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AGRICULTURAL ADAPTATION TO CLIMATE CHANGE IN THE SAHEL:

A REVIEW OF FIFTEEN CROPS CULTIVATED IN THE SAHEL

AUGUST 2014

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ARCC

African and Latin American
Resilience to Climate Change Project

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AFRICAN AND LATIN AMERICAN RESILIENCE TO CLIMATE CHANGE (ARCC)

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ACRONYMS AND ABBREVIATIONS

APSIM	Agricultural Production Systems Simulator
ARCC	African and Latin American Resilience to Climate Change
CROPSYST	Cropping Systems Simulation Model
CERES	Crop Estimation through Resource and Environment Synthesis
CSM	Cropping System Model
DVS	development stage
EGF	effective grain filling
GPD	growing point differentiation
GS	growth stage
CropSyst	Cropping Systems Simulation Model
FAO	Food and Agriculture Organization of the United Nations (FAO)
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IER	*Institut d'Economie Rurale*
NRC	National Research Council
PI	panicle initiation
RECAP	Resource capture and resource use efficiency
SPOTCOMS	Sweet Potato Computer Simulation
USAID	U.S. Agency for International Development
WOFOST	World Food Studies

ABOUT THIS SERIES

THE STUDIES ON CLIMATE CHANGE VULNERABILITY AND ADAPTATION IN WEST AFRICA

This document is part of a series of studies produced by the African and Latin American Resilience to Climate Change (ARCC) project that address adaptation to climate change in West Africa. Within the ARCC West Africa studies, this document falls in the subseries Agricultural Adaptation to Climate Change in the Sahel. ARCC has also produced subseries on Climate Change and Water Resources in West Africa, Climate Change and Conflict in West Africa, and Climate Change in Mali.

THE SUBSERIES ON AGRICULTURAL ADAPTATION TO CLIMATE CHANGE IN THE SAHEL

Upon the request of the United States Agency for International Development (USAID), ARCC undertook the Sahel series of studies to increase understanding of the potential impacts of climate change on agricultural productivity in the Sahel and identify means to support adaptation to these impacts. Other documents in the Agricultural Adaptation to Climate Change in the Sahel series include An Approach to Conducting Phenological Screening, An Approach to Evaluating the Performance of Agricultural Practices, Profiles of Agricultural Management Practices, Expected Impacts on Pests and Diseases Afflicting Selected Crops, and Expected Impacts on Pests and Diseases Afflicting Livestock.

1.0 INTRODUCTION

The following profiles were produced under the African and Latin American Resilience to Climate Change (ARCC) project at the request of the U.S. Agency for International Development (USAID). This work constitutes one step in an approach to conducting a phenological screening of crops important to the Sahel. In that approach, the growth parameters presented in this document are to be used as a "screen" against trends in observed intra-seasonal climate characteristics to help determine when critical crop tolerance thresholds may be passed. (The complete process and rationale is described in the companion document, "An Approach to Phenological Screening".)

The 15 crops are presented by type: cereals (maize, pearl millet, rice, sorghum); fiber crops (cotton); fruit crops (cashew, mango, shea nut); grasses (bourgou [*Enchinochloa stagnina*]); legumes (néré [*parkia biglobosa*], cowpea, groundnut); oilseed crops (sesame); and root crops (cassava, sweet potato). For each crop, the profiles provide a brief overview and description of its geographic distribution and importance. A presentation of the crop's life cycle follows, and graphics then illustrate known rainfall requirements and temperature requirements at different stages of physiological development. The presentation continues with further details of growth thresholds related to soil conditions, water availability, and temperature. Each crop profile concludes with a discussion of the crop's adaptability to a changing climate, consisting of additional background on the crop's performance under different conditions and variation in these parameters among different varieties. Select citations are provided for each profile.

The profiles below are based on the review of research literature. They focus on crops and conditions found in the Sahel, with emphasis on Niger, Burkina Faso, Mali, and Senegal. Additionally, interviews with researchers who are experts in key food and economic crops were conducted to add to and refine the initial findings of the desktop review. Persons interviewed include staff of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and, in Mali, researchers at the *Institut d'Economie Rurale* (IER). Throughout the document, specific information relevant to Mali is included.

In an accessible and updated format, this document assembles critical information useful in understanding potential climate-related threats to the principal crops important to the food security and economies of countries in the Sahel. Beyond its potential application in a phenological screening, this document provides a useful reference tool in assessing climate-based threats to crops across the Sahel, where specific climate information is available. As such, it makes a contribution to the larger effort to provide decision makers with an evidence-based approach to defining strategies for agricultural adaptation that can be supported or extended by the government, nongovernmental organizations (NGOs), and other implementing partners; thus, it represents one element of the development community's larger effort to contribute to a more complete understanding of the potential impacts of climate change on overall agricultural productivity in the Sahel.

Regarding the temperature requirements presented: The temperature values presented below should be used as broad guidance concerning the upper and lower limits for crop development. Crops do have basic requirements to complete a given phenological stage; crop growth and development, and thus yields, can be seriously affected if the temperature falls outside of these limits. However, in some cases, a crop can still be viable beyond expected limits if other conditions are optimal. For example, high levels of soil moisture can redress excessive heat and enable a plant to counteract high evapotranspiration. The values graphed in this document are based on information collected from a large number of reports on crop performance in diverse situations. In most cases, the values presented

here represent the consensus of several reports, with outliers excluded. They represent the temperatures at which the crop is still viable under normal conditions.

Regarding rainfall requirements presented: The reader must also take caution in interpreting the rainfall limits. Researchers have produced few papers and less data on this, especially regarding agriculture in the Sahel. Outside a controlled context, such as an irrigated field, water requirements at each phase are extremely difficult to correlate with external water inputs because numerous intervening factors affect the moisture available to a plant. For example, plants grown in soils with a lower retention capacity require more rain. Plants grown on steep slopes from which moisture drains quickly also require higher rainfall. After germination, evapotranspiration levels — which are dictated by temperature, solar radiation, and plant architecture — also affect the amount of moisture available to a plant. Even surrounding vegetation may have an impact and limit useable water. Because of the impact of these interactions, and the consequent variability in rainfall limits, the graphics in the main body of the document do not breakdown rainfall by requirements by phenophase.

To provide the reader with an indication of water requirements by phase, graphs in Annex II provide estimates of water (not rainfall) required at each stage of development. These values are drawn from modeling studies and controlled experiments. They are recalculated using coefficients based on Sahelian evapo-transpiration rates; thus, they take into account plant ability to uptake water, levels of transpiration, and the rate of evaporation, but they do not take into account other interactions, such as those with soil, slope, and surrounding vegetation.

To provide the reader with more precise plant rainfall thresholds, graphs in Annex III and IV present optimal and absolute annual rainfall requirements drawn from the Food and Agriculture Organization of the United Nations (FAO) EcoCrop database, based on reports of crop growth across the globe. They cover a broad range of genotypes and are not limited to varieties cultivated in the Sahel.

Regarding soil requirements: Each profile includes a discussion of soils and indicates relationships between the crop, soil types, and other growth parameters, focusing on moisture and temperature. The interactions among these various factors differ in different soils. In general, clay soils and soils with greater organic matter have more water-holding potential than sandy soils. Such water retention characteristics mitigate the impacts of decreased rainfall, dry spells, and high temperatures. Conversely, soils with limited retention protect less well against conditions that are expected as the Sahel's climate changes. As a result, the moisture and temperature requirements for a crop differ in each of the complex and diverse soils across the Sahel.

Researchers continue to explore the complexity of the feedbacks in soil moisture–climate interactions, yet they possess a scarcity of observations for characterizing the relevant processes. More accurate information regarding factors that influence plant water availability — soil drainage capacity, water retention ability, aeration levels, levels of erosion, buffering capacity, and ion exchange capacity — is necessary to improve understanding of these interactions.

To provide the reader with an overview of soil requirements, Annex V presents the following selected parameters for the profiled crops: soil pH, depth, preferred types and textures, fertility, salinity, and drainage.

Regarding requirements by crop variety: In all cases, the profiles present information on general crop types and the range of varieties cultivated in the Sahel, but not specific varieties. A phenological profile by variety would require extensive specific data on varietal performances, genetic background, breeding pedigrees, and agronomic features. Research literature does not currently contain these specifics for varieties cultivated in the Sahel.

Regarding crop modeling: This study provides an overview of characteristics of crops grown across a large and varied geographic area to serve as a basic reference document and as a tool for Sahel-wide screening. Various approaches have been developed to calculate the complex interactions among crops, soil, temperature, and rainfall, which result in much of the imprecision in the requirements presented here. Annex VI provides an overview of 21 strategies to model crop growth. It includes a general description of each model, with an emphasis on the treatment given to phenological parameters. To accurately estimate growth, this software requires the characteristics of the variety under consideration as well as site-specific parameters for soil, weather, and other factors. This approach produces results at the plot level. Modeling climate change impact on crops across the Sahel is currently constrained by a lack of necessary data. The ARCC document, An Approach to Phenological Screening, discusses in greater detail the differences between phenological screening and crop modeling, and how they might be used.

2.0 MAIZE

2.1 BRIEF OVERVIEW OF THE CROP

Maize is an annual grass that can grow up to 4 m tall. It is a warm-weather annual crop with a deep root system that requires abundant moisture for best development. It is grown widely throughout the world in a range of agro-ecological environments. Globally, more maize is produced annually than any other grain. Maize was introduced into Africa in the 1500s and now represents one of the continent's most crucial cereal crops (Bonavia, 2013). Maize is consumed fresh as a vegetable, although the vast majority is conserved as dry grain. Stored grain is susceptible to aflatoxin contamination, and dried grain should be stored with less than 16 percent moisture content. The grains are rich in vitamins A, C, and E; carbohydrates; and essential minerals. They contain 9 percent protein. Most maize production in Africa is rain-fed. The limited use of nitrogenous fertilizers and the declining natural soil fertility are problems for maize production in Sub-Saharan Africa. Maize is susceptible to drought, waterlogging, and extreme temperature stresses.

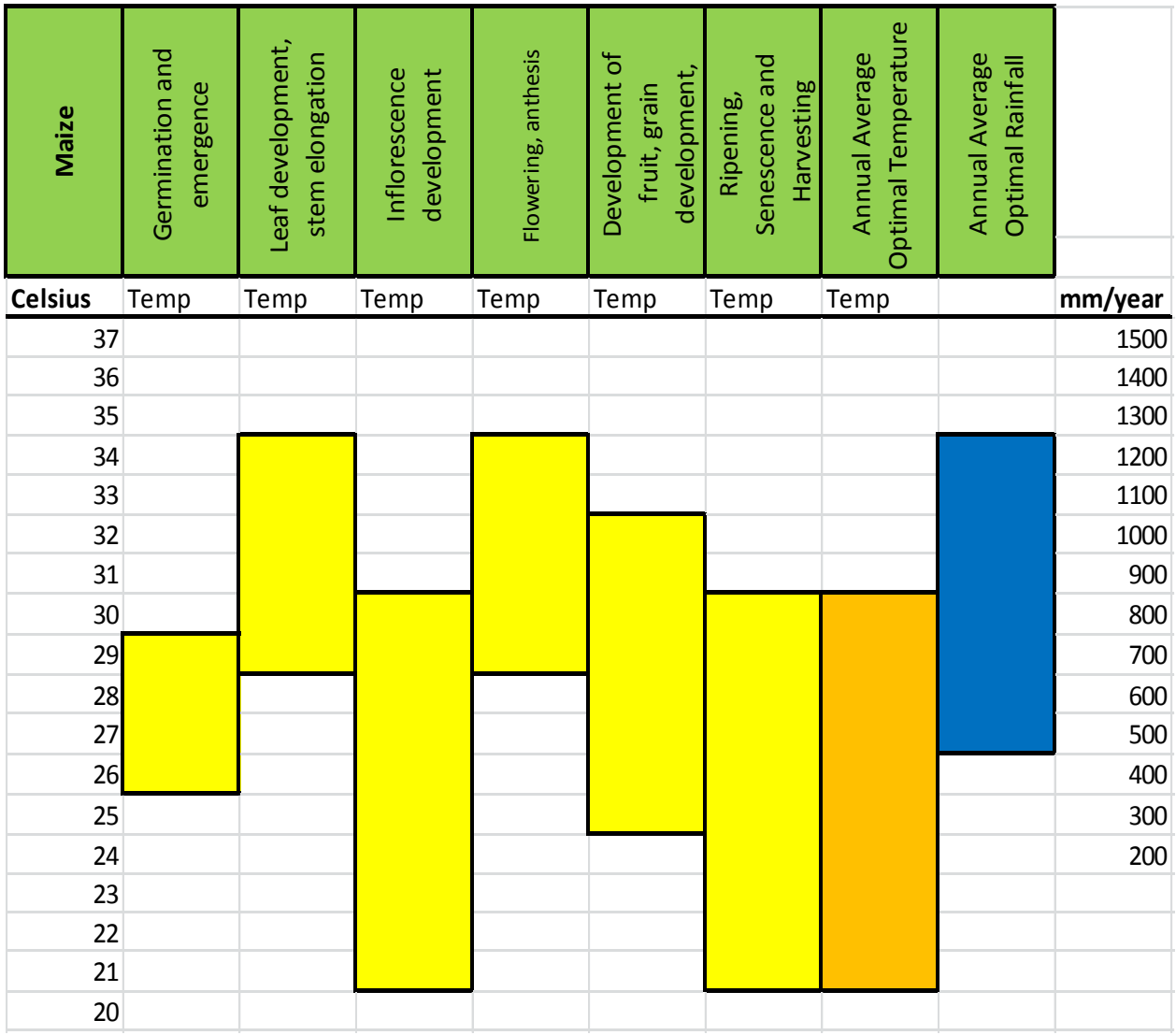
2.2 GEOGRAPHIC DISTRIBUTION AND GENERAL LEVEL OF IMPORTANCE

Maize is a versatile crop grown in a range of agro-climatic zones. In fact, the suitability of maize to diverse environments is unmatched by any other crop. It is grown from 58 °N to 40 °S, from below sea level to altitudes higher than 3,000 m, and in areas with 250 mm to more than 5,000 mm of rainfall per year (Shaw, 1988; Dowswell et. al., 1996), as well as with a growing cycle ranging from three to 13 months (Shaw, 1988). However the major maize production areas are located in temperate regions of the globe. The United States, China, Brazil, and Mexico account for 70 percent of global production. Maize is a major cereal crop in West and Central Africa, currently accounting for a little more than 20 percent of domestic food production in Africa. Its importance has increased as it has replaced other food staples, particularly sorghum and millet (Smith et al., 1994). In sub-Saharan Africa, maize is mostly grown by small-scale farmers, generally for subsistence as part of mixed agricultural systems (Smale et al., 2011).

2.3 LIFE CYCLE

The staging system divides maize development into vegetative and reproductive stages. The vegetative phases include seedling emergence, internode elongations, ear and tassel initiation, stem elongation, and tassel emergence. The reproductive stage includes silking, ripening, and maturity. Silking (pistillate flower maturity) is considered by many as the most critical developmental stage since it strongly influences kernel quality and yield (Bennetzen and Hake, 2009). Depending on the genetic background, corn plants can develop either 20 or 21 total leaves. The plant silks about 65 days after emergence. Most varieties require 100 to 140 days from seeding to full ripeness of the kernels, though some kinds will ripen in 80 days or less (Bennetzen and Hake, 2009). The crop is very sensitive to frost, particularly in the seedling stage, but it tolerates hot and dry atmospheric conditions so long as sufficient water is available to the plant and temperatures for the non-flowering stages are below 45 °C.

FIGURE 1. TEMPERATURE AND RAINFALL REQUIREMENTS OF MAIZE AT DIFFERENT STAGES OF DEVELOPMENT



2.4 PRODUCTION PARAMETERS

Soil type

Maize plants perform well in most soils but are negatively affected when they grow in very heavy, dense clay and infertile sandy soils. In general, the soil preferably should be well-aerated and well-drained, as the crop is susceptible to waterlogging. Soil fertility requirements for grain production are relatively high, and for high-producing varieties up to about 200 kg/ha Nitrogen, 50 to 80 kg/ha Phosphorus, and 60 to 100 kg/ha of available Potassium are required. In general, the crop can be grown continuously in one location as long as soil fertility is maintained. Maize is moderately sensitive to salinity, and yields decrease under increasing soil salinity. Maize also does not tolerate acidic soils well, growing best in soils with a pH of 6 or 7 and above.

Water

The crop requires a considerable amount of moisture to develop. Between 500 and 700 mm of well-distributed rainfall is favorable for proper growth. In the case of Mali, these conditions correspond to the 800-1,000 mm isohyet zone, which constitutes the major production area in that country. Maize plants use water efficiently and thus can be considered a relatively drought tolerant crop, although plants are negatively affected with dry periods of 10 days or more, and with dry periods of seven days if soil moisture reserves are low. The plants are particularly sensitive to drought damage in the germination and seedling stages. After germination and up to tasseling stage, the crop can stand less moisture. In general, the plant requires more water during the reproductive period and eventually will require less moisture as the crop matures. Maize is sensitive to waterlogging throughout its development, more so than drought, particularly up through the grain-filling stage. Overall, flowering is the crop's most critical stage in terms of abiotic stresses.

Temperature

Maize is a hot-season crop and is grown principally in areas where the average temperatures range between 21 and 30 °C, with 25-30 °C considered optimal. The plant requires an average temperature of around 22 °C and night temperatures above 15 °C, and in particular requires considerable warm temperatures from germination to flowering. Cultivation is not viable when day temperatures are less than 19 °C, with growth stopping at temperatures below 10 °C. During flowering, temperatures at midday that reach 35 °C or above for several days can destroy pollen, and yields are drastically compromised and reduced. Temperature effects are magnified with conditions of low soil moisture and by wind.

Adaptability

Adaptability of maize varieties to different climate conditions varies broadly (Fischer et al., 1983); however, it is very important to select those varieties with a growing period that matches the length of the growing season, with early maturation serving as an important characteristic for drought avoidance. Breeding and extension efforts in Mali characterize varieties maturing in less than 82 days (from planting to harvest) as extra-early, and these are targeted for planting in the 200-500 mm rainfall zone. Varieties maturing in 83 to 95 days are characterized as early and are recommended in the 500-700 mm rainfall zone. Varieties maturing in 96 to 120 days are characterized as medium, and over 120 days as traditional long-duration varieties; both are planted in the areas receiving 800-1000 mm of rainfall and above. Farmer recommendations for planting are to plant after an accumulated 20 mm of rainfall during the planting period. The country is divided into three successively drier zones, with planting generally occurring in May in the Southern zone (Sikasso, Bougouni); June in the Central zone (Bamako, Kita, Kéniéba, Ségou and Kolokani); and July (Mopti and Nara) in the northern maize zone. Faster maturing varieties are recommended in northern zones with shorter growing seasons and less annual rainfall.

Crop maturation is sensitive to temperature, with cooler temperatures prolonging maturation. For example, early grain varieties normally require 80-100 days to mature; however, when the average daily temperatures during the growing season are less than 20 °C, maturation increases by 10 to 20 days for each 0.5 °C decrease, depending on variety; at 15 °C, the maize grain crop can take from 200 to 300 days to mature. With a mean daily temperature of 10 to 15 °C, maize is mostly grown to be used as a forage crop because of the problem of seed set and grain maturity under cool conditions. In this case, for germination the lowest average daily temperature has to be about 10 °C, with 18 to 20 °C being optimum.

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3.0 PEARL MILLET

3.1 BRIEF OVERVIEW OF THE CROP

Pearl millet (*Pennisetum glaucum* L..) is a high nutritive value annual grain crop, popular among livestock producers for grazing, silage, hay, and green crop. Pearl millet is an open-pollinated (more than 85 percent outcrossing) diploid annual crop grown on about 26 million hectares in the warm tropics divided equally between Africa, particularly in the West African Sahel region, and the Indian subcontinent. In these areas, pearl millet is grown almost exclusively as human food; in fact, pearl millet is the staple cereal of 90 million people who live in climate zones where severe abiotic stresses limit crop production due to heat, low and erratic rainfall, and poor soils. Fertilizers typically are not used, and cultivation is carried out by hand or animals. Actual grain yields are low under such conditions (~500 to 600 kg/ha), yet higher and more reliable than those obtained from other dryland cereal crops such as sorghum or maize. Without irrigation, pearl millet is the only cereal planted in areas receiving less than 400 mm of rainfall. Grain is always the principal object of cultivation, but the stover is secondarily important as animal fodder. Stems can be used as fuel, fencing, and roofing.

3.2 GEOGRAPHIC DISTRIBUTION AND GENERAL LEVEL OF IMPORTANCE

Pearl millet is a widely grown Old World tropical cereal crop well adapted to the hot drought prone areas of Africa and the Indian subcontinent, where about 26 million ha are under production. Archaeological evidence suggests that pearl millet was first domesticated in the grasslands and park lands at the edge of the Savanna-Sahel desert of West Africa ca 2,500 BC, and spread rapidly out from there. Presently, it is an important, highly nutritional forage crop of Africa, India, and, on limited scale, in Oceania and North and South America (Dakheel et al., 2009; Maiti and Rodriguez, 2010). In Africa, the majority of pearl millet is produced in semi-arid extensive cultivation systems stretching more than 7,000 km from Senegal to Somalia.

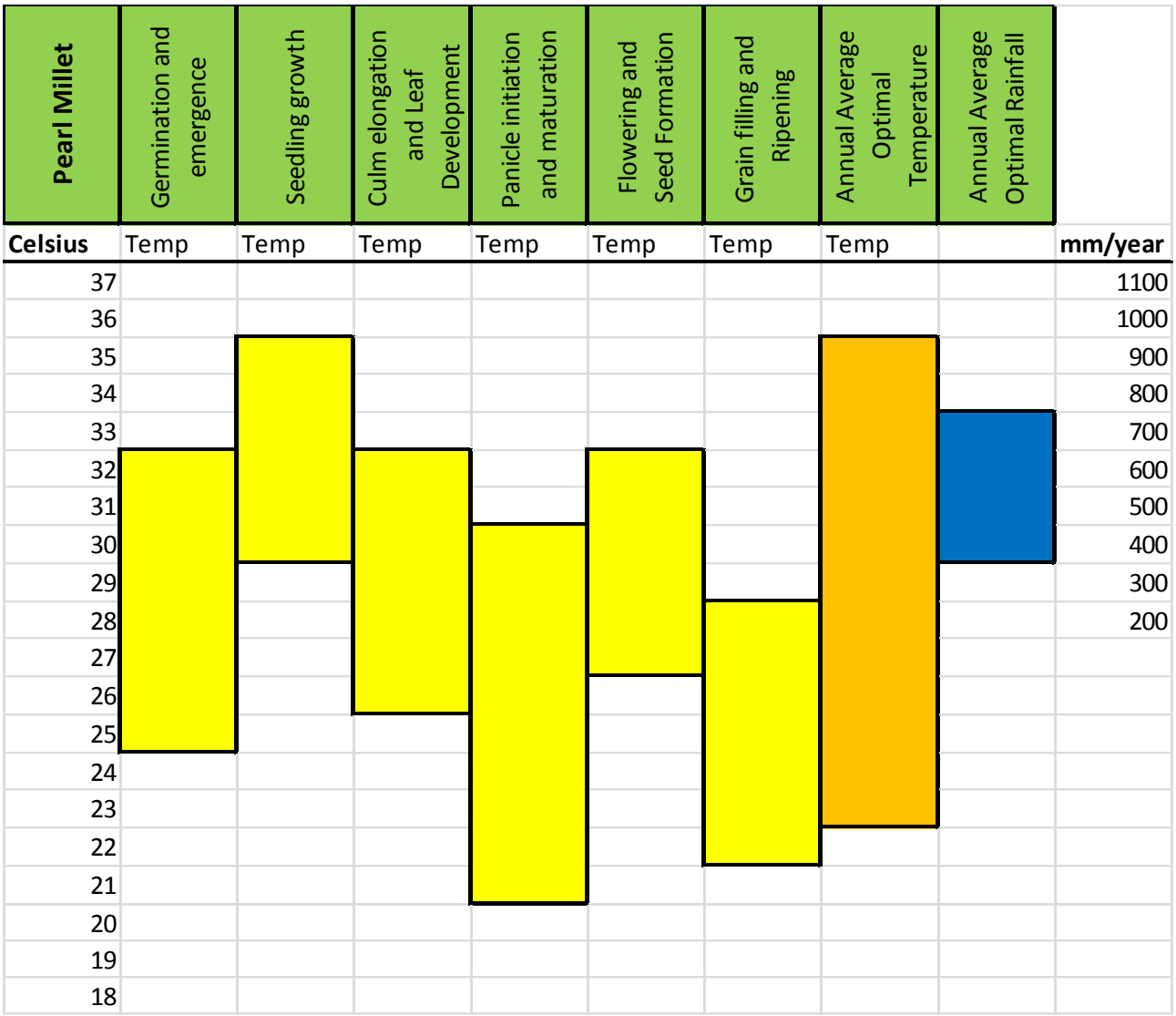
3.3 LIFE CYCLE

Pearl millet is an erect annual that grows between 50 cm and 4 m tall. It produces several flowers, tucked tightly around a cylindrical spike (called a rachis). The inflorescence is typically of greenish yellow color. Flowers can be either cross-pollinated or self-pollinated. The female part (stigma) emerges before the male part is ready to shed its pollen, thus promoting cross-pollination; however, where the timing overlaps, some levels of self-pollination are possible. Grain develops as soon as fertilization takes place and becomes fully developed after 20 to 30 days. The whole process, from flowering to grain ripening, takes 30 to 50 days. The seeds vary in color (from white to brown, blue, or almost purple). Average seed weight is about 8 mg. Some thresh free from glumes, while others require husking. The seeds germinate rapidly if conditions are favorable; they can sprout in about five days. Freshly harvested seed may not germinate immediately, however, as a dormancy of several weeks after harvesting has been reported

Even more so than sorghum, the vast majority of millet varieties grown in West Africa are traditional varieties. Nearly all are photoperiod-sensitive, meaning that decreasing day-length triggers the physiological shift in plant development from vegetative growth to flowering. Irrespective of planting date and seasonal conditions (rainfall or temperature), different varieties initiate flowering when day-length passes a specific threshold. Seasonal day-length is determined by latitude, so the same variety,

planted on the same date, will begin flowering at different calendar dates depending on the latitude where it is planted. This feature of pearl millet physiology holds tremendous potential for climate change adaptation. It also makes traditional classification of varieties as early-, medium-, and late-maturing difficult, if not irrelevant under farmers' conditions. Different pearl millet varieties mature 60-180 days after seeding. In the Mali pearl millet breeding program, researchers generally classify varieties maturing from 90-100 days as early, 110-120 days as intermediate, and more than 120 days as late.

FIGURE 2. TEMPERATURE AND RAINFALL REQUIREMENTS OF PEARL MILLET AT DIFFERENT STAGES OF DEVELOPMENT



3.4 PRODUCTION PARAMETERS

Soil

Pearl millet does best in light and well-drained soils, whereas sorghum prefers somewhat heavier soils. Millet responds well to soil fertility, though it performs poorly in clay soils due to the potential for

excessive moisture retention. It tolerates subsoils that are acidic (as low as pH 4-5) and high in aluminum content.

