground truthing of the soil climate regimes of Kenya by measuring the real soil temperature and moisture was not done due to time and resource constraints.

6.4 Future work

- Ground truthing of the soil climate regimes of Kenya to increase the accuracy and reliability of the output.
- Calculation of soil aquic moisture regimes should be done in order to provide information on poor drainage conditions.
- Use of climatic data that is more spread which helps to correlate with the future climate projected scenarios.
- Soil climate-crop relationships should be made, especially those that relate to the soil moisture regimes. This would require a more up-to-date digital crop map.

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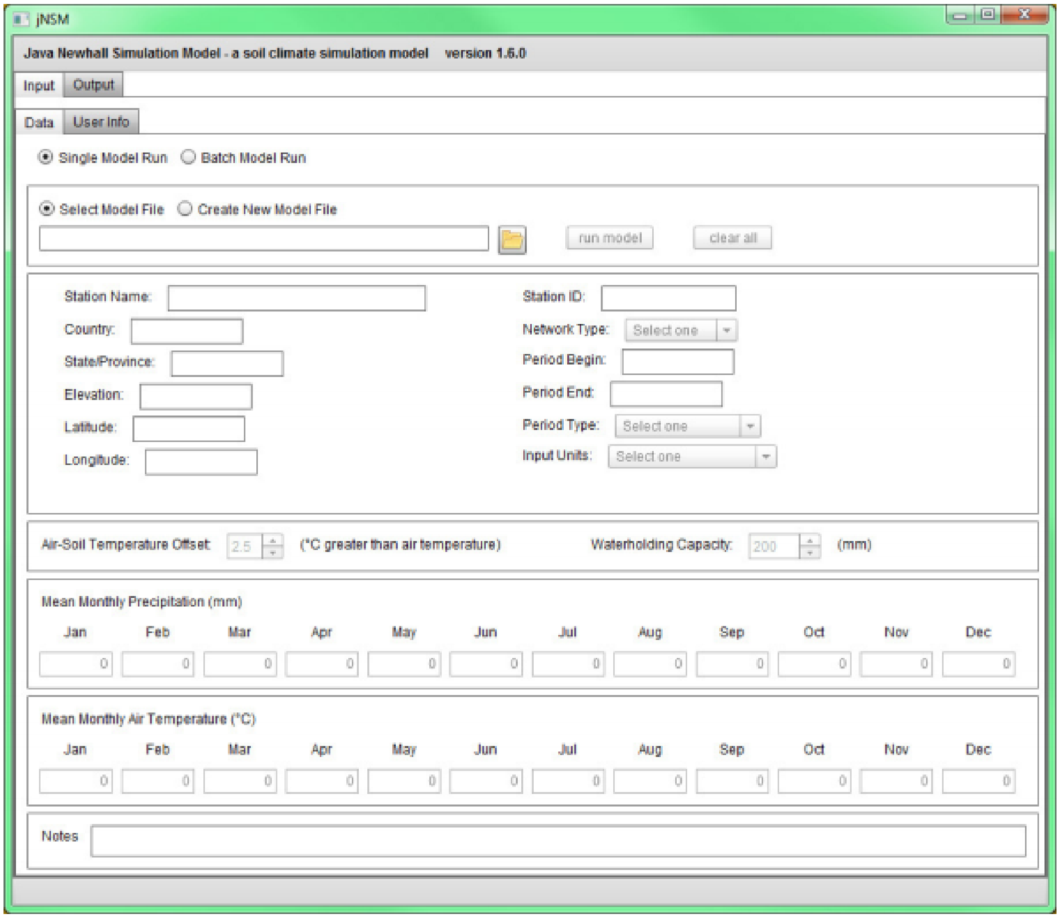
APPENDICES

Appendix I: Installing the jNSM

Currently the model runs only under MS Windows XP and 7 operating systems. The model can be freely accessed in the USDA- NRCS website. The jNSM is a Flex application that calls a Java application. This requires you to have both Adobe AIR and Java Runtime installed. You may, therefore, need to allow the installation of Adobe AIR during the installation. To download and install the most recent version of Java Runtime (Java 5 or later is required), go to http://www.java.com/en/download/manual.jsp and find the options for Microsoft Windows. Select either the online or offline installer, either will work. Run the program you download, follow the instructions. It is recommended that you opt-out of any software or toolbar offers the installer provides you, these programs are generally not worth the effort of installing them.

Appendix II: Running the jNSM application

To run the jNSM application simply double-click the desktop icon that was placed on your desktop after download, or go to the Start | All Programs menu and click the jNSM icon (Windows). The application will open in this view:



Appendix III: Input Batch Data File Format

- File Type: comma separated values (CSV)
- File must include required elements
- First line of file must be header of element names from table below
- File must include all element names/columns in the order specified
- Each subsequent line must contain the element data values for a single model run
- File may have only one unit system (i.e. metric and standard units may not be mixed)
- Columns that hold non-required data (N) must either hold valid data values or be left blank

Element	***Description***	***Required***	***Data type***	***Units/values***
stationName	station name	Y	text	cannot contain slash
netType	network type	Y	text	SCAN, HCN, SNOTEL
LatDD	station latitude decimal degrees	Y	float	degrees
LonDD	station longitude decimal degrees	Y	float	degrees
Elev	station elevation	Y	int	ft, m
TJan	January temperature	Y	float	degrees F, C
TFeb	February temperature	Y	float	degrees F, C

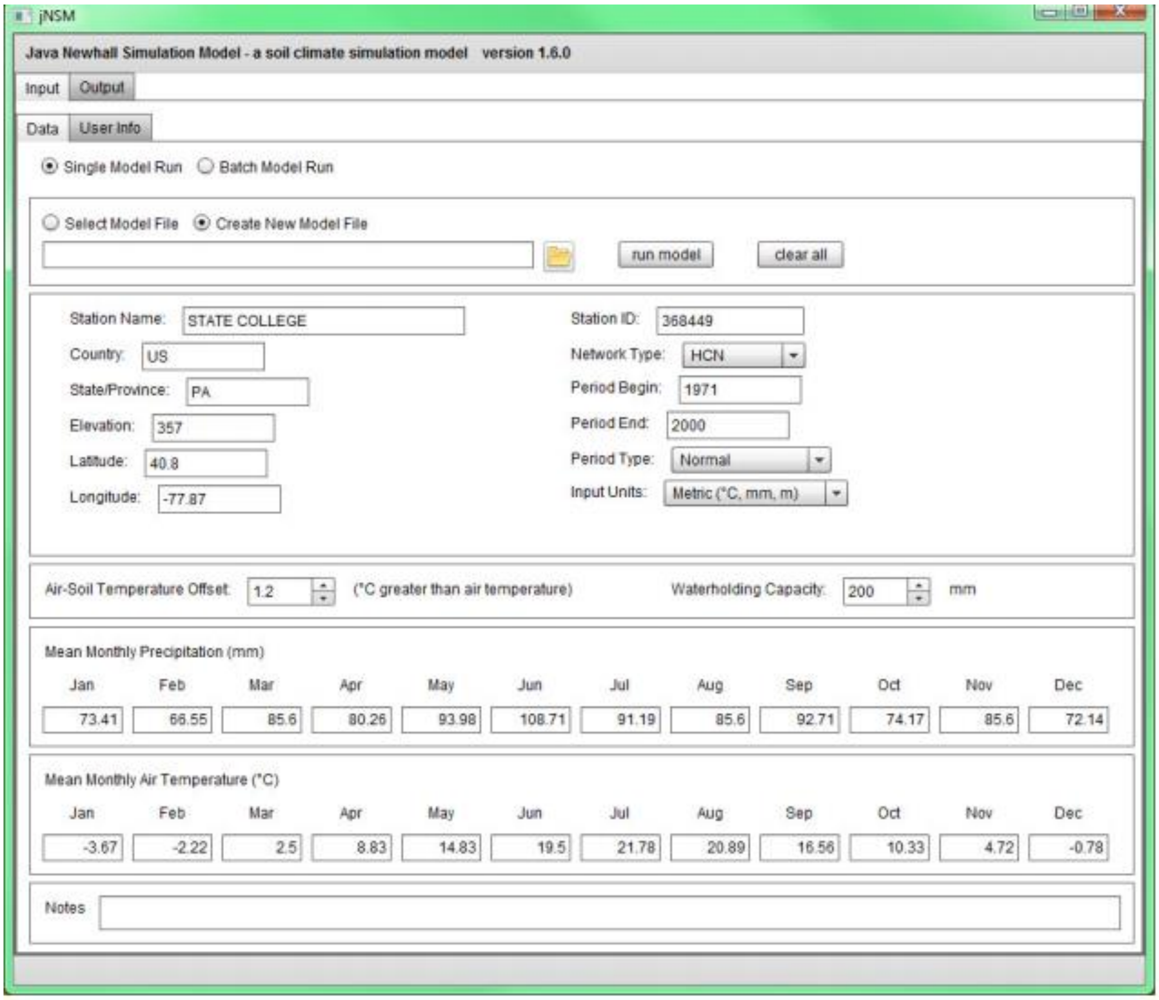
Element	***Description***	***Required***	***Data type***	***Units/values***
tMar	March temperature	Y	float	degrees F, C
tApr	April temperature	Y	float	degrees F, C
tMay	May temperature	Y	float	degrees F, C
TJun	June temperature	Y	float	degrees F, C
TJul	July temperature	Y	float	degrees F, C
tAug	August temperature	Y	float	degrees F, C
tSept	September temperature	Y	float	degrees F, C
TOct	October precipitation	Y	float	degrees F, C
tNov	November temperature	Y	float	degrees F, C
tDec	December temperature	Y	float	degrees F, C
PJan	January precipitation	Y	float	in, mm
pFeb	February precipitation	Y	float	in, mm
pMar	March precipitation	Y	float	in, mm
pApr	April precipitation	Y	float	in, mm
pMay	May precipitation	Y	float	in, mm
PJun	June precipitation	Y	float	in, mm
PJul	July precipitation	Y	float	in, mm
pAug	August precipitation	Y	float	in, mm
pSep	September precipitation	Y	float	in, mm
pOct	October precipitation	Y	float	in, mm
pNov	November precipitation	Y	float	in, mm

