GENETIC COEFFICIENTS AND AGROECOLOGICAL POTENTIAL OF DUAL PURPOSE SOYBEAN VARIETIES FOR UP-SCALING IN KENYA

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Declaration

This is my original work and has not been presented for a degree in any University or any other award.

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Dedication

This work is dedicated to my parents Mr. and Mrs. John Nyang'au and the rest of the family. They sacrificed everything for me. Your prayers, encouragement, understanding and unwavering support made it possible for me to complete this study.

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Abbreviations and Acronyms

ANOVA	Analysis of Variance
CSM CROPGRO	Crop Simulation Model – Crop Growth
DAS	Days after Sowing
DSSAT	Decision Support System for Agro-technology Transfer
GTZ	Deutsche Gesellschaft für Technische Zusammenarbeit
IBSNAT	International Benchmark Sites Network for Agro-technology Transfer Project
IDRC	International Development Research Centre of Canada
IITA	International Institute of Tropical Agriculture
ISFM	Integrated Soil Fertility Management
JICA	Japan International Cooperation Agency
KEPHIS	Kenya Plant Health Inspectorate Services
KENSOTER	Kenya Soil and Terrain Database
MDGs	Millennium Development Goals
MGs	Maturity Groups
NPT	National Performance Trial
RMSE	Root Mean Square Error
SIDA	Swedish International Development Agency
SSA	Sub-Saharan Africa
TVP	Textured Vegetable Protein
TGX	Tropical Glycine Cross
TSBF	Tropical Soil Biology and Fertility
USDA	United States Department of Agriculture

Abstract

Soybean (*Glycine max*) is one of the popular pulses in the world. Despite its importance as a source of edible oils, cheap proteins and vitamins, as well as its contribution in the animal feed industry, its cultivation by farmers in Kenya is below the demand, which is however fulfilled through imports. Soybean production fluctuates in response to agro-environmental conditions. It is in this light that it is important to understand the reasons behind the lack of uptake of soybean in Kenya and identify measures that are required to reverse this trend. Although reasons for lack of uptake are likely more of socio-economics or infrastructural than of a biophysical nature, virtually no agronomic studies have been carried out with dual purpose soybean varieties to evaluate whether they retain their dual purpose nature under Kenyan conditions. This study therefore aimed at determining the genetic coefficients of these dual purpose soybean varieties using Inverse Modeling Method. These coefficients representing various varieties were then used in the simulation of selected agro-ecological zones to gauge their performance. The simulation of their growth and productivity under different environments in Kenya was done using CROPGRO model, a component of Decision Support System for Agro-technology Transfer (DSSAT) model. Areas in Kenya with highest potential for cultivation of particular varieties were identified, hence shedding light on the uptake bottlenecks at the biophysical level and consequently aiding in identification of agro-ecological zones where these varieties can do best. The high potential areas were found to be the most productive for soybean varieties. The dual purpose varieties studied were the TGX varieties developed in West Africa whose names were coded to SB for simplification. SB 8, SB 3 and SB 20 were the most stable across sites. However, the early maturing varieties such as SB 9 and SB 19 also did well in areas with a short growing season compared to the local variety- SB 23 (Nyala). Differences among varieties for phenological coefficients were rather small, with the Coefficient of Variation (CV) among varieties for individual characters ranging from 4.19 to15.24%. Varieties should be selected appropriately depending on the length of the growing period or can be grown back to back to take advantage of the short rains in order to maximize production. The results clearly demonstrate that CROPGRO model simulated phenology and yields quite well for most of the varieties across contrasting sites.

CHAPTER ONE

INTRODUCTION

1.1 Background to the Problem

Soybean (*Glycine max*) otherwise known as soya or soyabean is one of the most popular pulses in the world and its success stems from a number of factors related to its composition and productivity. The biochemical composition of soybean is unique among the pulses. It has the highest protein content of all pulses. In human food, soybean is regarded as one of the most important source of proteins, edible oils and vitamins in the world (Borget, 1992). After extracting the oil for human consumption, the cake forms a cheap and protein rich ingredient for animal feed. Furthermore, the productivity of soybean is much higher than for common bean and cowpea. Moreover the crop has a short to medium maturity period between 85 and 125 days (Mpepereki *et al.*, 2000) and develops a relatively large amount of biomass, has relatively few pest and disease problems and good grain storage capacity.

United States is the leading world producer of soybeans. Large quantities are exported, chiefly to Japan and China. Brazil, Argentina, and Paraguay are also significant soybean-exporting nations. Production of soybean in Africa is still disappointing. However, there has substantial contribution that soybean has made to rural livelihoods in West and Southern Africa. The production in sub-Saharan Africa (SSA) has been spreading slowly but unevenly. For instance in Kenya, soybean was introduced in the 1960s and disseminated through many projects but does not show up in the Food and Agricultural Organization (FAO) statistics, though small amounts can be seen in the market. Small amounts are consumed by households especially where they have been trainings by special projects. Soy meal is also often mixed in baby food and sold in local supermarkets. Currently about 80 percent of soybean required in Kenya is imported, amounting to 65,000 metric ton per year. Demand for human consumption, for example, is expected to rise to 150,000 tons per year by 2010 (GTZ, 1996).

Soybean is ideal for intercropping and crop rotation as it is a short duration (85-125 days) crop and is comparatively tolerant to drought (Lawn, 1982; Yeates *et al.*, 2000) and excessive soil moisture conditions (Wright *et al.*, 1988; Shangguan *et al.*, 2000). Its high capacity to fix nitrogen, low phosphorous requirement and tolerance to low pH and high levels of aluminium (Tanaka, 1983; Tanaka *et al.*, 2008) make it a suitable choice for adoption in a wider area. Compared to sorghum and corn, soybean has been reported to fetch higher price and net returns (Soni *et al.*, 1990).

Dual purpose soybean varieties that do not only provide grains and/or cash, but also have the capability of producing effective nodules with indigenous rhizobia (promiscuous nodulation) to fix atmospheric nitrogen without the need to inoculate seed with purchased rhizobia inoculum, have been developed. They have the potential to solve some farming problems. For instance, when these dual purpose varieties are planted in rotation with maize or sorghum, crop productivity and sustainability is enhanced (Kaleem, 1993; Carsky *et al.*, 1997; Sanginga *et* *al.,* 2001; 2003). Furthermore, the soybean biomass if incorporated into the soil can substantially improve the soil chemical and physical properties. While the search for and use of promiscuous soybean varieties in cropping systems in other African countries has been reported extensively (Javaheri *et al.,* 1994; Kasasa *et al.,* 1999; Giller *et al.,* 2000; and Mpepereki *et al.,* 2000), research on promiscuous varieties has been limited in Kenya. Therefore, there is need to carry out research on the performance of these soybean varieties for up-scaling purposes in Kenya.

1.2 Problem Statement and Justification

About 75 percent of the farmers in Kenya are resource constrained small-scale farmers. With the ever-escalating costs of agricultural inputs (fertilizers, pesticides, seeds and manures), farmers continually find it difficult to apply any of the external inputs often leading to low crop yields (Bationo *et al.,* 2004). The situation is unlikely to improve given the increasing poverty levels in Kenya, often exceeding 50 percent in most districts. A suitable, cheap and sustainable substitute for the external inputs is the promotion and use of dual purpose and promiscuous soybean varieties and the utilization of superior indigenous *bradyrhizobium* strains as inoculants. Production of soybean has stagnated over the years due to the fact that past efforts were aimed at promoting the crop as a cash crop in the face of low market demand, limited utilization awareness and research and extension constraints. Besides, there was no real need for soybean until the economic situation in Kenya began to deteriorate causing alternative sources of proteins to become increasingly unaffordable (Kaara *et al.,* 1998).

Currently, dual purpose varieties recently developed under West African conditions and tested in limited parts of western Kenya have shown both promiscuity and the ability to produce a large amount of biomass while maintaining acceptable grain yield levels comparable to that of recommended local varieties. These varieties offer the best hope for farmers to engage in sustainable soybean/crop production. The use of dual purpose varieties, with positive effects on soil fertility status could trigger acceptance of soybean by farming communities. Although reasons for lack of uptake are likely to be more of socio-economics or infrastructural than of a biophysical nature, virtually no agronomic studies have been carried out with dual purpose soybean varieties to determine whether they retain their dual purpose nature under the varying agronomic Kenyan conditions.

Scaling up of soybean requires data on the performance of the different varieties under different agro-environments. Kenya's agro-climates are highly variable and it is not clear which variety to promote for where. This is because these varieties were imported and their performance in Kenyan climatic conditions is not known. The availability of data on the performance of these varieties under different agro-environments would help scaling up soybean adoption. Knowledge acquired on which dual purpose varieties retain their dual purpose nature under different environmental conditions and management will be useful to extension workers, researchers and most importantly to farmers. This will enable maximization of production and also the net nitrogen fixed in the soil thereby improving the income of farmers.

This study, therefore, sought to investigate the various agronomic factors that influence soybean cultivation and subsequently explore the areas in Kenya which have greatest potential for its production using modeling methods. Best bet varieties will be recommended for particular agro-ecological zones or clusters of zones.

1.3 Research Questions

i. What are the genetic coefficients of the dual purpose soybean varieties in Kenya?

ii. How do biophysical factors influence the growth of different soybean varieties?

iii. Which agro-ecological zones in Kenya have the greatest potential for soybean cultivation?

1.4 Research Objectives

The main objective of this study was to determine the genetic coefficients agro-ecological potential of dual purpose soybean varieties for up-scaling and the agro-ecological zones with the highest potential for dual purpose soybean cultivation in Kenya. The specific objectives were:

i. To determine genetic coefficients of dual purpose soybean varieties and evaluate the performance of CROPGRO model (DSSAT) in Kenya.

ii. To assess the effect of inherent soil fertility, temperature and rainfall on growth of dual purpose soybean varieties.

iii. To determine the performance of dual-purpose soybean varieties in various selected agro-ecological zones in Kenya.

1.5 Research Hypotheses

i. There is no significant variation in the cultivar traits of dual purpose soybean varieties.

ii. Soil fertility, temperature and rainfall do not significantly influence the growth of soybean.

iii. There is no significant variation in the potential production of soybean between the high and low potential areas.

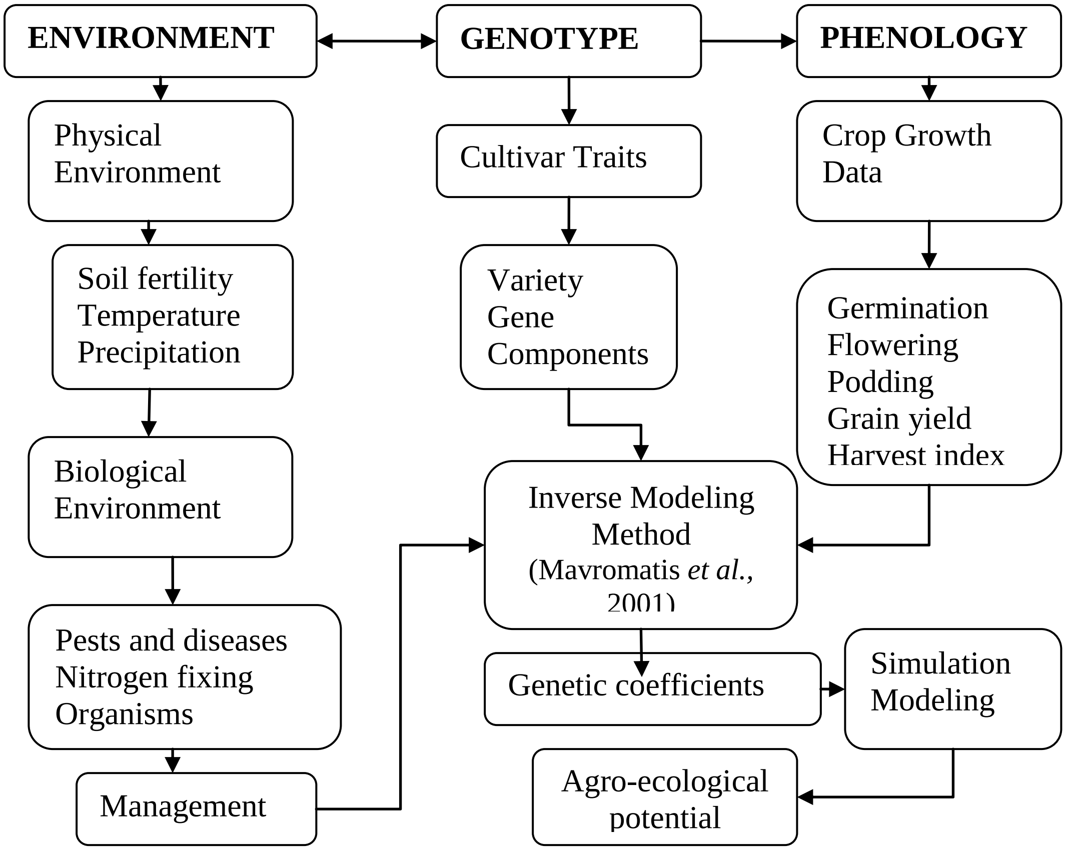
1.6 Significance of the Study and Anticipated Output

Given the low uptake of soybean production in Kenya and the related high cost of importing additional supplies of the same to meet the demand, more efforts need to be put in finding and reversing the causes of the low uptake. It is in this light that this study is based. The findings of this study will help sort out the problems facing soybean production in Kenya. This is through provision of vital information on the requirements of soybean growth at the biophysical level. If many farmers commenced growing of soybean, with time, there would be immense improvement in rural livelihoods and also increased sustainability of land productivity due to the beneficial characteristics of soybean to the soil. There will be reduced inputs in the soil in terms of fertilizers and pesticides due to the low susceptibility of soybean to attack by pests. Availability of crop performance information in different environments will benefit farmers by allowing use of improved site-specific decision support tools. It will also give researchers new ways to compare and characterize cultivar groupings.

Understanding of parent-progeny relations among cultivars along with the performance prediction ability of the models will help breeders in their efforts to develop higher yielding genotypes. The research findings will provide policy makers with strategies of achieving the Millennium Development Goals (MDGs) sooner than later. This is especially so in the reduction of poverty and hunger, improved health, gender empowerment and environmental sustainability among others as a result of increased productivity which leads to higher incomes and easy access to cheaper sources of protein and oil.

1.7 Conceptual Model

The conceptual model shows (Figure 1.1) the steps that were followed in determining the genetic coefficients and the agro-ecological potential of the dual purpose soybean varieties. This is the inverse modeling method (Mavromatis *et al*., 2001) where the phenology was used in assigning genetic coefficients for the varieties. The concept here is to move from phenology to genotype given the environmental conditions (GXE = P, where G is the genotype, E is the environment and P is the phenology).



Source: Author

Figure 1.1: Conceptual model showing the relationship and the steps of determining genetic coefficients and agro-ecological potential of dual purpose soybean varieties

1.8 Operational Definitions of Key Concepts and Terms

Agro-ecological zones (AEZ)- is a system that enables rational land use planning on the basis of an inventory of land resources and evaluation of biophysical limitations and potentials.

Model calibration- Model calibration is the process of changing values of model input parameters in an attempt to match field conditions within some acceptable criteria. This requires that field conditions at a site be properly characterized.

Model validation- is the process of gaining confidence in a model. Essentially this is achieved by "twisting and turning" the model to scrutinize all aspects of it. Of particular importance is the model's ability to reproduce the behavior of the validation data sets.

Model evaluation- this involves model calibration and validation processes in order to gauge the performance of the model.

Genetic coefficients- these are cultivar specific traits that interact with the environment to express a specific phenological trait. They vary from model to model and crop to crop. Each set of coefficients represents a particular variety.

CHAPTER TWO

LITERATURE REVIEW

2.1 General Overview

Soil fertility depletion has been described as the major biophysical root cause of the declining per-capita food availability in smallholder farms in sub-Saharan Africa (SSA) (Sanchez *et al.*, 1997), with a decline from 150 to 130 kg per person over the past 35 years in production of cereals (Nandwa, 2003; Bationo *et al.*, 2004). Emerging evidence attributes this to insufficient nutrient inputs relative to exports, primarily through harvested products, leaching, gaseous losses and soil erosion (Sanchez and Leaky, 1997). This results in yields that are about 2-5 times lower than the potential for cereals (Bationo *et al.*, 2004). Adequate and effective solutions to combat nutrient depletion where known, are often limited in application because of the dynamics and heterogeneity of the African agro-ecosystems in terms of biophysical and socio-economic gradients (Tittonell *et al.*, 2005). This calls for system-specific or flexible recommendations, rather than monolithic technical solutions such as blanket fertilizer recommendations.

Despite diversity of approaches and solutions and the investment of time and resources by a wide range of institutions, soil fertility degradation continues to prove to be a substantially intransigent problem, and as the single most important constraint to food security in the continent (Sanchez and Leaky, 1997; Bationo *et al.*, 2004). For example, soil loss through erosion is estimated to be generally 10 times greater than the rate of natural formation. Return to investment in soil fertility has not been commensurate to research outputs (African Highlands Initiative, 1997). Farmers are only likely to adopt sound soil management techniques if they are assured of return on their investment. In the short term, integrated soil fertility management (ISFM) is now regarded as a strategy that helps low resource endowed farmers mitigate the characteristics of poverty and food insecurity by improving the quantity and quality of food, income and resilience of soil productive capacity.