Water

The optimum rainfall requirement of pearl millet ranges between 400 and 700 mm, but it can be grown in areas with far less than 300 mm of annual rainfall (e.g., 1.5 MT/ha yield with 150 mm of rainfall) if the rainfall is evenly distributed. With adequate soil fertility and rainfall, pearl millet can yield up to 6 MT/ha. Very young plants are susceptible to prolonged dry spells, and drought periods during grain filling stage can lead to yield decreases. Outside of these periods, pearl millet can withstand dry periods of up to one month without dying. Plants have the ability to remobilize nutrients from old tillers to support younger ones when rainfall returns. In Mali, as with other cereal crops, different maturation classes are targeted to different rainfall zones – early varieties in areas receiving 400-600 mm, intermediate varieties in areas with 600-800 mm of rainfall, and late varieties in areas receiving more than 800 mm of rainfall. The main pearl millet zone is the 400-600 mm rainfall isohyet band. As with sorghum, farmers are advised to plant after 20 mm of accumulative rainfall in their respective areas. Although somewhat more tolerant than maize, pearl millet cannot tolerate waterlogging or immersion.

Temperature

Pearl millet is a warm-weather crop and grows best at temperatures higher than 20 °C. For seed germination, temperatures of 23 to 32 °C are required. Pearl millet seed does not germinate and grow well under cool soil conditions. Poor emergence and seedling growth may result if planted before soil temperatures can reach 23 °C. In West Africa, pearl millet is typically grown in areas with temperatures ranging from 30-45 °C, with 30-35 °C considered optimal. Singh et al. (1998) indicated that temperatures of 10 °C or below stop pearl millet development; similarly, at temperatures higher than 46 °C (42 °C at flowering), no development takes place.

Adaptability

Pearl millet is more tolerant to higher temperatures than probably any other cultivated cereal. Although the crop can grow where rainfall ranges from 200 to 1,500 mm, most cultivated areas receive 250-700 mm. Early maturing varieties are planted in the lowest rainfall areas. However, pearl millet requires rainfall to be evenly distributed along the growing season (unlike sorghum, pearl millet cannot go into dormancy during droughts). Conversely, the excess of rain at the flowering stage can cause crop failure. The plant is generally sensitive to low temperatures at the seedling stage and at flowering. Winkel et al. (1997) reported that water deficits prior to flowering and at the beginning of flowering cause the flowering of tillers to be delayed or totally inhibited. High daytime temperatures are required for grain development.

The ability of pearl millet to develop under dry environmental conditions is due to a number of physiological and morphological characteristics. For example, root penetration is fast and deep (root depths of 3.6 m have been recorded). The root system has specialized cell walls that prevent desiccation (Payne et al., 1990). The tillering capacity of pearl millet compensates for any reduction in yield-contributing components such as number of heads, length of head, grain weight, etc.

Pearl millet is a potentially productive, high-quality grain or silage crop that appears superior to sorghum concerning establishment and production under limited soil moisture (Serraj and Sinclair, 2002; Purcell et al., 2002; Dakheel et al., 2009). This is why researchers world-wide are motivated to introduce this crop in arid and semiarid regions of their countries. Under favorable climatic conditions, pearl millet

plants can produce robust and extensive rooting, which can help farmers to harvest up to two or three cuts of green forage (Maiti and Rodriguez, 2010).

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4.0 RICE

4.1 BRIEF OVERVIEW OF THE CROP

Rice (*Oryza sativa*) is one of the oldest cultivated crops, as ancient records and archeological excavations show that it has been cultivated in India and China for thousands of years. Close to 90 percent of the world's area under rice cultivation is in Asia, and about 90 percent of the world's rice is produced and consumed in Asia. However, rice is also grown in more than 100 countries. Sub-Saharan Africa produces about 19 million tons, and Latin America some 25 million tons. In Asia and sub-Saharan Africa, almost all rice is grown on small farms of 0.5−3 hectares. Rice yields range from less than 1 ton per hectare under very poor rain-fed conditions to more than 10 t/ha in intensive temperate irrigated systems. Small, and in many areas shrinking, farm sizes account for the low incomes of rice farming families. Rice grows in a wide range of environments and is productive in many situations where other crops would fail. Rice-growing environments are based on their hydrological characteristics and include irrigated, rain-fed lowland, and rain-fed upland.

4.2 GEOGRAPHIC DISTRIBUTION AND GENERAL LEVEL OF IMPORTANCE

Oryza sativa was first cultivated in south-east Asia, India, and China between 8,000 and 15,000 years ago (Normile, 2004). Current cultivation for *O. sativa* is worldwide, extending from latitude 35°S (New South Wales and Argentina) to 50°N (Northern China), over 110 countries. Ninety percent of all rice is grown and consumed in Asia. Cultivation areas utilize approximately 10 percent of all available crop land worldwide (144 million ha), with only wheat covering more surface area. Rice is grown from sea level to 3,000 m and in both temperate and tropical climates. It is cultivated in most countries of West and North Africa (Egypt), as well as East and Central Africa. Its cultivation further extends to South and Central American countries (Latin America); Australia; the United States; and Southern European countries such as Spain, Italy, and France. Rice is quite adaptable and can grow in places having warm and humid climate with shallow water. Rice cultivation is now playing an increasingly important role in Africa. In West and Central Africa, rice is grown under subsistence conditions by about 20 million smallholder farmers. FAO statistics show that the demand for rice in these regions is growing by 6 percent a year, making these regions the sites of the fastest-growing rice demand in the world. Irrigation schemes in the Sahel provide farmers with a reliable water-supply that is highly valued in a region with scarce and unreliable rainfall (Connor et al., 2008). Rice (*Oryza sativa*) production in these schemes is one of the most important activities, with 50,000 ha being cultivated in Senegal (SAED, 2007).

4.3 LIFE CYCLE

Rice is a typical grass that has a fibrous root system exhibiting erect culms and developing long flat leaves. It has a semi-aquatic lifestyle, requiring water particularly during the reproductive phase. In general, there are three main developmental stages in rice: germination/vegetative growth, reproductive development, and grain ripening.

Germination begins with the emergence of the coleorhiza and coleoptile from the pericarp. The radicle gives rise to the seminal root system, which has limited branching. Germination can occur under aerobic or anaerobic conditions (Moldenhauer and Gibbons, 2003). Fibrous roots form from underground nodes. The coleoptile elongates along with the epicotyl, and when the coleoptile reaches the soil or water surface, it splits open and the primary leaf emerges (McDonald, 1979). During this early phase of

development, the plant can produce a leaf every four to five days as the primary culm develops. As the rice plant grows, primary tillers begin to emerge from the axial nodes of the lower leaves. These give rise to the secondary tillers, from which tertiary tillers can also develop. The internodes begin to elongate at, or near, panicle initiation (Moldenhauer and Gibbons, 2003).

The reproductive stage begins with panicle initiation. The timing of this may be linked to specific photoperiods and is highly cultivar-dependent (McDonald, 1979). Panicle initiation occurs at the growing tip of the tiller. As the panicle grows, senescence of the lower leaves begins. The panicle may emerge partially or fully, and greater emergence is selected for in cultivars as a means of decreasing disease occurrence (Moldenhauer and Gibbons, 2003). Flowering begins one day after heading and continues down the panicle until all florets on the panicle have opened. Anthesis begins with the opening of the florets followed by stamen elongation. As pollen shedding generally occurs within minutes of floret opening (Oka, 1988), pollen is usually shed onto the florets of the same panicle, resulting in self-fertilization. Fertilization can be completed in few hours. This is the stage when rice is most sensitive to cold temperatures (McDonald, 1979).

Grain ripening starts when the florets are fertilized and the ovaries begin to develop into grains. Initially, the grain fills with a white, milky fluid as starch deposits begin to form. The panicle remains green at this stage and begins to bend downwards. Leaf senescence continues from the base of the tillers, but the flag-leaf and next two lower leaves remain photosynthetically active. The grain then begins to harden into the soft dough stage. Husks begin to turn from green to yellow, and senescence of the leaves and tillers is at an advanced stage. During the final stage the grain matures, becoming hard and dry. The entire plant begins to yellow and dry out, at which point the grain can be harvested.

FIGURE 3. TEMPERATURE AND RAINFALL REQUIREMENTS OF RICE AT DIFFERENT STAGES OF DEVELOPMENT

4.4 PRODUCTION PARAMETERS

Soil

Rice can be grown in all types of soils, from light to heavy, but not in very sandy soils. Clay soils are considered the best for rice cultivation due to its high water-holding capacity. In addition, flat land having a smooth surface is better for rice cultivation, as it facilitates uniform and equal distribution of water. Soil textures that are good for paddy rice include clay, silt clay, and silt clay loam. Rice requires slightly acidic soils having a pH value of 6.0 to 7.0; however, it has been reported that rice can grow in soils with a wide range of pH, from 4.0 to 8.0.

Water

Rice crop requires about 1400 to 1800 mm of water in a year.

Temperature

Temperature has a considerable effect on growth and development of rice plants. Rice requires a relatively high temperature for its most favorable growth and development. The temperature requirement is different for different stages of development. The rice crop can be grown successfully where average air temperature is 21 °C or more for five to six months. The critical mean temperature for flowering and fertilization ranges from 16 to 20 °C. For vegetative growth, a temperature range of 25 to 30 °C was reported best, and for grain filling and ripening a temperature range of 20 to 25 °C. For higher grain yield, a daytime temperature of 25 to 32 °C and nighttime temperature of 15 to 20 °C is preferable.

Adaptability

Rice needs a hot and humid climate. It is best suited to areas with high humidity, extended sunshine, and a guaranteed supply of water. The average temperature required throughout the life period of the crop ranges from 21 to 37 °C. At the time of tillering, the crop requires higher temperatures. The temperature required for blooming is in the range of 26.5 to 29.5 °C; for ripening the temperature should be between 20 and 25 °C. Rice is a short-day plant; however, there are varieties that are non-sensitive to photoperiodic conditions.

High nighttime temperatures can lead to loss of reserved food through greater respiration. Temperatures beyond 35 °C would affect not only pollen shedding but also grain filling. A higher mean temperature would reduce the growth duration and accelerate flowering, whereas an average temperature of 15 °C and below would slow vegetative growth and cause plants to fail to flower. It is reported that mild temperatures at night and clear sunny daytime promotes high yields, but 15 °C or below is not favorable for panicle initiation.

Clear sunny weather during ripening and moist-humid weather during the vegetative phase is desirable for the rice crop. Low solar radiation would hamper ripening of grains and would increase chaff production enormously. Rice thrives in brighter and prolonged sunshine for enhanced photosynthetic activity and higher yield; it should receive more than 300 hours of sunshine during the last 45 days before harvest. In terms of humidity, moist humid weather during vegetative growth and dry-sunny weather during ripening is most desirable. A relative humidity of 60-80 percent is said to be optimum. High wind velocity and storms are not desirable, as they cause lodging or shattering depending upon the crop growth stage. Gentle wind is best for rice cultivation, because the supply of carbon dioxide (CO_2) and its utilization is regulated to the maximum.

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5.0 SORGHUM

5.1 BRIEF OVERVIEW OF THE CROP

Sorghum is Africa's contribution to the world's top crops. It belongs to the elite handful of plants that collectively provide more than 85 percent of all human energy, and today it is the dietary staple of more than 500 million people in more than 30 countries. Only rice, wheat, maize, and potatoes surpass it in contribution to feeding the human race (Smith et al., 2000). Sorghum is a grass similar to maize in its vegetative appearance, though sorghum has more tillers and more finely branched roots than maize (Doggett, 1988; Smith et al., 2000). The overall growth and development of sorghum is similar to maize and other cereals. Before the 1940s, most grain sorghums were 2-3 m tall, which created harvesting problems. Breeding efforts using dwarfing genes have since developed varieties that are 1-1.5 m tall. While there are several genetic groups, most current grain sorghum hybrids have been developed by crossing Milo with Kafir varieties. Other groups include Hegari, Feterita, Durra, Shallu, and Kaoliang (Doggett, 1988). Sorghum head is a panicle, with spikelets set in pairs. It is mostly self-fertilized but can also cross-pollinate. Sorghum flowers begin to open and pollinate soon after the panicle has completely emerged from the boot. Sorghum can branch from upper stalk nodes. If drought and heat damage the main panicle, branches can bear panicles and produce grain. The seed color is variable with yellow, white, brown, and mixed classes. Brown-seeded types are high in tannins, which lower palatability.

5.2 GEOGRAPHIC DISTRIBUTION AND GENERAL LEVEL OF IMPORTANCE

Sorghum is grown on 40 million ha in 105 countries of Africa, Asia, Oceania, and the Americas. The United States, India, Mexico, Nigeria, Sudan, and Ethiopia are the major producers. It is generally grown between 40 °N and 40 °S of the equator in warm and hot countries characteristic of the semi-arid environment, but sorghum can be grown under a wide range of conditions and at altitudes of up to 2300 m in the tropics. Sorghum and millet are the most important cereals in the semi-arid areas of Africa. Generally, the area of sorghum and millet in Africa has steadily increased over the years, but the average yield trends are downward (Matlon and Adesina, 1991).

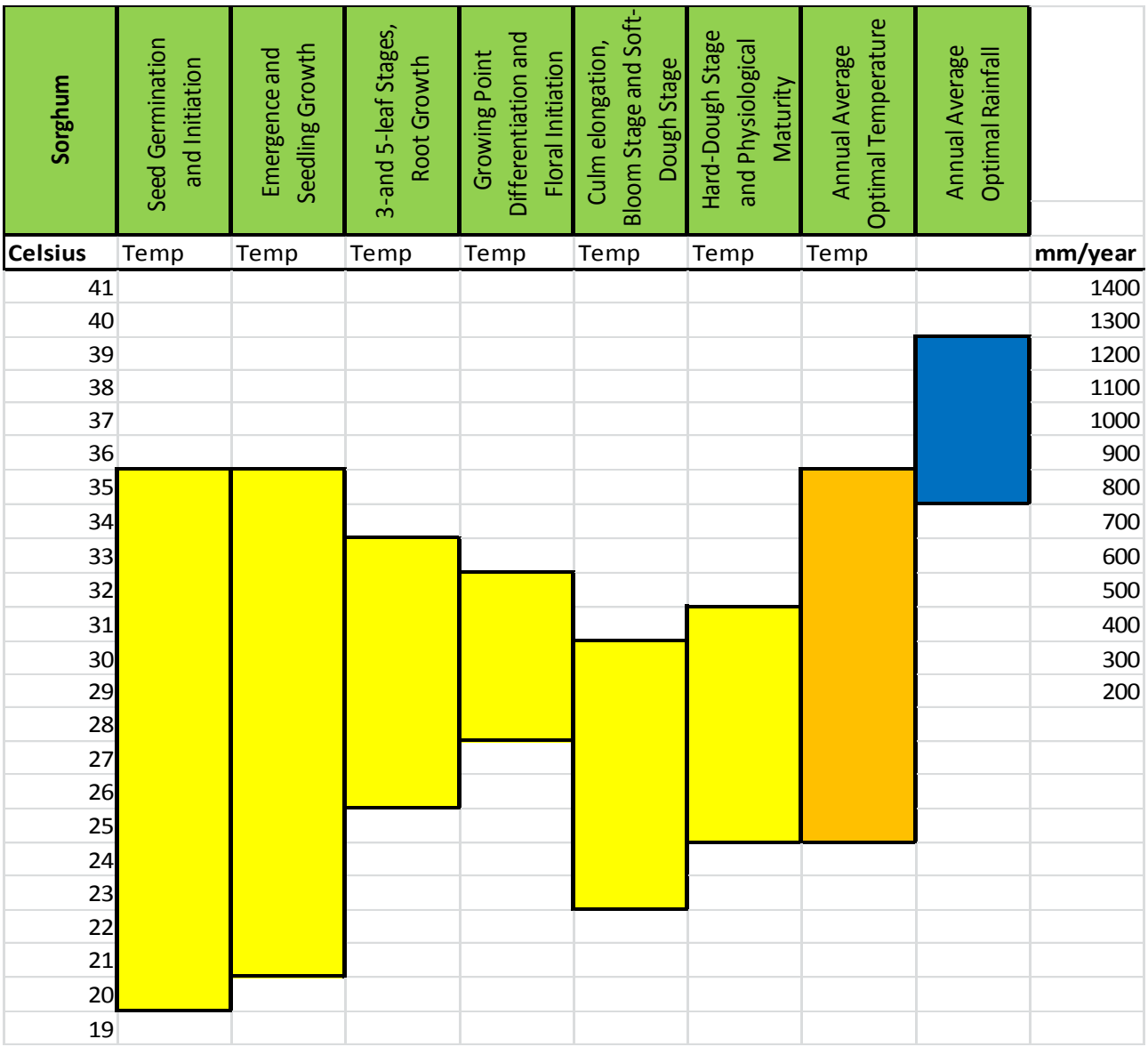
5.3 LIFE CYCLE

The phenological stages in sorghum start when seedlings emerge from the soil. Before emergence, the plant totally depends on food reserves in the seed from the endosperm for survival. Slow-emerging plants risk depleting these reserves, which are important to early plant growth. Once grain sorghum emerges, the plant develops in a predictable manner characterized by three distinct growth stages. This first growth stage is characterized by vegetative growth. The plant develops its vegetative structures, leaves and tillers, which ultimately support grain formation and growth. The second growth stage includes a period when reproductive structures of the panicle form and the maximum number of seeds per plant is set. It is the most critical period for grain production, because seed number per plant accounts for 70 percent of sorghum's final grain yield. The third and final growth stage is grain filling, which begins with flowering and continues until dry matter accumulation in the grain stops. In general, and depending on the variety, dry matter accumulation is complete at about 100 days after emergence (Quinby, 1974).

The majority of sorghum (and millet) varieties grown in West Africa are traditional varieties that are photoperiod sensitive, meaning that (decreasing) day-length triggers the physiological shift in plant

development from vegetative growth to flowering. Irrespective of plant age and seasonal conditions (rainfall or temperature), different varieties initiate flowering when day-length passes a specific threshold. Seasonal day-length is determined by latitude, so the same variety will begin flowering at different calendar dates depending on the latitude of where it is planted. This feature of sorghum physiology holds tremendous potential for climate change adaptation. It also makes traditional classification of varieties as early-, medium-, and late-maturing difficult, if not irrelevant in practice. In the Mali sorghum breeding program, researchers generally classify varieties maturing from 90-110 days as early, 110-120 as medium, and more than 120 days as late. Attention to extra-early varieties — those maturing as early as 65 days — has been abandoned due to extensive bird damage. In practice, farmers reportedly exploit sorghum's photoperiod sensitivity by planting it after sowing other, non-photoperiod sensitive crops, since the other crops mature over a fixed period of development that must be paired with the length of the rainy season.

FIGURE 4. TEMPERATURE AND RAINFALL REQUIREMENTS OF SORGHUM AT DIFFERENT STAGES OF DEVELOPMENT



5.4 PRODUCTION PARAMETERS

Soil

Sorghum does well on most soils, but better in light to medium textured soils. The optimal soil conditions are well-aerated and well-drained. Sorghum is relatively tolerant to short periods of waterlogging. The fertilizer requirements are up to 180kg/ha N, 20 to 45 kg/ha P, and 35 to 80 kg/ha K. Sorghum is moderately tolerant to soil salinity and can tolerate soil pH as low as 4.5 as well as high aluminum levels.

Water

The optimum growth requirements of sorghum plants include a medium to good and fairly stable rainfall pattern during the growing season. It is best adapted to areas with a well-distributed average annual rainfall between 450 and 650 mm. In Mali, the main sorghum production zone is found in the 700-900 mm isohyet band. This zone of production, however, is reportedly more a reflection of the location of heavier, more moisture-retentive soils than of rainfall levels. Farmers are recommended to begin planting after an accumulative 20 mm of rainfall during a 30-day period after May 1.

Sorghum is one of the most significant drought-tolerant crops available, which contributes much to its popularity in regions where the weather is very unpredictable. Sorghum tolerance to drought can be attributed to (a) an exceptionally well-developed root system; (b) small leaf area that limits transpiration; (c) leaves that fold up more efficiently during warm, dry conditions; (d) effective transpiration ratio; (e) corky epidermis and waxy layer protects plant from desiccation; (f) stomata that close rapidly; and (g) ability to remain in a virtually dormant stage during periods of moisture stress and then resume growth when conditions improve. The crop has its highest moisture demands and is most sensitive to moisture stress after flowering, during the grain-fill stage where gaps in rainfall of two weeks or more can have a significant detrimental impact on yields. Depending on the variety, and outside of the tillering stage, sorghum also tolerates waterlogging and even partial submergence for periods up to two weeks without significant yield impacts or mortality.

Temperature

Sorghum is a temperate to warm weather crop (20-40 °C) and requires a frost-free period of approximately 120 to 140 days. The plant can tolerate high temperatures throughout its life cycle better than any other crop. In Mali, temperatures of around 35 °C are considered optimal for sorghum production, and the crop can tolerate temperatures of at least up to 44 °C without harm. The minimum temperature for germination of the sorghum seed is 7 to 10 °C. Grain sorghum does not germinate and grow well under cool soil conditions. Poor emergence and seedling growth may result if planted before soil temperatures reach 35 °C.

Adaptability

Sorghum plants have diverse characteristics that make it a significant drought-tolerant crop. It is widely grown under rain-fed conditions suited for grain and forage production (Leuschner and Manthe, 1996). In dry areas with low and/or erratic rainfall, the crop responds positively to additional irrigation. Significant differences, however, are observed among varieties in their response to supplemental irrigation. Varieties and landraces that are highly drought tolerant respond only slightly to irrigation, while others can produce high yields under irrigation but are poor yielding when water is limiting.

Temperature is a critical factor in variety selection and cultivation. The optimum temperatures for high producing varieties are over 25 °C but some varieties are adapted to lower temperatures and produce acceptable yields. When the temperatures are below 20 °C, then there is an extension of about 10 to 20 days in the growing period for each 0.5 °C decrease in temperature, depending on variety, and at 15 °C a sorghum grain crop would take 250 to 300 days to mature. In addition, high temperatures (>35 °C) can lead to poor seed set, problems with ripening, and reduced yields.

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6.0 COTTON

6.1 BRIEF OVERVIEW OF THE CROP

Cotton is the leading plant fiber worldwide and is grown commercially in the temperate and tropical regions of more than 50 countries, covering more than 32 million ha across a wide range of environmental conditions (Khadi et al., 2010). Global cotton production is an approximately $20-billion annual business (Saranga et al., 2001). As the world's leading textile fiber plant, cotton forms a vital part of global agriculture and is a mainstay of the economy of many developed and developing countries. Cotton *(Gossypium hirsutum)* is grown for fiber and seed, and present world production is about 21 million tons (lint), from 59.7 million tons of seed cotton.

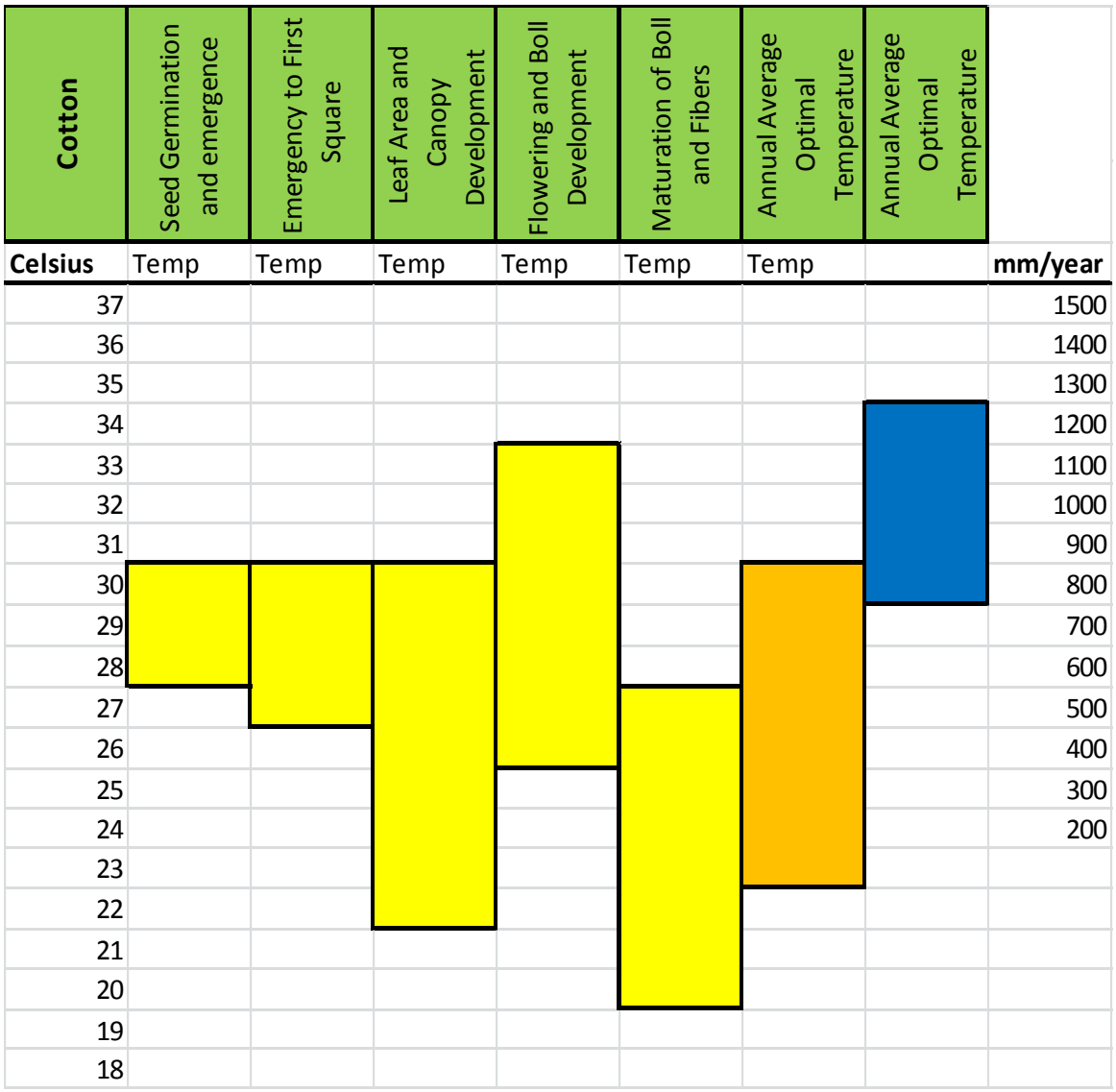
6.2 GEOGRAPHIC DISTRIBUTION AND GENERAL LEVEL OF IMPORTANCE

Cotton is considered as a crop of the hot, semi-arid regions of the world, but is also an important crop in arid-irrigated regions and extends to semi-humid tropics. The area under rain-fed cotton cultivation varies among countries. About 65 percent of world cotton production is between latitudes 30 °S and 37 °N. This geographical range includes the United States, parts of the former Soviet Union, and China. Approximately 25 percent of the total production comes from the Northern tropics. No single West African country plays a major role in international cotton production or trade. However, considered as a regional entity, West Africa is the world's third largest exporter, behind the United States and Central Asia (Baffes, 2004).