Element	***Description***	***Required***	***Data type***	***Units/values***
PdType	type of period of record	Y	text	Normal, actual, average
pdStartYR	start of year period represented by data	Y	int	
pdEndYr	endyr of year period represented by data	Y	int	
awc	available water holding capacity of the soil: if not specified, default of 200mm (7.874 inches) is used	N	float	in, mm
maatmast	mean annual air temperature to soil temperature offset soil; if not specified, default of 2.5 ^{0}C (4.5^{0}F) is used	N	float	degrees F, C
cntryCode	country abbreviation	N	text	
stProvCode	state/prov abbreviation	N	text	
mlraID	MLRA ID	N	text	
notes	free-form notes	N	text	
stationID	station ID	N	text	

Appendix IV: Two data input methods: 1) Single model run 2) Batch model run

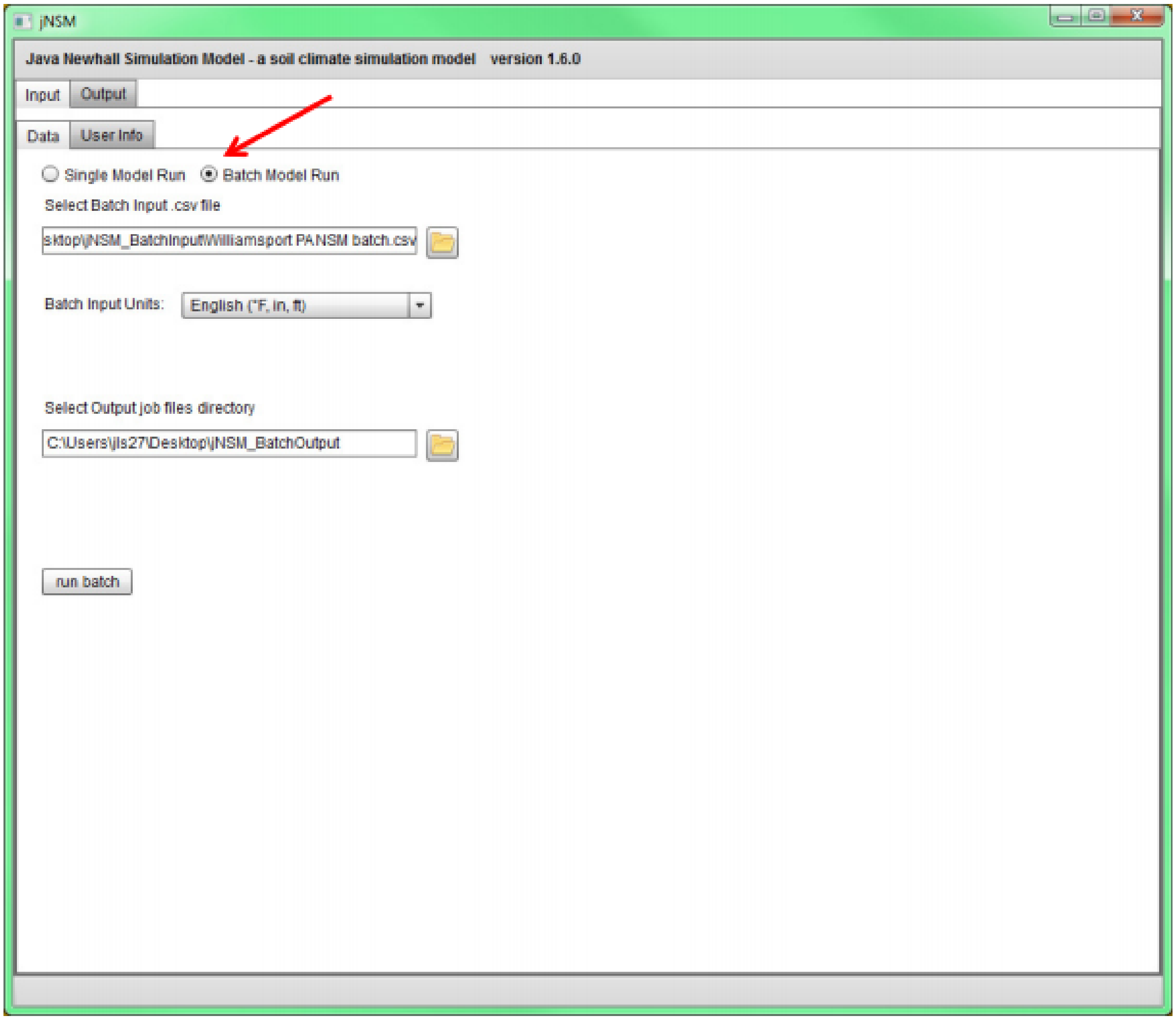
With the Single Model Run radio button selected on the Data page, the user interactively supplies: information about the sample station, information about the sampling period and the measurement units, air-soil temperature offset and water holding capacity parameters and serially-complete mean monthly precipitation and air temperature values. When the run model button is hit, the user will be prompted to designate the name and the destination for the output XML file.

Appendix IV: Data input method: Single model run



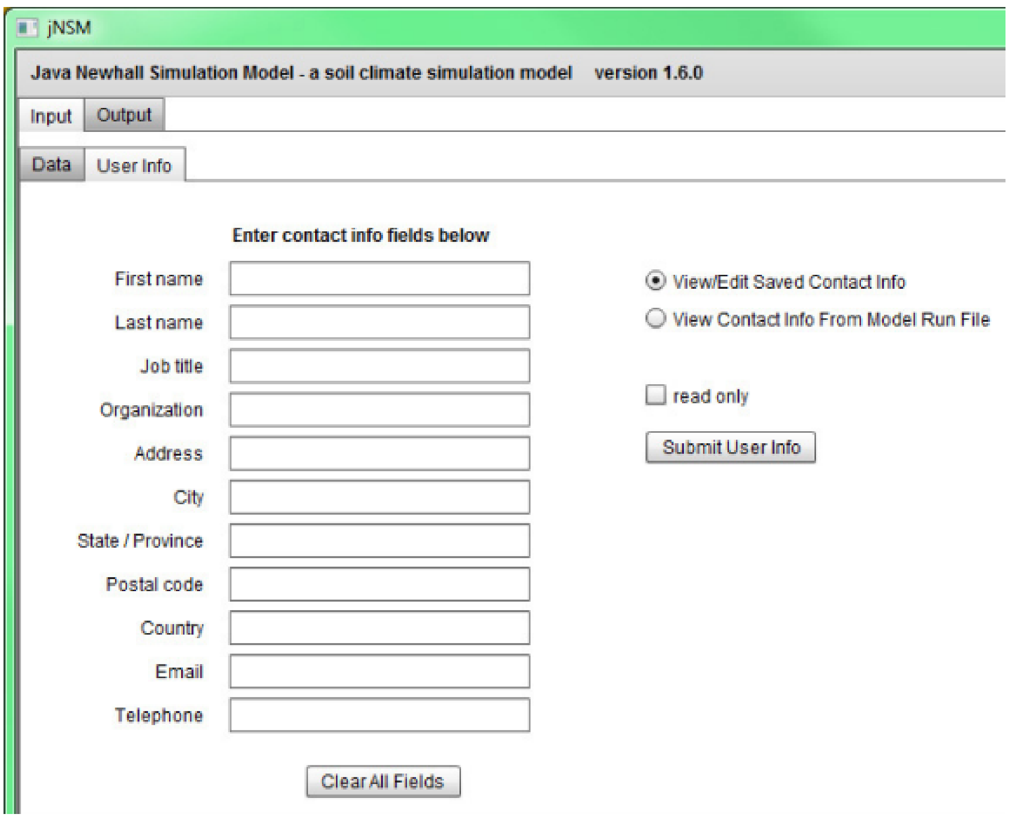
With the Batch Model Run radio button selected on the Data page, the user supplies: the name of a CSV file that contains input data, the unit system of the data in the batch CSV file, the name of a destination folder for the model output file. When the run batch button is hit, a counter will appear showing the progress of the model run.