Essentially, ISFM is the adoption of a systematic, conscious, participatory and holistic approach to research on soil fertility. It embraces a full range of driving factors and consequences such as biological, physical, chemical, social, economic and political aspects of soil fertility degradation (Bekunda *et al.*, 1997; Vanlauwe, 2004). The approach advocates for careful management of soil fertility aspects that optimize production potential through incorporation of a wide range of adoptable soil management principles, practices and options for productive and sustainable agro-ecosystems. It entails the development of soil nutrient management technologies for adequate supply and feasible share of organic and inorganic inputs that meet the farmers' production goals and circumstances. The approach includes other important aspects of the soil complex; soil life, structure and organic matter content. The approach integrates the roles of soil and water conservation; land preparation and tillage; organic and inorganic nutrient sources; nutrient adding and saving practices; pest and disease control; livestock husbandry; crop rotation and intercropping; multipurpose legumes and integration of different research methods and knowledge systems. The approach also includes social and economic dimensions (Bationo *et al.*, 2004).

Soybean (*Glycine max*) is a legume that grows in tropical, subtropical and temperate climates. Approximately half of the world's soybeans are produced in the developing world, and the other half in the developed world (FAO, 2006). Soybean is an important source of high quality but inexpensive protein and oil. It is second only to groundnut in terms of oil content among food legumes. Soybeans may be prepared for human consumption by being turned into soymilk. The curds from this soymilk may then be pressed into blocks (‘tofu’), in a process similar to that of making cheese from dairy milk. Whole soybeans may also be cooked slightly and then fermented using vinegar and the fungus *Rhizopus oligosporus* to make ‘tempeh’. The leftover soy flour from extracting the oil from soybeans is also used to create textured vegetable protein (TVP), which is often used in meat substitutes. Soybeans contain a full range of amino acids and high protein content, making them an ideal supplemental source (IITA, 2000), particularly for vegetarians and vegans.

Soybean is by far the cheapest compared to other protein-rich foods such as meat, fish and eggs. It also has a superior amino acid profile compared to other sources of plant protein. The amount of soybean protein consumed by humans worldwide is currently relatively low, but there is increasing public and commercial interest, and it has great potential as a major source of dietary protein for the future. The oil produced from soybean is highly digestible and contains no cholesterol. Soybean is the largest single source of edible oil and the byproduct from the oil production, called soybean cake, is used as a high-protein animal feed in many countries (IITA, 2000).

Growing of legumes in crop mixtures usually results in the legumes fixing most of N requirements (80-95%) when moisture and other plant nutrients are not limiting (Hardarson *et al.,* 1988). This is a major benefit in African farming systems, where soils have become exhausted by continuous cultivation without external inputs so as to produce more food for the increasing populations and where fertilizers are not available or are too expensive for farmers to buy.

The United States of America (USA) is the world’s leading soybean producer. However, Brazil is poised to take the leadership in worldwide soybean production by 2010 (USDA, 2003). Soybean is a sub-temperate crop but varieties have been developed to suit tropical growing conditions. The average yields in the USA and in Western Europe are 2.6 and 3.5 tons/ha respectively (IITA, 2000) where soybean is grown as a monocrop. In Brazil, it is grown as part of intensive crop rotation systems such as soybean-corn-millet or soybean-edible-beans-rice rotations. The average yield in 2003 was 3.4 tons/ha but the aim is to increase it further to 4 tons/ha (Truelsen, 2003). China, Japan, Korea, Indonesia and India are Asian countries with long history of planting soybeans (Shurtleff and Aoyagi, 2004).

2.2 Soybean Production in Sub-Saharan Africa (SSA)

Soybean production in sub-Saharan Africa (SSA) has been spreading steadily but unevenly. From only 70,000 tons in 1961, soybean production in SSA increased to 770,000 tons in 2002. In the 1960s, more than 80% was produced in Nigeria. By 1980, the production had reached to 200,000 tons, about equally split over Nigeria and Zimbabwe, where it was grown on large-scale commercial farms. Nigeria kept increasing its production and now has 56% of SSA's production (FAO, 2006). In Zimbabwe, production stayed more or less at the same level until 2000, when it declined with the problems in the commercial farming sector. In Uganda, production only took off in the 1990s and now reaches 8,064 tons per annum (FAO, 2006). The other countries where the crop was successfully introduced with good growth in output are Benin, Rwanda, Cameroon, Ethiopia, and Democratic Republic of Congo.

In Nigeria, increased soybean production has been stimulated through increases in home consumption and demand by food and feed industries. From 1987 to 1993, the International Development Research Centre (IDRC) of Canada and the Japan International Cooperation Agency (JICA) funded a project in which IITA, in partnership with a number of Nigerian institutions, developed new recipes using soybean to enhance nutritional value and taste of traditional Nigerian dishes without increasing cooking time and cost. Kormawa and Von Oppen (2001) also observed that local consumption of soybean and soybean products stimulated had domestic production and industrial processing of soybean into various products demanded by the Nigerian consumers.

In Kenya, soybeans were introduced in the 1960s and disseminated through many projects. Currently, about 80% of the soybean required in Kenya is imported, amounting to about 65,000 metric tons per year. In Kenya, demand for soybean for human consumption, is expected to rise to 150,000 tons per year by 2010 (GTZ, 1996). In a diagnostic survey conducted in 1993, covering 7 agro-ecozones in main soybean producing districts (Meru, Embu, Nakuru, Busia, Kisii and Kakamega), considerably low (452 kg/ha) soybean yields were reported (Wasike and Karanja, 1993). The survey also revealed that there was limited information available to farmers on utilization and marketability of soybean. This affected the farmers' decision to grow the crop. It was also observed that soybean was grown in varying cropping patterns; from pure stand to intercropping with other crops. Average yields of 821 kg/ha for the pure stand and 337 kg/ha and below for intercrops were reported. These low yields were attributable to the low plant stands and generally poor crop management. Additionally, none of the farmers applied fertilizer on Soya but most did apply it on the main crops. The main priority constraints reported were lack of adaptable high yielding varieties, use of sub-optimal fertilizer rates and inoculants and lack of suitable varieties for intercropping with other crops (Wasike and Karanja, 1993). Despite these studies, there is no clear understanding of the major factors underlying the relative absence of soybean in Kenyan farming systems. These factors could be situated at the biophysical level. For instance, there is limited knowledge on the nitrogen fixation capacity and adaptation of different soybeans varieties to heat and water stress variations in the various agro-ecological zones in Kenya (Hornetz, 1997), and certainly so for the dual-purpose soybean varieties.

2.3 Tackling Poverty and Soil Fertility Decline

A substantial part of the legume N fixed from the atmosphere is usually removed from the field through harvested grains and/or stover; often resulting in marginally positive or even negative N balances after a grain legume crop (Giller *et al.,* 2000). Understandably, researchers aiming at improving the soil fertility status have traditionally opted for green manure legumes. For instance, in West Africa, substantial efforts have been made to use *Mucuna pruriens* to reverse soil degradation (Versteeg *et al.,* 1998). In East Africa, *Sesbania sesban* tree fallows were proven to substantially enhance the soil N status (Sanchez and Jama, 2002). Unfortunately, although such technologies aimed solely at improving the soil fertility status were proven to work under on-station conditions, farmers have been and still are very reluctant to adapt such technologies, mainly because they do not derive any immediate benefits (Vanlauwe *et al.*, 2003).

In 1970s, the International Institute of Tropical Agriculture (IITA) identified soybean as an alternate source of inexpensive high quality protein for improving nutrition and health, and indeed the livelihoods of rural communities in Africa (Sanginga *et al.,* 2003). Agronomic and breeding research was therefore, initiated to develop management practices that would optimize yields and varieties that were better adapted to the African environment. In response to rapidly declining soil fertility and resultant low crop yields in sub-Saharan Africa, IITA breeders in the early 1990s focused on developing improved varieties that fixed a high proportion of their nitrogen from the atmosphere and produced large amounts of biomass that contribute to improved soil organic matter status. This biomass can be spread in the field or fed to livestock and their manure returned to the field. These ‘new’ varieties are often referred to as dual-purpose varieties as they do not only provide grains and/or cash but also leave a net amount of N in the soil from which subsequent cereals ad other crops can benefit. Inclusion of these varieties in existing cropping systems has potential to assist the small-scale farmers in Kenya to farm themselves out of the present poverty trap. The very promising preliminary screening observations in Western Kenya and North Rift Valley (Wanjekeche, 2004) warrant serious efforts to explore the potential to increase the production of dual-purpose soybeans in Kenya on a larger scale and to consequently reverse soil fertility depletion, rural poverty and decline in livelihood status.

2.4 Crop Models and Modeling

Crop models provide a dynamic simulation of crop growth and development through numeric integration of the underlying physiological processes with the aid of computers (Sinclair and Seligman, 1996). Computer simulation models have been used in various agronomic disciplines for nearly 40 years, becoming more complex with advances in scientific knowledge and computer science. Such models are used to examine the underlying physical, chemical and biological processes of phenomena that are studied, such as water movement in soils or evapotranspiration in the soil–plant–atmosphere continuum, and to express the known science as mathematical equations. Models can simulate known processes and predict responses of the system to changes in boundary conditions and inputs. These models can be useful tools for the synthesis of research understanding on the interactions of genetics, physiology and environmental factors that influence crop growth and yield (de Wit *et al.,* 1982; Whisler *et al.,* 1986; Uehara, 1998). In addition, they can be used to support the decision making process for cropping system management and agricultural policy (Boote *et al.,* 1996). Crop simulation models also have the potential to contribute to the crop improvement process (White, 1998; Matthews and Stephen, 2002). These include assisting with multi-location evaluation (Aggarwal *et al.,* 1995; Banterng *et al.,* 2003), understanding of the genotype by environment interaction (GXE) (Hammer *et al.,* 1996; Chapman *et al.,* 2002), identification and evaluation of desirable traits or combination of traits leading to the design of a crop ideotype for a specific environment (Boote and Tollenaar, 1994; Aggarwal *et al.,* 1995; Bastiaans *et al.,* 1997; Boote *et al.,* 2001) and evaluation of breeding strategies for drought tolerance (Spitters and Schapendonk, 1990).

Crop models have been well received in fields where describing physical processes is common, such as soil physics and agro-meteorology. Applications include impacts of global warming (Mearns *et al.,* 1999; Alexandrov and Hoogenboom, 1999; Carbone *et al.,* 2003; Jones and Thornton, 2003), crop response to sowing dates (Singh *et al.,* 1994a,b; Acosta-Gallegos and White, 1995; Hunt *et al.,* 1993), crop response to spacing (Egli and Bruening, 1992), characterizations of production environments (White *et al.,* 1995; Chapman *et al.,* 2000), and regional targeting of technologies (Hartkamp *et al.,* 2004). Simulation models have seen less enthusiastic reception in the general fields of agronomy and crop science, where the perception appears to prevail that the models are unable to simulate the soil–plant–atmosphere system due to inherent complexity (Boote *et al.,* 1996; Monteith, 1996; Sinclair and Seligman, 1996). Modeling involves the process of calibration and validation of the model before it can be used or applied (Colson *et al.,* 1995; Sau *et al.,* 1999; Mercau *et al.,* 2007). For practical use of models, representative and accurate model input data are of critical importance (Addiscot *et al.,* 1995; Aggarwal, 1995). The sensitivity of crop models to input parameters not only depends on the model itself but also on the crop and the specific environmental characteristics of the site the crop is growing (Eitzinger and Dirmhirn, 1994; Eitzinger and Zalud, 1995). Weather input data especially, should be representative and accurate to get realistic simulation results (Nonhebel, 1993; 1994).

Crop modeling is a technology that has been applied in precision farming, farm planning and policy development. Crop models effectively integrate numerous factors affecting crop environment and yield (Tsuji *et al.,* 1994). They can not only be used to predict yield but can also be used to evaluate the variability and risks of different management strategies over a range of locations and climatic conditions (Tsuji *et al.,* 1994). Crop modeling can help decision makers reduce the time and human resources required for developing alternative and/or optimal management strategies.

The Decision Support System for Agro-technology Transfer (DSSAT) (Tsuji *et al.,* 1994) is composed of various crop models that are executed under one shell. The crop models available are: the CERES models for cereals (barley, maize, sorghum, millet, rice and wheat); the CROPGRO models; and models for root crops (cassava and potato) and other crops (sugarcane, tomato, sunflower and pasture). DSSAT is a suite of crop models integrated into a single software package in order to facilitate the application of crop simulation in research and decision-making. These models share a common input and output file format. The DSSAT package is specifically designed to answer ‘‘what if’’ questions frequently asked by policy makers and farmers concerned with sustaining an economically and environmentally safe agriculture (Tsuji *et al.*, 1994).

The CROPGRO model is one of the crop simulation models that encompass the DSSAT (Tsuji *et al.,* 1994; Hoogenboom *et al.,* 1999; 2004a; Jones *et al.,* 2003a) for legumes (dry bean, soybean, peanut and chickpea). The crop model architecture differs from one model to another. Under this shell, simulation controls and management scenarios can be invoked in the system to simulate crop growth. The model can simulate seasonal, sequential cropping systems and a single cropping. This model is process-oriented and designed to simulate growth and development on a daily basis, using carbon, nitrogen and water balances. The model requires inputs that include environmental conditions, management practices and characteristics of crop genotype or cultivar-specific genetic coefficients (Boote *et al.,* 1998). Prior to the application of a crop simulation model, it is necessary to determine the genetic coefficients and evaluate model performance if the cultivars are new breeding lines or local cultivars that have not been used previously with the model. The experiments to determine cultivar coefficients should be conducted under optimum conditions and be free from drought and other environmental and biotic stresses. Data to be collected include the duration of phenological development stages and dry matter accumulation of different plant parts, leaf area index (LAI) and specific leaf area (SLA) at different growth stages (IBSNAT, 1988). In addition, it is recommended that these cultivar coefficient determination experiments are conducted across several planting dates at the same location or across multiple locations for the same planting date (Hoogenboom *et al.,* 1999). This makes the determination of cultivar coefficients a laborious and time-consuming process. The recommended procedure, therefore, is not very practical for plant breeding programs that have large numbers of breeding lines. Banterng *et al.,* (2004) reported a study in which data from detailed experiments grown in two seasons were found to be sufficient to determine cultivar coefficients of peanut lines for breeding applications of the CROPGRO-Peanut model.

2.5 Knowledge Gaps

Despite the fact that soybeans have in the past been grown in Kenya, only limited research (Wasike, 1998) has been done on the dual purpose soybean varieties to gauge their performance in Kenya. The search for and use of promiscuous soybean varieties in cropping systems in other African countries has been reported extensively (Javaheri *et al.,* 1994; Kasasa *et al.,* 1999; Giller *et al.,* 2000; Mpepereki *et al.,* 2000). Research on these new dual purpose varieties will shed more light on their productivity and consequently provide a basis for their increased promotion in Kenya. DSSAT crop model has never been used or evaluated in Kenya before, more so with soybean. This research, therefore, provided an opportunity to test it under Kenyan conditions so that it can be used by farmers and researchers more frequently to solve farming problems.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Sites Description

Three sites (Kakamega, Kitale and Msabaha) covering a wide range of agro-ecological zones based on rainfall, temperature/altitude and soil were selected. Msabaha site is located on the outskirts of Malindi town in Coastal Kenya. It receives mean annual bimodal rainfall ranging between 750 and 1100 mm, which is bimodal, and the mean maximum and minimum daily temperatures being 29.5^{0}C and 22^{0}C respectively. This site which lies 91 m above sea level is classified under Coastal Lowlands (CL1) agro-ecological zone. The soils essentially range from sandy loam to clay loams with top soil consisting of silty sands and are sometimes affected by salt intrusion from sea water.

Kitale site is located in Trans Nzoia district in western Kenya. It lies at an altitude of 1890 m above sea level and receives a mean annual rainfall ranging between 900 and 1200 mm (Jaetzold and Schimdt, 1983; Jaetzold *et al.*, 2006), with the highest amount falling between April/May and July/August. The dry spells set in December - February. Kitale falls within the Upper midland-4 (UM4) and Lower Highlands (LH3-LH4) agro-ecological zones.

Kakamega site is located in Kakamega district in western Kenya and lies at 1580 m above sea level. The mean annual rainfall ranges between 760 and 1880 mm and its well distributed throughout the year and generally bimodal. The mean minimum and maximum daily temperatures are 16^{0}C and 28^{0}C respectively.

Soils in Kakamega are generally red loams (Acrisols) and are well drained. Kakamega is classified under Lower Midlands (LM1-LM2) agro-ecological zones. These (Kakamega, Kitale and Msabaha) sites were all on-station at the Kenya Plant Health Inspectorate Services (KEPHIS) National Performance Trial (NPT) sites. These sites cover a range of varying weather conditions, soil, and altitude and therefore, appropriate for model testing and evaluation. Table 3.1 below shows the study sites that were used for calibration and validation of the CROPGRO model.

Table 3.1: Study sites that were used for calibration and validation of CROPGRO model

Site	**Longitude (^{o})**	**Latitude (^{o})**	**Rainfall (mm)**	**Altitude (m)**
Kakamega	34.75 E	0.28 N	760-1880	1580
Kitale	35.98 E	1 N	900-1200	1890
Msabaha	40.05 E	-3.27 S	750-1100	91

3.2 Screening Trials

Screening trials were implemented in Kakamega, Kitale and Msabaha in 2006 and 2007. These trials involved growing eight (8) varieties of soybean at different locations for two seasons covering a range of temperatures, photoperiods, rainfall, and soil characteristics. In addition, soil samples for each site were taken. Daily weather data (Rainfall, temperature and solar radiation) was measured during each experiment. The inverse modeling method described by Mavromatis *et al.* (2001) was used to estimate genetic coefficients and uncertainties in model predictions for each variety using the data described above. Genetic coefficients were used to simulate the different varieties across locations, soils and climatic conditions to determine the varieties with the highest potential for yield.