6.3 LIFE CYCLE

The biological cycle of the cotton plant can be divided into five stages. First is germination, which includes the period from sowing to emergence, when the hypocotyl with cotyledons breaks through the soil surface. Germination usually lasts four to seven days but under unfavorable conditions can be longer. The next stage is the period from leaf development to the apparition of the first square (eight to 10 days) depending on the variety and the weather conditions. Inflorescence emergence follows. The period from the formation of the first square to the detection of the first flowers takes 55 to 60 days. After this, flowering and development of fruits is observed. This stage initiates with the opening of the first flowers (reproduction occurs over five to seven days) and ends when almost all bolls have reached their final size; it takes between 55 and 60 days depending on the variety and the weather conditions. The development of the crop is sensitive to temperature. Cool nights and low daytime temperatures result in vegetative growth with few fruiting branches. The crop is very sensitive to frost. No clear distinction can be made in crop growth periods, since vegetative growth is continued during flowering and boll formation, and flowering is continued during boll formation. In Mali five varieties are grown, all requiring 120 to 130 days from germination to harvest, differing mainly in fiber quality.

FIGURE 5. TEMPERATURE AND RAINFALL REQUIREMENTS OF COTTON AT DIFFERENT STAGES OF DEVELOPMENT



6.4 PRODUCTION PARAMETERS

Soil

Cotton is grown on a wide range of soils, but medium and heavy textured, deep soils with good water-holding characteristics are preferred. Acidic or thick sub-soils limit root penetration. The pH range is 5.0 to 8.0, with 7.0 to 8.0 regarded as optimum. The fertilizer requirements of cotton under irrigation are 100-180 kg/ha N, 20-60 kg/ha P, and 50-80 kg/ha K. Two-thirds of the nutrients are taken up during the first 60 days of the growing period. Without fertilization all plant growth stages are prolonged. The crop is relatively tolerant to soil salinity and intolerant to deficits of micronutrients, such as boron.

Water

Depending on climate and length of the total growing period, cotton needs between 700 and 1,300 mm to meet its water requirements; 800-1,200 mm of well-distributed rainfall is considered optimal in Mali. In the early vegetative period, crop water requirements are low (10 percent of the total). Water requirements are highest during the flowering period, or some 50-60 percent of total, and during boll development. Later in the growing period, the requirements decline. Cotton can survive up to 20 days without rain, and up to 10 days under flooded conditions.

In Mali, planting recommendations are from May 15-30 in the Southern zone and June 1-10 in the Northern zone, and anytime up to June 20 following 15 mm of rainfall.

Temperature

Cotton is a short-day plant, but day-neutral varieties exist. However, the effect of day length on flowering is influenced by temperature. Germination is optimum at temperatures of 18 to 30 °C, with a minimum of 14 °C and maximum of 40 °C. Delayed germination exposes seeds to fungus infections in the soil (Mills et al., 2005). For early vegetative growth, temperature must exceed 20 °C, with 30 °C as desirable. For proper bud formation and flowering, daytime temperature should be higher than 20 °C and night temperature higher than 12 °C, but should not exceed 40 and 27 °C, respectively. Temperatures between 27 and 32 °C are optimum for boll development and maturation, but above 38 °C, yields are reduced.

Adaptability

Strong and/or cold winds can seriously affect the fragile young seedlings, and at maturity can blow away fiber from opened bolls and cause soiling of the fiber with dust. Cotton is extensively grown under rain-fed conditions. Although the crop is relatively resistant to short periods of waterlogging, heavy rainfall can cause lodging. Continuous rain during flowering and boll opening will impair pollination and reduce fiber quality. Heavy rainfall during flowering causes flower buds and young bolls to fall.

In general, temperatures above 35 °C are not desirable (Lu et al., 1997; Mauney, 1966); however, when moisture levels are adequate, cotton plants are capable of enduring very high temperatures (43-45 °C) for short periods without permanent injury. If these high temperatures persist for several days, however, the yields will be adversely affected. During maturation of bolls and fibers, which is essentially a drying process, relatively high temperatures are desirable with an average daily temperature of 22 °C; 68 days are required for boll maturation. When the average daily temperature is 38 °C, the period of maturation is still further shortened, but the bolls are smaller, the fibers do not develop fully, and yields are reduced (Pettigrew 2008; Reddy et al., 1995). For optimal development and high fiber quality, hot and clear days are required. Under these conditions, the quantity of fibers per boll increases, and the fiber is somewhat shorter but thicker and stronger, provided that the moisture supply is adequate.

When soil temperature fall below 20 °C, even for short periods, the uptake of water is slowed down, and the cotton plants may wilt even when there is ample soil moisture. At still lower soil temperatures (below 10 °C) the geotropism of the cotton roots are affected, and abnormal root-growth results. Excessively high soil temperatures (>40 °C) also have adverse effects.

High light intensities throughout the growing period are essential for satisfactory vegetative development, for minimal shedding of buds and bolls, and thus for higher yields. Reduced light intensities, as a result of cloudiness, reduce the rate of boll-set and cause excessive vegetative development. The increased shedding that is frequently observed following rains that occur during

cotton's growing period can probably be ascribed to the reduced light intensity rather than to the effects of the rainfall per se. Reduced light intensity can decrease cotton yield by up to 47 percent (Zhao and Oosterhuis, 1998). All wild species of Gossypium are short-day plants and do not flower as long as the day-length exceeds 12 hours.

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7.0 CASHEW

7.1 BRIEF OVERVIEW OF THE CROP

The cashew tree, *Anacardium occidentale* L., belongs to the Anacardiaceae family. Cashew is an important nut crop that provides food, employment, and economic growth to many in developing nations. The FAO reports that cashew is produced commercially in 32 countries, on more than 7.5 million acres. According to the FAO, cashew is now the most important tree nut crop in the world since its production surpassed that of almond in 2003. Vietnam, India, Nigeria, and Brazil are the four biggest producers of cashew nuts today. Most of the cashew lands are owned by small farmers who account for 97 percent of cashew production (Rosengarten, 1984). The African Cashew Alliance (2012) reports that in Africa, 2 million farmers presently grow about 48 percent of the world's cashews. The plant produces not only the well-known nut, but also a pseudo fruit known as the cashew "apple", which is used for industrial and medicinal purposes. The cashew tree is also used for reforestation, in preventing desertification, and as a roadside buffer tree.

Cashew was planted in India in the 1600s in order to prevent erosion on the coast (Morton, 1960). The wood from the tree is used for carpentry, firewood, and charcoal. The tree exudes a gum called cashawa that can be used in varnishes. Cashew bark is about 9 percent tannin, which is used in tanning leather. The tree has an extensive root system, which helps it to tolerate a wide range of moisture levels and soil types. Most cashew trees start bearing fruit in the third or fourth year and are likely to reach their mature yield by the seventh year if conditions are favorable. Although the cashew tree is capable of living for 50 to 60 years, most trees produce nuts for about 15 to 20 years (Ohler, 1979).

7.2 GEOGRAPHIC DISTRIBUTION AND GENERAL LEVEL OF IMPORTANCE

Cashew is native to Brazil but has expanded to other parts of tropical South and Central America, Mexico, and the West Indies. In the 1600s, Portuguese traders introduced the cashew tree into India and Africa to prevent soil erosion. It is now widely cultivated for its nuts and other products in the coastal regions of South Africa, Madagascar, and Tanzania; and in South Asia, from Sri Lanka to the Philippines. Cashew processing, using manual techniques, was started in India in the first half of the twentieth century. It was exported from there to the western markets, particularly the United States. In the 1960s, some producer countries in East Africa began to process nuts domestically rather than sending them to India for processing. This allowed them to benefit from the sale of both processed nuts and the extracted cashew nut shell liquid.

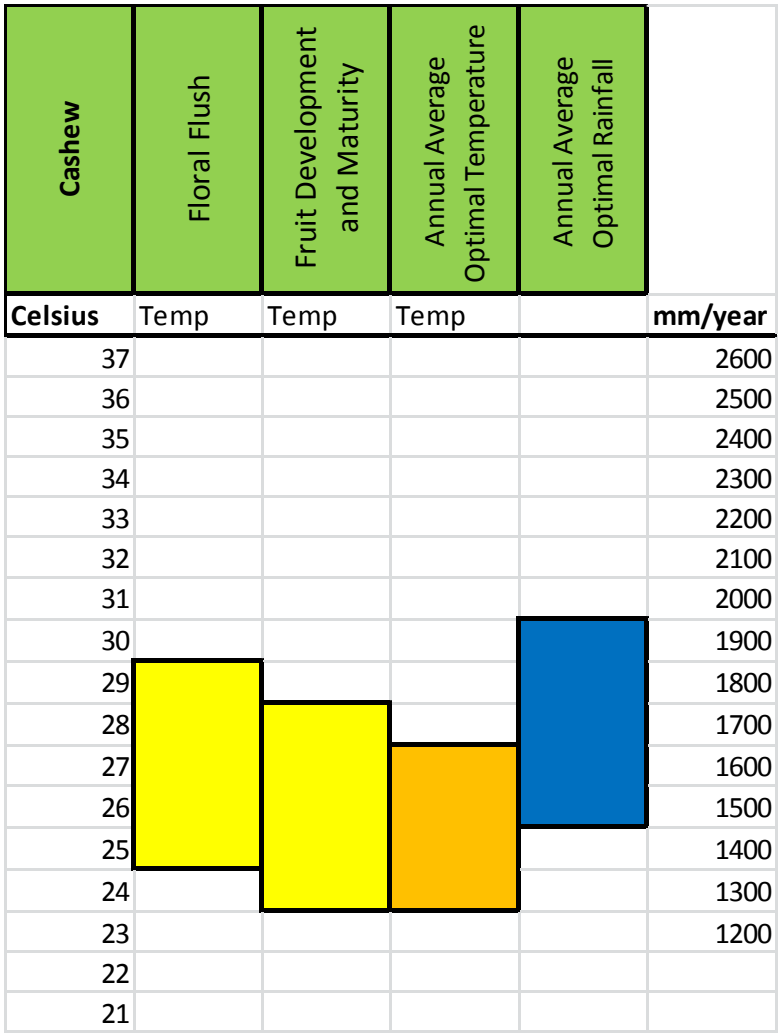
7.3 LIFE CYCLE

The cycle of vegetative and reproductive growth of the mature cashew tree follows a distinct pattern, in which the monthly timing of each phase depends on regional climate conditions and especially on temperature and availability of water. In tropical areas, up to three flushes of growth can be expected during the year. Flowering, fruit development, and cropping occurs during the dry season. At ripening stage, nuts and apples will fall to the ground. The first growth flush (also called post-harvest flush) takes place after the harvesting has finished. The second growth flush (wet season flush) occurs during the main wet season period, and during this time the major vegetative growth occurs. The final flush (pre-floral flush) occurs soon after the beginning of the dry season. The cashew tree produces both male and hermaphrodite flowers on the same panicle. More male flowers are produced than hermaphrodite

flowers (the ratio is 10 males to one hermaphrodite flower); however, this proportion can vary depending on the variety and can also vary during the flowering period. More than 80 percent of the hermaphrodite flowers fall before they produce a mature nut. In terms of timing, male flowers typically open earlier in the day, while hermaphrodite flowers open later in the early afternoon. The female part of the hermaphrodite flower is receptive to pollen from the male flower for about six hours.

Cashew is pollinated by insects (native bees, honey bees, flies, wasps). Although a large number of flowers are produced on a panicle, nut set is relatively low because of the low sex ratio and poor pollination. Sometimes poor pollination is caused by a lack of pollinating insects. Nutrition, water availability, and pest damage can influence nut set.

FIGURE 6. TEMPERATURE AND RAINFALL REQUIREMENTS OF CASHEW AT DIFFERENT STAGES OF DEVELOPMENT



7.4 PRODUCTION PARAMETERS

Soil

Well-drained red, sandy, and laterite soils are ideal for good growth and yield of cashew. The cashew is a strong plant that is renowned for growing in soils that are generally unsuitable for other fruit trees.

Thus, for the best production, deep and well-drained sandy or sandy loam soil is recommended. Cashew trees will not grow in poorly drained soils or heavy clay, water-logged, or saline soils.

Water

Cashew is drought resistant, so the tree can grow in areas with rainfall ranging from 600 to 4500 mm per annum. Fruit setting in cashew is best facilitated if rains are not abundant during flowering and nuts mature in a dry period. The cashew tree has a well-developed root system, which helps it to tolerate drought conditions.

Temperature

Cashew trees are genuinely tropical and very frost sensitive. The trees grow in a wide spectrum of climatic regions. Although the cashew can withstand high temperatures, a monthly mean of 25 °C is regarded as optimal. Cashew is a sun loving tree and does not tolerate excessive shade. It can tolerate temperatures of more than 36 °C for a shorter period, but the most favorable temperature range is 24 to 28 °C. Areas receiving extremely low (less than 18 °C) and high temperatures (more than 40 °C) for prolonged periods are not suitable for cashew cultivation.

Adaptability

Cashew is essentially a tropical crop and grows best in warm, moist, and typically tropical climates with a well-defined dry season of at least four to five months followed by a rainy season of four to five months. The distribution of cashew is restricted to altitudes below 700 m, where the temperature does not fall below 20 °C for prolonged periods, although it may be found growing at elevations up to 1200 m. The cashew is hardy and drought resistant (Blaikie and Chacko, 1998) but can be damaged by frost (Hubbard, 2008). Some of the climatic factors that influence cashew growth and production follow: (a) dry spells during flowering and fruit setting ensure better harvest, (b) cloudy weather during flowering enhances scorching of flowers due to tea mosquito infestation, (c) heavy rains during flowering and fruit set damage production, and (d) high temperature (39-42 °C) during the stage of fruit set development causes fruit drop. Damage to young trees or flowers occurs below a minimum temperature of 7 °C and above the maximum of 45 °C. Only prolonged cool temperatures will damage mature trees; cashew can survive temperatures of about 0 °C for a short time (Ohler, 1979).

Cashew can survive long periods of low humidity, but it is sensitive to stretches of high relative humidity (over 80 percent) during flowering and fruit set, which can adversely affect quantity and quality. Under high humidity, the tree becomes susceptible to the attack of the mosquito bug, *Helopeltis antonii,* and secondary infection of the dieback fungus. On the contrary, in optimum rainfall areas, high humidity during dry season enables the plant to balance its water requirement; in prolonged drought during the blossoming period, the tender flowers may wither. In areas with less than 60 percent relative humidity, the growth and productivity of cashew is greatly affected.

The presence of violent wind or storm is harmful to flowers and immature fruits, but moderate wind plays an important part in the dispersal of pollen and helps cross-pollination. Continuous dry wind increases the evaporation of water and causes physiological imbalance, resulting in flower and fruit-drop. High-speed winds during the fruiting period and excessive hot winds are undesirable and definitely harmful. The optimum wind speed for cashew growing may be estimated at around 20 km/hour. Salty air current may lead to scorching of tender leaves and buds.

Fruit set in cashew is hindered by abundant rains during flowering, and nuts mature in a dry period. Some regions where cashew has become naturalized have an average annual rainfall of only 600 mm.

Heavy rains during flowering are harmful, as they wash away the pollen, which adversely affects fruit set and encourages occurrence of die-back disease.

Cashew does not tolerate excessive shade. It does best with high sunshine hours throughout the year. It must have a lot of sunlight uniformly distributed over its entire foliage to complete its reproductive cycle and to give a satisfactory yield. This is a light-demanding crop, particularly during flushing and fruiting season. Cashew can tolerate a wide pH range and even salt injury.

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8.0 MANGO

8.1 BRIEF OVERVIEW OF THE CROP

The mango is the tropical fruit of the mango tree belonging to the Anacardiaceae family. Native to eastern India and Burma, several hundred varieties of mango exist, but only a few of them have high commercial value. After banana, mango is the most consumed tropical fruit in the world. More than 90 countries grow it. The fruit provides substantial nutritional benefits because it is rich in minerals; fiber; vitamins A, B, and C; and pro-vitamins. The mango tree is erect, 10-30 m high, with either a broad and rounded canopy that with age can reach 30 to 38 m in width, or a more upright, oval, relatively slender crown. In deep soil, the taproot can descend to a depth of up to 6 m; the profuse, wide-spreading, feeder root system also sends down many anchor roots that penetrate for several meters. The tree is long-lived, with some specimens being known to be 300 years old and still fruiting (Singh, 1978)

8.2 GEOGRAPHIC DISTRIBUTION AND GENERAL LEVEL OF IMPORTANCE

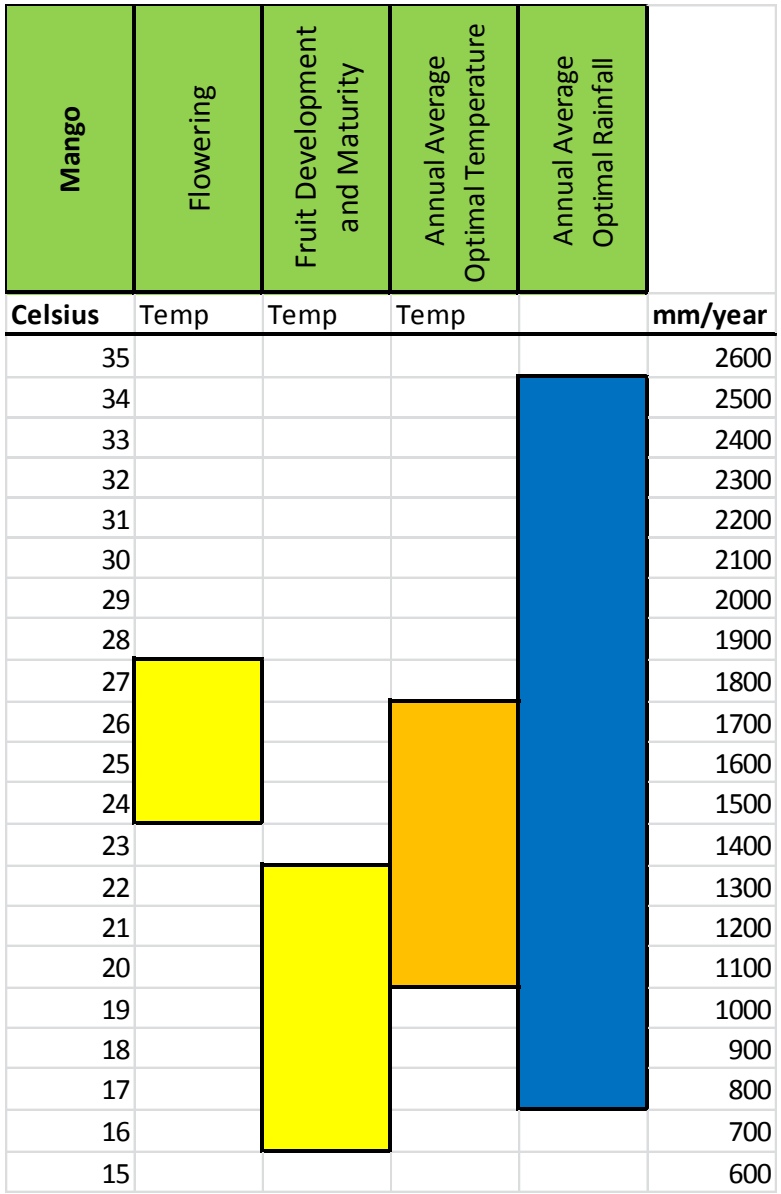
Cultivation of mango is believed to have originated in Southeast Asia, and the fruit has been cultivated in southern Asia for nearly 6,000 years. Global production of mango has doubled in the past 30 years. Asia is the largest mango producer, representing 77 percent of global production, followed by the Americas with 13 percent and Africa with 10 percent. The main African mango-producing country is Nigeria, followed by Egypt. Mango is one of the most familiar domesticated trees in dooryards or in small or large commercial plantings throughout the humid and semi-arid lowlands of the tropical world and in certain areas of the near-tropics such as the Mediterranean basin, southern Africa, and southern Florida.

8.3 LIFE CYCLE

Flowering is the first of several events that set the stage for mango production each year. Given favorable growth conditions, the timing and intensity of flowering greatly determines when and how much fruit are produced during a given season. The vegetative growth is never continuous; rather, it displays intermittent dormancy (Chacko, 1986). This cyclic growth pattern is usually called flushing – each flush finishes when all new leaves are fully expanded. Reproductive growth events usually have temporal separation from shoot growth, thereby reducing competition between sinks (vegetative vs. reproductive) during times of critical nutritional demand. Flowering generally follows a period of sustained vegetative 'dormancy' following summer shoot growth.

The mango tree is nearly an evergreen; the alternate leaves are borne mainly in rosettes at the tips of the branches and numerous twigs from which they droop like ribbons on slender petioles. The new leaves appear periodically and irregularly on a few branches at a time. Full-grown leaves may be 10 to 32 cm long and 2 to 5.4 cm wide. Hundreds and even as many as 3,000 to 4,000 small, yellowish or reddish flowers, 25 to 98 percent male, and the rest hermaphroditic, are borne in profuse, showy, erect, pyramidal, branched clusters (Ramirez and Davenport, 2010). There is great variation in the form, size, color, and quality of the fruits. They may be nearly round, oval, ovoid-oblong, or kidney-shaped, often with a break at the apex. The skin can be leathery, waxy, smooth, or fairly thick, and shows diverse colors. Some have a "turpentine" odor and flavor, while others are richly and pleasantly fragrant. Within the stone is the starchy seed, monoembryonic (usually single-sprouting) or polyembryonic (usually producing more than one seedling).

FIGURE 7. TEMPERATURE AND RAINFALL REQUIREMENTS OF MANGO AT DIFFERENT STAGES OF DEVELOPMENT



8.4 PRODUCTION PARAMETERS

Soil

Mango grows well on all types of soil provided they are deep and well drained. Red loamy soils are ideal. Soils that are alkaline or ill drained, and soils with a rocky substratum are not suitable for successful cultivation of mango crop. Very poor, or stony soils, and soils with hard substratum should be avoided. The vigor and cropping behavior of a mango tree are affected by the soil type. On shallow soils of hill slopes, mango trees grow to a large size, but the yields are not satisfactory. The deep black cotton soils are generally considered not suitable for mango cultivation. Such soils need to be reclaimed by leaching out salts using good quality water, replacing the harmful sodium from the soil with calcium, or by

establishing effective drainage to avoid salt buildup. Mango-growing soils should preferably have very low total water soluble salt content of 0.04 to 0.05 percent. Mango is rated as moderately tolerant to salts.

Water

It is not the amount of rainfall but the timing that is of importance in growing mango. Mango grows equally well both under low and heavy rainfall of 250-2500 mm annually; however, with annual rainfall of 750 mm and above it can be grown with little or no irrigation. One of the requirements for effective growing of mango is the absence of rain during the flowering time. Rain at flowering not only washes away the pollen, which adversely affects fruit set, but also encourages greater incidence of mango hoppers, mealy bugs, and diseases like powdery mildew and anthracnose that can damage the crop and sometimes completely ruin it. Cloudy weather with resultant increased humidity in the atmosphere also encourages greater incidence of such pests and diseases. It also interferes with the activity of pollinating insects, thus adversely affecting fruit set. In areas of excessive rainfall and high humidity even during the time of fruit maturity, commercial mango growing may not be profitable due to the attack of fruit fly. If high temperature, rainfall, and humidity persist throughout the year, there will be no distinct phases of vegetative growth and flowering in the mango tree, and bearing will be poor.

Temperature

Climatic conditions, particularly temperature, also govern the flowering time and ripening time of fruits. The annual mean temperature at which mango thrives best is around 27 °C. The optimum growth temperature for mango is 24 to 27 °C. Mango trees perform well both under tropical and subtropical climatic conditions. The trees can survive at 10 °C to 65 °C. Temperature plays a direct role in the flowering, fruit set, and fruit development in mango. When atmospheric temperature is high, fruits exposed to direct sunlight can be affected with spongy tissue disorder. Air temperatures higher than 41 °C causes the development of spongy tissue in mangoes. Though fruit splitting in mango is a very rare phenomenon, it is related to variation in maximum and minimum temperature and relative differences in humidity between day and night.

Adaptability

Mango can be adversely affected by frosts and freezes if the tree is not properly protected. The severity of the damage depends on several factors, such as the age of the tree, moisture content of the soil, condition of growth, timing, severity, and duration of the frost. Generally, young trees with immature wood and those under active growth are affected more severely than are well-grown trees with mature wood and those in dormant condition. Trees that are alike in growth and physiological age and growing on dry soils can be critically injured as compared to those growing in wet soils (Nadler et al., 2006). Moisture raises the soil temperature and provides protection against mild frosts.

It is reported that early and late frosts can cause more damage than the mid-season frosts of the same intensity (Sharma et al., 1991). It seems that mango trees are affected more severely by early frost because they are not fully dormant. Frost injury causes bark splitting, but this is not evident in the young plants. Discharge of latex-like secretion from stem bark, death of new shoots, charred appearance of leaves, and burned appearance of developing fruit buds are other symptoms of frost injury. Temperatures below 1.0 °C affect the mango plants, and a short period of -3.0 °C and consequent cold spell led to the drying out of the young shoots and leaves, killing the tree from the top down. Young mango trees in dynamic growth stages may be injured seriously at 0 °C. If the location gets temperatures in the range of -0.6 to 0 °C for one hour for two consecutive days, appreciable damage to mango trees can result (Naphrom et al., 2004; Sharma et al., 1991; Zhao et al., 2006).

Mango trees are most productive in climates that have a well-defined, relatively cool dry season with high heat accumulation during the flowering and fruit development period (Rameshwar, 1989). Highest production of quality fruit occurs in areas with distinctive non-freezing cool periods and extended dry periods before the flowering phase, warm temperatures during fruit development, and sufficient water levels from flowering to harvest. Drought taking place during fruit set and development may result in reduced yields and fruit size.

Another detrimental factor is the exposure to strong winds; regardless of the climate condition, winds can be harmful to mango crop. In fact, high velocity winds can affect mango trees in several ways. Winds of high velocity lead to rapid evaporation of water from the soil and thus reduce the moisture availability that is necessary for ideal growth and development of the plant. The occurrence of hailstorms is a natural phenomenon that can cause partial or total loss of mango crop; the damage caused to fruit occurs with the physical hitting of hail, which leads to rupture of tissue and the bruising, discoloration, and rotting of the affected areas of the fruit. These affected fruits do not ripen and are unfit for consumption. The presence of rain, heavy dews, or fog during the blooming season is also damaging because they can stimulate tree growth but interfere with flower production as well as promote fungus diseases in the inflorescence and fruit. In most cases, the amount of rainfall is not as critical as when it occurs.

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9.0 SHEA NUT

9.1 BRIEF OVERVIEW OF THE CROP

Shea (*Vitellaria paradoxa)* may not be a well-known species from a global perspective, but it certainly is well known in West Africa. In that region, shea constitutes the principal useful tree in a band of savanna nearly a thousand kilometers long. Traditionally, this species, not unlike oak in general appearance, provided the primary edible vegetable fat to people inhabiting an estimated 1 million km^2 of wooded grassland. Almost every part of the tree has a use: the fruit is eaten, and the leaves are used as fodder and serve as an ingredient for making alkaline and paint (Lovett and Haq, 2000). Presently, shea is exported to France, Great Britain, the Netherlands, Denmark, North America, and Japan (Elias and Carney, 2007).