Appendix IV: Data input method: Batch model run



Appendix V: User information

As part of the metadata for each model run the user must supply contact information via the form pictured below. The form is accessed via the User Info tab, and must be filled in and submitted before the user can execute a model run. After entering User Information the first time you run the model, it will be saved and automatically supplied to subsequent model runs. You can change it when necessary by resubmitting the form.



Appendix VI: Example of excel jNSM input table

1	stationNa	netType	latDD	longDD	elev	tJan	tFeb	tMarch	tApril	tMay	tJune	tJuly	tAug	tSept	tOct	tNov	tDec	pJan	pFeb	pMarch	pApril	pMay
2	1	SRTM	35.2925	5.42421	1111	24.9	25.2	25.3	23.7	23.6	23.2	22.7	22.6	23.1	23.4	23.5	23.9	19	44	81	119	[illegible]
3	2	SRTM	35.3011	5.42425	967	25	25.5	25.7	24	23.9	23.5	22.9	23	23.4	23.8	23.8	24.1	18	43	79	117	[illegible]
4	3	SRTM	35.3098	5.42428	881	25.3	25.7	25.9	24.4	24.2	23.9	23.3	23.3	23.8	24	24	24.4	18	42	77	114	[illegible]
5	4	SRTM	35.3185	5.42431	829	25.7	26	26.3	24.7	24.5	24	23.6	23.6	24	24.4	24.4	24.8	17	41	75	112	[illegible]
6	5	SRTM	35.3271	5.42435	905	25.9	26.4	26.7	25	24.8	24.6	24	23.9	24.4	24.7	24.7	25	16	40	73	110	[illegible]
7	6	SRTM	35.3358	5.42438	785	25.9	26.3	26.5	24.8	24.6	24.4	23.7	23.8	24.2	24.6	24.6	24.9	17	40	74	111	[illegible]
8	7	SRTM	35.3444	5.42442	792	26.4	26.8	27	25.5	25.3	25	24.4	24.4	24.8	25.1	25.1	25.5	16	38	70	107	[illegible]
9	8	SRTM	35.3531	5.42445	801	26.4	26.7	27	25.3	25.2	24.8	24.4	24.4	24.8	25.1	25.1	25.5	16	38	71	108	[illegible]
10	9	SRTM	35.3617	5.42448	781	26.2	26.7	26.9	25.4	25.1	24.9	24.3	24.3	24.7	25	25.1	25.4	16	39	71	108	[illegible]
11	10	SRTM	35.3704	5.42452	873	25.9	26.4	26.7	25	24.8	24.6	24	23.9	24.4	24.7	24.7	25	17	40	73	111	[illegible]
12	11	SRTM	35.3791	5.42455	771	26.3	26.8	27.1	25.5	25.3	25	24.4	24.4	24.9	25.2	25.2	25.5	16	38	70	108	[illegible]
13	12	SRTM	35.3877	5.42458	749	26.6	27	27.2	25.5	25.4	25.1	24.6	24.6	25.1	25.2	25.4	25.6	15	38	69	107	[illegible]
14	13	SRTM	35.3964	5.42462	849	26.4	26.7	26.9	25.3	25.1	24.9	24.3	24.4	24.8	25.1	25.1	25.4	16	39	71	109	[illegible]
15	14	SRTM	35.405	5.42465	805	26.7	27.2	27.4	25.8	25.6	25.3	24.8	24.7	25.2	25.3	25.4	25.7	15	37	69	106	[illegible]
16	15	SRTM	35.4137	5.42469	715	26.8	27.3	27.6	25.8	25.8	25.5	25	24.8	25.3	25.5	25.6	25.9	15	36	68	105	[illegible]
17	16	SRTM	35.4224	5.42472	652	27.1	27.6	27.8	26	25.9	25.6	25.1	25	25.5	25.7	25.8	26.2	15	36	66	103	[illegible]
18	17	SRTM	35.431	5.42475	641	27.2	27.7	27.9	26.3	26	25.7	25.2	25.3	25.6	25.9	25.9	26.2	14	35	66	102	[illegible]
19	18	SRTM	35.4397	5.42479	615	27.2	27.6	27.9	26.2	26.1	25.9	25.3	25.2	25.7	25.9	26.1	26.4	14	35	65	102	[illegible]
20	19	SRTM	35.4483	5.42482	612	27.3	27.7	28	26.3	26.3	26	25.4	25.3	25.8	26	26.2	26.5	14	35	65	101	[illegible]
21	20	SRTM	35.457	5.42486	599	27.4	27.9	28.1	26.5	26.2	26	25.5	25.4	26	26.2	26.1	26.4	14	34	64	101	[illegible]
22	21	SRTM	35.4657	5.42489	589	27.4	27.8	28.1	26.4	26.3	26.1	25.5	25.4	25.9	26.2	26.3	26.4	14	34	64	101	[illegible]
23	22	SRTM	35.4743	5.42492	572	27.5	28	28.2	26.5	26.3	26.2	25.7	25.5	26.1	26.3	26.3	26.5	14	34	64	100	[illegible]
24	23	SRTM	35.483	5.42496	560	27.5	28.1	28.4	26.7	26.5	26.2	25.7	25.6	26.2	26.3	26.4	26.6	14	34	63	100	[illegible]
25	24	SRTM	35.4916	5.42499	553	27.5	28.1	28.4	26.7	26.6	26.4	25.7	25.6	26.2	26.4	26.5	26.8	14	33	63	99	[illegible]
26	25	SRTM	35.5003	5.42503	541	27.6	28.2	28.4	26.8	26.5	26.4	25.9	25.7	26.2	26.5	26.4	26.7	14	33	63	99	[illegible]
27	26	SRTM	35.509	5.42506	532	27.7	28.2	28.4	26.7	26.6	26.4	25.8	25.7	26.2	26.4	26.6	26.8	14	33	63	99	[illegible]
28	27	SRTM	35.5176	5.42509	536	27.7	28.3	28.6	26.9	26.7	26.5	26	25.8	26.4	26.5	26.6	26.9	14	33	62	98	[illegible]
29	28	SRTM	35.5263	5.42513	522	27.7	28.3	28.6	26.9	26.6	26.5	26	25.8	26.4	26.6	26.5	26.9	14	33	62	98	[illegible]
30	29	SRTM	35.5349	5.42516	515	27.8	28.3	28.6	26.8	26.7	26.6	25.9	25.8	26.4	26.5	26.7	27	14	33	62	98	[illegible]

Appendix VII: jNSM XML file tag descriptions

Element name	**Description**
nettype	Network to which the station belongs (e.g. SCAN, HCN, SNOTEL, NCSS, other)
stnname	Station name
stnid	Station ID
stnelev	Elevation in meters
stateprov	State or province
country	Country
mlraname	MLRA name (not yet implemented)
mlraid	MLRA ID (not yet implemented)
firstname	Contact person first name
midname	Contact person middle name
lastname	Contact person last name
title	contact person title

Element name	**Description**
Cntorg	contact organization name
address	contact street address
city	contact city
stateprov	contact state or province
postal	contact zip/postal code
country	contact country
cntemail	contact email address
cntphone	contact telephone number
note	free-form note (s)
rundate	time-date stamp of model run (e.g MM/DD/YYYY HH:MM:SS)
nsmver	version of NSM software
srcunitsys	unit system in which the input data were entered; important: all data stored in XML file are in metric units
lat	station latitude in signed decimal degrees
lon	station longitude in signed decimal degrees
srccoordfmt	coordinate system (e.g. decimal degrees, degrees-minutes-seconds, or degrees-decimal minutes) in which the input data were entered; important: all coordinates stored in XML file are decimal degrees [No yet implemented]
pdtype	period of record type; actual year, normal, or monthly average
pdbegin	period of record begin year