3.2.1 Experimental Design and Treatments

Randomized complete block design was used for the trials with three (3) replicates. Eight varieties were studied. They included SB 3, SB 8, SB 9, SB 15, SB 17, SB 19 and SB 20. Nyala (SB 23), a local variety was used for comparison or control purposes. The SB is a TSBF coding of TGX (Tropical Glycine Cross) varieties to simplify the naming of the varieties. The varieties were selected based on the preliminary findings of ongoing research by TSBF-CIAT where early, medium and late maturing varieties were represented (Table 3.2). The eight varieties were grown in each site on plots of 6 x 2.35 m, with 0.45 x 0.1 m inter-row and interplant spacing and 4.5 x 2.7 m, with 0.45 x 0.1 m inter-row and interplant spacing for year 1 (2006) and year 2 (2007) respectively. All treatments received a blanket application of 120 kg/ha DAP fertilizer at planting.

Table 3.2: Variety codes as used by IITA and TSBF and classification of Varieties in terms of maturity period

TSBF Code	IITA Code	Maturity
SB 3	TGX 1835-10E	Early
SB 8	TGX 1895-33F	Early
SB 9	TGX 1895-49F	Early
SB 15	TGX 1889-12F	Medium/ Late
SB 17	TGX 1893-10F	Medium/ Late
SB 19	TGX 1740-2F	Early
SB 20	TGX 1448-2E	Medium/ Late
SB 23 (Nyala)	-	Early

3.2.2 Soil Characterization

Soil samples were taken per site at a depth of 15 cm using alderman auger. For each site, several sub-samples of soils were collected and bulked (mixed) to reduce variability and a composite sample taken for analysis. The samples were analyzed for total soil N where nitrate nitrogen was extracted using 2M KCl and determined by Cadmium reduction (Dorich and Nelson, 1984), while ammonium was determined in the 2M KCl extract by the salicylate-hypochlorite colorimetric method (Anderson and Ingram, 1993). The sum of nitrate and ammonium gave the total inorganic nitrogen. The pH in a soil-water suspension was determined using the method described by Okalebo *et al.* (2002) in order to capture the initial conditions of the soil. In addition to the 15 cm depth sampling of soils for initial conditions, a pit of 1x1 m and 2 m deep was dug and soil sampled at depths of 15 cm (15 cm intervals) all through up to 150 cm from each of the four walls of the pit. For each level, the soil sampled from the four walls of the pit was bulked, mixed thoroughly and a composite sample taken for analysis. The samples were analyzed for texture [percentage clay (CL), silt (SI) and percentage sand], percentage organic carbon (OC), and percentage nitrogen (NI). These were entered in the soil file and since the values for Drained Upper Limit (DUL), Lower Limit (LL), Saturation (SAT), Bulk Density (BDM), Saturation Hydraulic conduct (SSKS) and Root Growth Factor (RGF) were not measured, we used the calculated values from the model. Profile data in Kenya Soil and Terrain Database (KENSOTER) and from literature were also used for subsequent simulations.

3.2.3 Plant Observations

Plant measurements were taken to quantify phenological development, biomass production and grain yield. Data collected included planting date, plant density, date of 50% emergence, time to first flower, time to first pod, physiological maturity, and final grain yield.

3.2.4 Weather Data

Weather data for all the sites was acquired from the Meteorological Department. The data included daily rainfall, solar radiation/ sunshine hours (the latter was used in estimation of the former where it was unavailable), and daily minimum and maximum temperatures.

3.3 Model Calibration and Validation

Models provide compact ways of summarizing observed relationships and are essential for making predictions and inferences. Therefore, the growth of dual purpose soybean was simulated using DSSAT model, and inverse modeling techniques were used to determine their genetic coefficients. Model calibration is the adjustment of input parameters of a model (Table 3.3) to provide an acceptable fit between the simulated and observed plant characters (Boote, 1999). The coefficients provided in the DSSAT model for various maturity groups provided the starting point in the process of determining the genetic coefficients (Grimm *et al.,* 1993; Boote *et al.,* 1997). Data collected from the screening trials were used for calibration and validation of the model. The Kakamega KEPHIS data 2007 was used in the calibration process while the rest of the data (Kakamega 2006, Kitale 2006 and Msabaha 2006) were used in the validation/ evaluation of the model.

3.3.1 Decision Support System for Agro-technology Transfer (DSSAT)

The model CROPGRO is one of the crop models that comprises the Decision Support System for Agro-technology Transfer (DSSAT) v 4.2 (Tsuji *et al.,* 1994; Hoogenboom *et al.,* 1999; Jones *et al.,* 2003b) and was used in the simulation modeling. Potential production of soybean and other crop growth information was generated for the eight varieties under different predetermined environmental conditions representing various agro-ecological zones.

Table 3.3: Definition of parameters from the CROPGRO-soybean model

Parameter	Definition	Units
EM-FL	Time between plant emergence and flower appearance (R1)	PTD
FL-SH	Time between first flower and first pod (R3)	PTD
FL-SD	Time between first flower and first seed (R5)	PTD
SD-PM	Time between first seed (R5) and physiological maturity (R7)	PTD
FL-LF	Time between first flower (R1) and end of leaf expansion	PTD
SLAVR	Specific leaf area of cultivar under standard growth conditions	cm^2/g
SIZLF	Maximum size of full leaf (three leaflets)	cm^2
WTPSD	Maximum weight per seed	g
For the following, the default DSSAT values were used		
CSDL	Critical Short Day Length below which reproductive development progresses with no day-length effect (for short-day plants)	hour
PPSEN	Slope of the relative response of development to photoperiod with time (positive for short-day plants)	1/hour
LFMAX	Maximum leaf photosynthesis rate at 30 ^{0}C, 350 vpm CO_2, and high light	mg $CO_2/m^2/s$
XFRT	Maximum fraction of daily growth that is partitioned to seed + shell	
SFDUR	Seed filling duration for pod cohort at standard growth conditions	PTD
SDPDV	Average seed per pod under standard growing conditions	#/pod
PODUR	Time required for cultivar to reach final pod load under optimal conditions	PTD

*PTD = Photo-thermal days

3.3.2 Calibration

Model calibration was first conducted for soil parameters and then for genetic coefficients (Table 3.3). For the calibration of soil parameters, soil sample data were used to calculate soil parameters for the entire profile and for each soil layer with the soil data retrieval program of DSSAT (Tsuji *et al.*, 1994). Parameters that were obtained for each soil layer were: saturated water content, drained upper limit, and the lower limit of plant-extractable water. Soil surface parameters determined included reflectance or albedo, evaporation limit, drainage rate, runoff curve number, and mineralization factor, while the soil fertility factor was determined for the whole profile.

The CROPGRO model uses 15 genetic coefficients to define development and growth characteristics of a soybean cultivar (Table 3.3). To determine the genetic coefficients of the soybean varieties, the minimum data set collected was used as inputs in the standard format of DSSAT Version 4.2. Measured plant characteristics were used as initial coefficients. The calibration process is a systematic search of possible values that the model will use to be able to predict accurately the observed parameters. The procedures described by Mavromatis *et al.* (2001) were used. Candidate cultivars provided by the model were run in the sensitivity analysis mode shell from maturity group (MG) IV onwards. This is because materials in the tropical areas are bred to be less sensitive to photoperiod. The best varieties that predicted maturity close to the observed value were adopted for further adjustments.

3.3.3 Inverse Modeling Method

CROPGRO, a component of the DSSAT model was used to study soybean response to management (Egli and Bruening, 1992), environmental conditions (Curry *et al.*, 1995), and genetic yield potential (Boote and Tollenaar, 1994). CROPGRO was used to simulate carbon, water, and nitrogen balances for the soybean plant and soil. The model uses cultivar-specific traits (Table 3.3) to predict daily growth and development as the plant responds to weather, soil characteristics and management practices (Boote *et al.*, 1998). Most cultivar coefficients are generally similar for cultivars within a maturity group (Boote *et al.*, 1998). This provided a starting point, as approximate values are known for all maturity groups (Grimm *et al.*, 1993; Boote *et al.*, 1997). Attempts were made to account for uncertainties in soil characteristics in specific fields, by modifying a soil fertility factor (SLPF) and soil water holding characteristics.

3.3.4 Goodness of Fit

The fitting of cultivar coefficients and soil parameters was a systematic, stepwise procedure in which (i) candidate coefficients or parameters were selected; (ii) the values of the coefficients or parameters were then changed by running CROPGRO in an optimization shell until the error sum of squares (simulated minus observed) was minimized; and (iii) the set of coefficients or parameters that produced the lowest Root Mean Square Error (RMSE) were adopted. The success of this procedure was shown by a reduction in RMSE from one step to the next.

3.3.5 Statistical Analyses

Data obtained from the field trials and the data generated from simulations by CROPGRO model were subjected to Analysis of Variance (ANOVA) using GenStat Discovery edition (Buysse *et al*., 2004). ANOVA was used to determine if there were significant differences between the various soybean varieties in terms of yields and other variables. Separation of means was done using Least Significant Difference (LSD) at 5% level of significance. Regression analysis was used to determine and establish the goodness of fit between the simulated and the observed data especially for the flowering, podding and maturity.

3.4 Determining the Agro-ecological Potential

To determine the agro-ecological zones in Kenya where dual purpose soybean could grow best, representative sites of the major agricultural zones of Kenya were selected and simulations run. The criterion of selection of the sites for simulation was sites with weather and soil data. Based on the simulation results, the varieties were ranked and recommendations were made on the best bet varieties for the different agro-ecological zones in Kenya.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 General Overview

In this chapter the results are presented and discussed in sections. Each section has attempted to answer the research questions in Chapter One. The sections are divided according to the objectives of the study which are further subdivided into subsections. The overall aim was to clarify on the processes involved to achieve the desired objectives.

4.2 Site Characteristics

Three major sites were studied; these are Kakamega, Kitale and Msabaha. Kakamega site provided the field for determination of coefficients using data collected in 2006 and 2007. The other two sites were used for model validation. The sites have unique characteristics in terms of altitude, weather and soil, thus providing a good basis for model testing. Other sites used in the simulation for determining the agro-ecological potential included: Njoro, Chepkoilel, Embu, Mtwapa and Busia.

4.2.1 Soil Data

Soil characteristics such as percentage clay, silt, organic carbon and nitrogen, pH, bulk density, drained upper limit, saturation, lower limit and others with depth for the three sites were measured. They are summarized in Tables 4.1, 4.2 and 4.3 for

Kakamega, Kitale and Msabaha respectively. The various characteristics presented in the tables show the state of the soil and its potential to support plant life. Some of the characteristics such as Root Growth Factor (RGF) tried to quantify the ability of the soil to allow root growth/penetration. This has been generated by the model and is dependent on the ratio of sand to silt to clay in a soil and the other soil parameters like bulk density (BDM).

Table 4.1: Soil characteristics for the first 150 cm for Kakamega site

Layer (cm)	**LL (cm3 cm^{-3})**	**DUL (cm3 cm^{-3})**	**SAT (cm3 cm^{-3})**	**RGF (0-1)**	**SKS (cm h^{-1})**	**BDM (g/cm^3)**	**OC (%)**	**NI (%)**	**SA (%)**	**CL (%)**	**SI (%)**	**pH in H_2O**
0-15	0.252	0.433	0.516	1	0.23	1.17	2.23	33	61.8	38	0.21	5.5
15-30	0.241	0.404	0.493	0.638	0.23	1.24	1.82	33	65.8	34	0.21	5.4
30-45	0.286	0.432	0.487	0.472	0.06	1.26	1.67	43	75.9	24	0.15	5.5
45-60	0.339	0.465	0.48	0.35	0.06	1.29	1.01	57	81.9	18	0.1	5.8
60-75	0.371	0.481	0.49	0.259	0.06	1.27	0.72	65	83.9	16	0.07	5.8
75-90	0.391	0.484	0.493	0.192	0.06	1.26	0.73	69	84.0	16	0.03	6.2
90-105	0.368	0.482	0.487	0.142	0.06	1.28	0.62	65	85.9	14	0.06	6.2
105-120	0.377	0.479	0.491	0.105	0.06	1.27	0.58	67	86.0	14	0.05	6.4
120-135	0.365	0.477	0.484	0.078	0.06	1.29	0.53	65	86.0	14	0.05	6.3
135-150	0.334	0.441	0.462	0.058	0.06	1.35	0.49	59	86.0	14	0.04	6.5

*****DUL- Drained Upper limit, LL- Lower limit, SAT- Saturation, RGF- Root growth factor, SKS- Saturated Hydraulic conduction, BDM- Bulk Density, OC- Percentage Organic carbon, CL- Percentage Clay, SI- Percentage Silt, NI- Percentage Nitrogen, SA- Percentage Sand

Table 4.2: Soil characteristics for the first 150 cm for Kitale site

Layer (cm)	LL (cm3 cm^{-3})	DUL (cm3 cm^{-3})	SAT (cm3 cm^{-3})	RGF (0-1)	SKS (cm h^{-1})	BDM (g/cm^3)	OC (%)	NI (%)	SA (%)	CL (%)	SI (%)	pH in H_2O
0-15	0.214	0.353	0.462	1	0.43	1.33	1.57	29	73.9	26	0.15	5.4
15-30	0.222	0.333	0.432	0.638	0.43	1.42	1.13	33	83.9	16	0.09	4.9
30-45	0.228	0.337	0.426	0.472	0.12	1.44	0.99	35	83.9	16	0.07	5.1
45-60	0.203	0.316	0.427	0.35	0.43	1.44	0.8	31	78.0	22	0.05	5.6
60-75	0.181	0.29	0.421	0.259	0.43	1.46	0.73	27	78.0	22	0.05	5.6
75-90	0.168	0.285	0.429	0.192	1.32	1.44	0.61	25	72.0	28	0.05	6
90-105	0.176	0.289	0.422	0.142	0.43	1.46	0.55	27	74.0	26	0.05	6
105-120	0.187	0.297	0.418	0.105	0.43	1.47	0.57	29	76.0	24	0.05	5.1
120-135	0.174	0.289	0.423	0.078	1.32	1.46	0.47	27	72.0	28	0.05	5.1
135-150	0.184	0.296	0.419	0.058	0.43	1.47	0.46	29	74.0	26	0.05	5

Table 4.3: Soil characteristics for the first 150 cm for Msabaha site

Layer (cm)	LL (cm3 cm^{-3})	DUL (cm3 cm^{-3})	SAT (cm3 cm^{-3})	RGF (0-1)	SKS (cm h^{-1})	BDM (g/cm^3)	OC (%)	NI (%)	SA (%)	CL (%)	SI (%)	pH in H_2O
0-15	0.145	0.223	0.366	1	0.43	1.62	0.43	23	98.0	2	0.04	6.8
15-30	0.153	0.232	0.369	0.638	0.43	1.61	0.32	25	98.0	2	0.04	7.2
30-45	0.169	0.253	0.377	0.472	0.43	1.59	0.20	29	96.0	4	0.03	7.2
45-60	0.186	0.269	0.377	0.35	0.43	1.59	0.15	33	98.0	2	0.04	7.3
60-75	0.186	0.271	0.38	0.259	0.43	1.58	0.11	33	96.0	4	0.03	7.3
75-90	0.169	0.253	0.377	0.192	0.43	1.59	0.10	29	96.0	4	0.02	7.3
90-105	0.152	0.237	0.377	0.142	0.43	1.59	0.07	25	94.0	6	0	7.4
105-120	0.161	0.243	0.377	0.105	0.43	1.59	0.08	27	96.0	4	0.02	7.3
120-135	0.161	0.243	0.377	0.078	0.43	1.59	0.07	27	96.0	4	0.03	7.2
135-150	0.161	0.241	0.373	0.058	0.43	1.6	0.07	27	98.0	2	0.03	7

Soils from the three sites differed in texture, pH, percentage carbon and percentage nitrogen. The pH was highest in Msabaha soils due to intrusion of salts from the sea and it also had the highest sand content and lowest clay content among the three sites.

4.2.2 Weather Data for the Study Sites

The weather data (rainfall, minimum and maximum temperatures, and solar radiation) for the three sites were recorded in the site stations. Monthly rainfall received for the respective years for the three sites is presented in Figures 4.1, 4.2 and 4.3 for Kakamega, Kitale and Msabaha respectively. The total amount of rainfall received in Kakamega was 2,407 mm in 2006 and 2,025 mm in 2007. Temperatures were fairly the same with the mean annual minimum temperatures recorded to be 14.9 ^{0}C and 14.4 ^{0}C for year 2006 and 2007 respectively. Mean annual maximum temperatures recorded for the two years averaged 27.6 ^{0}C. Total rainfall received in Kitale was 1,445 mm with mean annual minimum temperatures of 13.7 ^{0}C and mean annual maximum temperatures of 26.6 ^{0}C for the year 2006. In 2006, Msabaha recorded a total annual rainfall of 1,506 mm, with mean annual minimum and maximum temperatures of 23.6 ^{0}C and 30.4 ^{0}C respectively.