9.2 GEOGRAPHIC DISTRIBUTION AND GENERAL LEVEL OF IMPORTANCE

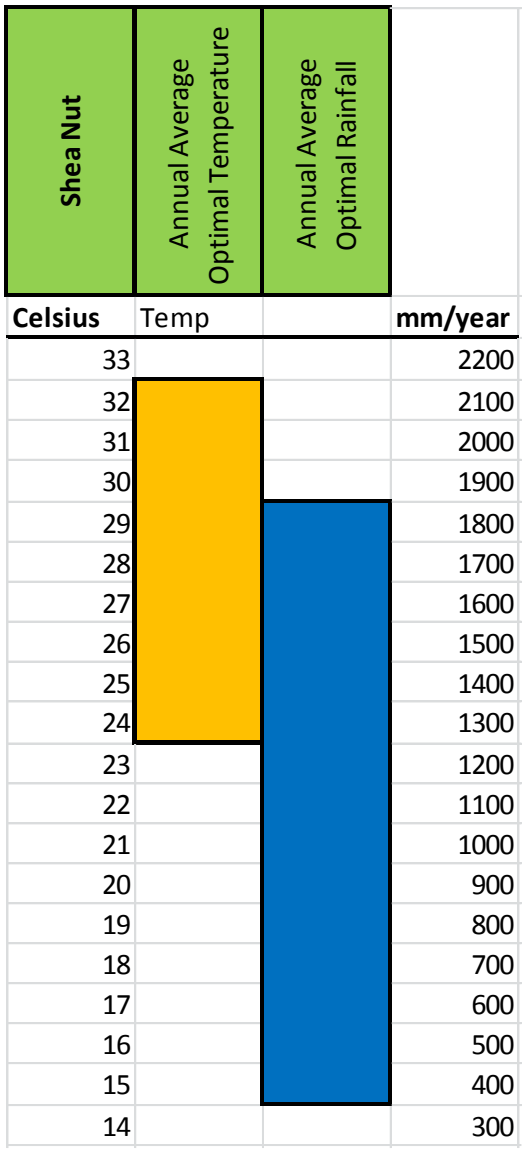
Shea occurs in the southernmost parts of the Sahel and the adjacent Sudan and Guinean savannas. Senegal is the western extent of its range. Dense stands are found from Guinea through Mali, Burkina Faso, and Niger. The trees also occur in Guinea Bissau, Sierra Leone, Côte d'Ivoire, Ghana, Togo, and Benin as well as Nigeria and Cameroon. East of this region, there are scattered occurrences across Central Africa from Chad through Sudan to far-western Ethiopia, Uganda, and Congo. Typically, the shea distribution zone lies in regions of 600 to 1,400 mm of annual rainfall.

9.3 LIFE-CYCLE

Despite all these uses and economic advantages, there are still no routine plantings of *Vitellaria paradoxa*. Little is known about the agronomy of this tree (Ugese, 2010). Production of shea nut is mostly based on the collection of fallen fruits from the wild. The tree produces flowers from December to March, and fruits are harvested from May to September (Awoleye, 1996), which coincides with the planting of the main crops and inevitably competes for labor. The tree's biology and physiology are also very unclear. For example, nothing is known about shea's irregular fruiting cycle. It is probable that bush fires and the hot dusty wind called *harmattan* contribute to the flowers and buds dying prematurely. Drought may also play a part. However, none of these explanations is sufficient by itself. Basic research on the influence of climate and soil on the tree's productivity, growth, and unreliable bearing is needed.

Fresh seed germinates readily, but viability declines significantly within a week or so unless the seed is cooled. The deep-rooted seedlings can be difficult to establish if transplanted. There has been some success with air-layering and grafting of superior clones, as well as tissue-culturing, but more experience is needed before standard practices are fully developed and acceptable. One special difficulty is the long period needed to reach fruiting age. Traditionally, shea is believed to take about 20 years to bear fruit, with full production only reached after about 50 years. However, some trees can produce fruits after a dozen years. Whether such substantial difference is genetic or environmental is not known; it offers significant prospects for domestication and non-seed propagation. There is also high yield variability among different trees. Vegetatively propagated materials can reduce initial fruiting to one year or two. The seedlings grow a long taproot, which provides good levels of drought resistance but makes them difficult to transplant. Trees raised from seed mature very slowly. An important insect for the shea tree, like for many other trees, is the bee, which is responsible for the pollination of the fruits (Dwomoh, 2003).

FIGURE 8. TEMPERATURE AND RAINFALL REQUIREMENTS OF SHEA NUT



9.4 PRODUCTION PARAMETERS

Soil

Shea occurs naturally on the dry slopes of the savanna zone, but not in alluvial hollows or land subject to flooding. It is found on various soil types but seems to prefer dry and sandy clay soils with a good humus cover. Nonetheless, it tolerates stony sites and lateritic subsoils, although its yields may not be as great under these conditions.

Water

Shea is found in areas with 400-1,800 mm rainfall per year. However, the trees are most common and healthy where they receive 600-1,200 mm, and where the dry season lasts no more than eight months.

Temperature

It grows in areas characterized by average annual temperatures of 24-32 °C. The minimum is reported to be 21 °C. Temperatures where shea is found commonly climb into the lower 40s °C.

Adaptability

Shea grows in the dry forests and savanna with a very marked dry season of six to eight months and with periodic droughts that last several years. It also occurs scattered in dry forests throughout the Sudano-Sahelian zone, but does not extend into coastal areas. It is a light-demanding species of open sites, mostly solitary. The tree grows generally at low altitude, although on Cameroon's Adamaua Plateau, this range ascends to 1,200 m above sea level.

One of the difficulties facing establishment of *Vitellaria paradoxa* is poor seed longevity and limited success using vegetative propagation methods to produce seedlings. The nut has a short period of viability. This species has recalcitrant seeds that need to maintain high critical moisture content. Seed viability declines rapidly if they are dried. When nuts are planted immediately after collection, there is prolonged dormancy in which shoots take between 51 and 79 days to emerge from the soil (Jackson, 1968; Ugese, 2010).

Excess humidity can be detrimental to shea, and the tree does not grow in locations where rainfall and humidity are high. The reasons for this are unknown. Although the tree might possibly thrive under good rainfall, it seems unlikely that it would be a viable resource in any location where oil palm, other oilseeds, or cacao grow well. The growth in dry areas is rated fair to good, and this is the climatic zone where the tree finds its greatest usefulness. In the dry areas of West Africa it has reasonable commercial potential; on the other hand, growth in upland areas is poor or limited. Shea grows at an altitude of 1,200 m in Cameroon, but most African highlands can find more reliable alternatives for producing the same type of products that this tree yields.

Bush fires, the presence of insects, and parasites can have significant influence on the yield of the trees (Dwomoh, 2004). According to Dwomoh (2004), droughts can lead to wrinkling of the seed or even abortion of shea fruit growth. Strong winds or heavy rain showers can cause flowers to detach and fall.

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10.0 BOURGOU

10.1 BRIEF OVERVIEW OF THE CROP

Echinochloa stagnina, "bourgou" or "burgu," occurs throughout tropical Africa and is also found in tropical Asia, where it has possibly been introduced. Occasionally, it is naturalized in other tropical regions. It is a perennial or sometimes annual semi-aquatic tropical grass. It reaches up to 10 m when floating, most of the plant being under water (it has stout floating rhizomes). Bourgou can be used for food – the sweet culms are sun-dried to extract sugar, and people consume the grains in periods of scarcity. However, bourgou is mainly used as forage, and bourgou pastures on floodplains provide dry-season fodder for cattle. Ibiwoye and Okaeme (1991) indicated that the plant contained sufficient quantities of nutrients to qualify as a feedstuff for livestock. The plant contains 6.78 percent crude protein, 33.7 percent crude fiber, 2.60 percent ether extract, 51.82 percent nitrogen-free extract, 5.10 percent ash, and gross energy of 22.94 MJ/kg. It can be made into hay. The stems are used for thatching and mat-making, and the leaves for caulking boats. The ash of burnt leaves has been used in the manufacture of soap and as a mordant with indigo dye.

10.2 GEOGRAPHIC DISTRIBUTION AND GENERAL LEVEL OF IMPORTANCE

Bourgu is widespread in tropical Africa and Asia where it has probably been introduced. It is growing along rivers and in lakes and lagoons in water up to 3-10 m deep. It may be found up to 2,000 m altitude in Tanzania. In the Central Delta of Niger, *Echinochloa stagnina* used to cover more than 250,000 ha but has been replaced by rice fields (National Research Council [NRC], 1996). Grasslands of *Echinochloa stagnina* (called "bourgoutières") are important dry-season grazing areas for the herds of pastoralists in West Africa (Baclbasa-Dobrovici, 1971). In Chad it is sown to improve pastures; it is also sown as a fodder grass in Egypt.

10.3 LIFE CYCLE

Echinochloa stagnina is propagated by seed, stem cuttings, or plant division. Under natural conditions, the seeds are shed in water. In experiments, seeds stored under water in the dark at a temperature of 20 °C showed no dormancy and had a germination percentage of almost 100 percent, whereas seeds kept under dry conditions had a dormancy period of six to seven months. The dormancy is broken by removing the glumes, but it results in rapidly reduced viability. An investigation showed that variations in the embryo sac development and unorganized aposporous embryo sacs contribute to the failure of seed set (Muniyamma, 1978). Seeds germinate within a week after sowing. In regeneration programs, seedlings or rooted cuttings are planted out into the field at densities of 10,000-16,000 plants/ha.

This is a perennial aquatic grass that can grow up to 2.5 m, or taller (up to 10 m) when floating. The stem (culm) is decumbent, often spongy, rooting and branching at the lower nodes. The leaves alternate, simple and entire with leaf sheath of 15-25 cm long. The inflorescence is composed of racemes along a central axis with spikelets in pairs. Spikelets are narrowly ovate with prickly hairs on the veins. The fruit is of caryopsis type (grain). Stem elongation enables it to support a water level increase of 4 cm per day, and it can be found in water depths of up to 4 m. The stems are trampled by animals and covered by soil from roots at the nodes, which is an important mode of natural regeneration. It is a self-pollinating species and follows the C_4-cycle photosynthetic pathway. In the central Niger delta in Mali, the grains of *Echinochloa stagnina* are traditionally harvested using boats and by beating the inflorescences over a net.

As the grains shatter easily, they are harvested at an early stage. The vegetative phase of *E. stagnina* happens during winter, spring, and summer, while flowering and fruiting takes place during fall (Shaltout et al., 2009).

10.4 PRODUCTION PARAMETERS

Soil

In tropical Africa, *Echinochloa stagnina* occurs from sea level up to 2,300 m altitude, in shallow water, in swamps, and on periodically inundated clay soils. Bourgou grows best in wetlands in flooded conditions, in well-prepared clay soils of high lime content. It often forms large floating mats, rooting in the mud. It is frequently the dominant species of the natural flood-plain grasslands in the central Niger Delta and the shores of Lake Chad. It may occur in massive, nearly pure stands, sometimes large enough to obstruct waterways.

Water

Due to its very quick growth in water, *Echinochloa stagnina* can survive in flooded lowlands that remain waterlogged or under water for months (and up to three to 10 m high). At the end of the rainy season and after culm harvesting, bourgou re-seeds quickly and provides new pastures for livestock (NRC, 1996).

Temperature

The range of temperature requirements is very broad, as this species is widely distributed in different regions in Africa.

Adaptability

Bourgou is tolerant of non-saline sodic soils, which are often found on river banks. It is somewhat tolerant of droughts; however, severe droughts between 1968 and 1985 destroyed many "bourgoutières" in the inner Niger delta. In the late 1990s, re-introduction programs helped to establish 4,000 ha of *Echinochloa stagnina* pastures in this region (NRC, 1996). Bourgou plays the role of substrate for heterotrophic bacteria that remove water pollutants such as nitrates, ammonium, and phosphates in irrigation and drainage canal systems (Haroon and Daboor, 2009). It may also be used for alkaline and sodic soils reclamation (Helalia et al., 1992). Unfortunately, under the effect of water deficit, overgrazing, the exploitation of grass tufts (the grass is used for fattening domestic animals that are then sold on markets), extensive rice growing, and cultivation of the river banks, it is noted that a clear regression of the bourgoutières has led to a drastic reduction in the fodder resources. Asuquo Obot (1985) reported that standing crop varies with the phenological state of the plant and is negatively correlated with the lake water temperature.

Rice farming competes for land with bourgou pastures, and many bourgou fields have been converted to rice plots as a consequence of decreased flooding due to droughts and hydropower development. Bourgou grows on deeper water than rice does, and when the water level decreases, rice fields tend to invade bourgou fields, weakening a key resource and grazing reserve during the dry season for the pastoralists (Pedersen and Benjaminsen, 2008).

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11.0 PARKIA BIGLOBOSA (NÉRÉ)

11.1 BRIEF OVERVIEW OF THE CROP

Néré (*Parkia biglobosa*) is a traditional economic tree legume of considerable multipurpose importance. It provides fodder, human food, fuel wood, timber, green manure, medicine, and shade for forage grasses and livestock; protects soil from heat; and is important in soil nutrient cycling. The fermented seed (dawadawa or soumbala) is a popular, protein-rich condiment in many West African countries (Teklehaimanot, 2004). It is a large tree, up to 20 m high, with a wide-spreading crown. Farmers deliberately maintain these trees on farms for their fruits and nuts. Despite its important uses, the populations are in decline and they remain semi- or undomesticated (Hopkins, 1986; Nchoutpouen et al., 2009; Tee, 2009).

11.2 GEOGRAPHIC DISTRIBUTION AND GENERAL LEVEL OF IMPORTANCE IN THE COUNTRY

The natural distribution of *Parkia biglobosa* extends from Senegal and Guinea in West Africa eastward to Uganda. In the western part of its range, it occurs more or less throughout the area, but east of Cameroon its distribution is more scattered and restricted. The species grows in multiple climatic zones with precipitation ranging from 600 to 2,500 mm a year.

11.3 LIFE CYCLE

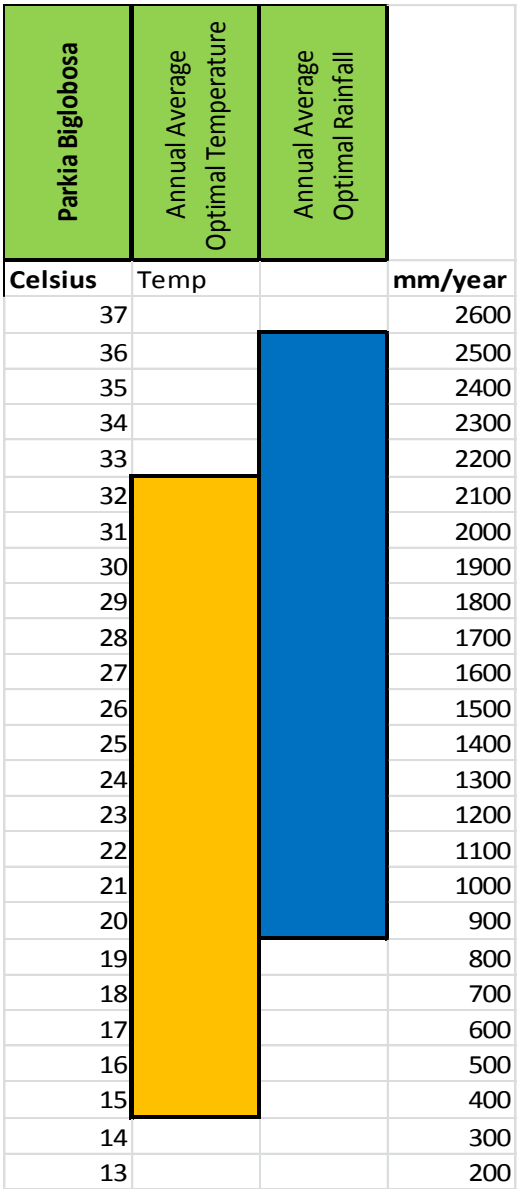
The seedling shows semi-hypogeal germination; the testa splits but remains associated with the fleshy, pale green cotyledons. The first leaf is a cataphyll, and subsequent juvenile leaves are bipinnate. The taproot develops first during germination and gives rise to lateral roots. Growth is comparatively fast; seedlings may reach a height of 1 m in one year, and young trees of superior provenances can reach 7 m in six-year-old plantations. In tree development, the trunk is formed by superposition of renewal shoots from lateral buds; the new shoot is initially orthotropic but later becomes plagiotropic. Trees start flowering at five to seven years while still comparatively small. They reach their maximum height after 30 to 50 years, and can reach an age of 100 years.

The tree flowers in the dry season in the Sahel region from December to April and slightly earlier in less dry regions. Flowering coincides with loss of leaves; new foliage develops after peak flowering. The flowering period lasts three to eight weeks depending on the region. Mature fruits develop by April to May; however, two periods of flowering and fruiting per year may occur. The anthesis occurs at dusk, when large quantities of nectar and pollen are produced. The capitulum can produce a rotted and fruity smell like cow manure. The pollination is carried out by diverse species of bats; however, seed set can also occur in the absence of bats. Other pollinators such as honeybees, flies, wasps, ants, tenebrionid beetles, and tettigometid bugs may be involved. Some type of sunbirds can also visit the capitula, but their role in pollination is negligible. It is suggested that some degree of self-incompatibility is possible.

Fruits are produced for the first time when the tree is five to 10 years old. Trees have different levels of precocity. The fruits start to ripen just before the first rains and continue over most of the season; each hermaphrodite flower is potentially capable of producing a single pod; however, this does not happen – potentially, up to 20 pods may develop per floral head, but the actual number is often lower. The seeds are dispersed by animals and birds that eat the fruits and/or the seeds. The pods are eaten by

chimpanzees (which sometimes spit out the seeds), baboons, parrots, and possibly hornbills. The *néré* seeds have a thick, resistant testa that can possibly pass through the animal gut unharmed and dormant.

FIGURE 9. TEMPERATURE AND RAINFALL REQUIREMENTS OF PARKIA BIGLOBOSA



11.4 PRODUCTION PARAMETERS

Soil

The major soils include Savanna Ochrosols, classified as Alfisols, Ultisols, and Inceptisols. Most of these soils are shallow soils overlying ironpans. These soils are generally low in organic matter, cation exchange capacity, and fertility (Quansah, 1990).

Organic matter in the soil contributes to the cation exchange capacity, regulates soil temperatures, and enables soil organisms, such as earthworms, to be active (Pelig-Ba, 2009). Generally, as organic matter

decomposes, it adds nutrients to the soil. The soils in this area are deficient in nutrients, especially phosphorous and nitrogen. Crop production yields are reduced as result of the low concentrations of nutrients. For example, the average phosphorous content of these soils is 80-150 ppm, compared to temperate soils that average 1,500-3,000 ppm.

Water

Parkia biglobosa grows in multiple climatic zones with precipitation ranging from 700 mm to 2500 mm a year. This amplitude indicates that the species can grow under quite different environmental conditions.

Temperature

Mean annual temperature in the tree's natural range is 15-32 °C, but it tolerates high temperatures reaching higher than 40 °C.

Adaptability

P. biglobosa occurs in a diversity of agroecological zones, ranging from tropical forests with high and well-distributed rainfall to arid zones where mean annual rainfall may be less than 400 mm (Hopkins, 1986). It has a capacity to withstand drought conditions because of its deep taproot system and an ability to restrict transpiration (Teklehaimanot et al., 1998). The species is currently disappearing from the northern range of the distribution area, at least in part because of a decrease in rainfall since the 1970s (Ouedraogo et al., 2009). However, there is also evidence of strong genetic differentiation between *P. biglobosa* populations within West Africa expressed in the form of superior adaptive capacity. This evidence could explain the species' ability to thrive under quite different climatic conditions across West Africa (Ouedraogo et al., 2012). Treatment of seeds with wet heat was found to induce germination of dormant seeds, which could be applied to raise seedlings of the plant for field propagation (Aliero, 2004).

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12.0 COWPEA

12.1 BRIEF OVERVIEW OF THE CROP

Cowpea (*Vigna unguiculata* L.) is a member of the Phaseoleae tribe of the Leguminosae family. Members of the Phaseoleae include many of the economically important warm season grain and oilseed legumes such as soybean, common bean, and mungbean. Cowpeas are annual crops grown for their leaves and seed. The growth habit is climbing, spreading, or erect. Cowpeas are native to Africa, where they were domesticated more than 4,000 years ago. The crop exhibits much variation in growth habit, leaf shape, flower color, and seed size. Cowpea is a food and animal feed crop grown in the semi-arid tropics. The grains contain up to 25 percent protein and several vitamins and minerals. The crop is adaptable to harsh environments, including extreme temperatures and water-limiting conditions. The plant tolerates drought and performs well in a wide variety of soils, and being a legume helps to replenish low-fertility soils. It is grown mainly by small-scale farmers in developing regions, where it is often cultivated in association with other crops as it tolerates shade. More than 5.4 million tons of dried cowpeas are produced worldwide, with Africa producing nearly 5.2 million. Nigeria, the largest producer and consumer, accounts for 61 percent of production in Africa and 58 percent worldwide (Ng and Monti, 1990; Singh and Rachie, 1985).

12.2 GEOGRAPHIC DISTRIBUTION AND GENERAL LEVEL OF IMPORTANCE IN THE COUNTRY

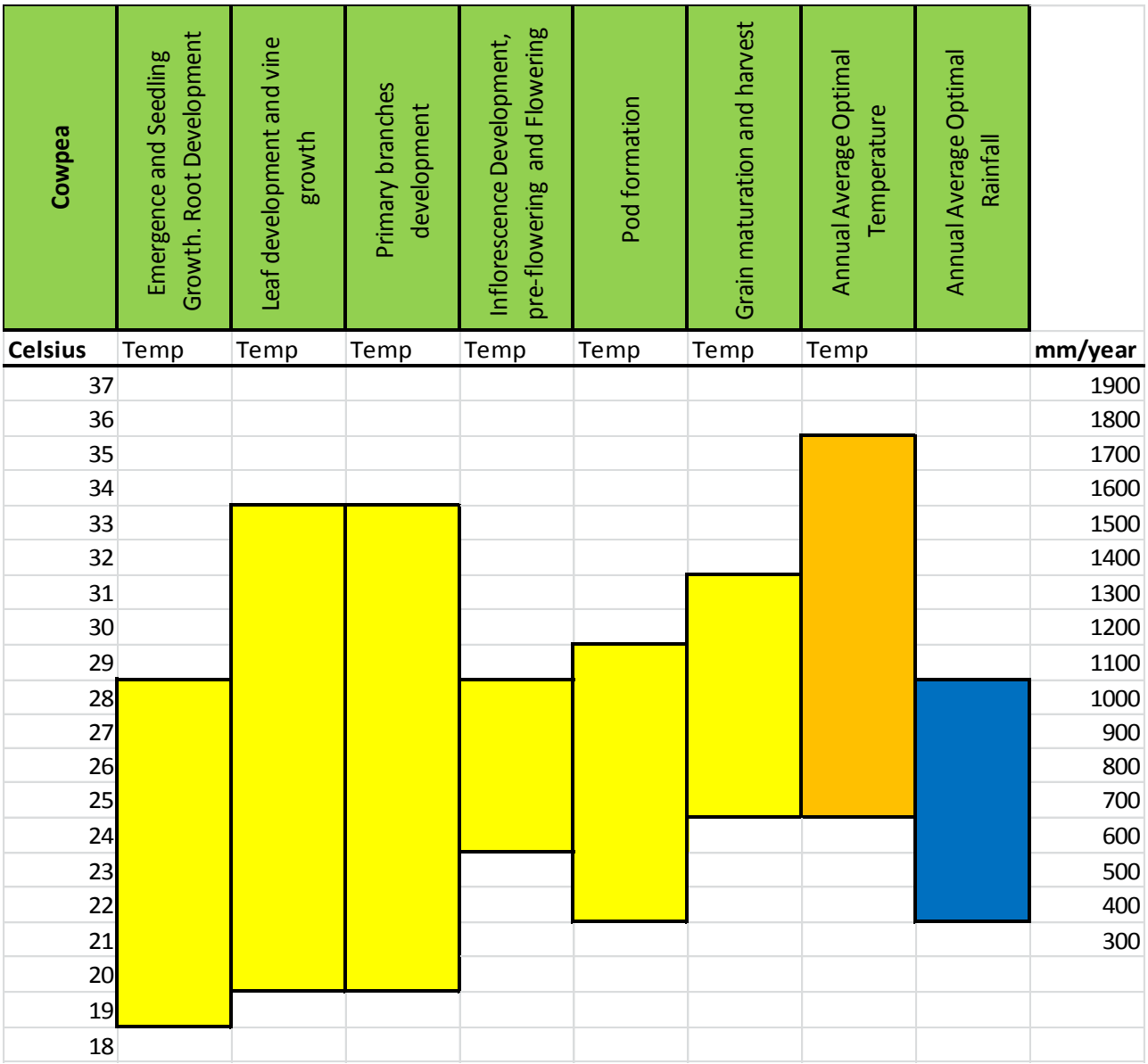
Cowpea originated in ancient West African farming systems, 5,000-6,000 years ago. It was closely associated with the domestication and cultivation of sorghum and pearl millet. It is now grown on a commercial scale in 33 countries in Asia, Africa, and Central and South America, as well as parts of southern Europe and the United States. Subsistence farmers in sub-Saharan Africa usually intercrop their cowpea with maize, sorghum, millet, and/or cassava. In rice farming, cowpea can be grown either before or after a crop to increase food production from a land area. In these systems, cowpea contributes by enriching the soil with nitrogen, helping to break the pest and disease cycle that occurs in continuous grain cropping, and serving as an additional source of farm income.

12.3 LIFE CYCLE

Cowpea is an herbaceous warm-season annual that is similar in appearance to the common bean except that leaves are generally darker green, shinier, and less pubescent. Cowpeas also are generally more robust in appearance than common beans, with better-developed root systems and thicker stems and branches. Seedling emergence is of epigeal type (which is similar to common bean and lupinus), in which the cotyledons come out from the ground during germination. This type of emergence makes cowpea more susceptible to seedling injury, since the plant does not regenerate buds below the cotyledonary node. Leaves are smooth and rarely pubescent. There is a broad range in leaf size and shape. Flowers originate in multiple racemes. Two or three pods per peduncle are common, and often four or more pods are carried on a single peduncle. The presence of these long peduncles is a distinguishing feature of cowpea and this characteristic also facilitates harvest. Cowpea is primarily self-pollinating. Cowpea pods are six to 10 inches long, cylindrical and curved. The flowering period can be altered by warmer and humid conditions, leading to asynchronous maturity. Early-sown crops tend to have elongated internodes, are less erect and more vegetative, and have a lower yield than those sown at the optimum time.