Element name	Description
Pdend	period of record end year
precip	input precipitation value in millimeters (mm)
airtemp	input air temperature value in degrees Celsius
smcsawc	input soil moisture control section (SMCS) available water capacity in mm
ampltd	difference in amplitude between soil and air temperature sine waves
maatmast	difference, in degrees Celsius, between mean annual air and soil temperatures
smrclass	soil moisture regime classification computed by model
subgrpmod	soil subgroup modifier
strclass	soil temperature regime classification computed by model
awb	annual water balance in mm [total precip minus PET] jan-dec
	summer water balance in mm [total precip
	minus
swb	jun-aug (N hemisphere); dec-feb (S hemisphere)
yrdry	cumulative days the SMCS is dry during the year
yrmd	cumulative days the SMCS is moist/dry during the year
yrmst	cumulative days the SMCS is moist during the year
bio5dry	cumulative days the SMCS is dry when soil temperature >5° C
bio5md	cumulative days the SMCS is moist/dry when soil temperature >5° C
bio5mst	cumulative days the SMCS is moist when soil temperature >5° C

Element name	**Description**
Yrmst	consecutive days the SMCS is moist in some part during the year
bio8mst	consecutive days the SMCS is moist in some part when soil temperature >8° C
Smrdry	consecutive days the SMCS is dry after summer solstice
wtrmst	consecutive days the SMCS is moist after winter solstice
pet	output potential evapotranspiration value in mm (Thornthwaite, 1948)
stlt5	soil temperature calendar period where soil temperature <5° C
st5to8	soil temperature calendar period where soil temperature is between 5° and 8° C
stgt8	soil temperature calendar period where soil temperature >8° C
dry	soil moisture calendar period where SMCS is dry
moistdry	soil moisture calendar period where SMCS is moist/dry
moist	soil moisture calendar period where SMCS is moist
beginday	soil temperature/moisture calendar period begin day (1-360)
endday	soil temperature/moisture calendar period end day (1-360)

Appendix VIII: Larger Versions of Output Product – Report, Climograph and Model Run Summary

Report

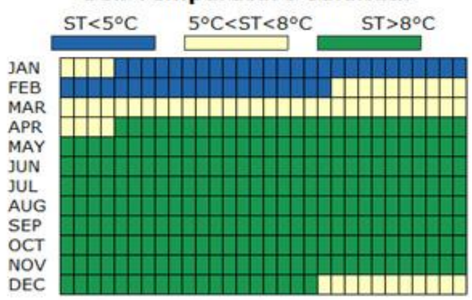
Station: Mammoth Cave
Station ID: 155097
Period of Record: 1999 - 1999
Period Type: normal
Mean Annual Precipitation: 667 mm
Soil Temperature Regime: Thermic

Latitude: 37.18°
Longitude: 86.09°
Elevation: 241 m
Waterholding Capacity: 152 mm
Soil Moisture Regime: Xeric
Subgroup Modifier*: Typic Xeric

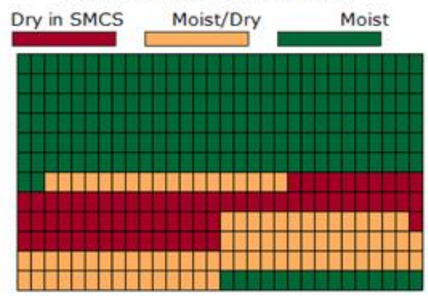
Soil Climate Regime--Newhall Simulation Model
(MAST = MAAT + 2 °C; Amplitude 0.66)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Annual
Mean Monthly Air Temperature (°C)													
	3.61	6.28	6.39	14.83	18.61	23.00	27.56	26.11	22.17	15.67	12.61	5.67	15.20
Mean Monthly Precipitation (mm)													
	121.67	22.10	41.40	56.39	51.56	69.09	24.64	18.29	54.10	74.68	41.40	91.95	667.27
Modeled Estimate of Monthly Total Potential Evapotranspiration (mm)													
	4.46	10.76	13.57	57.38	92.22	131.43	179.62	153.81	103.65	55.36	34.02	9.00	845.28
Modeled Estimate of Monthly Total Water Balance (mm)													
	117.21	11.34	27.83	-0.99	-40.66	-62.34	-154.98	-135.52	-49.55	19.32	7.38	82.95	-178.01

Soil Temperature Calendar



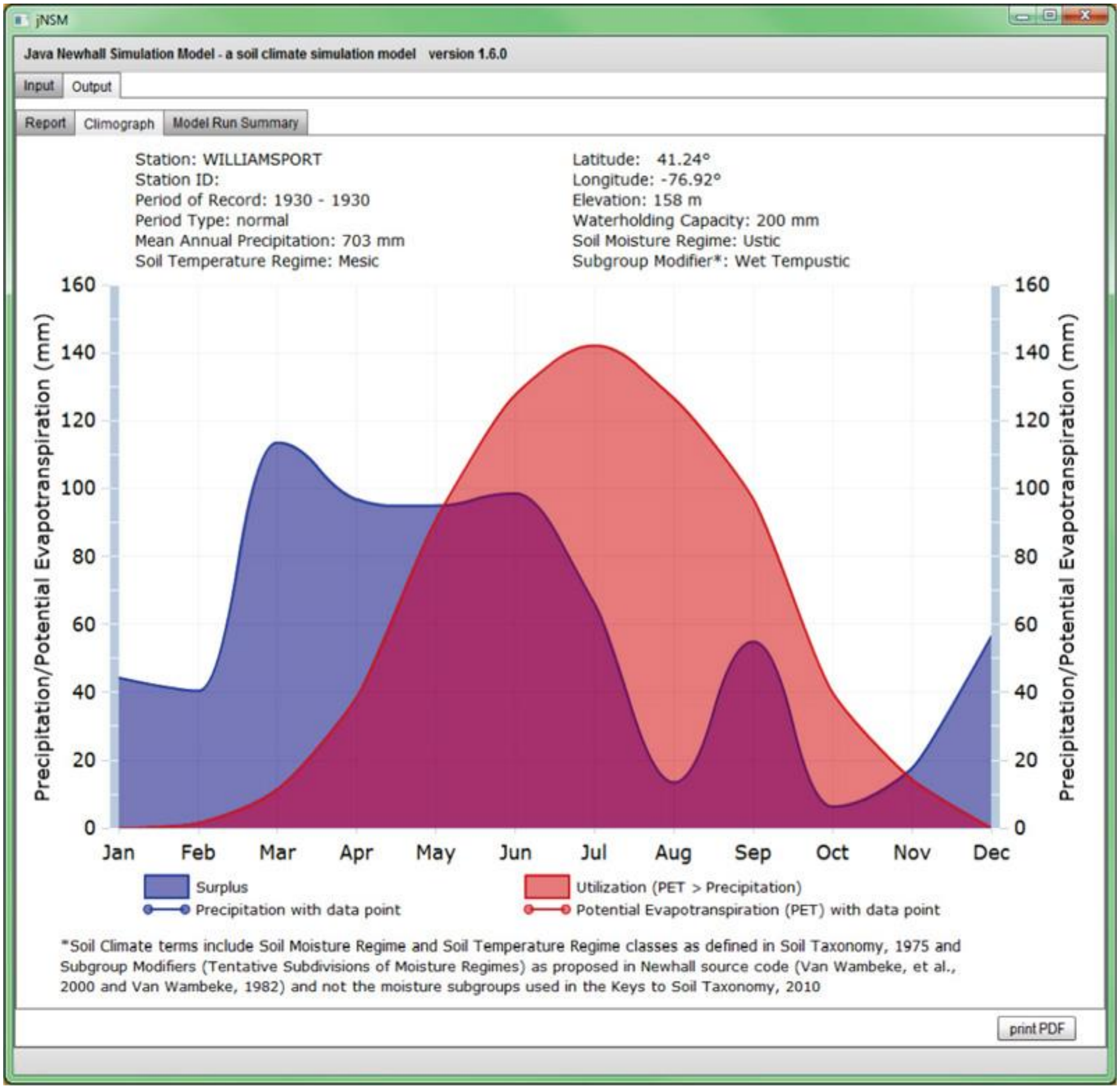
Soil Moisture Calendar



*Soil Climate terms include Soil Moisture Regime and Soil Temperature Regime classes as defined in Soil Taxonomy, 1975 and Subgroup Modifiers (Tentative Subdivisions of Moisture Regimes) as proposed in Newhall source code (Van Wambeke, et al., 2000 and Van Wambeke, 1982) and not the moisture subgroups used in the Keys to Soil Taxonomy, 2010