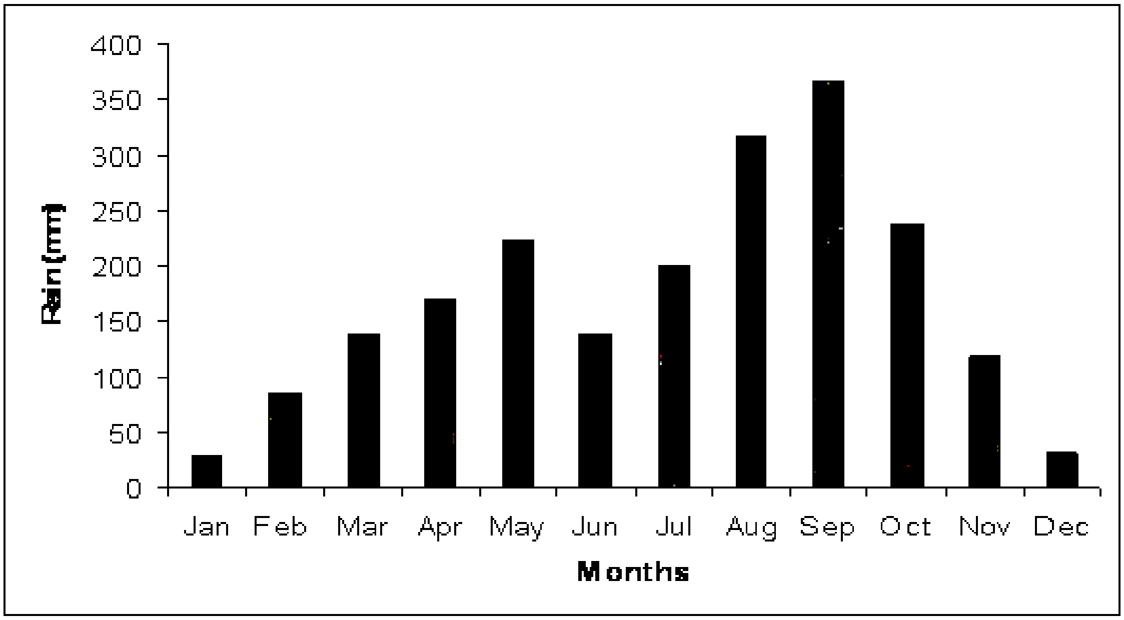


Figure 4.1: Rainfall for Kakamega site for the year 2006

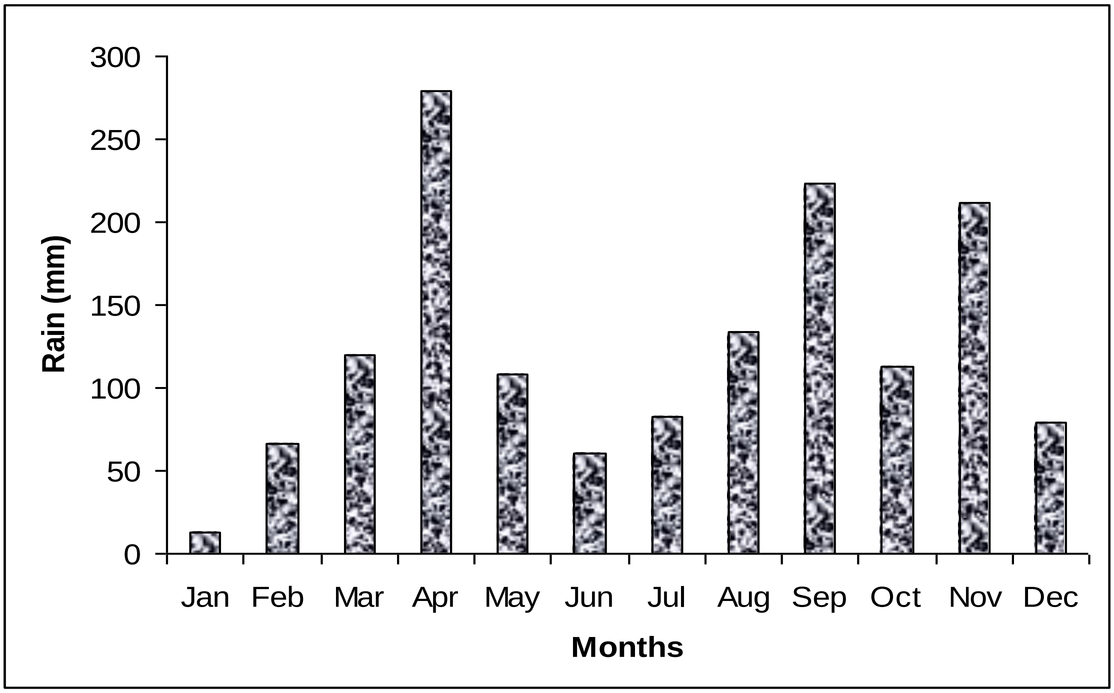


Figure 4.2: Rainfall for Kitale site for the year 2006

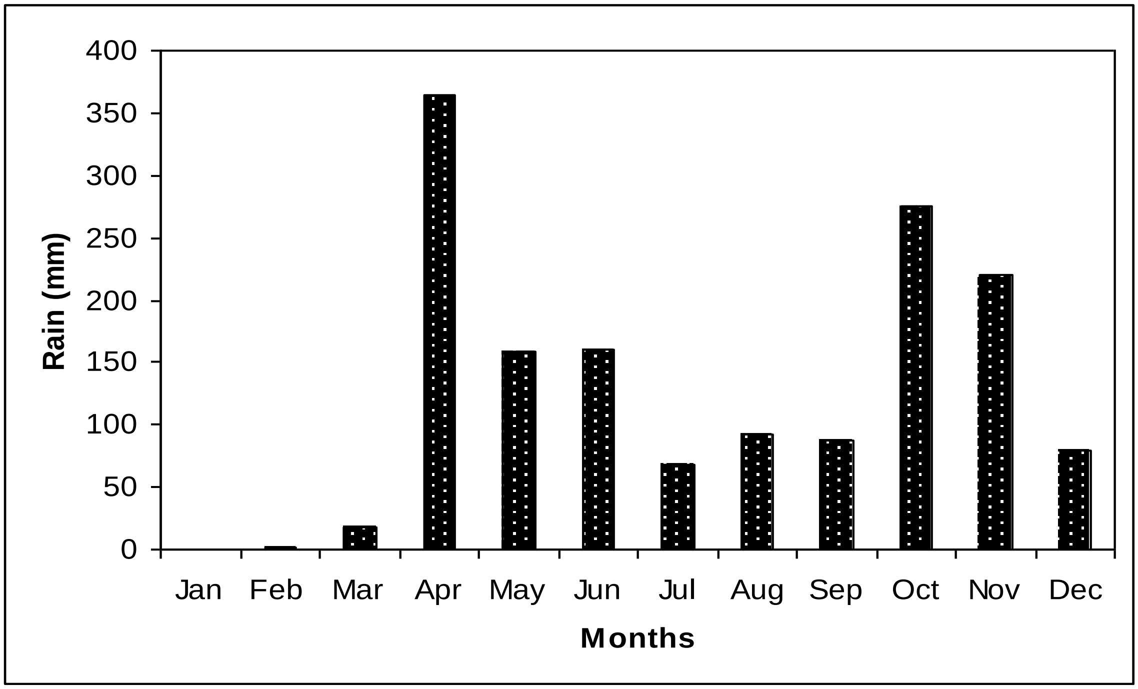


Figure 4.3: Rainfall for Msabaha site for the year 2006

4.3 Model Calibration

The calibration was done from the generic genetic coefficients provided by the model (Table 4.5) and the assigned genetic coefficients are shown in Table 4.6. The results are explained in details in the sections that follow.

4.3.1 Estimated Genetic Coefficients

The predictions of the CROPGRO generic maturity groupings (MG) selected for each variety gave the results that are shown in Table 4.4. Soybean variety (SB) 19, SB 23 (Nyala), SB 3, and SB 8 originated from Maturity group (MG) IV, SB 15 and SB 20 from MG IX, SB 17 from MG V, and SB 9 from MG VI (Table

4.4). The genetic coefficients used for this simulation are the generic ones shown in Table 4.5.

Table 4.4: Maturity groupings of the varieties and their initial predictions before calibration for Kakamega site, 2007

Variety	MG	Simulated Flowering (DAS)	Mean Observed Flowering (DAS)	Simulated Podding (DAS)	Mean Observed Podding (DAS)	Simulated Maturity (DAS)	Mean Observed Maturity (DAS)
SB 15	IX	50	63	68	75	137	135
SB 17	V	42	58	53	72	106	121
SB 19	IV	39	54	52	65	97	109
SB 20	IX	50	63	68	74	137	135
SB 23(Nyala)	IV	41	50	51	61	103	103
SB 3	IV	39	53	52	67	97	106
SB 8	IV	39	60	52	74	97	117
SB 9	VI	43	59	56	70	108	106

*MG- Maturity group of soybean; depends on period required to mature; DAS- Days after sowing

The idea here was to set the simulated dates for maturity closer to the observed. However, not all the varieties gave the desired 2-3 days difference between the simulated and observed maturity days for example SB 17, SB 19, SB 3 and SB 8. This could partly be explained by the fact that maturity period does not only depend on the Critical Short Day Length below which reproductive development progresses with no day-length effect (CSDL) and the slope of the relative response of development to photoperiod with time (PPSEN) (both related to maturity grouping) but also the other coefficients such as time between first seed and physiological maturity (SD-PM). This was solved by optimizing the other coefficients in consideration of the other parameters such as days to flowering, days to podding and yield.

Time between plant emergence and flower appearance (EM-FL), time between first flower and first seed (FL-SD), time between first flower and first pod (FL-SH) and time between first seed and physiological maturity (SD-PM) were optimized until the Root Mean Square Error (RMSE) between the simulated and the observed was lowest in the sensitivity analysis mode as described by Mavromatis *et al.* (2001) and Hoogenboom *et al.* (1999). The resulting genetic coefficients are shown in Table 4.6. The values for specific leaf area of cultivar under standard growth conditions (SLAVR) measured from the field were very low; hence, the lowest value of 300 provided by the model was used for all the varieties. Other values for the rest of the coefficients were left as provided in the respective (generic values) maturity groupings (Table 4.5).

Table 4.5: Original unmodified varieties that were used in the calibration of the CROPGRO model

VARIETY NAME	*ECO#	CSDL	PPSEN	EM-FL	FL-SH	FL-SD	SD-PM	FL-LF	LFMAX	SLAVR	SIZLF	XFRT	WTPSD	SFDUR	SDPDV	PODUR
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
IB0059 **SB 15**	SB0901	11.88	0.340	23.0	10.0	16.0	37.40	18.00	1.030	375	180.0	1.00	0.18	23.0	2.05	10.0
IB0058 **SB 17**	SB0501	12.83	0.303	19.8	8.0	15.5	34.80	18.00	1.030	375	180.0	1.00	0.18	23.0	2.05	10.0
IB0057 **SB 19**	SB0001	13.09	0.294	20.0	9.0	16.0	30.00	30.00	1.030	390	200.0	1.00	0.18	22.0	2.05	10.0
IB0056 **SB 20**	SB0901	11.88	0.340	23.0	10.0	16.0	37.40	18.00	1.030	375	180.0	1.00	0.18	23.0	2.05	10.0
IB0012 **SB 23 Nyala**	SB0401	13.09	0.294	19.4	7.0	15.0	34.00	26.00	1.030	375	180.0	1.00	0.19	23.0	2.20	10.0
IB0062 **SB 3**	SB0301	13.09	0.294	19.0	8.2	13.8	33.20	28.00	1.000	390	180.0	1.00	0.195	25.5	2.40	10.5
IB0061 **SB 8**	SB0301	13.09	0.294	19.0	8.2	13.8	33.20	28.00	1.000	390	180.0	1.00	0.195	25.5	2.40	10.5
IB0060 **SB 9**	SB0601	12.58	0.311	20.2	9.0	16.0	35.60	18.00	1.030	375	180.0	1.00	0.18	23.0	2.05	10.0

Table 4.6: Modified genetic coefficients for the new varieties used for subsequent simulations in the CROPGRO model

VARIETY NAME	* ECO#	CSDL	PPSEN	EM-FL	FL-SH	FL-SD	SD-PM	FL-LF	LFMAX	SLAVR	SIZLF	XFRT	WTPSD	SFDUR	SDPDV	PODUR
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
IB0059 **SB 15**	SB0505	11.88	0.340	28.9	9.0	9.0	32.00	18.00	1.000	300	150.0	1.00	0.18	22.0	2.05	10.0
IB0058 **SB 17**	SB0504	12.83	0.303	27.0	10.0	14.0	33.00	18.00	1.000	300	150.0	1.00	0.18	23.0	2.05	10.0
IB0057 **SB 19**	SB0503	13.09	0.294	25.0	8.0	14.0	33.20	26.00	1.030	300	180.0	1.00	0.19	23.0	2.20	10.0
IB0056 **SB 20**	SB0502	11.88	0.340	28.9	7.0	13.5	31.50	15.00	1.030	300	180.0	1.00	0.18	22.0	2.05	10.0
IB0012 **SB 23 Nyala**	SB0501	13.09	0.294	23.0	8.0	15.0	26.00	26.00	1.030	300	180.0	1.00	0.19	23.0	2.20	10.0
IB0062 **SB 3**	SB0508	13.09	0.294	25.0	9.0	13.8	30.00	25.00	1.000	300	190.0	1.00	0.19	25.5	2.40	10.5
IB0061 **SB 8**	SB0507	13.09	0.294	28.9	10.0	13.8	30.00	28.00	1.000	300	190.0	1.00	0.19	25.5	2.40	10.5
IB0060 **SB 9**	SB0506	12.58	0.311	28.9	9.0	11.0	25.00	18.00	1.000	300.	150.0	1.00	0.18	22.0	2.05	10.0

***** Code meanings explained in Table 3.3

4.3.2 Calibration Results

The calibrated model predicted phenology and yields as shown in Tables 4.7 and 4.8 below.

Table 4.7: Comparison between simulated and observed data (Phenological stages) of the soybean varieties in Kakamega for the year 2007

Variety	MG	Simulated Flowering (DAS)	Mean Observed Flowering (DAS)	Simulated Podding (DAS)	Mean Observed Podding (DAS)	Simulated Maturity (DAS)	Mean Observed Maturity (DAS)
SB 15	IX	61	63	77	75	126	135
SB 17	V	55	58	69	72	114	121
SB 19	IV	51	54	63	65	111	109
SB 20	IX	61	63	74	74	133	135
SB 23	IV	48	50	59	61	100	103
SB 3	IV	51	53	64	67	107	106
SB 8	IV	58	60	73	74	114	117
SB 9	VI	58	59	71	70	104	106
LSD	-	-	0.82	-	0.84	-	2.52

*F test: Variety=p<0.001 at 5% level of significance. MG- Maturity group; DAS- Days after sowing

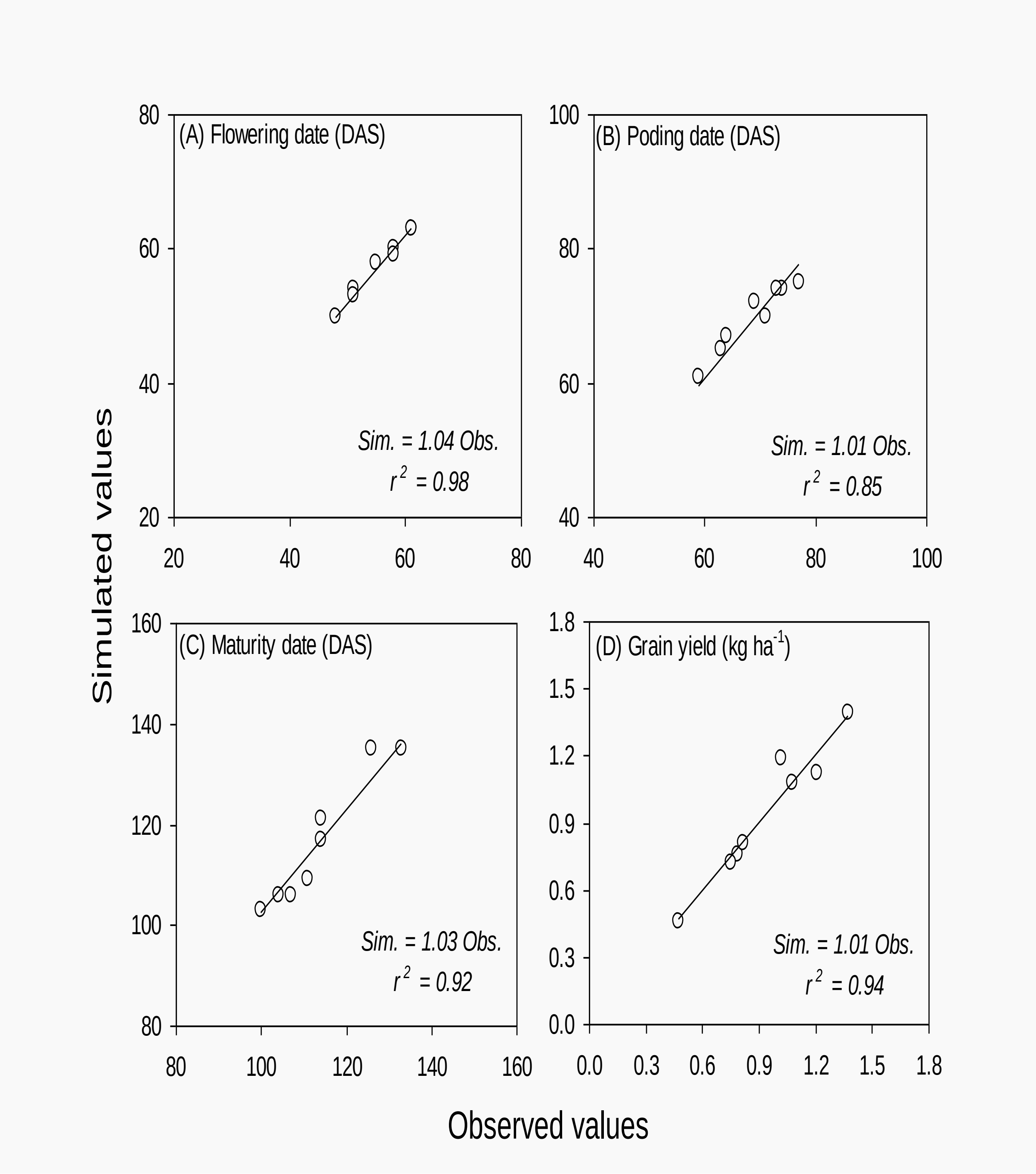
Table 4.8: Comparison between simulated and observed yield and canopy height with their RMSEs in Kakamega for the year 2007

Variety	Simulated Yield (kg ha^{-1})	Mean Observed Yield (kg ha^{-1})	RMSE (kg ha^{-1})	Simulated Canopy Height (m)	Mean Observed Canopy Height (m)	RMSE (m)
SB 15	473	461	12	0.61	0.89	0.204
SB 17	788	757	31	0.55	0.53	0.107
SB 19	1075	1080	5	0.51	0.56	0.041
SB 20	1374	1395	21	0.62	0.56	0.127
SB 23	816	811	5	0.49	0.29	0.249
SB 3	1017	1189	172	0.51	0.30	0.236
SB 8	1207	1119	88	0.57	0.61	0.057
SB 9	751	724	27	0.56	0.94	0.286
LSD	-	129.7	-	-	0.25	-

*F test: Variety= p<0.001 at 5% level of significance. RMSE gives the accuracy of model prediction

The model predicted the first flowering dates within 2-3 days of the observed values, and predicted the first pod dates within 0-3 days of the observed values (Table 4.7). The days to flowering and podding across varieties were significantly different at 5% level of significance (Table 4.7). The yields across varieties were also significantly different. In assessing the accuracy of the genetic coefficients derived from model calibration, simulated values for four of the most critical developmental stages of the 8 tested soybean varieties for the two growing seasons were compared with the corresponding observed values.