Cowpea is one of the fastest-maturing grain crops. In Mali, breeders distinguish between extra-early varieties, maturing in 50-55 days; early varieties, maturing in 60-65 days; intermediate varieties, maturing in 70-80 days; and late varieties, maturing in 90-120 days from planting to harvest. Some varieties are photoperiod sensitive. The different maturation classes are targeted to different agroecological zones, with the shortest-maturing varieties promoted in areas receiving the least rainfall (e.g., extra-early and early varieties in the 400-600 mm isohyet zone, intermediate varieties in the 700-800 mm zone, and long varieties in the 900-1,000 mm zone).

FIGURE 10. TEMPERATURE AND RAINFALL REQUIREMENTS OF COWPEA AT DIFFERENT STAGES OF DEVELOPMENT



12.4 PRODUCTION PARAMETERS

Soil

Cowpea performs well on a wide variety of soils and soil conditions, but it performs best on well-drained sandy loams or sandy soils where soil pH is in the range of 4.5 to 7. Adequate phosphorous is essential for cowpea growth. In very poor soils, an initial dose of nitrogen fertilizer is beneficial as a "starter." Sandy soils tend to be less restrictive on root growth. On heavy fertile soils, they show a vigorous vegetative growth, but not necessarily a good grain yield. Adaptation to lighter soils is coupled with drought tolerance through reduced leaf growth, less water loss through stomata, and leaf movement to reduce light and heat load under stress. Cowpeas are much less tolerant to cold soils than common beans are.

Water

Cowpea can tolerate lower rainfall conditions than any other major crop grown in the Sahel. It grows well under rainfall ranging from 400 to 700 mm per annum and can produce a crop with as little as 300 mm of rainfall or less, though it generally prefers well-distributed rainfall to support normal growth and development. Cowpea can tolerate dry periods of up to seven and 10-15 days without harm during emergence and grain filling stages respectively but is sensitive to dry periods of three to five days during flowering. Cowpeas can tolerate waterlogging up to five days during vegetative growth.

Temperature

In Mali, the reported optimal temperature range for cowpea growth and development is 30 to 35 °C during the day and 25-30 °C at night. From the literature, the best vegetative growth occurs when temperatures range from 20 to 33 °C, while higher temperatures can cause earlier flowering and flower abscission, resulting in poor pod set. Germination occurs faster at temperatures higher than 19 °C, while colder temperatures slow germination. Warm and moist conditions can extend the flowering period, leading to asynchronous maturity, even in early flowering varieties.

Adaptability

Cowpea is a warm-season crop well adapted to many areas of the humid tropics and temperate zones. It tolerates heat and dry conditions but is intolerant of frost. Cowpea is more drought resistant than the common bean is. Drought tolerance explains why cowpea is such an important crop in Sub-Saharan Africa; it can perform well in as little as 300 mm of rainfall. The deep root system helps stabilize the water balance, and the canopy covers the ground thus preventing moisture escape. These traits are particularly important in the drier regions. In terms of moisture stress, the most critical period is just prior to and during flowering.

Cowpea in the Sahelian region can experience both heat and drought stress which forces farmers to use varieties adapted to those conditions (Hall et al., 2002; Hall, 2004). As much as 1,000 kg /ha of dry grain has been produced in a Sahelian environment with only 181 mm of rainfall and high evaporative demand (Hall and Patel, 1985). But in general, changes in temperature and rainfall can create a moderate potential for a decrease in productivity, particularly during emergence and seedling growth, leaf, and pod development phases. Screening for heat tolerance under field conditions is difficult in the Sahel, but screening cowpea for reproductive-stage heat tolerance under screen-house conditions during the dry season determined that the daily minimum air temperatures varied from 24 to 27 °C, and daily

maximum air temperatures varied from 38 to 42 °C. Poor production practices including choice of cultivar, adaptability, as well as lack of information on the right planting date has contributed to low cowpea productivity. The crop can be harvested in three stages: while the pods are young and green, mature and green, and dry.

Cowpea is a short day plant, and many cowpea accessions present photoperiod sensitivity with respect to floral bud initiation and development (Ehlers and Hall, 1996; Craufurd et al., 1997). For some varieties, the degree of sensitivity to photoperiod can be modified by temperature (Wein and Summerfield, 1980; Ehlers and Hall, 1996). In West Africa, selection for differing degrees of photosensitivity has occurred in different climatic zones such that pod ripening coincides with the end of the rainy season in a given location regardless of planting date (Steele and Mehra, 1980). This attribute allows pods to escape damage from excessive moisture and pathogens. Cowpeas are very susceptible to a variety of insects and diseases and do not do well in poorly drained and cool areas.

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13.0 GROUNDNUT

13.1 BRIEF OVERVIEW OF THE CROP

Groundnut (*Arachis hypogaea* L.) is known by many names, including peanut, earthnut, monkey nut, and poor man's nut. Although groundnut is native to South America, it is successfully grown in other parts of the world and has become an important oil seed and food crop in tropical, sub-tropical, and warm temperate zones. Most groundnut is grown in India and China. Millions of smallholder farmers in Sub-Saharan Africa also grow groundnut for food and as a cash crop. Most of the world production of groundnuts is crushed for oil that is used mainly for cooking. The press cake from oil extraction is rich in protein and used in animal feed; it is also used to produce groundnut flour, used in human foods. The seeds or kernels are eaten raw, boiled, or roasted; made into confectionery and snack foods; and used in soups or made into sauces with meat and rice dishes. The vegetative residues from the crop are excellent forage.

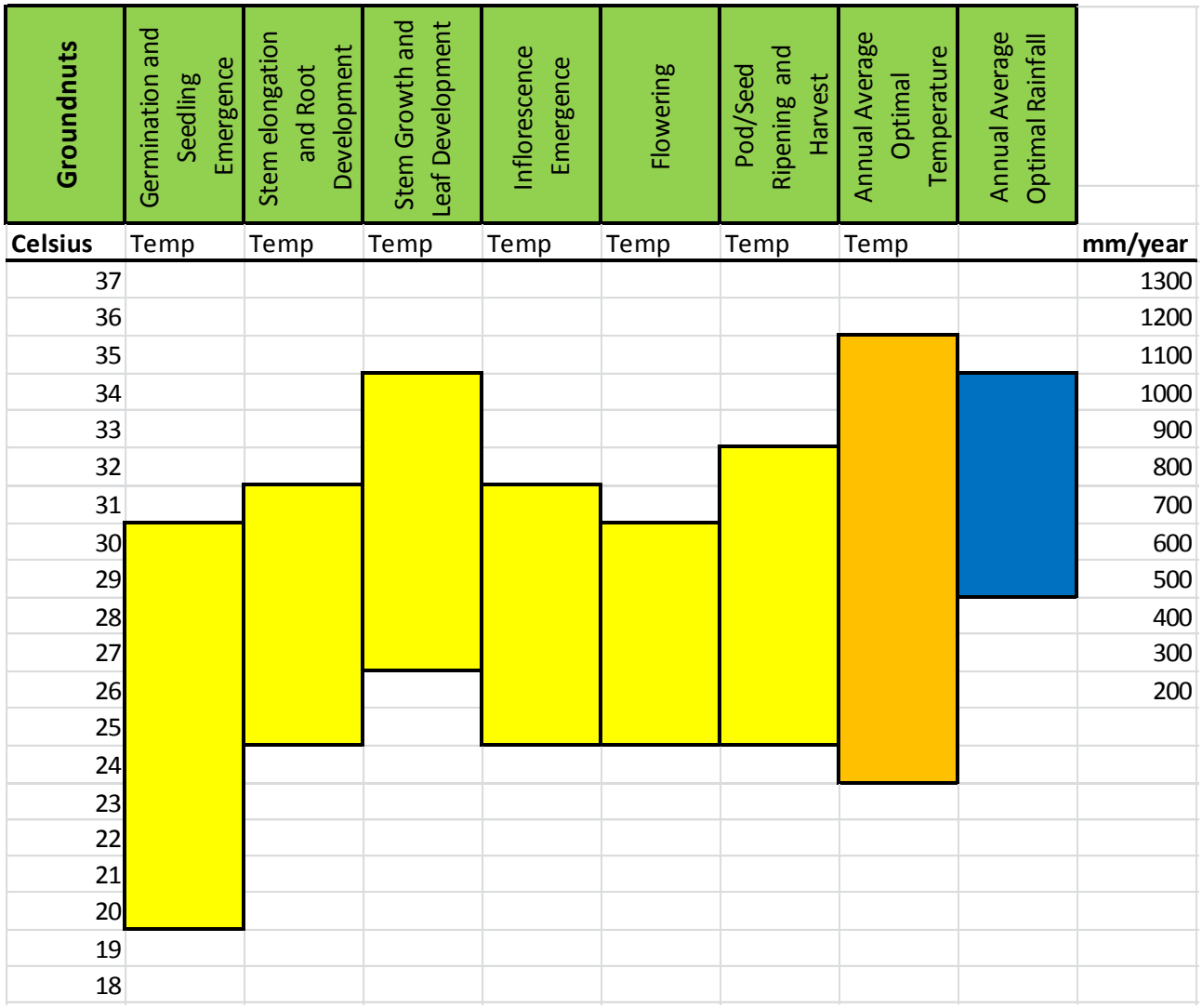
13.2 GEOGRAPHIC DISTRIBUTION AND GENERAL LEVEL OF IMPORTANCE IN THE COUNTRY

Asia and Africa account for 97 percent of the groundnut area. Groundnut is also cultivated to some extent in North and South America, Europe, and Oceania. The average groundnut yield in Asia (1600 kg/ha) and Africa (856 kg/ha) are low, as it is mostly cultivated as a rain-fed crop. In sub-Saharan Africa, groundnuts are a basic staple crop, cultivated mainly by small-scale farmers both as subsistence and as a cash crop. It is an important source of protein and other nutrients. In Africa, groundnut yields are traditionally low due to unreliable rains, poor soils, pest and disease occurrence, poor seed variety, and increased cultivation on marginal land.

13.3 LIFE CYCLE

Groundnuts are a small erect or trailing herbaceous legume, about 15 to 60 cm high. The fruit is a pod with one to five seeds that develops underground within a needle-like structure called a peg. The seeds are rich in oil (38-50 percent), protein, calcium, potassium, phosphorus, magnesium, and vitamins. Groundnuts show five crucial phenological stages: emergence and establishment, vegetative growth, flowering, yield formation (which includes pod setting and pod filling), and ripening. Groundnut emergence is intermediate between hypocotyl elongation and cotyledon emergence. The hypocotyl elongates but stops before the cotyledons can emerge. The leaves are alternate and pinnate. The groundnut plant can be erect or prostrate with a well-developed taproot and many lateral roots and nodules. Plants develop three major stems. The flowers are yellow, with male and female parts located on inflorescences resembling spikes. One to several flowers may be present at each node, and they are usually more abundant at lower nodes. Pegs will grow between eight and 14 weeks after pollination and then will turn to the horizontal position to mature as a pod. Pods reach their maximum size after two to three weeks in the soil and maximum oil content between six and eight weeks. Flowering continues during part of the yield formation, but the pods from the late-formed flowers do not reach maturity. In Mali, breeders recognize three variety classes: early varieties maturing in fewer than 90 days (seeding to harvest), intermediate maturing in 90-110 days, and late varieties maturing in more than 110 days. Most are Spanish varieties.

FIGURE 11. TEMPERATURE AND RAINFALL REQUIREMENTS OF GROUNDNUTS AT DIFFERENT STAGES OF DEVELOPMENT



13.4 PRODUCTION PARAMETERS

Soil

Groundnuts grow best in well-drained sandy to sandy loam soils. The crop is adapted to well-drained, loose, friable medium textured soils. Heavy textures cause problems in lifting the crop at harvest. Also, the topsoil should be loose to allow the pegs (on which the fruits are formed) to enter the soil easily. Being a legume, groundnut can fix nitrogen from the air (except in acidic soils, which inhibit development of nitrogen fixing bacteria). However, a pre-planting nitrogen application is often recommended to assure good crop establishment. Phosphorous requirements are 15 to 40 kg/ha and can be a limiting element if not present; potassium requirements are 25 to 40 kg/ha. Excess potassium can cause a decrease in yield. For proper kernel formation and pod-filling, 300 to 600 kg/ha of calcium is required at the beginning of pod formation in the top soil where the fruits are formed. Limestone is used when soil acidity needs to be corrected and gypsum when only the Ca level needs to be increased.

The crop is not tolerant of saline soils, nor of low pH, preferring soils with a pH range of 6 to 7.5. At pH lower than 6, liming may be necessary to avoid aluminum and manganese toxicity.

Water

Sufficient and well-distributed rainfall during the growing season, especially during flowering, pegging, and pod formation stages, is essential for maximum yield and quality of groundnut. For good yields, the crop requires 500 to 1,000 mm of rainfall over the growing period. Overall, the distribution of rainfall is more important than total amount for good yields. Groundnuts are considered to be a moderately drought-tolerant crop, capable of withstanding dry periods during the growing season of 10 to 12 days before yields are affected. As with other crops the plants are particularly susceptible during germination and flowering stages. Some levels of rain required at different stages are: pre-sowing operations – 100 mm; sowing – 150 mm; and flowering and pod development – 400-500 mm. Groundnuts benefit from drier conditions after 60-90 days of plant growth.

In Mali, short-season varieties are targeted in areas receiving 400-600 mm of rainfall and 800-1,200 mm for late maturing varieties, with planting for all varieties recommended after a cumulative 25 mm of rainfall at the start of the season depending on variety types and planting locations (e.g., June 15-30 for early varieties and June 30 to July 15 for late maturing varieties). Groundnuts do not tolerate excessive moisture. Plant mortality will occur with two to four days of inundation.

Temperature

Temperature is a major factor influencing the rate of crop development. The optimum mean daily temperature to grow is 30 °C, with 28-35 °C noted as optimal for vegetative growth in Mali, and 24-33 °C for flowering and fruiting. Growth ceases below 15 °C and above 45 °C. The optimum temperature for the most rapid germination and seedling development is about 30 °C, with ideal germination temperatures in Mali noted at 32-34 °C. A minimum of 100 days with optimum temperatures during the growing season is necessary for successful groundnut crop production.

Adaptability

Climatic conditions such as temperature and rainfall significantly influence the groundnut production. Warm and moist conditions are more favorable than a cool and wet climate, which results in slow germination and seedling emergence, increasing the risk of seed rot and seedling diseases. For best yields, groundnuts require high temperatures and frost-free periods of about 160 days (Cox, 1979; Clifford et al., 1995). They will not attain optimal maturity in regions with fewer heat units during the growing season. Groundnuts are reported to be very sensitive to low temperatures, and seeds are recommended to be planted only when the minimum temperature stabilizes above 18 °C. Germination can reach 95 percent when soil temperatures are in the range of 18 °C to 30°C. The suitable vegetative growth temperature ranges from 20 °C to 30 °C; however, at 33 °C growth can decline by up to 84 percent. A beneficial temperature for flowering and pod formation is about 28 °C. Higher altitudes with cooler climates or cool, off-season production under irrigation are not adequate for groundnut. The crop is grown between 40 °N and 40 °S latitudes. Its growing period is 90 to 115 days for the sequential, branched varieties, and 120 to 140 days for the alternately branched varieties.

Water availability is a critical factor for groundnut development. Planting is recommended in humid warm soils so that the germination processes can develop properly. Research has shown that poor germination occurs in drier soils (Kumar et al., 2012). Rainfall of 400 to 700 mm per year is indicated as the minimum for groundnuts in drier climates (Dreyer et al., 1981). Keating et al. (2003) suggested that

increasing temperature (and not reduced rainfall) will have the most dramatic impact on crop yields for groundnuts.

Vegetative and reproductive phases show a significant response to water availability. However, excessive soil water is harmful, because lack of oxygen in the soil limits the activity of the N-fixing bacteria. This limitation results in an unhealthy growth pattern and yellowing of the leaves. Excessive soil water in heavy soils at harvest can cause the pods to be torn easily from the pegs with the pods remaining in the soil. The flowering period is most sensitive to water deficit, followed by the yield formation period. In general, water deficits during the vegetative period cause delayed flowering and harvest as well as reduced growth and yield. Water deficits during flowering cause flower drop or impaired pollination, whereas water deficits during the yield formation period result in reduced pod weight. The early part of the yield formation period (pod setting) is particularly sensitive to water deficit.

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14.0 SESAME

14.1 BRIEF OVERVIEW OF THE CROP

Sesame (*Sesamum indicum* L.) is one of the oldest cultivated plants in the world. It is one of the most ancient oilseeds crop known to mankind. It was a highly prized oil crop of Babylon and Assyria at least 4,000 years ago. Upon ripening, sesame capsules split, releasing the seed (hence the phrase, "open sesame"). Because of this shattering characteristic, sesame has been grown primarily on small plots that are harvested by hand. Langham's discovery of an indehiscent (non-shattering) mutant in 1943 began the work toward development of a high yielding, shatter-resistant variety. Although researchers have made significant progress in sesame breeding, harvest losses due to shattering continue to limit domestic production. Due to its relatively low productivity, sesame ranks only ninth among the top 13 oilseed crops, which make up 90 percent of the world production of edible oil (Kinman, 1952; Singh, 1969; Weiss, 1971).

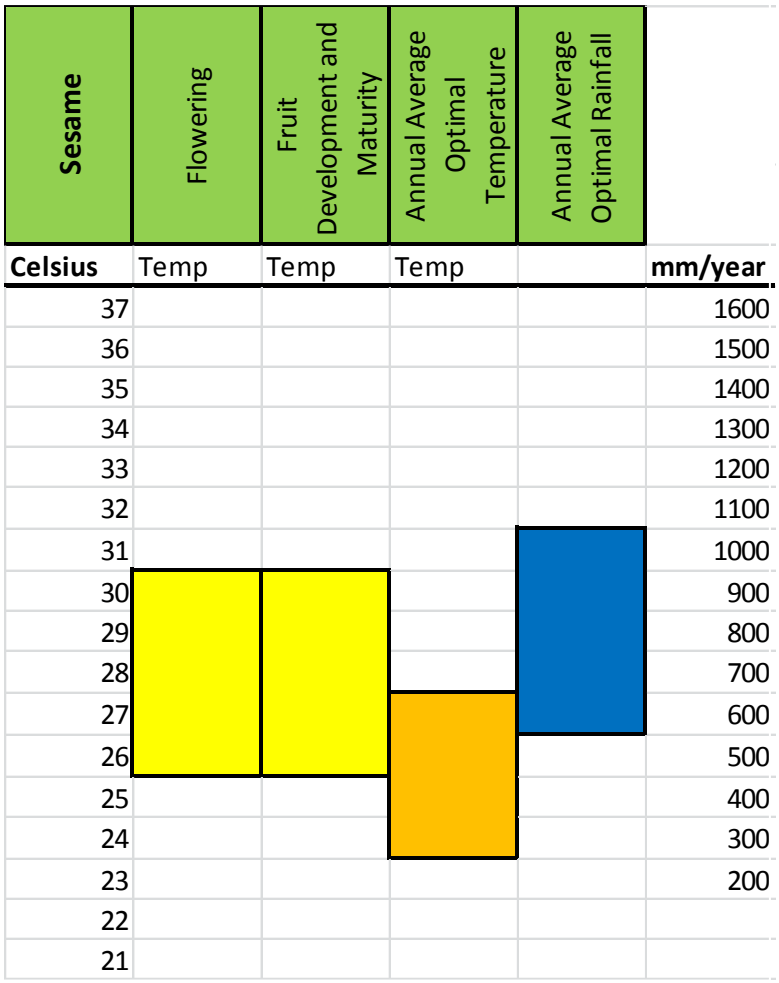
14.2 GEOGRAPHIC DISTRIBUTION AND GENERAL LEVEL OF IMPORTANCE IN THE COUNTRY

Today, India and China are the world's largest producers of sesame, followed by Burma, Sudan, Mexico, Nigeria, Venezuela, Turkey, Uganda, and Ethiopia. Sesame was introduced to the United States in the 1930s. Discussion continues about the exact origin of sesame. It is often asserted that sesame has its origin in Africa and spread early through West Asia, China, and Japan, which themselves became secondary centers of diversity. All the wild *Sesamum* species are found in Africa (Purseglove, 1977). This variability and the importance of sesame in the economies of several African countries further suggest the African continent to be the ultimate center of origin (Pham et al., 2010; Weiss, 1971).

14.3 LIFE CYCLE

Sesame is an annual plant that grows either bush-like or upright depending on the variety. The plant grows to between 60 and 120 cm in height and bears plenty of pink-white color fox-glove type flowers. During floral bud differentiation, sepals arise first, followed by petals and stamens. Then the carpels are initiated, forming a bi-carpelling, binocular superior ovary with several anatropous ovules. Flowers occur in leaf axils on the upper stem and branches, and the node number on the main shoot at which the first flower is produced is a characteristic of the cultivar and highly genetic (Furat and Uzun, 2010). The pod or fruit which is a dehiscent capsule held close to the stem and appears soon containing white, brown or black seeds depending up on the cultivar type, arranged in rows inside. Each pod (2-5 cm in length) is a long rectangular box like capsule with deep grooves on its sides and may contain up to 100 or more seeds. When ripe, the capsule shatters to release a number of small seeds. The seeds are protected by a fibrous hull or skin, which may be whitish to brown or black depending on the variety, with 1,000 seeds weighing some 4 to 8 g. Sesame varieties vary markedly in their branching pattern. Some cultivars have numerous branches, some have only a few, and others have no branches. There is variation for the location of the branches, which can grow from the base or higher up on the plant. The environment and genetics influence the degree of branching.

FIGURE 12. TEMPERATURE AND RAINFALL REQUIREMENTS OF SESAME AT DIFFERENT STAGES OF DEVELOPMENT



14.4 PRODUCTION PARAMETERS

Soil

Sesame can be planted in a wide range of soils, but optimal soil is well-drained, loose, fertile, and sandy alluvial with a pH between 5.4 and 6.75. Very low pH values have a drastic effect on growth, whereas some varieties can tolerate a pH value up to 8.0. Good drainage is crucial, as sesame is very susceptible to short periods of waterlogging. Sesame is intolerant of very acidic or saline soils (Chakraborti and Ghosh, 2010; Hack, 1980; Ramirez et al., 2005; Yol et al., 2010).

Water

The total amount of water required to grow sesame crop ranges from 600 to 1,000 mm, depending on the cultivar and the climatic conditions (Muhamman et al., 2010; Yol et al., 2010). Good harvests can be expected when rainfall of 300-600 mm is optimally spread throughout the vegetation period.

Temperature

Commercial varieties of sesame require 90 to 120 frost-free days. Daytime temperatures of 25 °C to 27 °C are optimal; below 20 °C, growth is reduced. Sesame needs long periods of sunshine and is generally a short-day plant. There are varieties that are unaffected by the length of the day. Sesame needs a constant high temperature; the optimum range for growth, blossoms, and fruit ripeness is 26-30 °C. The minimum temperature for germination is around 12 °C, yet even temperatures below 18 °C can have a negative effect during germination. Pollination and formation of capsules can be inhibited during heat-wave periods with temperatures higher than 40 °C.

Adaptability

S. indicum has a large tap-root that can reach up to 990 cm in length and a dense surface mat of feeder roots, which makes the plant drought tolerant. Moreover, under differing soil and moisture conditions, the plants may develop a stronger tap root or a stronger group of fibrous roots. Roots of short-season single-stemmed cultivars have a more rapid rate of elongation than longer-season branched ones. During each of its development stages, the plant is highly susceptible to water-logging and can therefore only thrive during moderate rainfall or when irrigation is carefully controlled in drier regions. The water requirement can be met from available soil moisture at sowing, rainfall during the growing season, and irrigation. When irrigated, or during summer rain spells, sesame grows better in sandy than in heavy soils. This is due to its sensitivity to high soil moisture contents.

Moisture levels before planting and flowering have the greatest impact on yield. Rainfall late in the season prolongs growth and increases shattering losses. Wind can cause shattering at harvest and is cited as one reason for the failure of commercial sesame production in France.

In regions with strong, hot winds, the plants only form smaller seeds with lower oil content. Sesame is sensitive to strong winds when the main stem is fully grown. Tall varieties should not be planted in regions with strong winds during the harvesting season. The response of sesame to both temperature and day length indicates that it should be only cultivated in the wet season in the tropics or in the summer in the warmer temperate areas (Yol and Uzun, 2012). While there is some variation between cultivars, the base temperature for germination is about 16 °C. Sesame is primarily adapted to areas with long growing seasons and well-drained soils. Initiation of flowering is sensitive to photoperiod and varies among varieties. The oil content of the seed tends to increase with increased photoperiod.

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15.0 CASSAVA

15.1 BRIEF OVERVIEW OF THE CROP

Cassava is a perennial woody shrub with an edible root. This crop grows in tropical and subtropical areas of the world. Cassava originated in tropical America and was first introduced to Africa in the Congo around 1558. Today, it is a dietary staple in much of tropical Africa. It is currently the fourth-most important food source for carbohydrates — after rice, sugarcane, and maize — for more than 500 million people in the developing countries of the tropics and sub-tropics. It is also rich in calcium, vitamins B and C, and essential minerals; however, nutrient composition differs according to variety and age of the harvested crop, as well as soil conditions, climate, and other environmental factors during cultivation. In some areas where the crop is grown, particularly in Africa, young leaves are also harvested and processed for human consumption as a vegetable or as a constituent in a form of sauce eaten along with main staple meals (Hillocks et al., 2002; Lancaster and Brooks, 1982).

15.2 GEOGRAPHIC DISTRIBUTION AND GENERAL LEVEL OF IMPORTANCE

Cassava originated in South America. The Amazon natives utilized cassava in addition to rice, potato, and maize. The Portuguese explorers introduced cassava to Africa during the 16th and 17th centuries through their trade with the African coasts and nearby islands. Africans then spread cassava further, and it is now found in almost all parts of tropical Africa. Today, Nigeria and the Democratic Republic of the Congo are the biggest producers of cassava after Brazil and Thailand. The crop is widely grown as a staple food and animal feed in countries of tropical and sub-tropical areas between 30 °N and 30 °S, with a total cultivated area of more than 13 million hectares – more than 70 percent of it being in Africa and Asia (El-Sharkawy, 1993). Africa now produces more cassava than the rest of the world combined. Cassava production in West Africa has doubled from 25.8 million tons in 1990 to 52.3 million tons in 2004 (Hillocks et al., 2002).