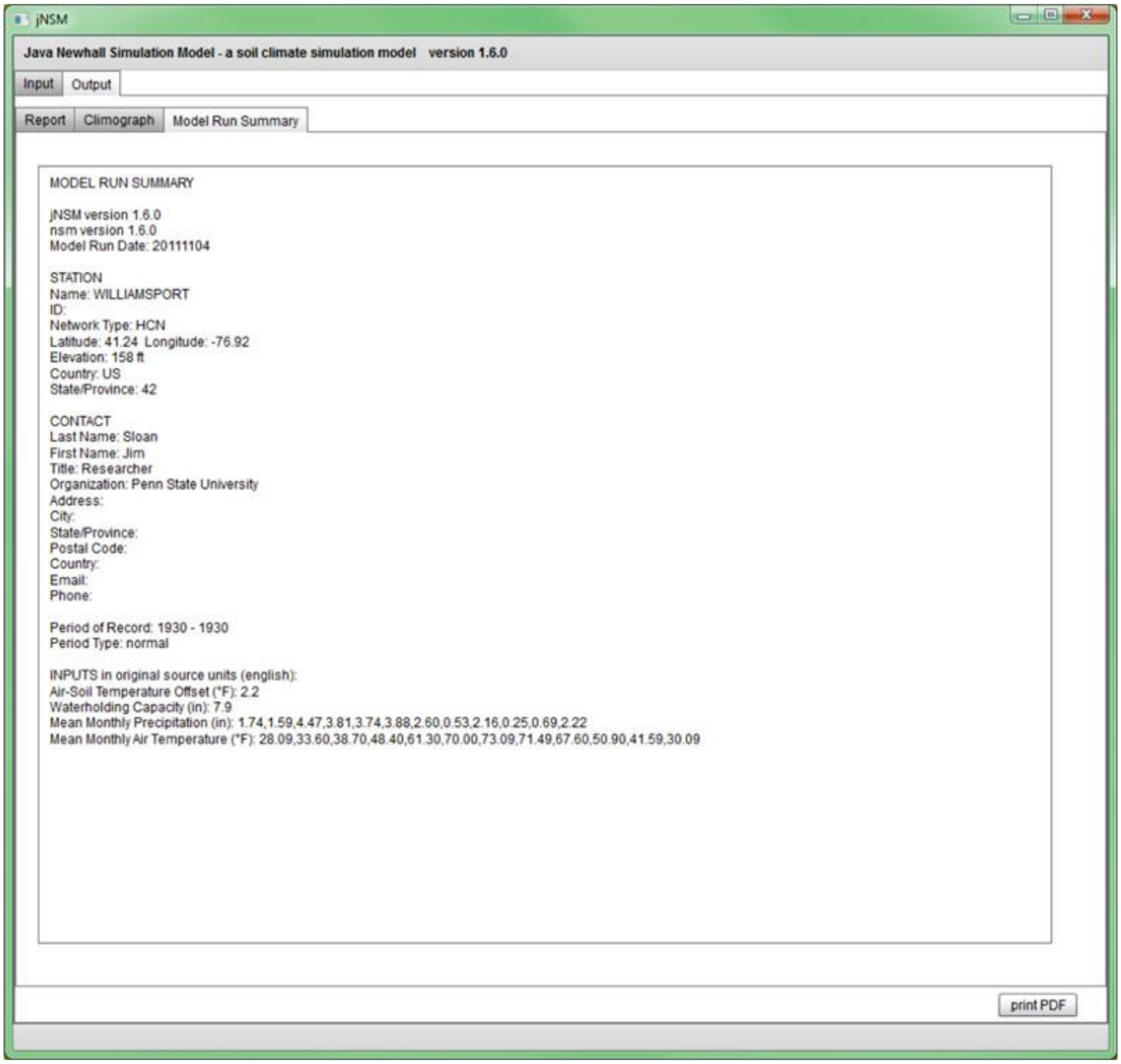
Appendix VIII: Larger Versions of Output Product – Report, Climograph and Model Run Summary

Climograph



Appendix VIII: Larger Versions of Output Product – Report, Climograph and Model Run Summary

Model Run Summary



Appendix IX: Example of model run output file

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<cntinfo>

<cntper>

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<lastname>Ngunjiri</lastname>

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</cntper>

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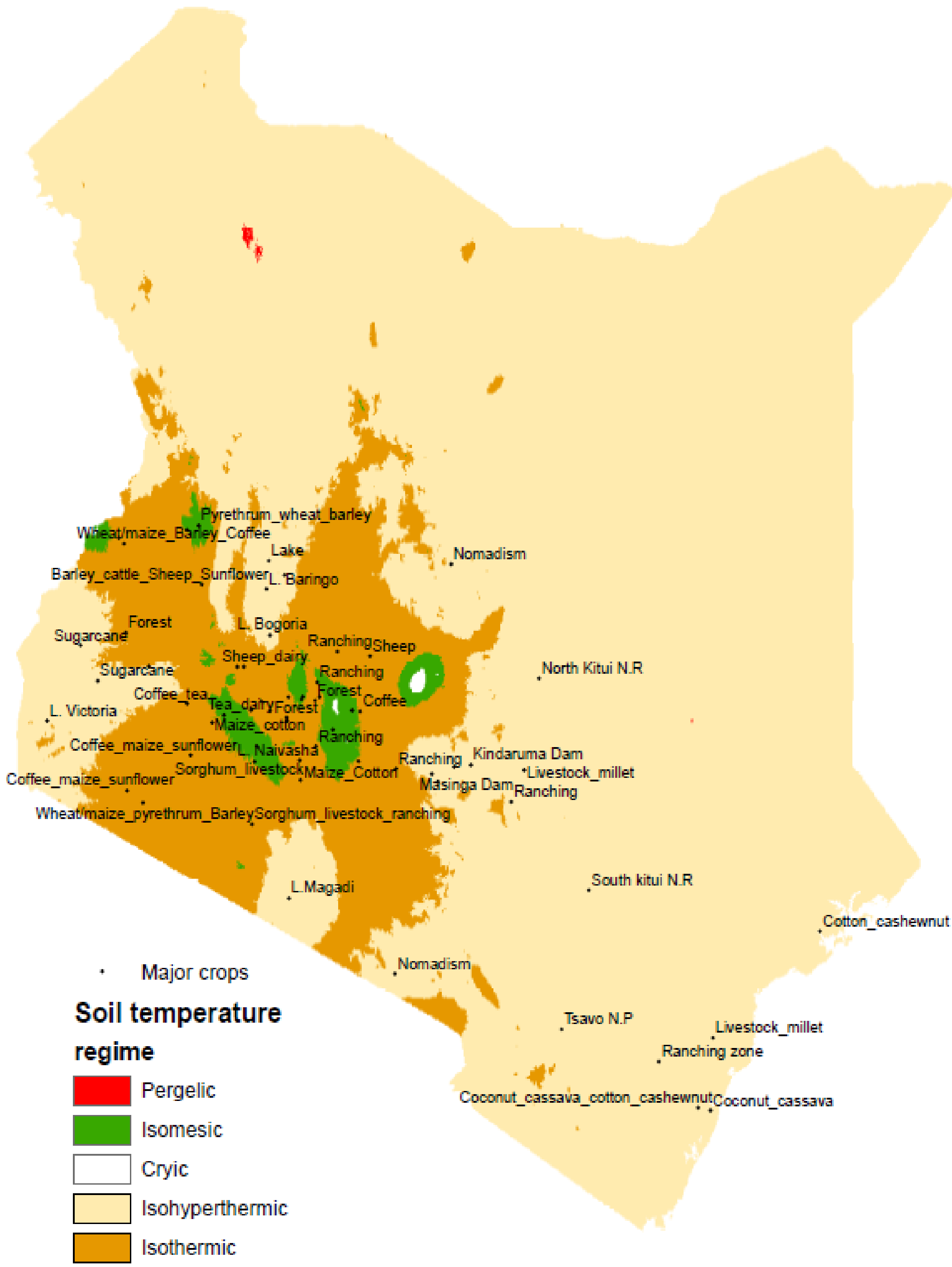
Appendix X: Example of excel output table