The RMSE for yields ranged from as low as 5 kg/ha to 172 kg/ha while for the canopy height the RMSE was high for some of the varieties. This is expected due to differences in the soil from plot to plot. The model only uses one soil profile for one site hence it cannot detect the improved or reduced fertility from plot to plot. However, for some varieties the canopy height simulations were well simulated. Close agreements between observed and simulated values were obtained for days to first flowering (Figure 4.4A), days to first pod production (Figure 4.4B) and maturity (Figure 4.4C). Grain yield correlation was also done (Figure 4.4D).



DAS- Days after sowing

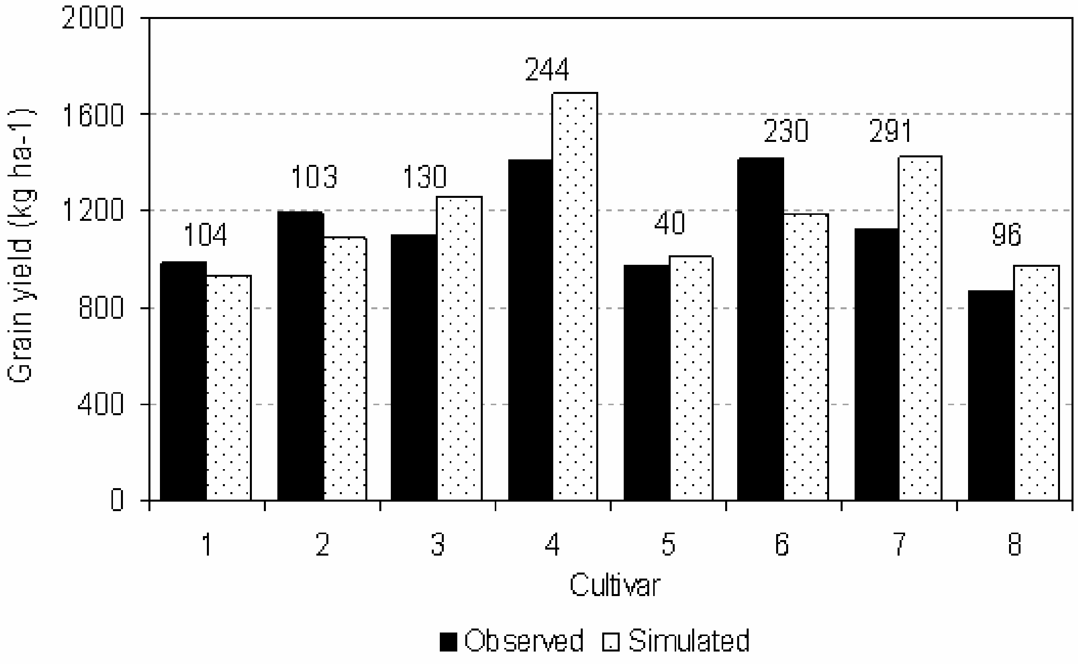
Figure 4.4: Correlation between the simulated and the observed values of flowering, podding and maturity dates, and grain yields for all soybean varieties tested for Kakamega data 2007

4.4 Model Validation and Evaluation

The capability of the model to predict crop development and yield was tested using an independent data set collected during 2006 at Kakamega, Kitale and Msabaha sites. Details are discussed in the subsections below.

4.4.1 Kakamega Site

After a thorough calibration process, the genetic coefficients given in Table 4.6 were run with the 2006 Kakamega Data set. The results for yield and their Root Mean Square Errors (RMSEs) are shown in Figure 4.5.



1- SB 15, 2-SB 17, 3- SB 19, 4- SB 20, 5- SB 23, 6- SB 3, 7- SB 8, 8- SB 9

Figure 4.5: Comparison between simulated and observed soybean grain yield for Kakamega 2006 data. RMSEs are also given on top of the bars for each variety

The model accurately predicted reproductive development with low bias. RMSE for yield ranged from as low as 40 to less than 300 kg/ha (Figure 4.5). These values are slightly higher than RMSE of the calibration (Kakamega 2007) data set (Table 4.8). Despite the small decrease in the model precision relative to the calibration values, these RSME are comparable in magnitude with the precision of the measurements and previous modeling results (Grimm *et al.*, 1993).

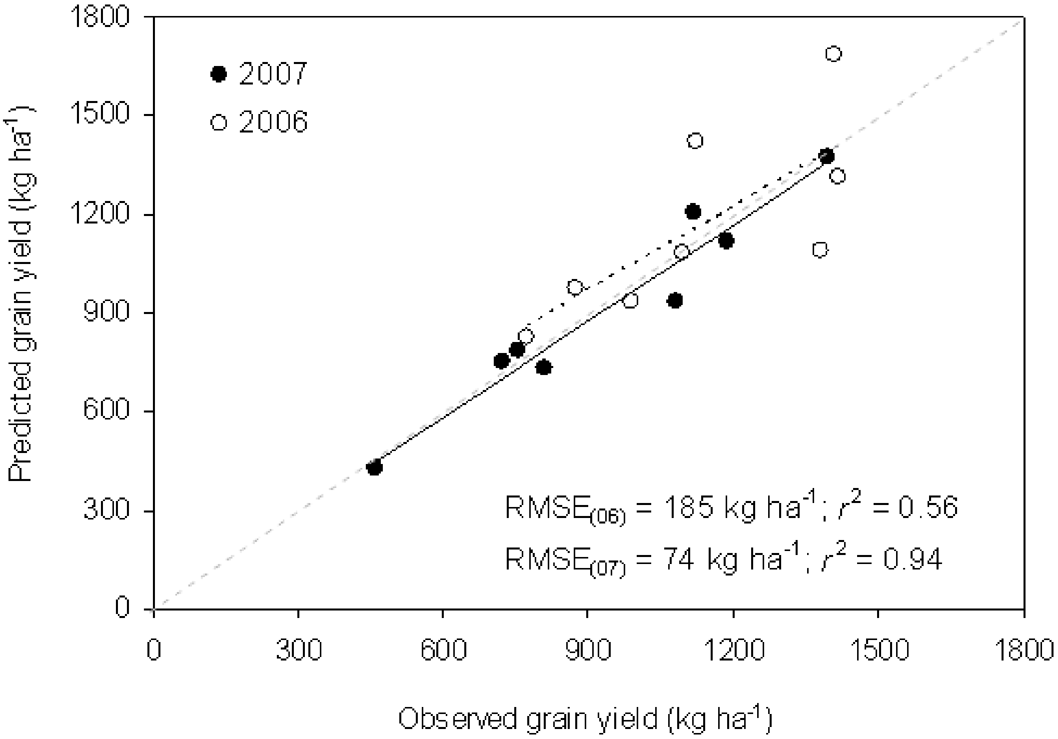


Figure 4.6: Comparison of soybean grain yield for Kakamega for 2006 and 2007

The differences observed between the phenological stages and yield (Figure 4.5, Figure 4.6, Table 4.7 and Table 4.8) at Kakamega site for the two years could be attributed to the differences in temperature (Butterfield and

Morison, 1992; Hoogenboom *et al.*, 2004a), rainfall, solar radiation and soil dynamics (Alagarswamy *et al.*, 2000). A total of 921.9 mm of rainfall was recorded in 2006 growing period compared to 1293.0 mm in 2007 growing period. The status of the soil and the differences in the planting dates (Hoogenboom *et al.*, 1999) may have also contributed to the differences in yield and phenology.

4.4.2 Kitale Site

The yields for Kitale were well simulated for all the varieties with RMSE ranging from 5 to 187 kg/ha (Table 4.9). Simulation of the model for phenology was within 3 days error for flowering and podding and within 5 days for physiological maturity. The varieties were significantly different at 5% level of significance for flowering, podding and maturity periods. The yields were also significantly different across the varieties at the site.

The growing period of the varieties was a bit lengthened due to the lower temperatures experienced at this site compared to those at Kakamega and Msabaha. The increase in growing period and the favourable conditions in Kitale could have led to higher grain yields compared to the other two sites. The high altitude at Kitale means that there is increased flowering period due to the low temperatures that are conducive for soybean flowering hence increased reproduction and therefore, higher yields. These conditions particularly favour the late maturing varieties such as SB 20 and SB 8 with the exception of SB 15. The early maturing varieties such as SB 23 (Nyala), SB 19 and SB 3 were delayed but still performed well.

Table 4.9: Simulated versus observed data for the varieties (of soybean) phenology and yield for Kitale 2006

Variety	Simulated Flowering (DAS)	Mean Observed Flowering (DAS)	Simulated Podding (DAS)	Mean Observed Podding (DAS)	Simulated Maturity (DAS)	Mean Observed Maturity (DAS)	Simulated Grain Yield (kg/ha)	Mean Observed Grain Yield (kg/ha)	RMSE (kg/ha)
SB 15	68	70	86	87	136	140	1107	1065	5
SB 17	60	61	75	77	122	126	2078	1914	164
SB 19	56	57	68	70	117	121	2244	2123	109
SB 20	68	68	82	85	143	147	2617	2531	86
SB 23 (Nyala)	51	53	64	64	105	108	1613	1667	73
SB 3	56	58	69	70	112	117	2016	2068	59
SB 8	64	64	79	82	122	126	2551	2623	187
SB 9	64	64	77	80	111	115	1811	1929	143
LSD	-	0.95	-	3.55	-	3.55	-	312.1	-

*F test: Variety=p<0.001 at 5% level of significance. RMSE-Root Mean Square Error; DAS-Days after sowing

4.4.3 Msabaha Site

Using separate independent data set (KEPHIS Msabaha 2006 data) (Table 4.10), the model predicted flowering and podding dates and yield very well. However, the canopy heights predicted were generally not close to those observed for most of the varieties. Physiological maturity dates for this site were not taken but clearly the high temperatures in this area substantially reduced the maturity period for the varieties gauging by the flowering and podding periods recorded. The days to flowering and podding were significantly different across varieties at 5% level of significance. Yields at Msabaha site were also significantly different across the varieties at the same significance level.

Large yield differences were observed for the early maturing soybean varieties (SB 23, SB 3 and SB 8). This was attributed to the fact that the varieties were harvested very late after maturity hence most of the grains were lost through shattering. Furthermore, the model does not consider the effects of pests and diseases (Banterng *et al.,* 2003) hence it overestimated the yields for this site. This site has high temperatures and humidity which favour some diseases and pests. The phenological stages were generally well simulated by the model for most of the varieties. The simulated flowering and podding dates were within an acceptable range except for SB 3, which gave an error of 7 days. The canopy heights were overestimated by the model as compared to the observed values. Observed data for days to maturity was unavailable. This was due to long intervals of field inspection for the site since it was situated some five kilometers away from the station. This also partly explains the disparities in the observed and simulated flowering and podding.

Table 4.10: Simulated versus observed data for the soybean varieties tested (phenology, yield and canopy height) for Msabaha 2006

Variety	Simulated Flowering (DAS)	Mean Observed Flowering (DAS)	Simulated Podding (DAS)	Mean Observed Podding (DAS)	Simulated Maturity (DAS)	Observed Maturity (DAS)	Simulated Grain Yield (kg/ha)	Mean Observed Grain Yield (kg/ha)	RMSE (kg/ha)	Simulated Canopy Height (m)	Observed Canopy Height (m)
SB 15	36	38	47	45	86	-	468	552	96	0.6	0.42
SB 17	34	39	44	49	83	-	512	605	79	0.54	0.31
SB 19	32	38	40	44	81	-	656	716	55	0.49	0.37
SB 20	36	40	44	50	91	-	699	802	110	0.59	0.29
SB23 (Nyala)	29	31	38	35	72	-	515	231	216	0.48	0.23
SB 3	32	39	41	48	77	-	595	265	235	0.49	0.47
SB 8	36	39	46	47	81	-	664	315	256	0.56	0.43
SB 9	36	38	45	45	73	-	476	438	22	0.57	0.45
LSD	-	0.95	-	3.55	-	-	-	191.1		-	0.15

*F test: Variety=p<0.001 at 5% level of significance. RMSE-Root Mean Square Error; DAS-Days after sowing

4.4.4 Model Evaluation

The results clearly demonstrate that CROPGRO simulated phenology and yields quite well for most of the varieties across contrasting sites. The most important thing in modeling using CROPGRO is to get accurate genetic coefficients (Addiscot *et al.*, 1995; Aggarwal, 1995) for the new varieties and soil parameters for the sites involved (Heiniger *et al.*, 1997). This involves collection of high quality data from the field. This means that the trials must be well managed with no water or nutrient limitations (Hodges and French, 1985; Muchow, 1985; Banterng *et al.*, 2003) and also free from diseases. Otherwise, the coefficients resulting from such trials will not be of quality hence the subsequent simulations will result in large margins of error compared to the observed data. The greatest challenge in the determination of genetic coefficients is the fact that the new varieties being developed or already developed must be well known. It is, therefore, critical for the modeler to get as much information on the varieties as possible. This is because some of the coefficients such as Critical Short Day-length (CSDL) and slope of relative response of development to photoperiod (PPSEN) are not easily determined. Hence, prior knowledge of the varieties is imperative.

The ratio of sand to silt and clay may have affected the yield and phenology. This was due to the fact that this affects the water holding capacity of the soil and consequently affected the growth and development of the plant. Kakamega, Kitale and Msabaha are extreme sites in terms of temperature regimes and altitude. Kitale is very cold (13.7-26.6 ^{0}C), Kakamega cold (14.9-27.6^{0}C) while, Msabaha is hot (23.6-30.4 ^{0}C). This, therefore, affected the maturity period of the varieties across the sites holding other factors constant. However, the general trend as impacted by the maturity groups (varieties) remained the same. The maturity period was significantly reduced at Msabaha compared to Kakamega and Kitale. These findings concur with studies conducted by Piper *et al.* (1996) where he studied performance of cultivars across diverse environments.

4.4.5 Differences among Cultivars

Differences among varieties for phenological coefficients were rather small, with the Coefficient of Variation (CV) among varieties for individual characters ranging from 4.19-15.24% (Table 4.11).

Table 4.11: Differences among soybean cultivars for the most important coefficients as determined by the calibration process

VARIETY	CSDL	EM-FL	FL-SH	FL-SD	SD-PM	FL-LF
SB 15	11.88	28.9	9	9.0	32.0	18
SB 17	12.83	27.0	10	14.0	33.0	18
SB 19	13.09	25.0	8	14.0	33.2	26
SB 20	11.88	28.9	7	13.5	31.5	15
SB 23 (Nyala)	13.09	23.0	8	15.0	26.0	26
SB 3	13.09	25.0	9	13.8	30.0	25
SB 8	13.09	28.9	10	13.8	30.0	28
SB 9	12.58	28.9	9	11.0	25.0	18
Mean	**12.69**	**26.95**	**8.75**	**13.01**	**30.09**	**18.75**
Standard deviation	**0.53**	**2.34**	**1.04**	**1.98**	**3.08**	**1.035**
Coefficient of variation (%)	**4.19**	**8.69**	**11.83**	**15.24**	**10.24**	**11.83**

CSDL- Critical Short Day Length below which reproductive development progresses with no day-length effect, EM-FL- Time between plant emergence and flower appearance, FL-SH- Time between first flower and first pod, FL-SD- Time between first flower and first seed, SD-PM- Time between first seed and physiological maturity, FL-LF- Time between first flower and end of leaf expansion.