15.3 LIFE CYCLE

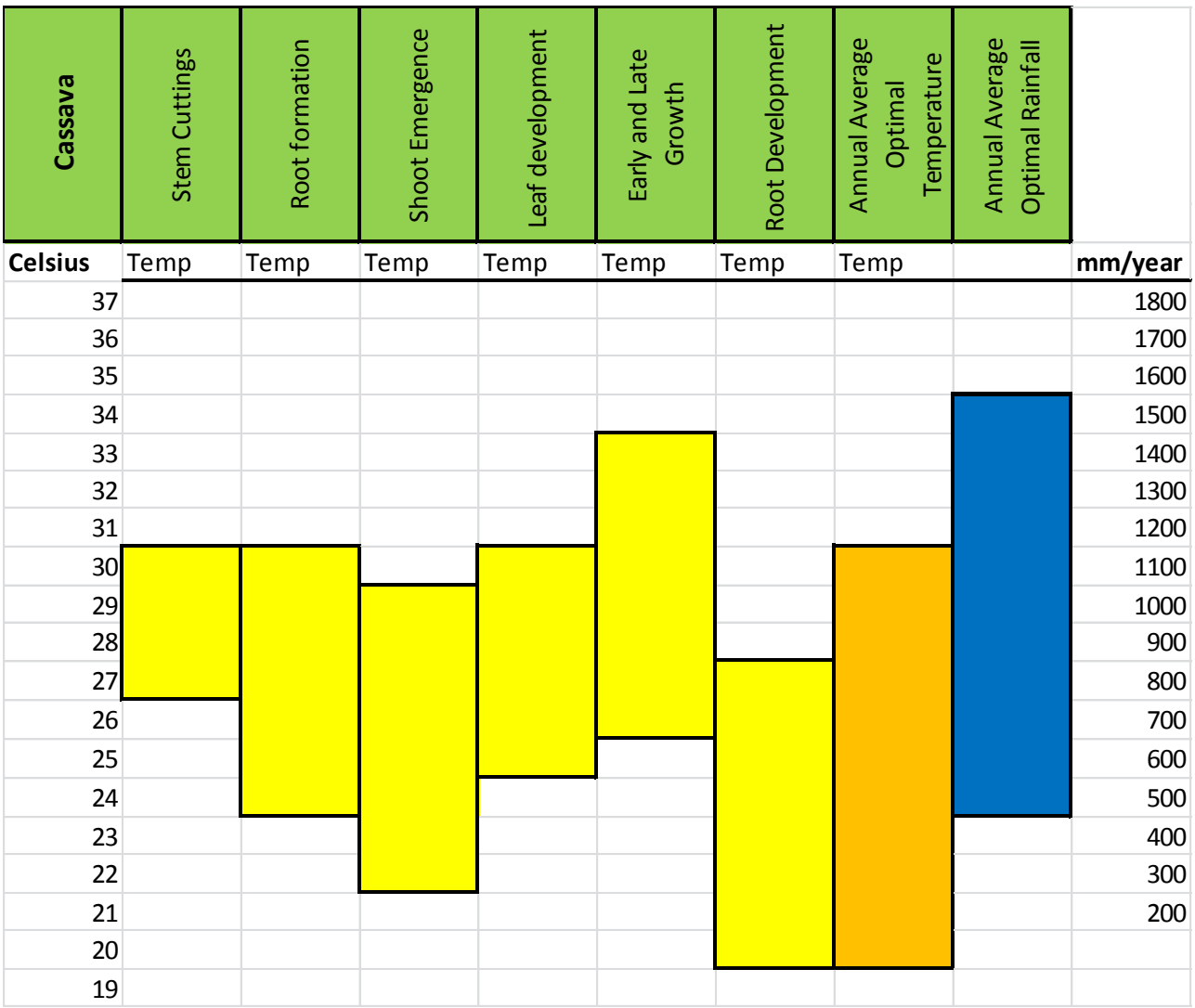
Unlike many other crops, foliage and storage roots of cassava grow simultaneously, and a typical growth pattern of a cassava plant includes two events: dry matter production and vegetative plant growth. Dry matter production implies the accumulation of starch in the roots during the life cycle of the crop. The vegetative stage implies a sequence of growth phases for a crop harvested after 12 months and five growth phases for a crop harvested after 18 months in a location with a short dry season (two to three months). The phases follow:

1. The establishment phase starts at stem cuttings sprout. Leaves form, and vegetative growth begins.
2. The storage root initiation phase begins with the initiation and formation of storage roots that start to compete for nutrients.
3. In the first storage root bulking phase, storage roots enlarge while the leaf area reaches a maximum. When the crop is exposed to a dry period at the latter part of this phase, the leaf area reduces, and crop growth slows down.
4. In the recovery phase, cassava sprouts again and produces a new canopy. Storage root growth and competition for assimilates continue.

5. The second storage root bulking phase is the phase following the recovery stage. The storage roots at this stage are the dominant sink.

The reproductive growth and vegetative growth in cassava takes place in parallel for most of the life cycle. Reproductive growth begins with the first reproductive branching or forking. Inflorescences are formed at the point of division of the main stem into two or three branches. Depending on genotype, forking may occur from six weeks after planting and ranges from sparsely branching to profusely branching types. Forking responds also to environmental stimuli (for example, temperature) and crop management practices such as spacing and planting dates. Branching and formation of inflorescences occur throughout the growth cycle by the subsequent division of the primary branches.

FIGURE 13. TEMPERATURE AND RAINFALL REQUIREMENTS OF CASSAVA AT DIFFERENT STAGES OF DEVELOPMENT



15.4 PRODUCTION PARAMETERS

Soil type

Cassava grows best on light, sandy loams or on loamy sands which are moist, fertile and deep, but it also does well on soils ranging in texture from sands to clays and on soils of relatively low fertility. In practice, it is grown on a wide range of soils, provided that the soil texture is friable enough to allow the development of the tubers. Saline, strongly alkaline, and stony soils, as well as soils with stagnant water, are unsuitable for the cultivation of cassava (Florchinger et al., 2000). Stony soils inhibit the formation of the roots. Cassava can produce an economic crop on soils depleted by repeated cultivation to the extent that they have become unsuitable for other crops. Even on acidic soils that are totally unsuitable for the cultivation of other plants, cassava will still provide a relatively good crop. On very rich soils, the plant may produce stems and leaves at the expense of tubers. In some parts of Africa, freshly cleared forest soils are regarded as highly suitable after they have produced a cereal crop.

Water

The plant produces best when rainfall is fairly abundant, but it can be grown where the annual rainfall is as low as 500 mm but well-distributed and where it is as high as 5,000 mm. The plant can stand prolonged periods of drought in which most other food crops would perish. This makes it valuable in regions where the annual rainfall is low or where seasonal distribution is irregular. In tropical climates, the dry season has about the same effect on cassava that a low temperature has on deciduous perennials in other parts of the world. The period of dormancy lasts two to three months, and growth resumes when the rains begin again. It is a valuable crop where rainfall is uncertain. If moisture availability becomes low, the plant will cease to grow and shed some older leaves, reducing the transpiration surface. When moisture is available again, growth is resumed and the plant produces new leaves.

Temperature

Cassava requires a warm, humid climate and finds the most favorable growing conditions at temperatures between 25 and 29 °C. Temperature is important for development, and all growth stops at about 10 °C. The crop is typically grown in areas that are free of frost all year round. The highest production can be expected in the tropical lowlands, below an altitude of 150 m, where temperatures average 25 °C and 29 °C; however, some varieties grow at altitudes of up to 1500 m. Sprouting is faster at a soil temperature around 28–30 °C but ceases at temperatures higher than 37 °C and lower than 17 °C (Keating and Evenson, 1979).

Adaptability

The development of cassava can be affected by long days (12 hours of light or more) during the early growing period, which can result in reduced yield. Development can also be affected by low temperatures (less than 19 °C) and high temperatures (above 42 °C), which delay growth of storage roots and drought. However, cassava's range of adaptation is wide. Cassava can be grown in areas where the annual rainfall is as low as 500 mm; it can survive in areas with dry seasons as long as eight months. Because of such hardiness, farmers in semiarid areas rely on cassava as a 'famine crop.' Cassava survives under such extreme conditions because the plant conserves water through several mechanisms – for example, at the beginning of a dry season, the production of new leaves is reduced, and excessive leaves are shed. However, cassava has the ability to regenerate new leaves while other leaves are shed. Apex mortality also contributes to a reduction in leaf area during the dry season. The decrease in leaf

area reduces canopy transpiration. In addition, cassava stomata are highly sensitive to water vapor differential – high stomatal resistance reduces water loss during the dry season. The decreased leaf area and stomatal closure also reduce photosynthesis and root yield.

Additional mechanisms ensure that drought does not seriously affect plant growth. For example, cassava plants have a photosensitive mechanism that allows leaves to maximize interception of sunlight when transpiration is low. For example, in the morning and late afternoon, leaves turn to the direction of the sun by movement of petioles. It also exhibits a drooping mechanism that causes the leaves to roll and droop when transpiration rates from leaves are too high. A rolled canopy conserves moisture in its microenvironment. The increased partitioning of dry matter to the fibrous root system during periods of drought improves access to soil moisture and absorption capacity of roots (Luo and Huang, 2012).

At high temperatures (24-30 °C), leaf development takes two weeks; at lower temperatures (15-22 °C), leaf development takes three to five weeks. Leaf size increases up to four to five months after planting, and then decreases. Adverse environmental conditions, such as low nutrient availability, water stress, and low temperatures, reduce leaf size. Flowering may be strongly influenced by environmental factors. A particular clone may produce no flowers in one environment, produce only aborted flowers or fail to produce viable seed in another environment, and yet flower profusely and set seed in a third environment. Seed germination is favored by dry heat and complete darkness. Germination takes place most often when temperatures exceeded 30 °C for part of the day, with a mean temperature of at least 24 °C. They suggest that an alternating temperature regime of 30 °C for eight hours and 38 °C for 16 hours for at least 21 days is the most appropriate for cassava seed viability under laboratory conditions.

Good drainage is essential for cassava; the crop does not tolerate water logging. High irradiance is preferred. Cassava growth and yield are reduced drastically on saline soils and on alkaline soils with a pH higher than 8.0. The optimum pH is between 5.5 and 7.5, but cultivars are available that tolerate a pH as low as 4.6 or as high as 8.0. Reasonably salt-tolerant cultivars exist. Very fertile soils promote excessive foliage growth at the expense of storage roots.

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16.0 SWEET POTATO

16.1 BRIEF OVERVIEW OF THE CROP

Sweet potato is a root crop that is native to the tropics and requires warm days and nights for optimum growth and root development. Sweet potato is considered a food security crop, mainly because of its reliable yields. This crop is easily propagated and grows with no inputs on poor soils under a broad range of rainfall patterns. Worldwide, sweet potato is the sixth-most important food crop after rice, wheat, potatoes, maize, and cassava. More than 105 million metric tons are produced globally each year, 95 percent of which are grown in developing countries. The importance of sweet potato as a food crop is growing rapidly in some parts of the world. In Sub-Saharan Africa, it is outpacing the growth rate of other staples. Sub-Saharan Africa produces more than 7 million tons of sweet potato annually, about 5 percent of global production. It should be noted that 50 percent of global supply is destined for human consumption and 30 percent for animal feed, with the remainder being used for seed and other agricultural applications (CIP, 1994; Woolfe, 1992).

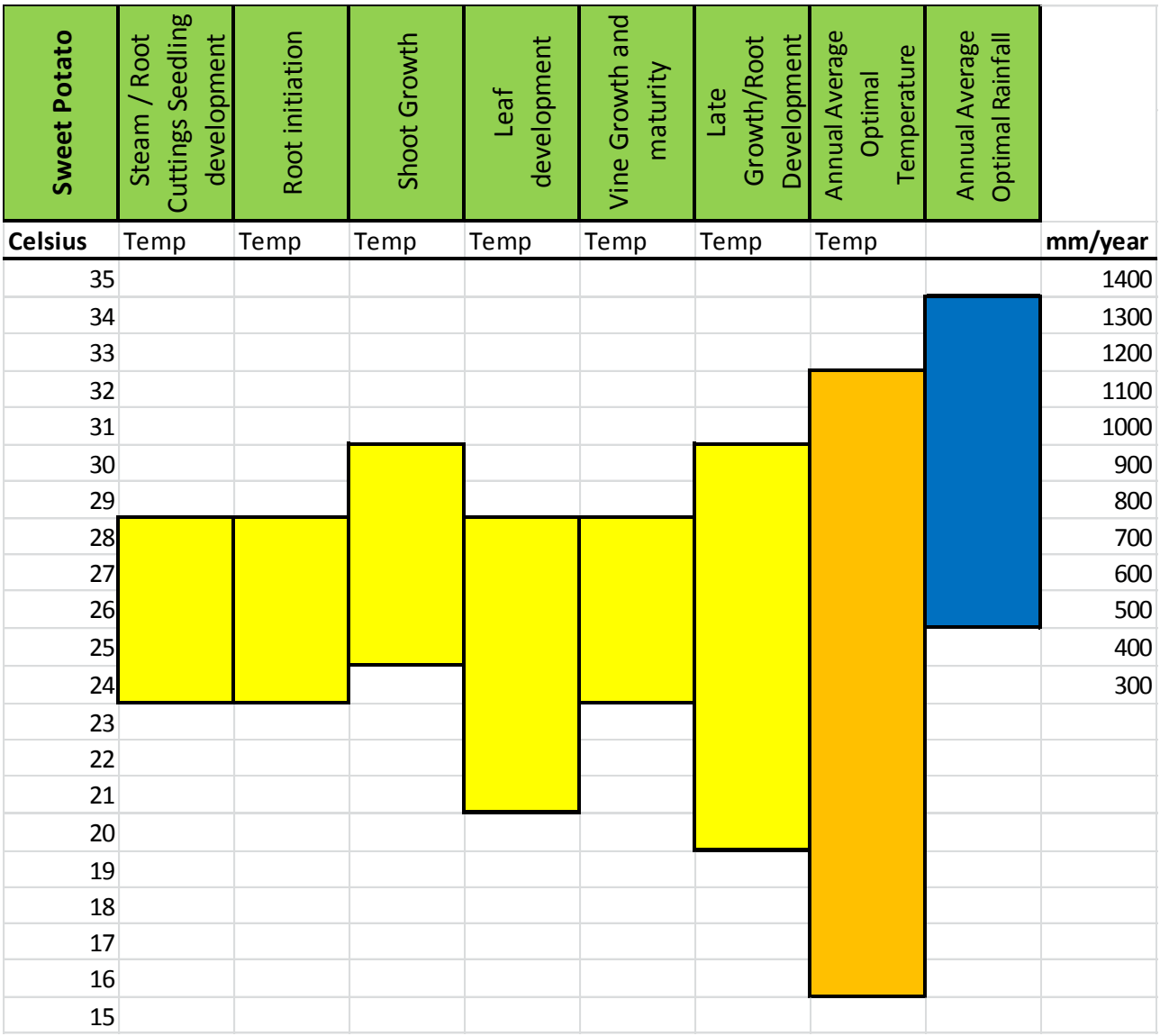
16.2 GEOGRAPHIC DISTRIBUTION AND GENERAL LEVEL OF IMPORTANCE

Sweet potato is one of the world's most important food crops in terms of human consumption, particularly in Sub-Saharan Africa, parts of Asia, and the Pacific Islands. First domesticated more than 5,000 years ago in Latin America, it is grown in more developing countries than any other root crop. Most sweet potato is grown in the temperate zone; 70 percent of the area is between 20 °N and 40 °N. Sweet potato is highly concentrated in some areas, notably in the lowlands of China and in the mid-elevations of the Lake Victoria area in Africa. About half the global sweet potato area occurs where it is an obligatory seasonal crop because of low temperatures during part of the year (Hijmans et al., 2001).

16.3 LIFE CYCLE

Sweet potato can grow at altitudes ranging from sea level to 2,500 m. It requires fewer inputs and less labor than other crops such as maize. Sweet potato develops by vegetative propagation. Farmers take stem cuttings from the vines, which then root and form new storage roots. In some colder climates, where vines do not develop well, producers will plant roots. Botanical seed is used in breeding programs. The plant's vine system expands rapidly horizontally on the ground, and planting material can be easily and quickly multiplied from very few roots. Large, fleshy, edible storage roots are formed on the underground stem nodes. Latex occurs in all parts of the plant. Roots mature on average about four months after planting, with some early maturing varieties ready at two months. Storage roots vary in shape and size according to the cultivar and type of soil where they are grown. Skin color can range from whitish-cream to yellow-orange and pink to red-purple and very dark purple. Flesh color can be white, cream, yellow, orange, or purple. Some cultivars have a base flesh color with specks or striations in a darker color.

FIGURE 14. TEMPERATURE AND RAINFALL REQUIREMENTS OF SWEET POTATO AT DIFFERENT STAGES OF DEVELOPMENT



16.4 PRODUCTION PARAMETERS

Soil

Sweet potatoes grow best in loamy soils. The best soil types are well-drained, fine sandy, or clay loams. Light, loamy soils usually result in roots with better shapes than those grown in heavy or clay soils, which result in rough, irregular roots. High (2 percent or more) organic soils can reduce production. Coarse, deep, sandy soils are generally low in fertility, subject to water stress, and require irrigation and fertilizer to grow a good crop. Poor aeration caused by poor drainage decreases yields. With severely impeded drainage, susceptible cultivars can produce either souring (tissue breakdown of the storage roots) or water blisters (enlargement of lenticels on the periderm) if the drainage problem is less severe. Sweet potatoes will grow at a soil pH of 4.5 to 7.5, but 5.8 to 6.2 is optimal.

Water

Sweet potatoes grow best with a well-distributed annual rainfall of 600-1,600 mm during the growing season. The presence of dry weather favors the formation and development of storage roots. Sweet potato is relatively drought tolerant; however, it cannot withstand long periods of drought. The yield is considerably reduced if drought occurs at about the time of planting or root initiation. The crop requires almost 25 mm of water per week uniformly distributed throughout the growing season for highest yields. Conditions after the sixth to seventh week of planting are particularly critical to the development of storage roots.

Temperature

Temperatures above 25 °C facilitate good growth; when temperatures fall below 12 °C or exceed 35 °C, growth is retarded and yield is impacted. In Senegal, sweet potato mostly grows in marginal conditions. The optimum temperature range to achieve sweet potato production is indicated between 21 and 29 °C. The storage roots are sensitive to changes in soil temperature and, depending on the stage of root development, slight potential for decrease in productivity can be expected.

Adaptability

Sweet potatoes can be grown where there is a long frost-free period with warm temperatures in the growing season. Most cultivars require a minimum frost-free period of 100-125 days. Sweet potato varieties grown in Africa are diverse landraces, selected for adaptation to local environments and for taste. Colors such as white, cream or yellow- fleshed varieties are the norm, and orange-fleshed varieties are still relatively rare. The local standards expect a dry-matter content ranging from 28 to 35 percent. Maturity is variable (three to eight months), and there is a strong preference for varieties that produce vigorous vines that can survive the dry season. Sweet potato is produced all year round in Senegal, and production conditions are best toward the end of the dry season (March-May). However, yield can be adversely affected by cold weather.

Sweet potatoes can adapt very well to warm climates and grow best during summer. Most developmental stages can counter climate change adequately. Ringler et al. (2010) indicate, however, that sweet potato could be, after wheat, the crop most affected by climate change in Sub-Saharan Africa. Significant levels of sunshine and temperatures below 13 °C for several days or 3 °C for one day can damage sweet potato plants. Remarkably, Biswas et al. (1996) found that increases in atmospheric CO_2 actually can lead to increases in sweet potato growth and yield, which could be a positive impact of climate change in the future.

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ANNEX I. ADDITIONAL REFERENCES CONCERNING PLANT WATER REQUIREMENTS AND SOIL PARAMETERS

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ANNEX II. WATER REQUIREMENTS BY PHENOPHASE

Figures in this annex indicate estimates of moisture (not rainfall) required at each stage of development. The values are drawn from modeling studies and controlled experiments and are recalculated using coefficients based on Sahelian evapo-transpiration rates. They take into account plant ability to uptake water, levels of transpiration, and the rate of evaporation; however, they do not take into account other interactions such as those with soil, slope, and surrounding vegetation.