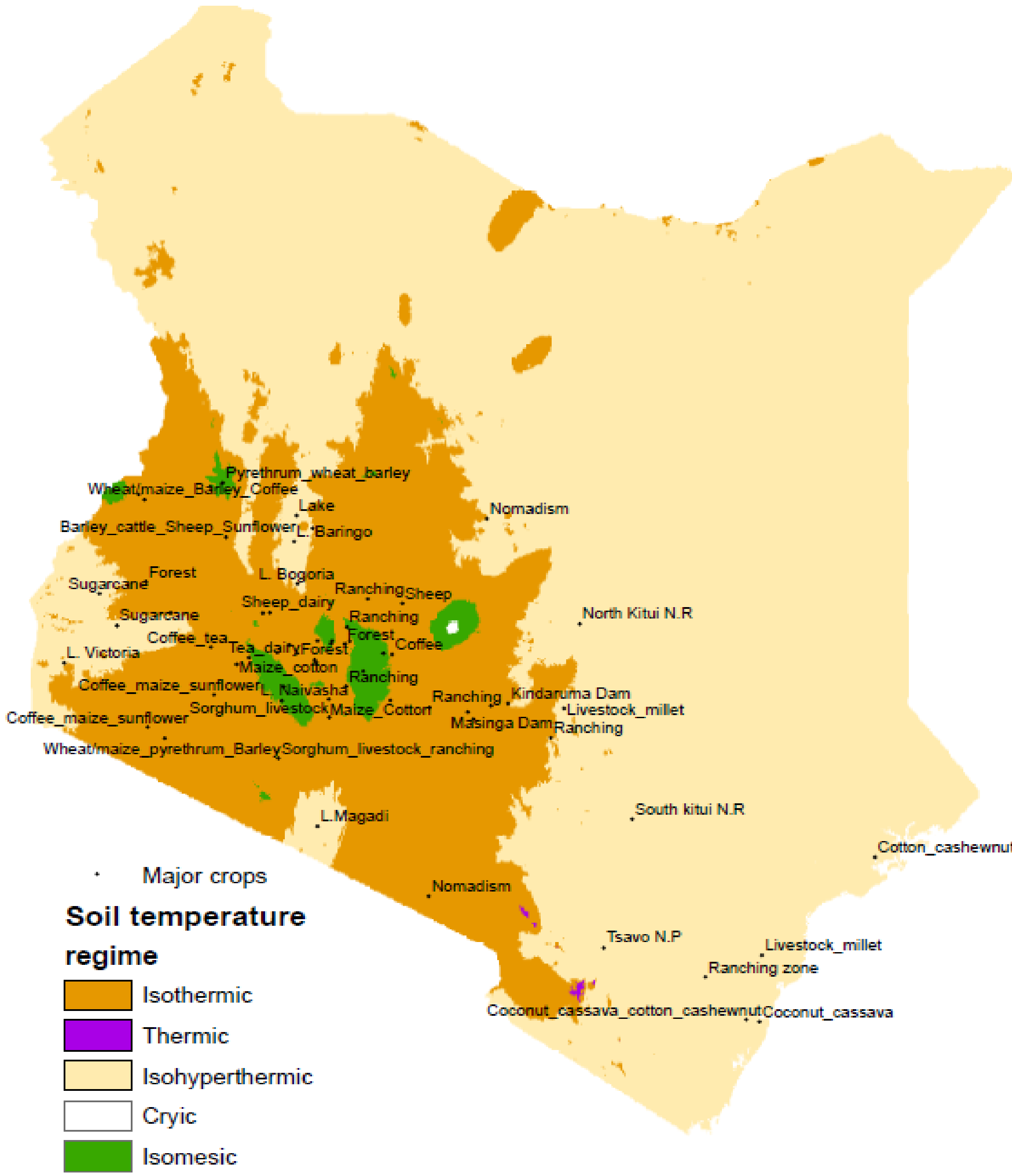
1	stnName	stnID	latDD	lonDD	elev	smrclass	subgrpmo	strclass	awb	swb	yrdryCum	yrmdCum	yrmstCum	bio5dryCu	bio5mdCu	bio5mstC	yrmstCon	bio8mstC	smrdryCo	wt
2	150000	150000	37.5596	2.8373	369	Aridic	Weak Aric	Isohypertl	-1141.25	-175.97	277	42	41	277	42	41	55	55	45	
3	150001	150001	37.5683	2.8374	365	Aridic	Weak Aric	Isohypertl	-1141.36	-176.08	277	42	41	277	42	41	55	55	45	
4	150002	150002	37.577	2.8374	366	Aridic	Weak Aric	Isohypertl	-1137.36	-175.07	276	43	41	276	43	41	55	55	45	
5	150003	150003	37.5857	2.8375	365	Aridic	Weak Aric	Isohypertl	-1137.36	-176.08	276	43	41	276	43	41	55	55	45	
6	150004	150004	37.5943	2.8375	367	Aridic	Weak Aric	Isohypertl	-1136.48	-176.2	276	43	41	276	43	41	55	55	45	
7	150005	150005	37.603	2.8375	367	Aridic	Weak Aric	Isohypertl	-1133.36	-176.08	276	43	41	276	43	41	55	55	45	
8	150006	150006	37.6117	2.8376	366	Aridic	Weak Aric	Isohypertl	-1126.85	-176.08	276	43	41	276	43	41	55	55	45	
9	150007	150007	37.6203	2.8376	364	Aridic	Weak Aric	Isohypertl	-1126.08	-176.31	275	44	41	275	44	41	55	55	45	
10	150008	150008	37.629	2.8377	367	Aridic	Weak Aric	Isohypertl	-1126.19	-176.42	275	44	41	275	44	41	55	55	45	
11	150009	150009	37.6377	2.8377	367	Aridic	Weak Aric	Isohypertl	-1115.11	-170.34	273	45	42	273	45	42	56	56	45	
12	150010	150010	37.6463	2.8377	370	Aridic	Weak Aric	Isohypertl	-1113.42	-172.92	273	45	42	273	45	42	56	56	45	
13	150011	150011	37.655	2.8378	375	Aridic	Weak Aric	Isohypertl	-1101.42	-169.19	272	45	43	272	45	43	57	57	45	
14	150012	150012	37.6637	2.8378	380	Aridic	Weak Aric	Isohypertl	-1096.61	-169.41	272	45	43	272	45	43	57	57	45	
15	150013	150013	37.6724	2.8379	384	Aridic	Weak Aric	Isohypertl	-1098.39	-171.38	272	47	41	272	47	41	56	56	45	
16	150014	150014	37.681	2.8379	389	Aridic	Weak Aric	Isohypertl	-1083.39	-164.72	269	48	43	269	48	43	58	58	45	
17	150015	150015	37.6897	2.8379	392	Aridic	Weak Aric	Isohypertl	-1072.67	-165.41	270	47	43	270	47	43	58	58	45	
18	150016	150016	37.6984	2.838	401	Aridic	Weak Aric	Isohypertl	-1056.37	-160.71	267	49	44	267	49	44	59	59	45	
19	150017	150017	37.707	2.838	405	Aridic	Weak Aric	Isohypertl	-1056.23	-160.6	267	49	44	267	49	44	59	59	45	
20	150018	150018	37.7157	2.8381	415	Aridic	Weak Aric	Isohypertl	-1036.91	-154.75	267	49	44	267	49	44	59	59	45	
21	150019	150019	37.7244	2.8381	427	Aridic	Weak Aric	Isohypertl	-1022.06	-151.1	259	57	44	259	57	44	65	65	45	
22	150020	150020	37.733	2.8382	430	Aridic	Weak Aric	Isohypertl	-1021.34	-151.33	259	57	44	259	57	44	65	65	45	
23	150021	150021	37.7417	2.8382	440	Aridic	Weak Aric	Isohypertl	-1011.86	-150.45	257	58	45	257	58	45	66	66	45	
24	150022	150022	37.7504	2.8382	440	Aridic	Weak Aric	Isohypertl	-1011.86	-150.45	257	58	45	257	58	45	66	66	45	
25	150023	150023	37.7591	2.8383	437	Aridic	Weak Aric	Isohypertl	-1012.78	-151.55	257	58	45	257	58	45	66	66	45	
26	150024	150024	37.7677	2.8383	434	Aridic	Weak Aric	Isohypertl	-1014.48	-151.44	257	59	44	257	59	44	66	66	45	
27	150025	150025	37.7764	2.8384	437	Aridic	Weak Aric	Isohypertl	-1008.88	-149.63	256	59	45	256	59	45	66	66	45	
28	150026	150026	37.7851	2.8384	435	Aridic	Weak Aric	Isohypertl	-1006.19	-149.75	255	60	45	255	60	45	67	67	45	
29	150027	150027	37.7937	2.8384	446	Aridic	Weak Aric	Isohypertl	-1003.57	-149.08	255	60	45	255	60	45	67	67	45	
30	150028	150028	37.8024	2.8385	447	Aridic	Weak Aric	Isohypertl	-982.56	-143.61	253	61	46	253	61	46	68	68	45	
31	150029	150029	37.8111	2.8385	441	Aridic	Weak Aric	Isohypertl	-992.32	-146.42	253	62	45	253	62	45	68	68	45	
32	150030	150030	37.8197	2.8386	447	Aridic	Weak Aric	Isohypertl	-978.94	-143.85	251	63	46	251	63	46	69	69	45	
33	150031	150031	37.8284	2.8386	446	Aridic	Weak Aric	Isohypertl	-978.67	-146.33	252	62	46	252	62	46	68	68	45	
34	150032	150032	37.8371	2.8386	451	Aridic	Weak Aric	Isohypertl	-968.8	-142.73	251	63	46	251	63	46	69	69	45	
35	150033	150033	37.8458	2.8387	453	Aridic	Weak Aric	Isohypertl	-963.4	-144.93	249	65	46	249	65	46	69	69	45	
36	150034	150034	37.8544	2.8387	458	Aridic	Weak Aric	Isohypertl	-959.71	-143.08	249	65	46	249	65	46	69	69	45	
37	150035	150035	37.8631	2.8388	458	Aridic	Weak Aric	Isohypertl	-951.34	-142.91	248	66	46	248	66	46	70	70	45	
38	150036	150036	37.8718	2.8388	461	Aridic	Weak Aric	Isohypertl	-948.76	-143.02	248	66	46	248	66	46	70	70	45	