The greatest variation among the varieties was FL-SD followed by SD-PM. This is due to the high differences in time to first seed and the time to maturity. The interaction between the genes and the environment led to variations among the varieties, hence the differences in the physical appearances of the plants and the seeds. However, it should be noted that despite the low CVs obtained from the analysis (Table 4.11) for some of the coefficients, the small differences in the genetic coefficients have a far much greater impact when they interact with the environment. This was evident from their field performance and maturity period. These coefficients do not only act singly but also have a collective effect. When the genetic coefficients (genotype) interact with the environment (GxE), they give varying responses (Hoogenboom *et al.,* 2004b), which are expressed by the phenology of each variety. These includes colour of the parts of the plant (stems, leaves, flowers and seeds), size of the plant parts and the plant itself, flowering, podding and maturity period and many other physically visible and invisible differences.

4.5 Biophysical Factors Affecting Soybean Production

Table 4.12 summarizes the conditions in the study sites and the mean soybean yield.

Table 4.12: Biophysical factors of Kakamega, Kitale and Msabaha sites that influenced the performance of soybean

Site	Mean Temperature Range (°C)	Altitude (m)	Average Rainfall Range (mm)	Soil Type	Mean Soybean Yields (kg/ha)
Kakamega	14.4-27.6	1580	760-1880	Acrisols	1081
Kitale	13.7-26.6	1890	900-1200	Acrisols	1990
Msabaha	23.6-30.4	91	750-1100	Sandy loams	490

The performance of soybean is influenced by several biophysical factors some of which have been described in Table 4.12 above for the study sites. Temperature, soil type and rainfall are the major factors. Generally, soybean responds differently under different conditions. The response differs from variety to variety as a result of the genotype-environment (GxE) interaction. Msabaha recorded the lowest mean yields of 490 kg/ha while Kitale had the highest with 1990 kg/ha. The differences in yield can be explained by the differences in the biophysical factors outline in Table 4.12.

The high temperatures at Msabaha have a limiting effect on the growth of soybean. Soybean like any other plant, when subjected to stress tend to grow very fast and therefore flowers within a very short time even before the plant fully establishes itself vegetatively. The low yields are therefore as a result of stunted growth. On the contrary, Kitale and Kakamega sites had relatively lower temperatures (higher altitude) hence favoured soybean flowering and growth. This led to higher yields in the sites compared to Msabaha.

Climate and soil moisture availability are key factors in determining the distribution (both in space and time) of rain-fed crops. In combination with solar radiation, these climatic factors condition photosynthesis and allow plants to accumulate biomass (and accomplish successive development stages) according to their eco-physiological rates and patterns. It is widely known that variations in altitude, climate and soils largely influence agricultural productivity within and across countries in Africa. These variations have been used in subdivisions of croplands into agro-ecological zones (AEZs) for management purposes in each country. Thus, in the East African region, low maize (staple) yields are common in the coastal, medium altitude and moisture stressed regions, whereas high yields occur on the cooler high altitude and high rainfall areas (Okalebo *et al.,* 2007). Just like maize, soybean has the same yield trends in Kenya within the same AEZs described above. Various biophysical factors that affect soybean are discussed in details below.

4.5.1 Inherent Soil Fertility and Soybean Production

The important soil components of the sites studied are presented in Table 4.13 overleaf. The percentage of clay is very low averaging 2% in the top 30cm of soil in Msabaha compared to 37% and 23% for Kakamega and Kitale respectively.

Table 4.13: Soil characteristics for the top 15 cm per site for Kakamega, Kitale and Msabaha

	Site			
Attribute	**Kakamega**	**Kitale**	**Msabaha**	**STD**
Percentage clay	38	26	2	18.33
Percentage silt	0.21	0.15	0.04	0.09
Percentage sand	61.79	73.85	97.96	18.42
pH range in water	5.5-6.5	5.0-5.6	6.8-7.3	-
Percentage organic carbon	2.23	1.57	0.43	0.91
Percentage organic nitrogen	33	29	23	5.03

*STD- Standard Deviation from the mean

This explains the poor performance of soybean in Msabaha. Clay has the capacity told water for longer periods of time hence enabling the soybean plant to have access to water for long. A very high percentage of sand in the soil means very low capacity for the soils to hold water and nutrients for the crops hence giving poor yields. Performance of soybean in these sites is shown in Tables 4.7, 4.8, 4.9 and 4.10. It is very clear that soil characteristic is very critical to performance of soybean as it is to other crops.

Soil fertility plays an important role in growth of crops. A soil is considered fertile when it has enough of the required minerals to support a crop for the entire crop period (Donavan and Casey, 1998). Percentage organic carbon and nitrogen is highest in Kakamega followed by Kitale and lowest in Msabaha. However, leaching and soil erosion have had their toll in these soils. Low inherent soil fertility in the highly weathered and leached soils largely accounts for low and unsustainable crop yields in most African countries (Dregne, 1990; Okalebo *et al.*, 2007). Soil fertility has been declining steadily over the years due to increased agricultural activities in the world to boost food production to feed the ever increasing world population. Therefore, farmers and scientists have and continue to look for options that will efficiently utilize the little minerals that are available in the soils.

Crop yields certainly are dependent on management factors, but low yields are widespread on highly weathered and nutrient depleted soils, mainly the acrisols (ultisols), ferralsols (oxisols), nitisols and luvisols (alfisols) (Woomer and Muchena, 1996). Generally, reduction in the productive capacity of the soil may be attributed to conditions when one or more of these soil factors are suboptimal and cause plant growth stress. Soil properties, such as soil texture, thickness of the A- horizon, organic matter content, soil pH, cation exchange capacity, bulk density, and soil profile wetness vary with landscape position (Mulla *et al.,* 1992; Brubaker *et al.,* 1994) and as such can cause spatial variation in crop yield.

Crop production variation is a function not only of spatially-variable landscape/soil factors, but also of temporally-variable climate factors. Climate interacts with soil and landscape resulting in a dynamic environment for plant growth. Improving our understanding of the interactive effects of management practices and soil and weather conditions, can enhance yield, improve the use efficiency of natural resources, and reduce the potential for environmental pollution. Other management factors that are important to soybean production include planting date (Cartter and Hartwig, 1963; Egli and Bruening, 1992), and irrigation (Dogan *et al.,* 2007).

Variable-rate application of crop inputs (fertilizer, irrigation, pesticide, and herbicide) is commonly used in some locations. A potential failure of this site specific management is that the decision rules are usually generalized recommendations. However, the improved dual purpose soybean varieties have the capacity to substantially fix nitrogen hence, the need for farmers to control their nitrogen inputs in order not to reduce the efficiency of this fixation. It is, therefore, imperative that knowledge of the relationships between soil properties, weather, and management practices and crop yield be provided in a wide range of situations in order to pretest management options being considered.

4.5.2 Effects of Moisture on Soybean Production

Table 4.14 shows the amount of rainfall received during the growing period of the soybean varieties.

Table 4.14: Amount of rainfall received at Kakamega, Kitale and Msabaha for the soybean growing period compared to the corresponding mean soybean yields

Site	Mean soybean yields (kg/ha)	Amount of Rainfall received (mm) within the growing period (About 120 days)
Kakamega	1081	720
Kitale	1990	700
Msabaha	490	730

The amount of rainfall received in the three sites is not significantly different from each other but, other factors influenced the availability of the moisture to the crops. Factors such as high evaporation rates especially in the high temperature areas may significantly affect this. Other factors that influence moisture availability are related to the soil composition. It is generally assumed (holding other factors constant) that the higher the rainfall amounts received within a certain limit, the higher the yields.

Moisture regimes within a site have impact on the growth of soybean as it is to other crops. However these impacts vary in intensity depending on other factors such as soil type and temperatures experienced at those sites. This is due to the fact that evaporation rates are seriously influenced by the temperature and the soil type. Sometimes year-to-year climate variability may have more impact on yield than spatial variability. This is demonstrated by the differences in yield for Kakamega site for the two years. Spatial variability can have negligible effects on crop yield in some years (Mulla and Schepers, 1997). On the other hand, high-producing areas of a field during ‘‘dry’’ years can be low-producing areas of the same field in ‘‘wet’’ years (Colvin *et al.,* 1997; Sudduth *et al.,* 1997). These complexities, therefore, are a havoc to farmers. The farmers invest a lot in their farms in terms of inputs and they end up not getting the benefits they expected. Variation in moisture regimes has been a problem and still is a problem in most African countries which depend on rain-fed agriculture.

While the moisture stress is crucial for the soybean yield at selected sites, the adverse impacts of likely rainfall decline on soybean crops would be relatively less pronounced under elevated CO_2 levels. Lal *et al.* (1999) found out that the combined effect of doubled CO_2 and anticipated thermal stress on soybean crop is about 36% increase in yield provided the total rainfall amount and its intra-seasonal variability do not change. A decline in daily rainfall amount by 10% should bring down this gain in soybean yield to about 32%.

The acute water stress due to prolonged dry spells could be a critical factor for the soybean productivity even under the positive effects of elevated CO_2 in the future. However, more studies about CO_2 and moisture stress were beyond the scope of this study.

The effect of moisture on soybean production in rain-fed agriculture can best be demonstrated by long term studies but generally it is difficult. This is because of other factors such as soil nutrients, temperature, management and other factors such as disease. These can only be controlled in a greenhouse. Therefore, results from this study may not necessarily reflect the effect of moisture on the yields of soybean because other factors were not kept constant. However, generally, from literature review, moisture is very critical for plant growth and hence, moisture stress has a very negative impact on soybean production.

For modeling purposes, the sites selected did not have and should not have moisture stress hence the effects of it were not captured. However, areas with low rainfall amounts during the growing period had relatively lower yields compared to the well watered areas. On the contrary, some areas recorded quite a substantial amount of rainfall (1506 mm) such as Msabaha during the growing period but that did not translate to high soybean yields. Factors relating to soil were largely responsible for the low yields recorded. The high sand content of the soils meant that despite the high amounts of rainfall received, virtually all of it percolated through and therefore, very little could be held by the soil for use by the plants. However, this was not solely the effects of low moisture (low rainfall) regime, but a combination of factors hence limiting our conclusion.

4.5.3 Effects of Temperature on Soybean Production

Table 4.15 gives the summary of the temperature regime in the study sites within the growing period.

Table 4.15: Mean minimum and maximum temperature range (°C) for Kakamega, Kitale and Msabaha sites within the growing period

Site	Mean yield range (Kg/ha)	Mean Minimum Temperature range (°C)	Mean Maximum Temperature range (°C)
Kakamega	765-1407	14.4	27.6
Kitale	1065-2623	13.7	26.6
Msabaha	224-802	23.6	30.4

Generally, Kitale has the lowest mean maximum temperatures as well as the mean minimum temperatures followed by Kakamega. Msabaha being in the coastal zone of Kenya experiences the highest temperatures. This has many implications on the growth and development of soybean. This ranges from the effect on time to flowering to the effect on time to maturity as well as the quantity and quality of the soybean grain. In general, the lower temperatures are more favourable, however different varieties are able to adapt and may not be seriously affected by fluctuations in temperature across sites.

Temperature plays a very important role in the growth and development of soybean. Time of flowering for soybean is cultivar specific and determined primarily by temperature and photoperiod. Soybean is a quantitative short-day plant that delays its rate of development when exposed to nights shorter than a cultivar-specific optimum night length (Borthwick and Parker, 1938; Piper *et al.,* 1996). Flowering is simulated to occur when the accumulative daily rates reach a threshold number of photothermal units to reach flowering (Grimm *et al*., 1993). The application of thermal or photothermal units in diverse environments with the same cultivar have indicated, however, inaccuracies in the approach (Seddigh *et al*., 1989; Ritchie and NeSmith, 1991; Piper *et al*., 1996). According to Piper *et al*., (1996), when night temperatures differ widely, phenology data sets for the same cultivar give different parameter estimates for the model with large RMSEs. The lack of compatibility between data sets of the same cultivar from different sources is caused by problems of lack of range in photoperiod and temperatures as reported by Grimm *et al*., (1993) and the association of minimum temperatures on development rate. Soybeans require a vernalization/springization period. This is a period of which the low (night) temperatures allow flowering to take place. If the temperatures are not low, the growing of the crop is affected and the plants end up not bearing enough flowers hence leading to very low yields.

The average temperatures of a site, generally has an effect on the growth rate of the plants. The effect of which depends on the type of the plant (C_3 or C_4). C_3 plants, accounting for more than 95% of earth's plant species, use rubisco to make a three-carbon compound as the first stable product of carbon fixation. C_3 plants flourish in cool, wet, and cloudy climates, where light levels may be low, because the metabolic pathway is more energy efficient, and if water is plentiful, the stomata can stay open and let in more carbon dioxide. However, carbon losses through photorespiration are high. C_4 plants on the other hand possess biochemical and anatomical mechanisms to raise the intercellular carbon dioxide concentration at the site of carbon dioxide fixation, and this reduces, and sometimes eliminates, carbon losses by photorespiration. C_4 plants, which inhabit hot, dry environments, have very high water-use efficiency, so that there can be up to twice as much photosynthesis per gram of water as in C_3 plants C_4 metabolism is however, inefficient in shady or cool environments. Less than 1% of earth's plant species can be classified as C_4.

Soybean is a C_3 plant like most legumes and has less tolerance to high temperature stress compared to the C_4 plants. It should be noted that high temperatures generally increase the growth rate of plants due to the effect they have on the enzymes. However, this is not so in areas affected by temperature inversion. Low night temperatures as discussed above allow soybean plants to flower hence increasing reproduction and thus high grain yields. Areas that have high night temperatures such as the coastal region end up having very fast growth with low production of grains due to insufficient flowering. Such regions are not very suitable for soybean growth. This is the reason why the coastal areas (Msabaha and Mtwapa) have low grain yields and recording very short growing period.

4.6 Agro-ecological Potential of the Dual Purpose Soybean Varieties

The sites selected for simulations are presented in Table 4.16. The mean soybean yield ranges for the sites are also given as simulated and as observed from the calibration trials.

Table 4.16: Simulated sites in Kenya, their general characteristics and the simulated mean yields

Sites	Altitude (m)	Longitude (^{0})	Latitude (^{0})	AEZ	Mean yield ranges (Kg/ha)
High Altitude Areas					
Kitale	1890	35.98	1	LH3-LH4, UM4	1065-2623
Njoro	2165	35.95	-0.33	UH1-UH2	1046-2585
Chepkoilel	2084	35.28	0.53	UM4	448-1512
Mid Altitude					
Embu	1508	37.35	-0.05	LM5	530-911
Busia	1500	34	0.5	LM1-LM2	559-1722
Kakamega	1580	34.75	0.28	LM1-LM2	765-1407
Lowland Areas					
Mtwapa	200	39.73	-3.93	CL1	93-1096
Msabaha	91	40.05	-3.27	CL1	224-802

*Classification adapted from Ayanga, (2003) and Jaetzold *et al*. (2006); AEZ- Agro-ecological Zones

The results show that the high altitude area have generally high soybean yields compared to the mid and the low altitude areas. LH3, LH4, UM4, UH1 and UH2 represent the agro-ecological zones that generally recorded the highest soybean yields. Reasons have been discussed in the previous sections of this chapter but generally the low high altitude temperatures favour soybean flowering and an extended flowering period.

This is in contrast to the Coastal Lowlands (CL) which have generally very high temperatures, poor soils with low water-holding capacity and which also have high pH due to salt intrusion from the sea. The Lower Midland sites are generally faced with issues of low inherent soil fertility and low soil organic matter content.

The agro-ecological potential of dual purpose soybean and indeed those of the local varieties is not known in Kenya. Sites representing various agro-ecozones were selected based on the past history of soybean growth. Soybean production has a lot of potential in Kenya according to initial trials conducted in the past. However, knowledge of where or which varieties to grow and how to grow them remains a big challenge to farmers. In a diagnostic survey conducted in 1993, (Wasike and Karanja, 1993), covering 7 agro-ecozones in main soybean producing districts (Meru, Embu, Nakuru, Busia, Kisii and Kakamega), considerably low (452 kg/ha) soybean yields were reported. There was limited information available to farmers on utilization and limited marketability of soybean also affected the farmers' decision to grow the crop.

4.6.1 Simulation Results

The agro-ecological zones of the sites simulated are shown in Table 4.16. Some sites had overlapping agro-ecological zonation and therefore, no particular zone was assigned to them. The yield results of the simulations representing various agro-ecological zones in Kenya are presented in Table

4.17. The varieties gave different yields in different sites due to the different environmental conditions at the sites.

Table 4.17: Variety yields across the selected simulated sites in Kenya

Site	**SB 15**	**SB 17**	**SB 19**	**SB 20**	**SB 23**	**SB 3**	**SB 8**	**SB 9**
Busia	1299^{a}	608^{b}	963^{ab}	840^{ab}	975^{ab}	1722^{c}	1031^{a}	559^{ab}
Chepkoilel	448^{a}	988^{b}	1512^{c}	1327^{bc}	1265^{bc}	994^{bc}	1019^{bc}	802^{abc}
Embu	649^{a}	591^{a}	643^{a}	514^{a}	501^{a}	548^{a}	911^{a}	530^{a}
Kakamega	988^{a}	1111^{a}	1065^{a}	1407^{b}	765^{ac}	1312^{ab}	1123^{ab}	873^{ac}
Kitale	1065^{a}	1914^{b}	2123^{b}	2531^{c}	1667^{d}	2068^{b}	2623^{c}	1929^{b}
Msabaha	552^{ab}	605^{ab}	716^{ab}	802^{ab}	224^{c}	265^{c}	315^{c}	438^{ab}
Mtwapa	602^{a}	340^{a}	340^{a}	1019b	93^{a}	756^{b}	1096^{b}	432^{a}
Njoro	1046^{a}	2401^{b}	2585^{b}	1640^{c}	2039^{d}	2467^{e}	2198^{d}	1998^{cd}
Variety Means	**831^{a}**	**1070^{a}**	**1243^{a}**	**1260^{a}**	**941^{a}**	**1267^{a}**	**1289^{a}**	**945^{a}**
LSD (Site)				(148)				
LSD (Variety)				(148)				
LSD (Interaction: Site*Variety)				(419)				

F test: Site =p<0.001; Variety = p<0.001; Interaction (Site*Variety) =p<0.001

* Means followed by different lower case superscript within rows are significantly different. Means followed by the same superscript are not significantly different at p<0.05

According to the F-test results, the sites are significantly different (0.001) at 5% level of significance from each other in terms of yields. The varieties were also very significantly different (0.001) from each other. The interactions between the sites and the varieties also showed very significant differences (0.001) at the same significance level.