FIGURE AII.1 WATER REQUIREMENTS BY PHENOPHASE, MAIZE

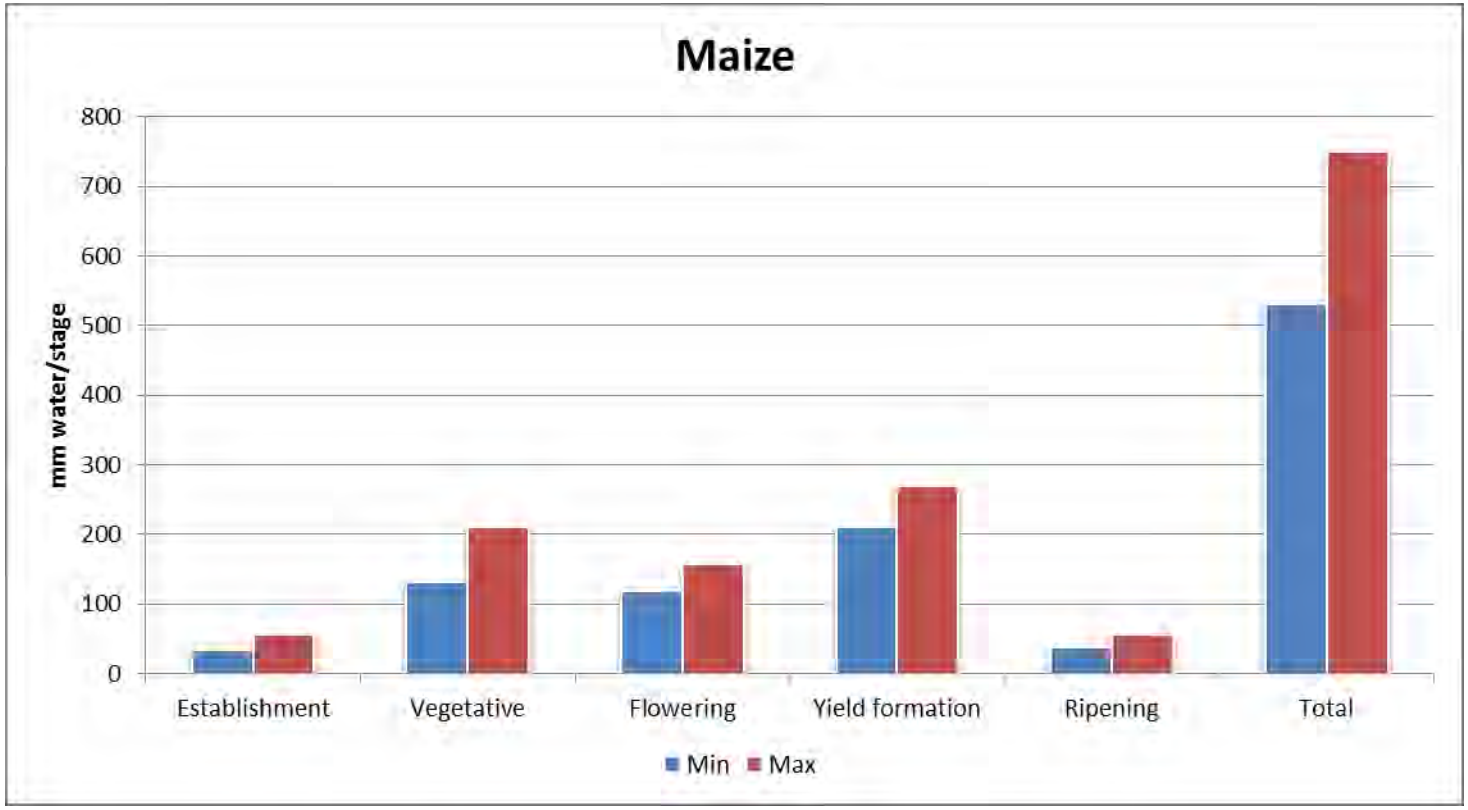


FIGURE AII.2 WATER REQUIREMENTS BY PHENOPHASE, PEARL MILLET

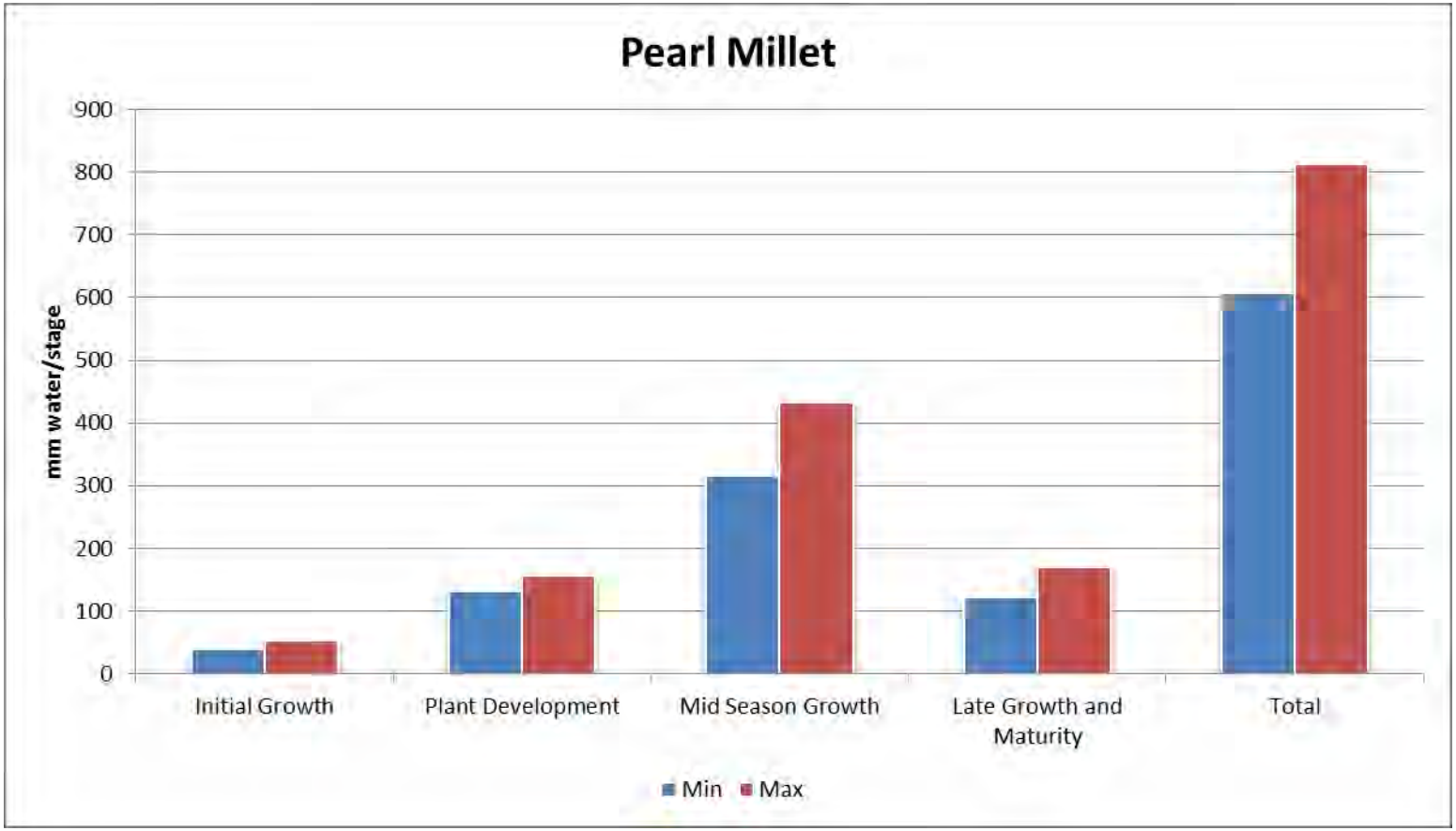


FIGURE AII.3 WATER REQUIREMENTS BY PHENOPHASE, RICE

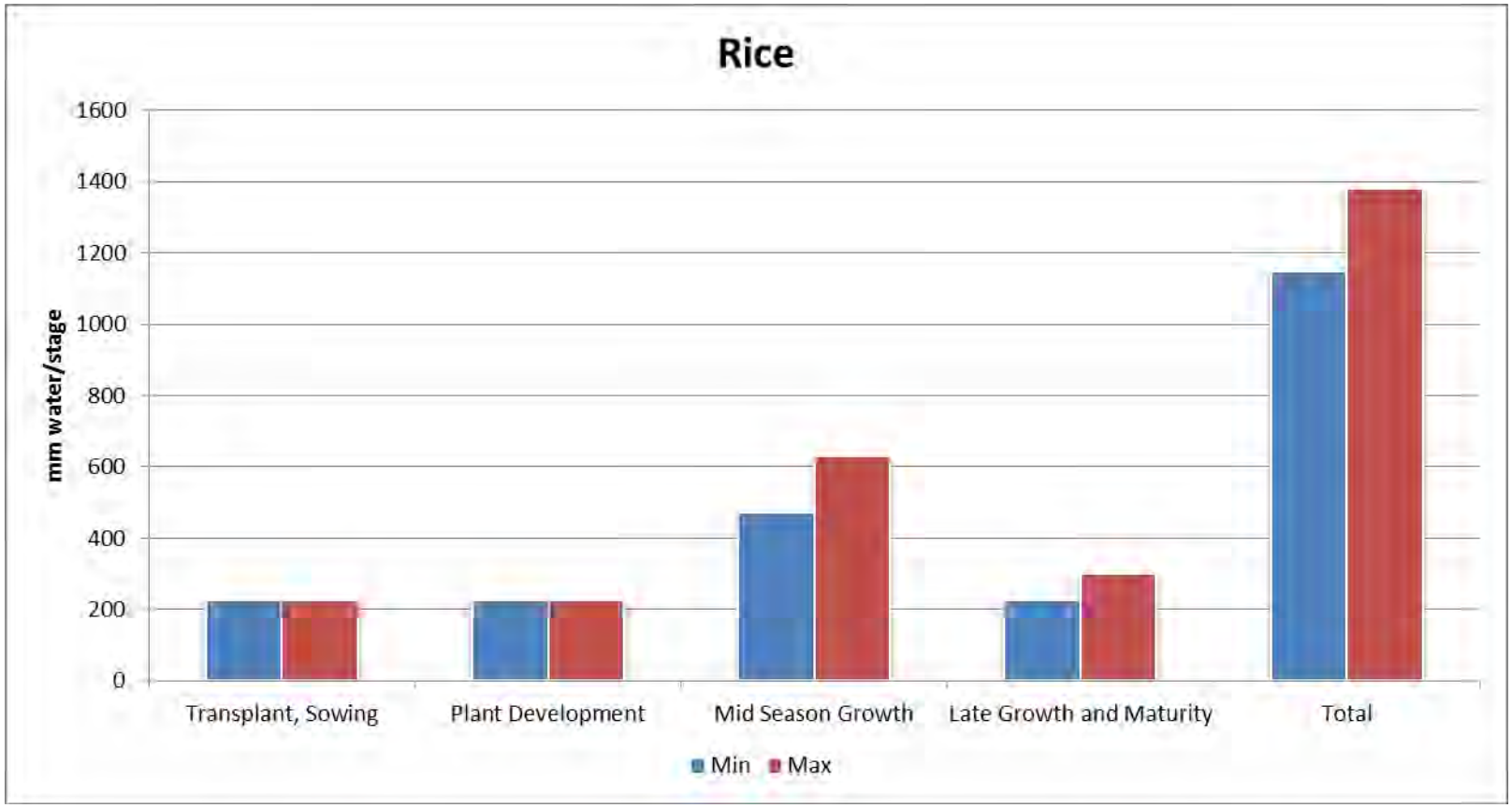


FIGURE AII.4 WATER REQUIREMENTS BY PHENOPHASE, SORGHUM

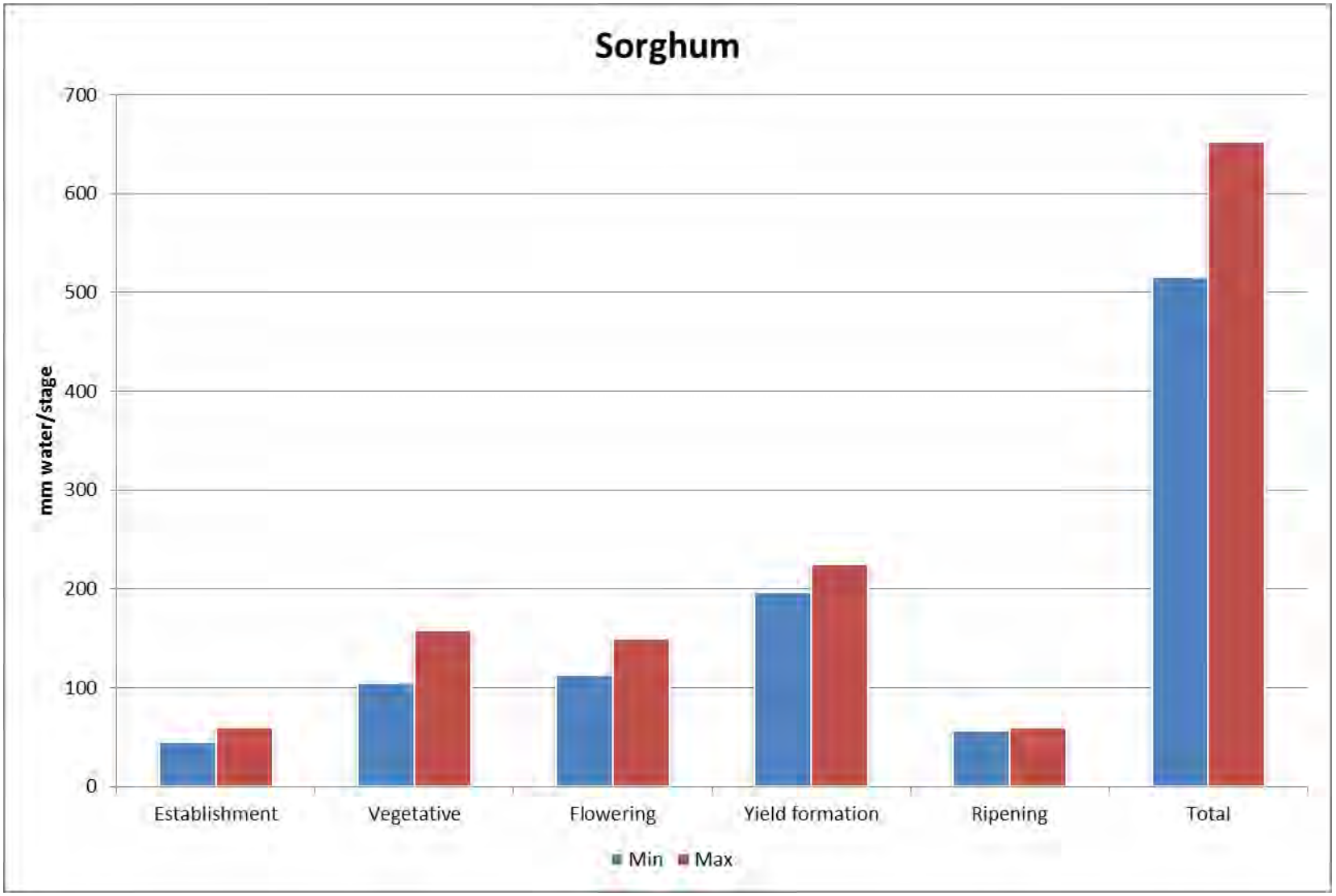


FIGURE AII.5 WATER REQUIREMENTS BY PHENOPHASE, COTTON

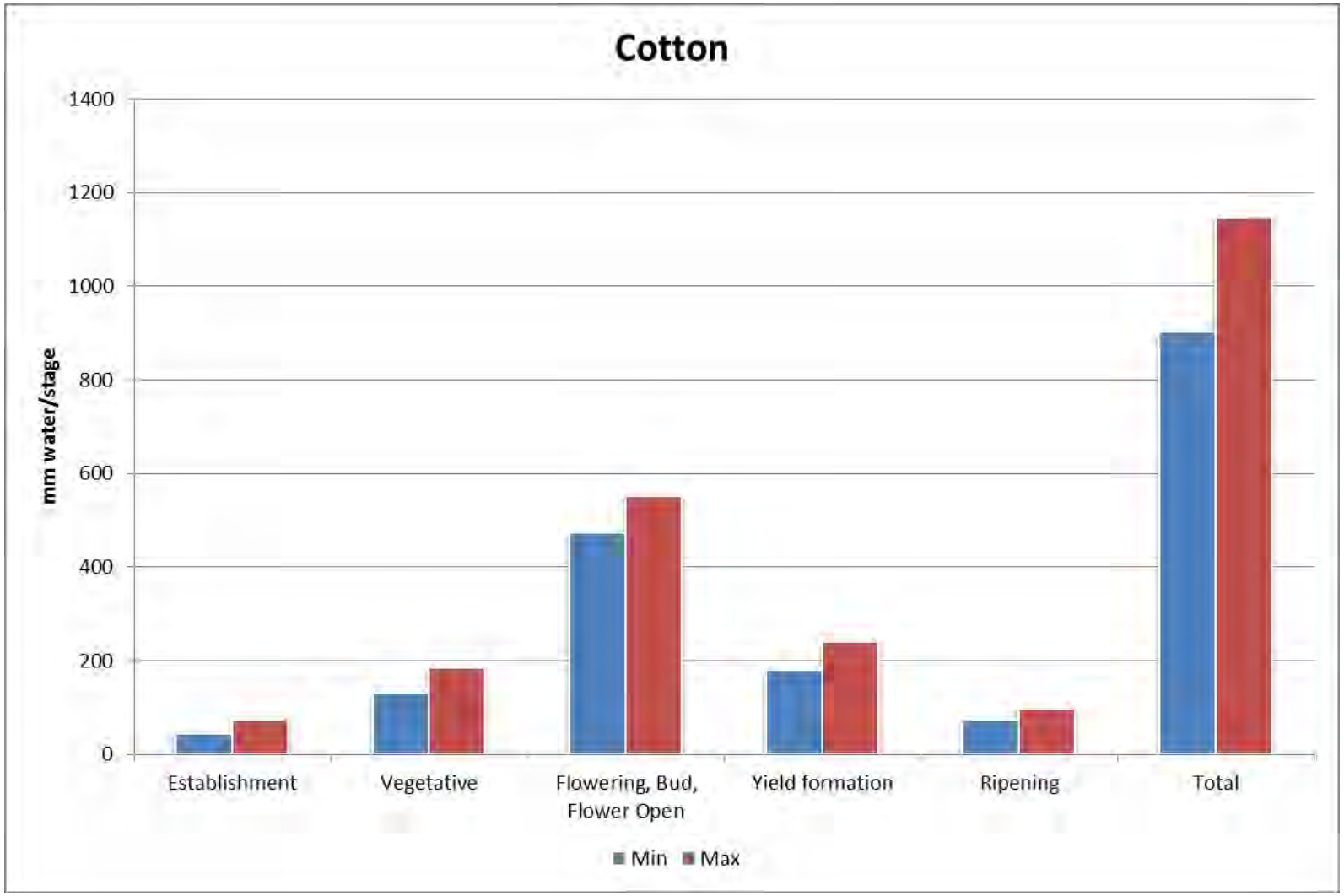


FIGURE AII.6 WATER REQUIREMENTS BY PHENOPHASE, MANGO

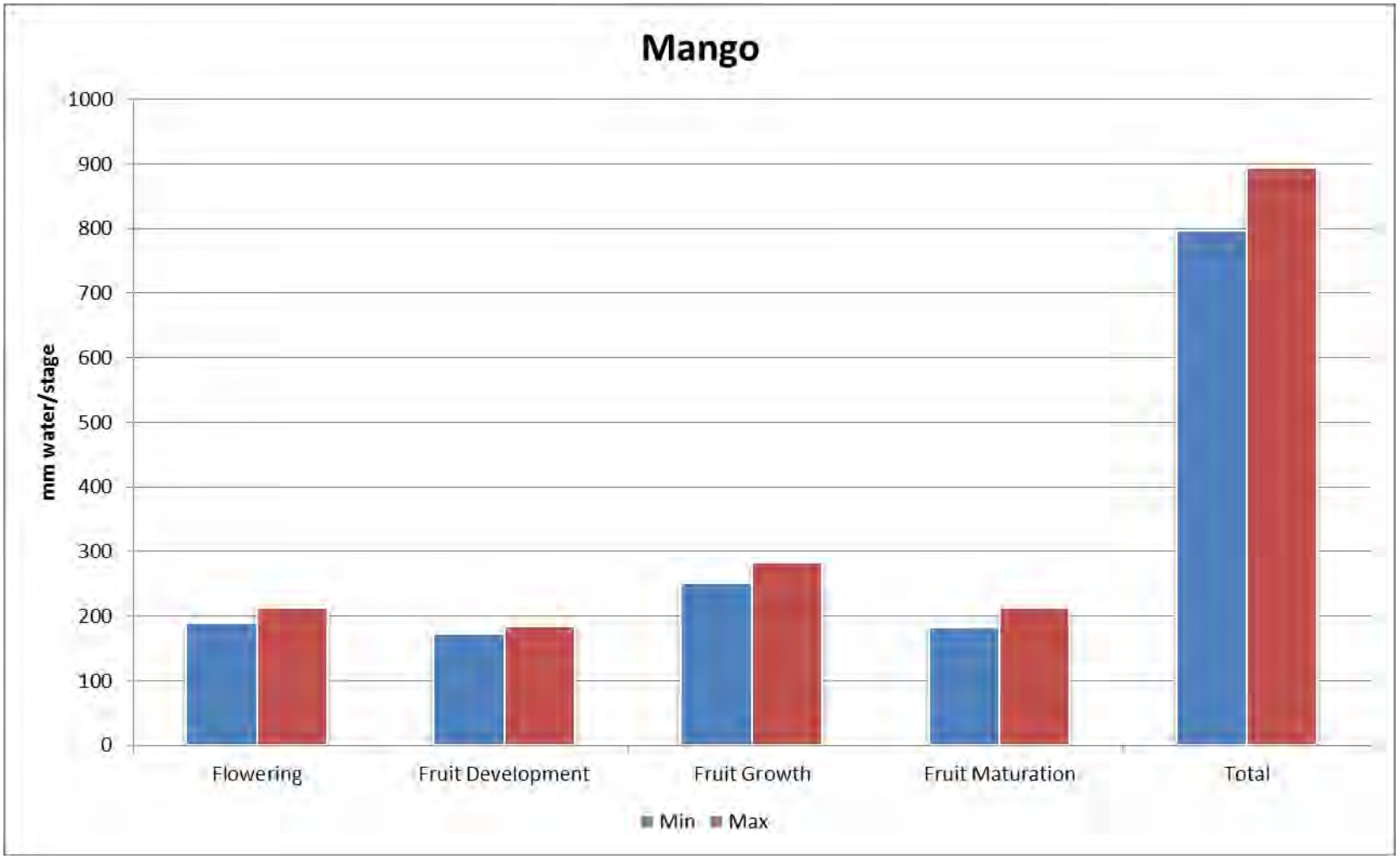


FIGURE AII.7 WATER REQUIREMENTS BY PHENOPHASE, COWPEA

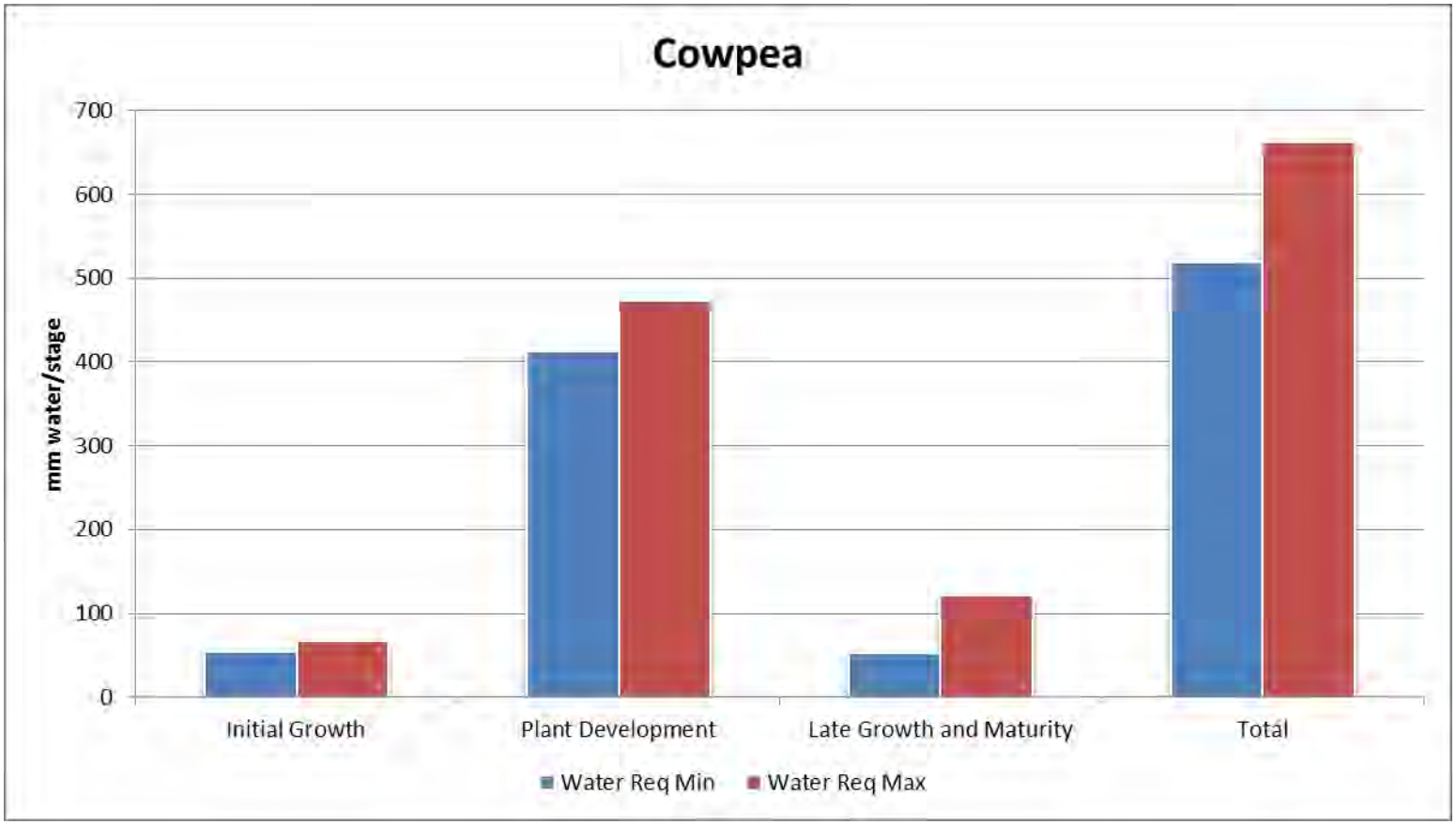
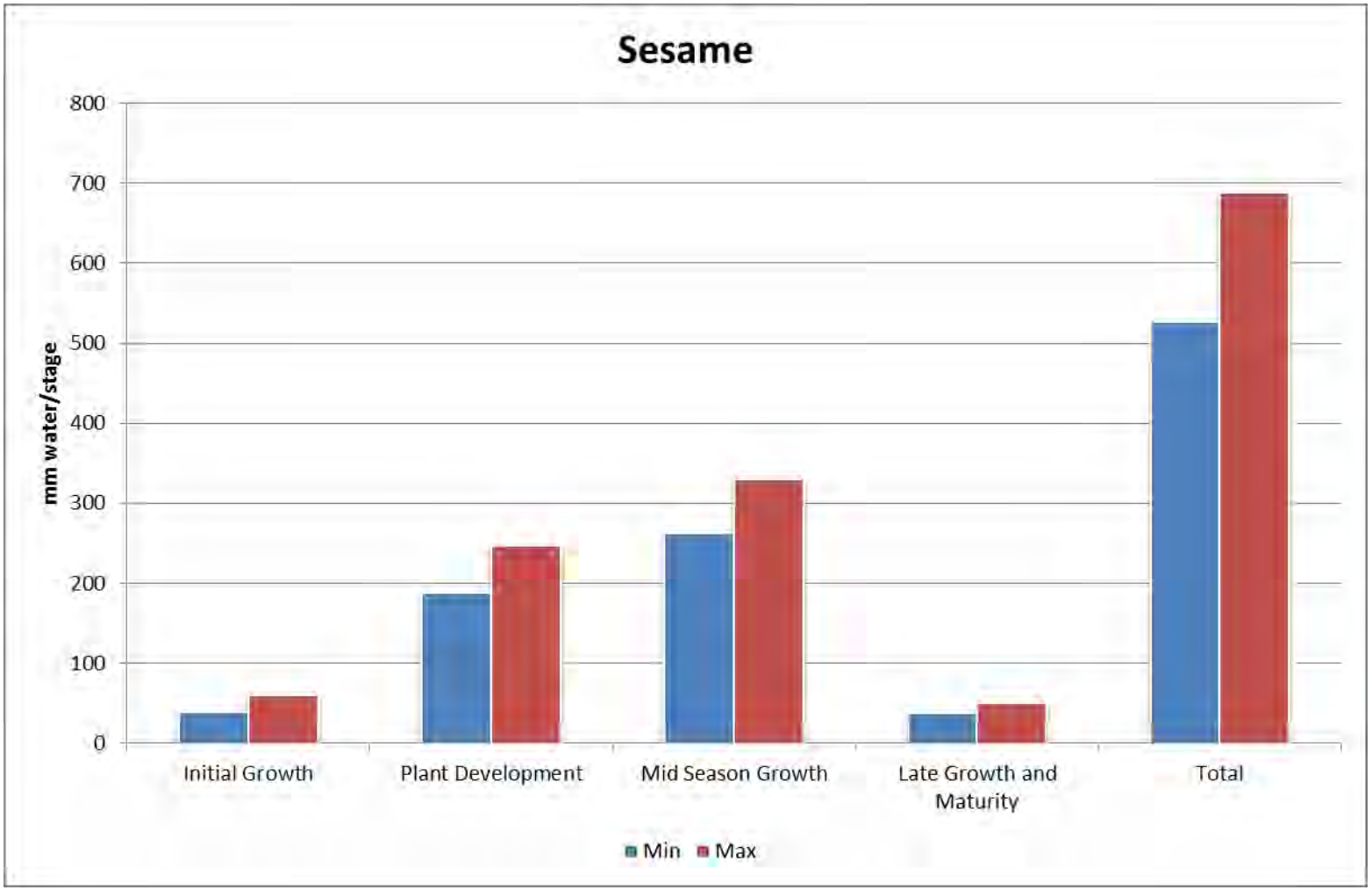
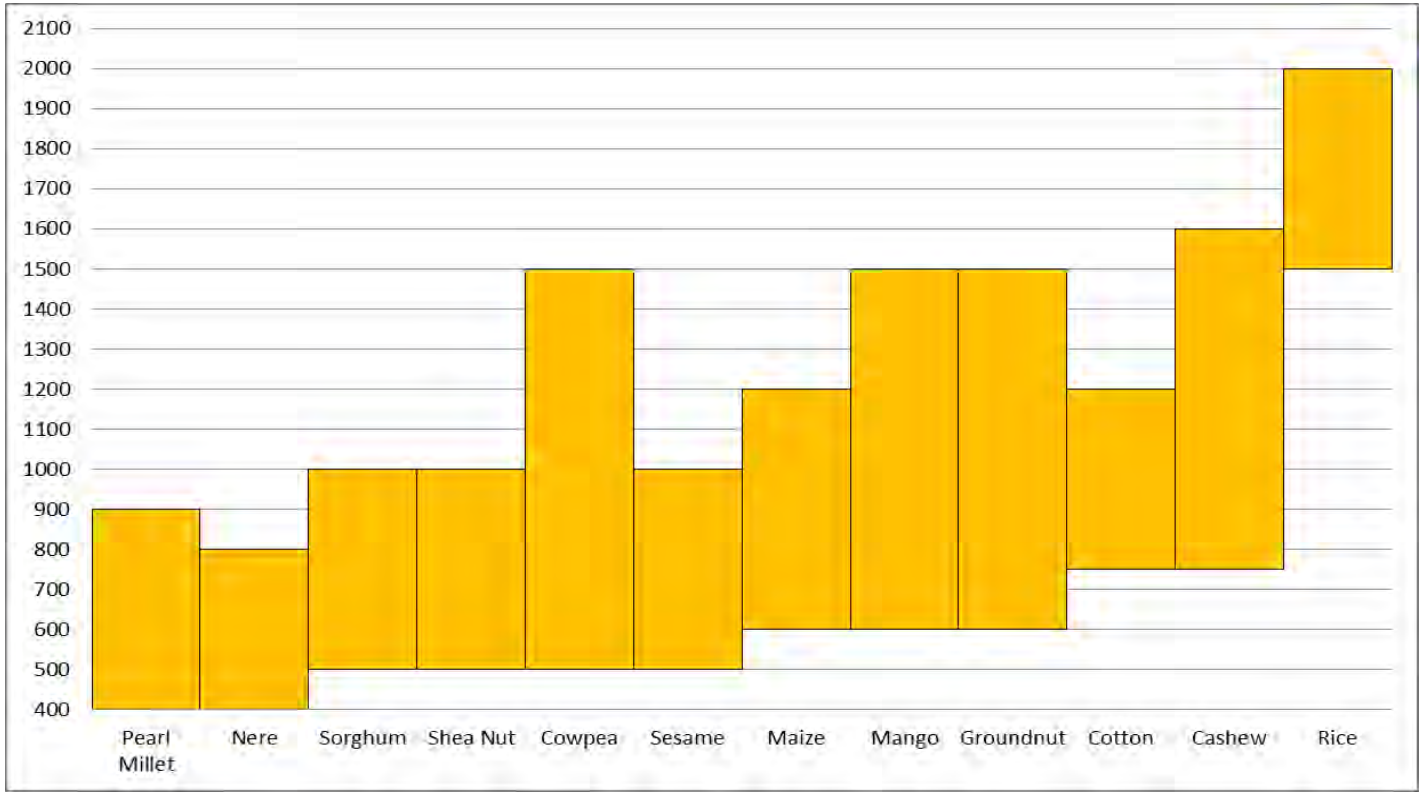