Appendix XI: Soil temperature regime-crop spatial comparison map for current conditions



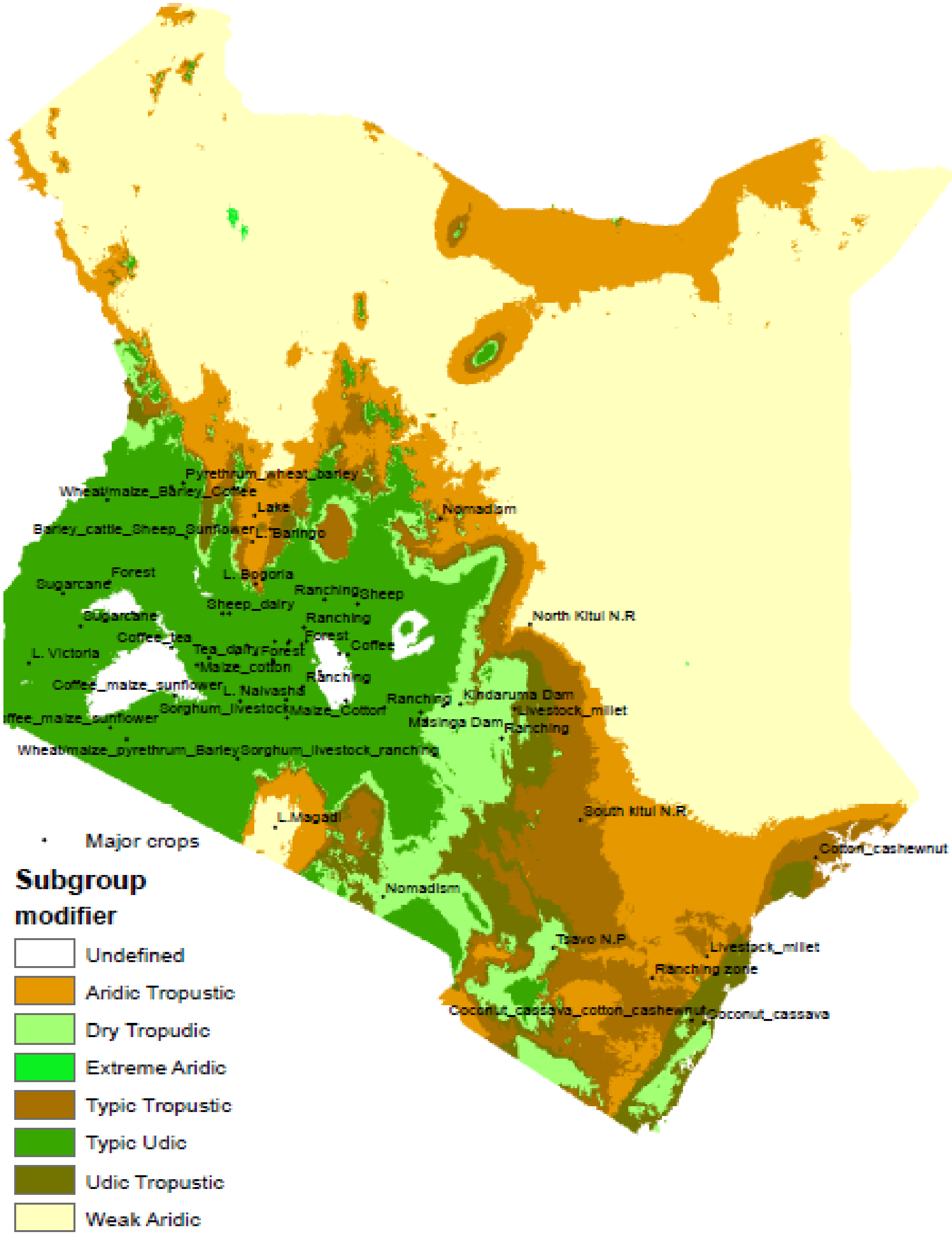
(Source: Author, 2014)

Appendix XII: Soil temperature regime-crop spatial comparison map for future conditions



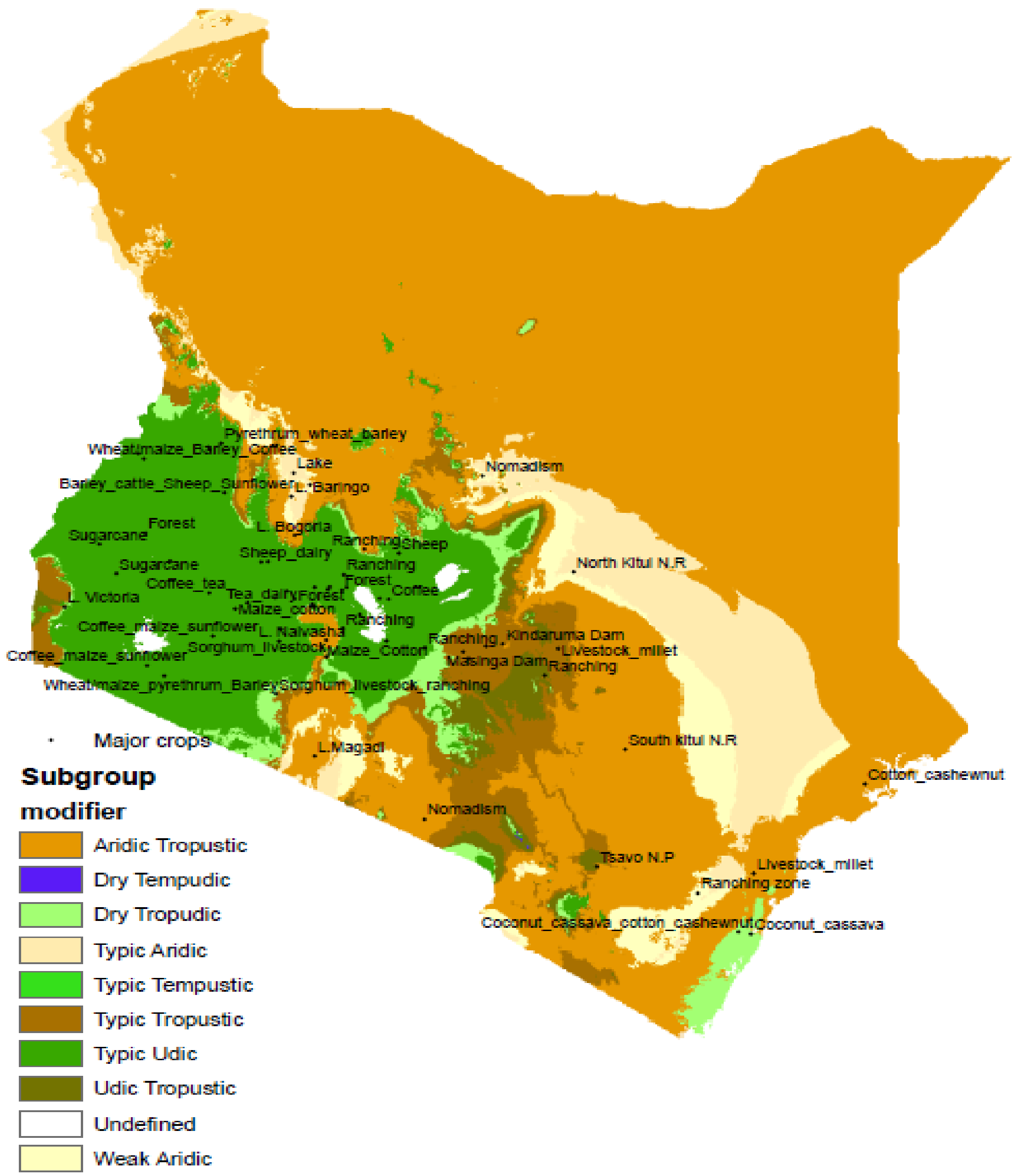
(Source: Author, 2014)