In Busia, yield for SB 3 was significantly higher than different from the rest of the varieties. SB 9 performed poorest among the varieties recording

559 kg/ha. In Embu there were no significant differences in yields among the cultivars recording a mean yield of 611 kg/ha. These yields were slightly higher than those reported by Wasike and Karanja (1993). In Kitale and Njoro however, the yields were significantly higher than the other sites for almost all the varieties. These are the high altitude areas where the growing season is lengthened by the low temperatures and more commonly the relatively higher rainfall amounts. On the contrary, Chepkoilel had relatively lower yields that could be attributed to the soil chemical status, that is, inherent soil fertility, soil acidity or other factors such as diseases and pests.

4.6.2 Cultivar Ranking and Performance of the Soybean Varieties

Different cultivars performed differently in different agro-ecological zones (sites) (Table 4.17). This means that the ranking of these cultivars would be difficult hence the need to come up with a criteria for ranking them. In this study, cultivars were ranked in relation to their mean yield across sites (Table 4.18).

Table 4.18: Soybean cultivar ranking based on yields across sites studied

Variety	MG	Mean yield across sites (kg/ha)	Average time to maturity (DAS)	Rank
SB 8	IX	1289	104	1
SB 3	V	1267	97	2
SB 20	IV	1260	121	3
SB 19	IX	1243	102	4
SB 17	IV	1070	105	5
SB 9	IV	945	95	6
SB 23 (Nyala)	IV	941	91	7
SB 15	VI	831	115	8

*MG- Maturity Group; DAS- Days after sowing

From Table 4.18, SB 8 was the best yielding variety across the sites presented in Table 4.17. SB 3 was second best and SB 15 was ranked lowest. SB 8 gave the highest yields in 4 out of 8 sites while SB 20 gave the highest yields in 3 sites. SB 3 yielded highest in only 1 site while SB 19 was best in 2 sites. SB 17, SB 9, and SB 23 (Nyala), were ranked 5th, 6th and 7th respectively. Legumes with a lower harvesting index or lower utilization such as SB 15, SB 17 and SB 9 contribute more to the N economy through leaf fall than those with a high harvest index (Thomas, 1992). Therefore, a farmer will choose a variety to plant depending on his/her objective (high yields or soil fertility improvement).

Carter *et al.* (1983), working with soybean concluded that, because of the presence of G x E, one should test in multiple environments for a reliable ranking of treatments and recommended testing in at least two environments to detect 20% of treatment differences and at least seven environments to detect at least 10% of treatment differences. This means that the higher the number of environments tested, the more accurate the results will be. The best varieties will be the ones that have the highest yields across many sites and have a maturity period well within the growing periods of the respective sites or agro-ecological zones. However, the ranking excluded vulnerability to diseases and pests. The DSSAT model is not designed to take care of diseases and pests; it was therefore impossible to simulate those effects. The ranking can only be based on the yields. The assumption is that the cultivar with the highest yield output was more resistant to diseases and pests and was well adapted and suited to the environment so as to give the high yields.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The objectives of this study were to determine the genetic coefficients of the dual purpose soybean varieties and assess their performance in various selected sites in Kenya with varying environmental conditions and recommend areas where these varieties can do best. This required modeling which involved calibration, validation and application. Several sites were simulated and the agro-ecological potential of these varieties determined. It is from this work that the following conclusions were drawn.

- The model successfully predicted growth, phenology and yield. Therefore the model can be reliably used for further simulations to gauge the performance of the soybean varieties under different environments in Kenya. It is also possible to use this model for breeding purposes of new improved varieties of soy beans and other legumes. This is in line with studies by Banterng *et al*. (2004) on peanut lines.
- The genetic coefficients determined and reported in Chapter Four are sufficiently accurate to be used to represent the various varieties for further simulations in future using DSSAT (CROPGRO). The cultivar traits gauged by the differences in genetic coefficients and the performance of the varieties in the field clearly showed that the varieties were significantly different. However, it is necessary to carry out long term trials in varying sites to validate these coefficients.

- Holding other factors constant, the amount of rainfall received by a crop especially during the growing period, had a very significant impact on the performance of the varieties. However, the impact varies from variety to variety depending on their genetic make up and the interactions with the environment.
- The environment also encompasses the soil environment and the biological environment both of which have significant effects on the production of soybean. Generally, fertile soils yielded highly compared to poor soils. The soil fertility factors used for the sites were 0.7 for Kakamega and Kitale sites, and 0.6 for Msabaha site. The CROPGRO model was able to capture these differences as impacted by soil. Soil type therefore played a critical role in the performance of these varieties.
- The performance of these dual purpose varieties under different soil types varied from variety to variety. Among the tested varieties, SB 8 was the best overall followed by SB 3 and SB 20 with SB 23 (Nyala) and SB 15 performing poorest.
- There were potential yield differences among cultivars within a maturity-group class (having the same maturity date) that were attributed to other genetic traits. Such variations in yield potential may have came from higher photosynthesis, better maintenance of photosynthesis during seed fill, and shift of life cycle phases from vegetative towards reproductive. There was a certain amount of overlap in maturity between groups within the country. Varieties within a group mature in a particular range when planted at recommended times. These dual purpose varieties gave

different yields based on their reproductive phase durations, which led to higher seed harvest index (Dunphy *et al.*, 1979; Gay *et al.*, 1980; Nelson, 1986; Smith and Nelson, 1986a, 1986b) for those which had a longer one like SB 20 as compared to SB 23 (Nyala).

5.2 Recommendations

This study sought to determine the genetic coefficients of the dual purpose soybean varieties and also to assess their potential production in various selected agro-ecological zones in Kenya. The following recommendations can be made from the study:

- Among the tested varieties, SB 8 was the best overall followed by SB 3 in terms of yield. They are highly recommended for areas with long growing period with sufficient rainfall. SB 20, SB 19, SB 17 and SB 9 also do perform well in Njoro (UH1-UH2) and Kitale (LH3-LH4, UM4). Soybean varieties from particular maturity groups that consistently outperform other maturity groups in quality and yield per acre should be recommended for those areas in which they are performing well. The early indeterminate varieties have been grown successfully in certain parts for example the Coastal Lowlands (CL1 and CL2) of Kenya. However, poor seed quality and excess shattering can be a problem with them if weather conditions before harvest are warm and wet. This was noted in the coastal areas of Kenya and it is therefore, recommended that the farmers harvest the seeds in time to avoid shattering and loss of grains.

- In situations where large pieces of land are involved, varieties from several maturity groups should be selected to stagger the harvest and avoid loss from shattering just as experienced in the coastal sites of Kenya especially for the early maturing varieties such as SB 3, SB 9, SB 19, and SB 23.
- Poor seed quality is more often found in early maturing varieties. This is especially true for indeterminate varieties which do not mature uniformly. However, in wet harvest seasons when temperatures and humidity remain high, most varieties will have the problem. The early maturing varieties such as SB 23 (Nyala), SB 3 and SB 19 in the hot humid areas of the coast of Kenya (Msabaha) were highly affected. Seed quality deteriorates when fields are not harvested when ready. When poor conditions occur between physiological maturity (maximum dry matter accumulation) and harvest, chances increase for a decline in seed quality. Height is important in rough, poorly drained or new ground, but is important for all varieties to set pods at least 4 to 5 inches above a reasonable distance from the soil surface. Varieties such as SB 23 had very low pod heights and that affected the quality of grains harvested. It is recommended that in regions with the above conditions, only varieties with a high height are planted, and harvesting should be properly timed.
- It is recommended that breeders specify the advantages and disadvantages of the varieties that they produce. This is so when certain soybean varieties are planted on heavy clay soils with poor internal drainage. They are superior to others under the same conditions. Where canopy closure has been a problem, taller varieties (such as SB 20, SB 19 and SB 17) should

be selected or closer row spacing adopted. On highly fertile soil, too much growth is sometimes a problem, and a shorter variety (SB 23) is the better choice. The dual purpose varieties are generally taller and have higher biomass and therefore, better suited for fodder or green manure compared to the local varieties such as Nyala.

5.3 Suggestions for Further Research

The DSSAT crop model has proven to be so useful in many fronts in agricultural research. For example in breeding as demonstrated by Banterng *et al*. (2004) for peanuts, soil research, agro-ecological potential and variety testing. However, in Kenya and the East African region as a whole, model use has been very limited. The DSSAT model provides us with an opportunity to do lots of work without necessarily using a lot of human and financial resources. However, more research needs to be done in order to ascertain the performance of the model in the region given the different agro-ecological regions and the variances in soil and climatic variability.

The DSSAT model has several major weaknesses. Firstly, it is not able to simulate the effects of pests and diseases, and it will therefore only be accurate in simulating the healthy crops. Secondly, its inability to simulate mixed cropping or intercropping limits its ability to give the effects of such farming methods. Furthermore, errors could also arise from the fact that the model uses a single soil profile for a particular site hence it is not able to capture the variations in soil within a particular site. There is, therefore, need to improve the model to take care of variations in soils.

There is also need to study in details the performance of these dual purpose varieties to find out which varieties are better suited in certain conditions such as flooding, salinity, pest and disease tolerance and dry conditions. Each variety should also be tested for varying row spacings, planting depths and other management factors such as irrigation, pesticide and herbicide tolerance. Socio-economic studies should also be conducted to gauge the level of use of soybean products and to find out the extent to which the farmers and the target population know about soybean and its uses.

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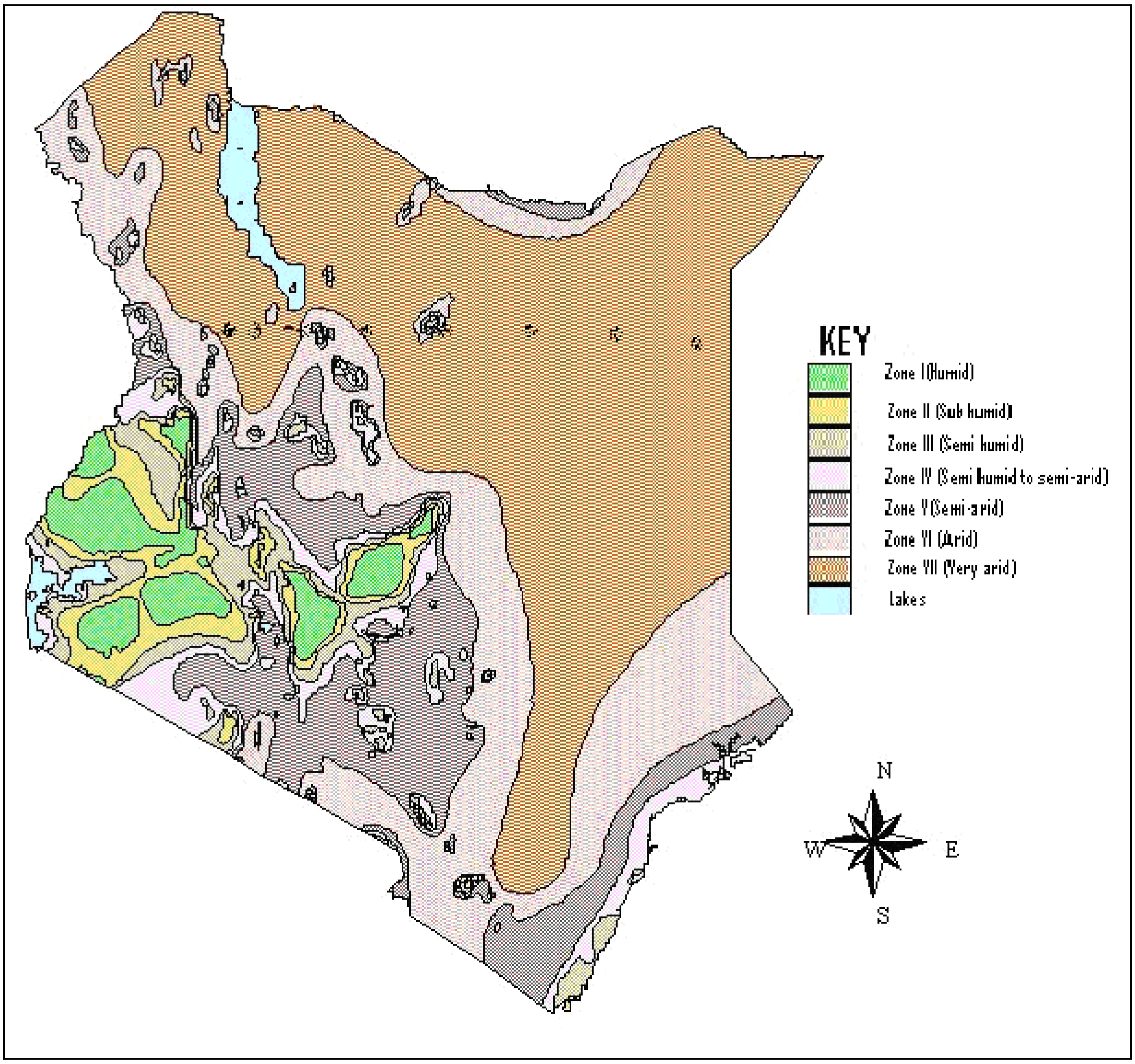
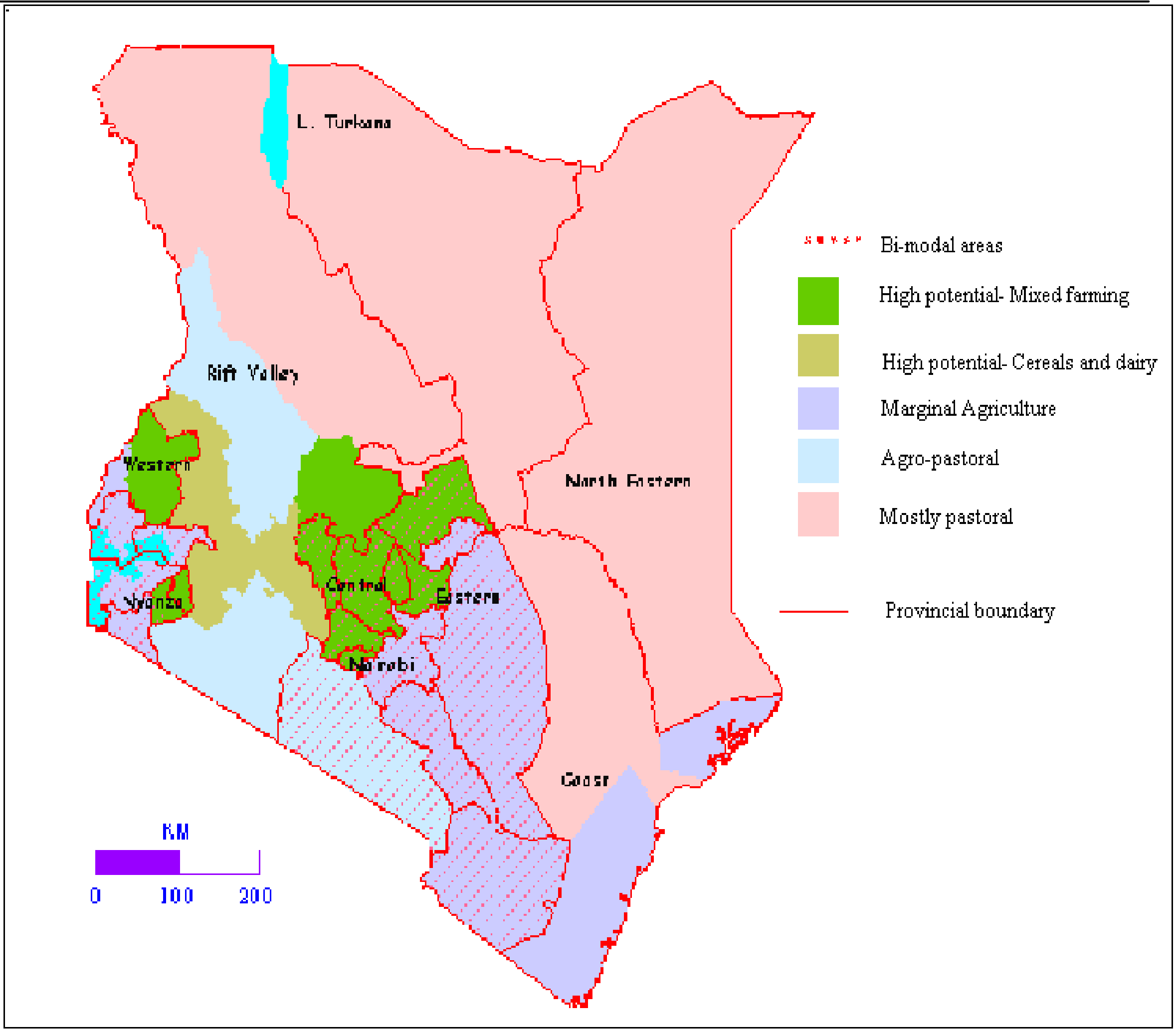
APPENDICES

Appendix 1: Agro-Ecological Zones (AEZ) of Kenya



Appendix 2: Kenya's Production/ Livelihood systems



Appendix 3: Soybean Classification Recommendations

SOYBEAN LR 2007 NPTs

Proposal for different soybean kits, grouped according to altitude and maturity classes
Present: T Riungu, G Rachier, B Vanlauwe
Venue: KEPHIS, 14 March 2007

LOWLAND AREAS

Mtwapa	**Chonyi**	**Msabaha**	**Katumani**
SB3	SB3	SB15	SB15
SB8	SB8	SB17	SB17
SB9	SB9	SB20	SB20
SB19	SB19	931/5/34	931/5/34
915/5/12	915/5/12	917/5/16	917/5/16
EAI3600 (check)	EAI3600 (check)	Nyala (check)	Nyala (check)
[Short duration kit]	[Short duration kit]	Hill (check)	Hill (check)
		[Medium-long duration kit]	[Medium-long duration kit]

MID-ALTITUDE AREAS

Kakamega	**Busia**	**Siaya**	**Lanet**	**Kaguru**
SB3	SB3	SB15	SB15	SB15
SB8	SB8	SB17	SB17	SB17
SB9	SB9	SB20	SB20	SB20
SB19	SB19	931/5/34	931/5/34	931/5/34
915/5/12	915/5/12	917/5/16	917/5/16	917/5/16
EAI3600 (check)	EAI3600 (check)	Nyala (check)	Nyala (check)	Nyala (check)
[Short duration kit]	[Short duration kit]	Hill (check)	Hill (check)	Hill (check)
		[Medium-long duration kit]	[Medium-long duration kit]	[Medium-long duration kit]

HIGH ALTITUDE AREAS

Bahati	**Kitale**	**Njoro**	**Chepkiolel**	**Embu**
SB3	SB3	SB3	SB3	SB3
SB8	SB8	SB8	SB8	SB8
SB9	SB9	SB9	SB9	SB9
SB19	SB19	SB19	SB19	SB19
917/5/16	917/5/16	917/5/16	917/5/16	917/5/16
Gazelle (check)	Gazelle (check)	Gazelle (check)	Gazelle (check)	Gazelle (check)

Appendix 4: ANOVA Table for Cultivar Performance across sites in Kenya

Source of variation	d.f.(m.v.)		s.s.	m.s.	v.r.	F pr.
REP stratum	2	1	4555	7278	0.11	
Site	7	6190	7657.8	843951	131.41	<.001
Variety	7	556	7970	795424	11.82	<.001
Site*Variety	49	1499	2162	305962	4.55	<.001

Table of means

Site	**Busia**	**Chepkoilel**	**Embu**	**Kakamega**	**Kitale**	**Msabaha**	**Mtwapa**	**Njoro**
	1000	1044	611	1081	1990	490	584	2047

Variety	**SB15**	**SB17**	**SB19**	**SB20**	**SB23**	**SB3**	**SB8**	**SB9**
	831	1070	1243	1260	941	1267	1289	945

	Variety							
Site	**SB15**	**SB17**	**SB19**	**SB20**	**SB23**	**SB3**	**SB8**	**SB9**
Busia	1299	608	963	840	975	1722	1031	559
Chepkoilel	448	988	1512	1327	1265	994	1019	802
Embu	649	591	643	514	501	548	911	530
Kakamega	988	1111	1065	1407	765	1312	1123	873
Kitale	1065	1914	2123	2531	1667	2068	2623	1929
Msabaha	552	605	716	802	224	265	315	438
Mtwapa	602	340	340	1019	93	756	1096	432
Njoro	1046	2401	2585	1640	2039	2467	2198	1998

***** Standard errors of means *****

Table	**SITE**	**VARIETY**	**SITE*VARIETY**
rep.	24	24	3
d.f.	124	124	124
e.s.e.	53	53	149.8

***** Standard errors of differences of means *****

Table	**SITE**	**VARIETY**	**SITE*VARIETY**
rep.	24	24	3
d.f.	124	124	124
s.e.d.	74.9	74.9	211.8

***** Least significant differences of means (5% level)**

Table	**SITE**	**VARIETY**	**SITE*VARIETY**
rep.	24	24	3
d.f.	124	124	124
l.s.d.	148.2	148.2	419.2

******* Analysis of variance ***** 2006 various sites**

Variate: No_DTF

```
Source of variation     d.f.       s.s.       m.s.    v.r.  F pr.

REP stratum               2     8.6944     4.3472    4.35

REP.*Units* stratum
SITE                      2      15029.5278  7514.7639   7519.30      <.001
VARIETY                   7    1055.6528         150.8075     150.90      <.001
SITE.VARIETY             14     280.4722          20.0337      20.05        <.001
Residual                 46    45.9722             0.9994

Total                  71 16420.3194


* MESSAGE: the following units have large residuals.

REP 1     *units* 14          2.51   s.e. 0.80
REP 2     *units* 1          -2.03   s.e. 0.80
REP 3     *units* 14         -2.15   s.e. 0.80
```

```
***** Tables of means *****

Variate: No_DTF

Grand mean  55.10

   SITE KAKAMEGA   KITALE  MSABAHA
               54.50       73.08       37.71

VARIETY NYALA SB15  SB17  SB19     SB20      SB3      SB8
           47.22    58.11    56.67    51.00    59.56    57.44    54.56

 VARIETY      SB9
        56.22

   SITE  VARIETY    NYALA     SB15     SB17     SB19     SB20      SB3
 KAKAMEGA              46.33      61.33       54.33    48.33    60.33    54.67
   KITALE              64.00      75.00       76.67    67.00    78.33    78.67
  MSABAHA              31.33     38.00       39.00    37.67    40.00    39.00

  SB8      SB9
 55.00    55.67
 70.00    75.00
 38.67    38.00


*** Standard errors of means ***

Table              SITE     VARIETY        SITE
                             VARIETY
rep.                 24          9           3
d.f.                46          46          46
e.s.e.           0.204       0.333       0.577

*** Least significant differences of means (5% level) ***

Table              SITE           VARIETY       SITE*VARIETY
rep.                 24                     9                 3
d.f.                46                     46                46
l.s.d.           0.581                     0.949             1.643
```

```
****Stratum standard errors and coefficients of variation

Variate: No_DTF

Stratum              d.f.        s.e.        cv%

REP                    2        0.426        0.8
REP.*Units*           46        1.000        1.8


***** Analysis of variance *****

Variate: No_DTM

Source of variation     d.f.       s.s.       m.s.    v.r.  F pr.

REP stratum              2      20.33      10.17    0.73

REP.*Units* stratum
SITE             2   21811.75   10905.88  780.20  <.001
VARIETY          7    5491.72     784.53   56.13  <.001
SITE.VARIETY     14    2864.69     204.62   14.64  <.001
Residual           46    643.00      13.98

Total              71   30831.50


* MESSAGE: the following units have large residuals.

REP 1     *units* 11          9.67   s.e. 2.99
REP 2     *units* 11          9.58   s.e. 2.99
REP 3     *units* 11        -19.25   s.e. 2.99

 ***** Tables of means *****

Variate: No_DTM

Grand mean  140.08

    SITE KAKAMEGA   KITALE  MSABAHA
          117.12          159.25          143.88

  VARIETY       NYALA    SB15     SB17     SB19     SB20      SB3      SB8
                        127.44   150.33   144.56   128.67   152.22   135.67   137.22
   VARIETY      SB9
                     144.56
     SITE  VARIETY    NYALA     SB15     SB17     SB19     SB20      SB3
```

```
  KAKAMEGA         109.33   127.00   119.67   110.33   132.67   112.00
  KITALE           140.00   177.00   167.00   140.00   177.00   148.00
  MSABAHA           133.00   147.00   147.00   135.67   147.00   147.00

    SITE  VARIETY     SB8      SB9
  KAKAMEGA         116.67   109.33
  KITALE          148.00   177.00
   MSABAHA         147.00   147.33


*** Standard errors of means ***

Table             SITE    VARIETY       SITE
                            VARIETY
rep.               24          9          3
d.f.              46         46         46
e.s.e.          0.763      1.246      2.159

*** Least significant differences of means (5% level) ***

Table             SITE    VARIETY       SITE*VARIETY
rep.               24              9                    3
d.f.              46             46                   46
l.s.d.          2.172           3.548                6.145


***** Stratum standard errors and coefficients of variation *****

Variate: No_DTM

Stratum                d.f.        s.e.        cv%

REP                      2       0.651        0.5
REP.*Units*             46        3.739        2.7
```

```
***** Analysis of variance *****

Variate: No_DTP

Source of variation     d.f.       s.s.       m.s.    v.r.  F pr.

REP stratum              2      21.53      10.76    0.77

REP.*Units* stratum
SITE                   2   20027.11   10013.56   715.47  <.001
VARIETY                7    2365.10     337.87   24.14      <.001
SITE.VARIETY          14    1489.78     106.41    7.60      <.001
Residual          46     643.81      14.00

Total                  71   24547.32


* MESSAGE: the following units have large residuals.

REP 1     *units* 9          -9.51   s.e. 2.99
REP 2     *units* 9          19.24   s.e. 2.99
REP 3     *units* 9          -9.72   s.e. 2.99



***** Tables of means *****

Variate: No_DTP

Grand mean  66.15

    SITE KAKAMEGA   KITALE  MSABAHA
                66.88           86.21              45.37

VARIETY    NYALA     SB15     SB17     SB19     SB20      SB3      SB8
                          56.44    71.67    71.22    57.89    71.56    66.78    64.22

  VARIETY      SB9
                      69.44

SITE  VARIETY    NYALA     SB15     SB17     SB19     SB20      SB3

KAKAMEGA            57.67    74.67        68.00    60.00    68.33    65.00
KITALE             77.00    95.00        96.67    69.33    96.33    87.67
MSABAHA             34.67    45.33        49.00    44.33    50.00    47.67
```

```
 SITE  VARIETY       SB8     SB9
KAKAMEGA            72.33   69.00
KITALE              73.33   94.33
MSABAHA             47.00   45.00


*** Standard errors of means ***

Table            SITE    VARIETY       SITE*VARIETY
rep.              24        9                3
d.f.             46            46                   46
e.s.e.          0.764     1.247              2.160

*** Least significant differences of means (5% level) ***

Table            SITE    VARIETY       SITE*VARIETY
rep.              24          9                     3
d.f.             46          46                    46
l.s.d.          2.174        3.550                 6.149


**Stratum standard errors and coefficients of variation

Variate: No_DTP

Stratum              d.f.        s.e.       cv%

REP                    2       0.670       1.0
REP.*Units*          46       3.741       5.7


***** Analysis of variance *****

Variate: YIELD

Source of variation    d.f.      s.s.       m.s.    v.r.  F pr.

REP stratum              2    128520.     64260.    0.59

REP.*Units* stratum

SITE                  2  25866271.  12933135.  119.58    <.001
VARIETY          7    823757.    117680.    1.09  0.386
SITE.VARIETY     14   3995961.    285426.    2.64  0.007
Residual         46   4975050.    108153.

Total                  71  35789558.
```

```
 ***** Tables of means *****

Variate: YIELD

Grand mean  1181.

 SITE   KAKAMEGA   KITALE  MSABAHA
            1101.         1952.          491.

VARIETY    NYALA    SB15    SB17    SB19    SB20     SB3     SB8
                1158.     1223.   1210.     1067.    1292.     1143.    1354.

  VARIETY     SB9
                1003.

SITE  VARIETY    NYALA    SB15    SB17    SB19    SB20     SB3
 KAKAMEGA         929.        988.    1111.     1065.    1407.    1312.
   KITALE             2315.       2130.    1914.     1420.    1667.    1852.
  MSABAHA          230.            552.     605.        716.     802.      265.

    SITE  VARIETY     SB8     SB9
 KAKAMEGA            1123.    873.
   KITALE                2623.   1698.
  MSABAHA              315.    438.


*** Standard errors of means ***

Table              SITE    VARIETY       SITE* VARIETY
rep.                 24            9                     3
d.f.                46            46              46
e.s.e.            67.1              109.6                    189.9

*** Least significant differences of means (5% level) ***

Table              SITE    VARIETY       SITE*VARIETY
rep.                 24                 9                    3
d.f.                46            46              46
l.s.d.           191.1              312.1                    540.5
```

```
***** Stratum standard errors and coefficients of variation *

Variate: YIELD

Stratum                  d.f.      s.e.       cv%
 REP                  2        51.7       4.4
REP.*Units*        46        328.9       27.8
```

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```
***** Analysis of variance *****
```

Variate: No_DTF

```
Source of variation    d.f.      s.s.       m.s.    v.r.  F pr.

REP stratum            2    1.5833     0.7917    3.59

REP.*Units* stratum
VARIETY           7   469.1667    67.0238  304.32  <.001
Residual         14     3.0833     0.2202

Total            23   473.8333


***** Tables of means *****

Variate: No_DTF

Grand mean  57.583

  VARIETY    NYALA     SB15     SB17     SB19     SB20      SB3      SB8
            50.333   63.333   58.000   54.000   63.000   53.000   59.667

  VARIETY      SB9
            59.333


*** Standard errors of means ***

Table              VARIETY
rep.                  3
d.f.                 14
e.s.e.             0.2709
```

```
*** Standard errors of differences of means ***

Table          VARIETY
rep.               3
d.f.              14
s.e.d.        0.3832

*** Least significant differences of means (5% level) ***

Table          VARIETY
rep.               3
d.f.              14
l.s.d.        0.8218


** Stratum standard errors and coefficients of variation

Variate: No_DTF

Stratum              d.f.        s.e.       cv%

REP                     2      0.3146       0.5
REP.*Units*            14      0.4693       0.8



***** Analysis of variance *****
```

Variate: No_DTM

```
Source of variation    d.f.      s.s.      m.s.    v.r.  F pr.

REP stratum              2     1.583     0.792    0.38

REP.*Units* stratum
VARIETY                  7  3493.167   499.024  240.22  <.001
Residual                14    29.083     2.077

Total                   23  3523.833
```

```
***** Tables of means *****

Variate: No_DTM

Grand mean  116.42

 VARIETY     NYALA    SB15    SB17    SB19    SB20     SB3     SB8
             103.33  135.00  120.67  108.67  135.00  106.00  117.00

 VARIETY     SB9
            105.67

 *** Standard errors of means ***

Table            VARIETY
rep.                 3
d.f.                14
e.s.e.           0.832


*** Standard errors of differences of means ***

Table            VARIETY
rep.                 3
d.f.                14
s.e.d.           1.177

*** Least significant differences of means (5% level) ***

Table            VARIETY
rep.                 3
d.f.                14
l.s.d.           2.524


*** Stratum standard errors and coefficients of variation

Variate: No_DTM

Stratum               d.f.        s.e.       cv%

REP                     2       0.315        0.3
REP.*Units*             4       1.441        1.2
```

```
***** Analysis of variance *****

Variate: No_DTP

Source of variation     d.f.       s.s.       m.s.    v.r.  F pr.

REP stratum               2     0.0833     0.0417    0.18

REP.*Units* stratum
VARIETY                   7   487.6250    69.6607  300.08  <.001
Residual                 14     3.2500     0.2321

Total                    23   490.9583


***** Tables of means *****

Variate: No_DTP

Grand mean  69.708

  VARIETY    NYALA    SB15     SB17     SB19     SB20     SB3      SB8
             61.333   74.667   71.667   65.000   73.667   67.000   74.000
  VARIETY     SB9
             70.333
 *** Standard errors of means ***

Table          VARIETY
rep.                3
d.f.               14
e.s.e.         0.2782

*** Standard errors of differences of means ***

Table          VARIETY
rep.                3
d.f.               14
s.e.d.         0.3934

*** Least significant differences of means (5% level) ***

Table          VARIETY
rep.                3
d.f.               14
l.s.d.         0.8438
```

```
***** Stratum standard errors and coefficients of variation *****

Variate: No_DTP

Stratum              d.f.       s.e.       cv%

REP                     2      0.0722       0.1
REP.*Units*            14       0.4818       0.7


***** Analysis of variance *****
```

Variate: YIELD

```
Source of variation     d.f.      s.s.      m.s.    v.r.  F pr.

REP stratum               2     11063.      5531.    1.01

REP.*Units* stratum
VARIETY          7   1961788.    280255.   51.07  <.001
Residual        14     76830.      5488.

Total          23   2049681.


***** Tables of means *****

Variate: YIELD

Grand mean  945.

  VARIETY    NYALA     SB15     SB17     SB19     SB20      SB3      SB8
                811.        461.     757.    1103.       1395.    1189.    1119.

  VARIETY      SB9
          724.

*** Standard errors of means ***

Table            VARIETY
rep.                 3
d.f.                14
e.s.e.             42.8
```

```
*** Standard errors of differences of means ***

Table          VARIETY
rep.              3
d.f.             14
s.e.d.           60.5

*** Least significant differences of means (5% level) ***

Table          VARIETY
rep.              3
d.f.             14
l.s.d.         129.7

***** Stratum standard errors and coefficients of variation **

Variate: YIELD

Stratum             d.f.       s.e.      cv%

REP                   2        26.3      2.8
REP.*Units*          14        74.1      7.8
```