Appendix XIII: Soil moisture subgroup modifiers-crop spatial comparison map for current conditions



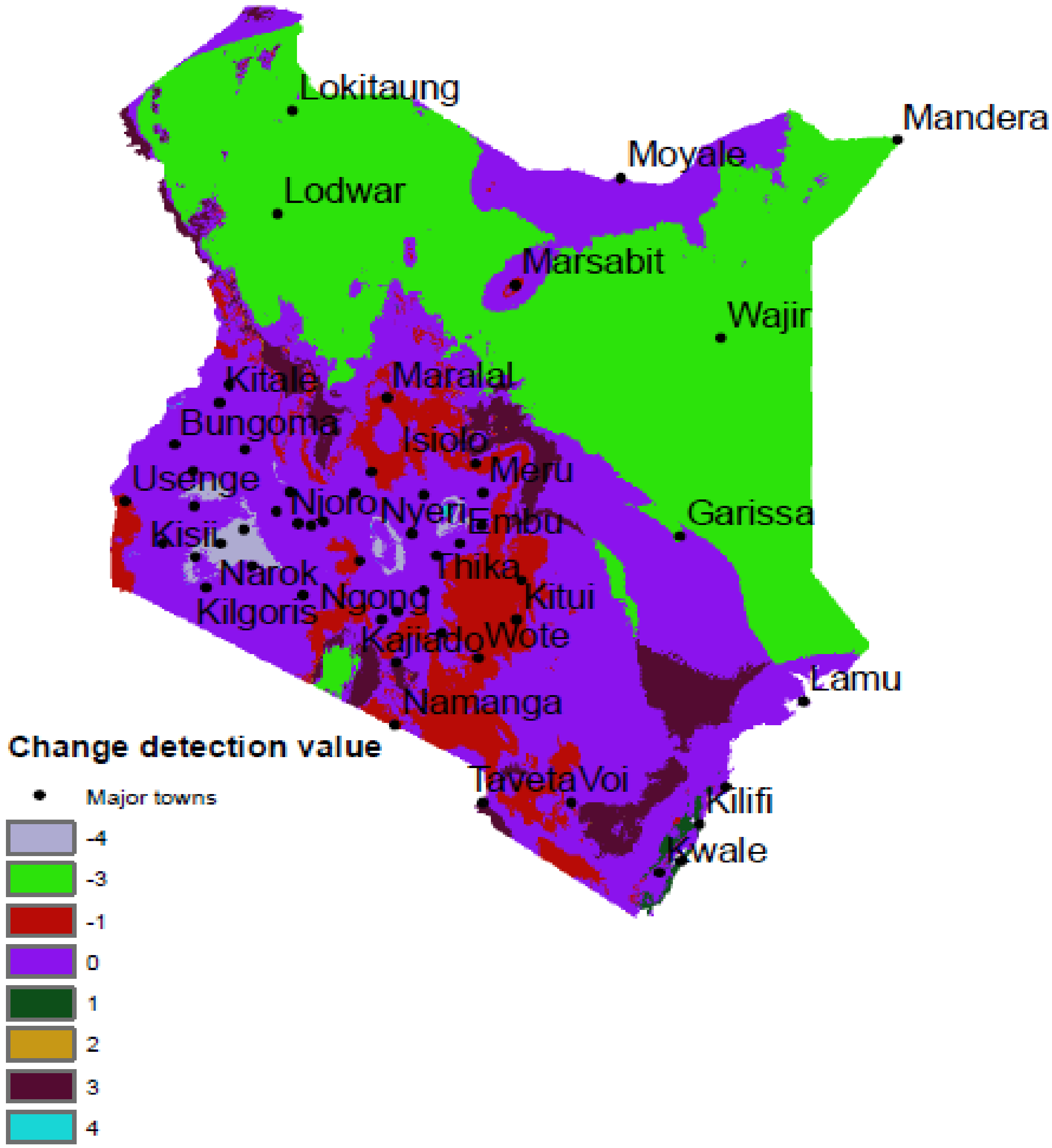
(Source: Author, 2014)

Appendix XIV: Soil moisture subgroup modifiers-crop spatial comparison map for future conditions



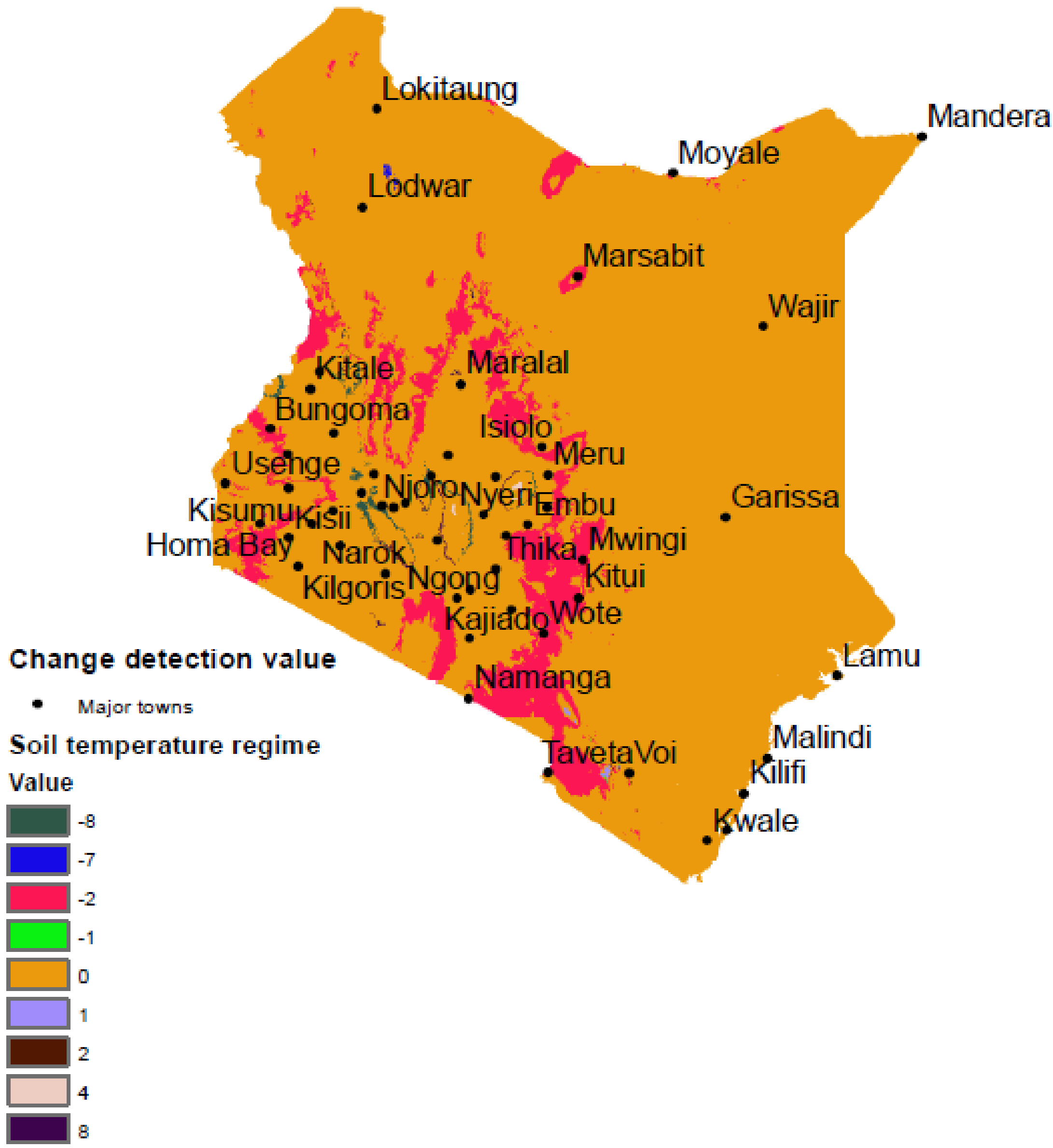
(Source: Author, 2014)

Appendix XV: Soil moisture spatial comparison map



(Source: Author, 2014)

Appendix XVI: Soil temperature spatial comparison map



(Source: Author, 2014)