FIGURE AII.8 WATER REQUIREMENTS BY PHENOPHASE, SESAME



ANNEX III. OPTIMAL ANNUAL RAINFALL REQUIREMENTS

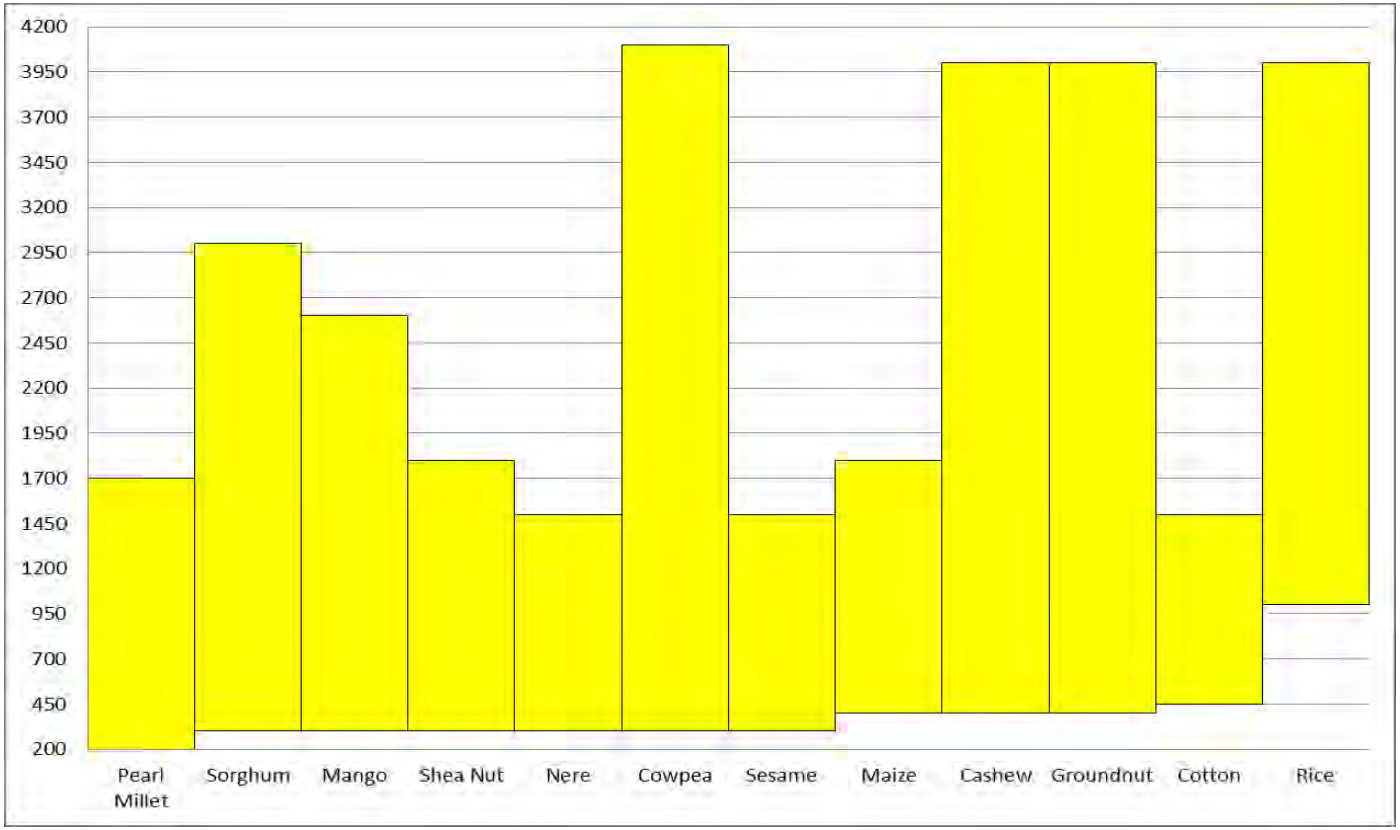
FIGURE AIII.1 OPTIMAL ANNUAL RAINFALL MINIMUM AND MAXIMUM REQUIREMENTS IN MILLIMETERS PER YEAR



Source: EcoCrop

ANNEX IV. ABSOLUTE ANNUAL RAINFALL LIMITS

FIGURE AIV.1 ABSOLUTE ANNUAL RAINFALL MINIMUM AND MAXIMUM LIMITS IN MILLIMETERS PER YEAR



Source: EcoCrop

ANNEX V. SELECTED SOIL PARAMETERS FOR PROFILED CROPS

TABLE AV.1 SOIL PARAMETERS

CROPS			Maize	Pearl Millet	Rice	Sorghum	Cotton	Cashew	Mango	Shea Nut	Nere	Cowpea	Groundnut	Sesame
Soil ph	Optimal	Min	5.0	5.0	5.5	6.0	6.0	4.5	5.5	6.0	4.5	5.5	5.5	5.5
		Max	7.0	6.5	7.0	7.0	7.5	6.5	7.5	7.0	5.5	7.5	6.5	7.5
	Absolute	Min	4.5	4.5	4.5	5.0	5.0	3.8	4.3	5.5	4.0	4.0	4.5	4.5
		Max	8.5	8.3	9.0	8.5	9.5	8.7	8.5	8.0	6.0	8.8	8.5	8.0
Soil Depth (cm)	Optimal	Min	50	>150	50	50	>150	>150	>150	>150	>150	50	50	>150
		Max	150	>150	150	150	>150	>150	>150	>150	>150	150	150	>150
	Absolute	Min	20	50	20	50	50	50	50	50	20	20	50	50
		Max	150	150	50	150	150	150	150	150	50	50	150	150

CROPS		Maize	Pearl Millet	Rice	Sorghum	Cotton	Cashew	Mango	Shea Nut	Nere	Cowpea	Groundnut	Sesame
Soil Type/Texture	Optimal	clay, sandy, loam	sandy, loam	wide	sand, loam	heavy, loam	loam, clay	loam, clay	sandy, loam, clay, wide, organic	loam, clay	loam, clay	loam	loam
	Absolute	clay	sandy, loam	wide	sandy, loam, clay	sandy, loam, clay, organic	sandy, loam, clay	sandy, loam, clay	sandy, loam, clay wide, organic	loam, clay	sandy, loam, clay, wide	sandy, loam, clay, organic	sandy, loam, clay
Soil Fertility	Optimal	high	moderate	high	moderate	moderate	moderate	moderate	low	moderate	moderate	high	moderate
	Absolute	low	low	moderate	low	moderate	low	low	low	low	low	moderate	low

CROPS		Maize	Pearl Millet	Rice	Sorghum	Cotton	Cashew	Mango	Shea Nut	Nere	Cowpea	Groundnut	Sesame
Soil Salinity (ds/m)	Optimal	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4
	Absolute	4 to 10	4 to 10	<4	4 to 10	4 to 10	<4	<4	<4	<4	<4	<4	<4
Soil Drainage	Optimal	well (dry spells)	well (dry spells)	poorly (saturated >50% of year)	well (dry spells)	well (dry spells)	well (dry spells)	well (dry spells)	well (dry spells)	well (dry spells)	well (dry spells)	well (dry spells)	well (dry spells)
	Absolute	well (dry spells)	well (dry spells), excessive (dry/moderately dry)	poorly (saturated >50% of year)	poorly (saturated >50% of year), well (dry spells), excessive (dry/moderately dry)	well (dry spells)	well (dry spells), excessive (dry/moderately dry)	well (dry spells), excessive (dry/moderately dry)	well (dry spells), excessive (dry/moderately dry)	well (dry spells)	well (dry spells), excessive (dry/moderately dry)	well (dry spells)	well (dry spells), excessive (dry/moderately dry)

ANNEX VI. REVIEW OF PHENOLOGICAL CHARACTERISTICS IN COMMON CROP MODELS

The table below provides an overview of 21 crop models organized by the crops for which they are designed, although some are applicable across several crops. Crops in this review include maize, sorghum, cowpea, sweet potato, pearl millet, groundnut, and cotton. For each model, columns present the name, phenological parameters, general characteristics, and type of model. A final column includes references for further information on the model. A larger amount of more specific information is available concerning the major crops such as maize. Less information is available concerning relatively minor crops such as sweet potato, and in some cases the models are quite rudimentary.

Phenological stages are commonly stored in separated modules where the data is collected for a given set of plant units (genotypes) that are characterized in the context of their developmental processes. Most often, this data consists of measurements of the growing periods in a given phenological period. These data points (measurements) are used to build the predictions in the models in conjunction with additional modules that include climate variables, soil data, etc. A review of the literature describing these models suggests that, in most cases, the most effective method to increase the model's skill at prediction is through greater accuracy and detail of the phenological information used. For example, greater specificity regarding the plant materials grown in target regions and improved climate data produce more accurate predictions. However, improvement of modeling of crops in African countries will also require additional sets of data currently not available, such as soil patterns in a broad range of geographies and systems.

TABLE AVI.1 PHENOLOGICAL CHARACTERISTICS, MAIZE

MAIZE				
Crop Model	**General Description of the Model**	**Type of Model**	**Phenological Parameters**	**References**
HYBRID-MAIZE	**Hybrid-Maize** is a computer program that	Process based	Four growth stages are slightly modified from CERES-Maize	

MAIZE				
Crop Model	**General Description of the Model**	**Type of Model**	**Phenological Parameters**	**References**
	simulates the growth of a corn crop (*Zea mays* L.) under non-limiting or water-limited (rain-fed or irrigated) conditions based on daily weather data.		(Jones and Kiniry, 1986), in particular the merger of stages 1 and 2 into one stage. The four periods used in the Hybrid-Maize model follow: • Stage 1: Emergence to tassel initiation • Stage 2: Tassel initiation to silking • Stage 3: Silking to effective grain filling • Stage 4: Effective grain filling to physiological maturity <u>Additional inputs</u> • Leaf Growth and Senescence Growth in both number and total area until flowering. • Stem and Cob Growth It assumes that stem growth starts from the beginning of Stage 2 until the end of Stage 3, when effective grain filling starts. • Root Growth	University of Nebraska-Lincoln. (2004). *Field Crops Research, 87,* 131–154. Jones, C.A., & Kiniry, J.R. (1986). CERES-Maize: A Simulation. Model of Maize Growth and Development. Texas A&M University Press: College Station, TX.

MAIZE				
Crop Model	**General Description of the Model**	**Type of Model**	**Phenological Parameters**	**References**
			Root growth from emergence until it stops, shortly after silking. • Grain Filling Grain filling is considered an active process in which temperature controls the daily filling rate.	
Crop Estimation through Resource and Environment Synthesis (CERES)-MAIZE	CERES-Maize is a crop specific model aimed at dynamic simulation of maize growth as affected by climatic, plant, and soil properties along with some farm management practices.	Process based	General growing periods considered in the CERES model phonological stages follow: • Sowing • Emergence • Tasselling • Silking • Maturity More specifically, phenology in this model considers nine stages: 1. Sowing 2. Germination 3. Emergence 4. Emergence to End of Juvenile 5. End of Juvenile to Tassel Initiation	Carberry, P.S., Muchow, R .C. & McCown, R.L. (1989). Testing the CERES-Maize Simulation Model in a Semi-arid Tropical Environment. *Field Crops Research, 20*: 297-315. Soler, C. M. T., Sentelhas, P. C., & Hoogenboom, G. (2007). Application of the CSM-CERES-Maize model for planting date evaluation and yield forecasting for maize grown off-season in a subtropical environment. *Eur. J. Agron. 27,* 165–177.

MAIZE				
Crop Model	**General Description of the Model**	**Type of Model**	**Phenological Parameters**	**References**
			6. Tassel Initiation to End of leave growth and silking 7. Silking to begin of effective grain filling 8. Effective grain filling 9. End of grain filling to physiology mature	
FAO AQUACROP[1]	The model predicts crop production under different water-management conditions (including rain-fed and supplementary, deficit and full irrigation) under present and future climate change conditions.	Process based	AquaCrop reports the following phenological stages in the model: • Emergence and Establishment • Vegetative (stem elongation) • Flowering (Tassel and Silk development) • Yield Formation • Ripening It also measures development of the root zone (minimum and maximum rooting depth, root expansion).	Hsiao, T. C., Heng, L., Steduto, P., Rojas-Lara, B., Raes, D., & Fereres, E. (2009). AquaCrop-the FAO crop model to simulate yield response to water: III. parameterization and testing for maize. *Agronomy Journal, 101*(3), 448-459. FAO. (2010). Reference Manual, Annexes – AquaCrop, January 2010.

[1] AquaCrop is a general model, in that it is meant for a wide range of herbaceous crops, including forage, vegetable, grain, fruit, oil, and root and tuber crops.

MAIZE				
Crop Model	**General Description of the Model**	**Type of Model**	**Phenological Parameters**	**References**
			Temperature standards follow: • Base temperature (° C) = 8 • Upper Temperature (° C) = 30 • Minimum air temperature below which pollination starts to fail (cold stress) (° C) = 10 • Maximum air temperature above which pollination starts to fail (heat stress) (° C) = 40	
Cropping Systems Simulation Model (CROPSYST)	CropSyst is a multi-year, multi-crop, daily time step crop growth simulation model, designed to serve as an analytical tool to study the effect of cropping system management on crop productivity and the environment.	Process based	Phenological growth stages in CropSyst: • Emergence • Maximum root depth (usually about the same time as "end of vegetative growth") • End of vegetative growth • Beginning of senescence (usually slightly later than the "end of vegetative growth") • End of flowering • Beginning of grain filling • Physiological maturity	Stöckle, C.O., Martin, S., & Campbell, G.S. (1994). CropSyst, a cropping systems model: water/nitrogen budgets and crop yield. *Agric. Syst., 46,* 335-339.

MAIZE				
Crop Model	**General Description of the Model**	**Type of Model**	**Phenological Parameters**	**References**
Agricultural Production Systems Simulator (APSIM)-MAIZE	APSIM is a biomass model that utilizes a radiation interception efficiency to determine daily biomass accumulation. The APSIM-sorghum module simulates the growth of a sorghum crop in a daily time-step (on a plant area basis, not single plants).	Process based	Phenological stages used by APSIM: • Sowing • Germination • Emergence • End of Juvenile stage • Floral Initiation • Flag leaf (Maize and Sorghum) • Start of grain filling • End of grain filling • Physiological maturity • Harvest	Wang, E., Robertson, M., Hammer, G.L., Carberry, P., Holzworth D., Meinke, H., Chapman, SC., Hargreaves, J., Huth, N., & Campbell, G.S. (2002). Development of a generic crop model template in the cropping system model APSIM. *European Journal of Agronomy 18*, 121-140. Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., et al. (2003). An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy 18*, 267-288.
World Food Studies (WOFOST)	WOFOST simulates the daily growth of a crop given the selected weather and soil data. Each simulation is conducted for selected, specific boundary conditions that comprise the crop calendar and the soil's water and nutrient status.	Process based	In WOFOST, phenology is described by the dimensionless state variable development stage (DVS). For most annual crops, DVS is set to the following numbers: • 0 at seedling emergence • 1 at flowering (for cereals) • 2 at maturity	Hijmans, R.J., Guiking-Lens, I.M., & van Diepen, C.A. (1994). WOFOST 6.0: User's Guide for the WOFOST 6.0 Crop Growth Simulation Model. Technical Document 12. DLO Winand Staring Centre, Wageningen, The Netherlands.

MAIZE				
Crop Model	**General Description of the Model**	**Type of Model**	**Phenological Parameters**	**References**
	It can be used to estimate crop production, indicate yield variability, evaluate effects of climate changes or soil fertility changes, and determine limiting biophysical factors.		The development rate is a crop-/cultivar-specific function of ambient temperature, possibly modified by photoperiod.	

TABLE AVI.2 PHENOLOGICAL CHARACTERISTICS, SORGHUM

SORGHUM				
Crop Model	**General Description of the Model**	**Type of Model**	**Phenological Parameters**	**References**
SORKAM	SORKAM is a radiation interception crop growth model that partitions biomass and leaf area based on plant development stages. It simulates sorghum tillering, seed number per tiller, and average mass per seed.	Process based	Phenological stages considered in SORKAM follow: • Emergence to growing point differentiation (GPD) • GPD to end of leaf growth • End of leaf growth to anthesis • Anthesis to physiological maturity • After physiological maturity	Rosenthal, W.D., Vanderlip RL, Jackson, B.S., & Arkin, A.F. (1989) SORKAM: A Grain Sorghum Crop Growth Model, TAES, Computer Software Documentation Series, MP 16-69, Texas A & M University: College Station, TX.
CERES-SORGHUM	Ceres-Sorghum is a biomass model that utilizes a radiation interception efficiency to determine daily biomass accumulation.	Process based	Growth stages of sorghum defined by CERES-SORGHUM follow: • Pre-Sowing • Sowing to germination • Germination to seedling emergence • Seedling emergence to end of juvenile stage • End of juvenile stage to panicle initiation (PI) • PI to end of leaf growth	Jones, C.A., & Kiniry, J.R. (ed.) (1986) CERES-Maize: A simulation model of maize growth and development. Texas A&M Univ. Press, College Station. Xie, Y., Kiniry, J.R., Nedbalek, V., & Rosenthal, W.D. (2001). Maize and Sorghum Simulations with CERES-Maize, SORKAM, and ALMANAC under Water-Limiting Conditions *Agron. J., 93*, 1148–1155.

SORGHUM				
Crop Model	**General Description of the Model**	**Type of Model**	**Phenological Parameters**	**References**
			• End of leaf growth to beginning of effective grain filling (EGF) • EGF to physiological maturity • Physiological maturity to harvest	
CROPSYST	CropSyst is a multi-year, multi-crop, daily time-step crop growth simulation model designed to serve as an analytical tool to study the effect of cropping system management on crop productivity and the environment.	Process based	Observed crop phenology is the basis for determining the thermal time requirement for each phenological stage. Phenological growth stages in CropSyst follow: • Emergence • Maximum root depth (usually about the same time as the end of vegetative growth) • End of vegetative growth • Beginning of senescence • End of flowering • Beginning of grain filling • Physiological maturity	Stöckle, C.O., Martin, S., & Campbell, G.S. (1994). CropSyst, a cropping systems model: water/nitrogen budgets and crop yield. *Agric. Syst., 46*, 335-339.

SORGHUM				
Crop Model	**General Description of the Model**	**Type of Model**	**Phenological Parameters**	**References**
APSIM-SORGHUM	APSIM is a biomass model that utilizes a radiation interception efficiency to determine daily biomass accumulation. The APSIM-sorghum module simulates the growth of a sorghum crop in a daily time-step (on a plant area basis, not single plants).	Process based	Phenological stages used by APSIM follow: • Sowing • Germination • Emergence • End of Juvenile stage • Floral Initiation • Flag leaf (Maize & Sorghum) • Start of grain filling • End of grain filling • Physiological maturity • Harvest	Wang, E., Robertson, M., Hammer, G.L., Carberry, P., Holzworth, D., Meinke, H., Chapman, S.C., Hargreaves, J., Huth, N., Campbell, G.S. (2002). Development of a generic crop model template in the cropping system model APSIM. *European Journal of Agronomy 18,* 121-140. Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., et al. (2003). An overview of APSIM, a model designed for farming systems simulation. European *Journal of Agronomy 18,* 267-288.

TABLE AVI.3 PHENOLOGICAL CHARACTERISTICS, COWPEA

COWPEA				
Crop Model	**General Description of the Model**	**Type of Model**	**Phenological Parameters Required**	**References**
APSIM-COWPEA	APSIM was developed to simulate biophysical process in farming systems, in particular where there is interest in the economic and ecological outcomes of management practice in the face of climatic risk. There are no papers describing validation of APSIM-Cowpea.	Process based	Phenological stages listed for APSIM follow: • Germination • Seedling emergence • End of juvenile phase • Floral initiation • Start of linear phase of grain filling • End of linear phase of grain filling • Physiological maturity • Harvest These stages are generic for this model, so they require adjustments to cowpea.	Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., et al. (2003). An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy 18,* 267-288. Carberry, P.S., Adiku, S.G.K., McCown, R.L. & Keating, B.A. (1996). Application of the APSIM cropping systems model to intercropping systems. In: O Ito, C Johansen, JJ Adu-Gyamfi, K Katayama, JVDK Kumar Rao, and TJ Rego (Eds.) Dynamics of Roots and Nitrogen in Cropping Systems of the Semi-Arid Tropics, pp. 637-648. Japan International Research Centre for Agricultural Sciences.
CROPGRO-COWPEA	The CROPGRO-cowpea model was established for simulating the growth and development of cowpea crop.	Process based	CROPGRO is initiated at or prior to planting. The model considers the following: • Germination and emergence • First flower occurrence	Boote, K.J., Jones, J.W., Hoogenboom, G., and Pickering, N.B. (1998). Simulation of crop growth: CROPGRO model. In: G. Y. Tsuji, G. Hoogenboom, and P. K. Thornton, eds.Understanding Options for Agricultural

COWPEA				
Crop Model	**General Description of the Model**	**Type of Model**	**Phenological Parameters Required**	**References**
	This model uses the codes and structure of CROPGRO, but the input parameters that define cultivar and ecotype files are changed in order to characterize the cowpea crop.		• First pod occurrence • First seed • Physiological maturity • Harvest	Production, pp. 99–128. Kluwer Academic Publishers: London.

TABLE AVI.4 PHENOLOGICAL CHARACTERISTICS, SWEET POTATO

SWEET POTATO				
Crop Model	**General Description of the Model**	**Type of Model**	**Phenological Parameters**	**References**
MADHURAM	This is a growth simulation model development for sweet potato, which predicts the crop phenology in response to environmental factors and computes total dry matter production. This model can be used for understanding the performance of the crop under different soil and environmental conditions.	Process based	This model indicates that growth phases of sweet potato are different as compared to other flowering crops. The growth is thus divided into three phases: <u>Initial phase</u> • Extensive growth of fibrous roots • At this phase, vines have only moderate growth rate <u>Middle phase</u> • Vines grow extensively and fast • Tubers are initiated • Very significant increase in leaf area <u>Final phase</u> • Tuber bulking occurs • Very little growth of vines and fibrous roots • Initially, leaf area remains constant and then decreases	Somasundaram, K., & Santhosh Mithra, V.S. (2008). Madhuram: A Simulation Model for Sweet Potato Growth. *World Journal of Agricultural Sciences 4* (2), 241-254.

SWEET POTATO				
Crop Model	**General Description of the Model**	**Type of Model**	**Phenological Parameters**	**References**
			This model defines optimum temperature for the growth of sweet potato at 25 °C. Base temperature is calculated as 8.1 °C. The highest temperature at which sweet potato grows is considered at 38 °C.	
Sweet Potato Computer Simulation (SPOTCOMS)	This model is used to predict the performance of sweet potato under different soil and environmental conditions. This model predicts crop phenology in response to environmental factors, water stress, and potassium and nitrogen deficit/deficiency.	Process based	Crop growth is divided into three phases: • First phase: from planting to root initiation • Middle phase: from root initiation to the beginning of root bulking • Final phase: from the beginning of tuber bulking to harvest This model defines optimum temperature for the growth of sweet potato at 25°C. Base temperature is calculated as 8.1°C.	Santhosh Mithra, V.S. & Somasundaram, K. (2008). A Model to Simulate Sweet Potato Growth. *World Applied Sciences Journal 4* (4), 568-577.

TABLE AVI.5 PHENOLOGICAL CHARACTERISTICS, PEARL MILLET

PEARL MILLET				
Crop Model	**General Description of the Model**	**Type of Model**	**Phenological Parameters**	**References**
CERES-MILLET	CERES-Millet is a crop simulation model that estimates growth and development of millet *(Penniserum* spp.). The model can be used to estimate millet production in contrasting seasons and to derive production anomaly estimates.	Process based	CERES-MILLET follows the standard model of phonological stages of CERES model: • Pre-Sowing • Sowing to germination • Germination to seedling emergence • Seedling emergence to end of juvenile stage • End of juvenile stage to PI • PI to end of leaf growth • End of leaf growth to beginning of effective grain filling • EGF to physiological maturity • Physiological maturity to harvest	Thorntonay, P.K., Bowen, W.T., Ravelo, A.C., Wilkens, P.W., Farmer, G., Brock, J., & Brink. J.E. (1997). Estimating millet production for famine early warning: an application of crop simulation modeling using satellite and ground-based data in Burkina Faso. *Agricultural and Forest Meteorology 83*, 95-112.
Resource capture and resource use efficiency (RESCAP)	RESCAP was developed primarily to predict the growth and yield of sorghum and pearl millet, given an appropriate set of	Process based	The phenological timetable in RESCAP is divided into three growth stages (GSs): • GS1: from emergence to panicle initiation	Virmani, S.M., Tandon, H.L.S., & Alagarswamy, G. (1989). *Modeling the Growth and Development of Sorghum and Pearl Millet.* Technical Report. International Crops Research Institute for the Semi-

PEARL MILLET				
Crop Model	**General Description of the Model**	**Type of Model**	**Phenological Parameters**	**References**
	environmental variables and genetic coefficients; however, it could readily be adapted to any cereal and indeed to any seed-producing crop.		• GS2: from panicle initiation to anthesis • GS3: from anthesis to maturity <u>Temperature standards</u> Length of each stage is indicated in terms of thermal time (units of degree days) above a base of 7 °C. The daily mean temperature is assumed to be the average of specifically reported maximum and minimum temperatures – except when T max exceeds 38 °C, in which case it is assigned a value of 38 °C.	Arid Tropics.

TABLE AVI.6 PHENOLOGICAL CHARACTERISTICS, GROUNDNUT

GROUNDNUT				
Crop Model	**General Description of the Model**	**Type of Model**	**Phenological Parameters**	**References**
PNUTGRO	PNUTGRO validates the effects of moisture stress on groundnut and their subsequent impacts on yields. It also predicts the ultimate impact of stress on other biometric characteristics of the crop.	Process based	PNUTGRO considers the following stages in the model: • Germination period, from planting to emergence • First full-leaf expansion • Start of flowering • First pod occurrence • Beginning of seed filling • End of leaf growth and expansion • End of pod growth and expansion • Physiological maturity • Harvest maturity Predictions of growth stages beyond podding are suggested to be less accurate because of difficulties associated with the indeterminate nature of the crop to note growth stages after pod growth has started in the soil.	Singh, P., Boote, K.J., Rao, A.Y., Iruthayara, D., Sheikh, A.M., Hundal, S.S., Narang, R.S., & Singh, P.H. (1994). Evaluation of the groundnut model PNUTGRO for crop response to water availability, sowing dates, and seasons. *Field Crops Research, 39* (2-3), 147-162. Boote, K.J., Jones, J.W. & Singh, P. (1992). *Modeling growth and yield of groundnut.* In: Groundnut- A global Perspective: Proceedings of an International Workshop., 25-29 Nov 1991, ICRISAT: Asia Centre, Patancheru.

GROUNDNUT				
Crop Model	**General Description of the Model**	**Type of Model**	**Phenological Parameters**	**References**
			Temperature ranges for this model follow: • This model proposes, for the vegetative stages, a base temperature of 13.5 °C, range of optimum temperature from 28.0 to 35 °C, and maximum temperature of 55 °C. • From emergence to flowering, Tbase = 9.5 °C and Topt = 27.2 °C. • From flowering to pod-initiation, Tbase = 9.5 °C and Topt = 25.8 °C. • Beginning seed growth to physiological maturity, Topt = 5.0 °C and Topt = 25.9 °C. However, it is important to note that base and optimum temperatures are calibrated by using the phenology data of previous experiments or other databases.	
PNUTMOD	The model simulates, with a daily time step,	Statistically based	This is a very simple model. PNUTMOD uses only three phenophases:	Boote, K.J., Jones, J.W., Hoogenboom, G., Wilkerson, G.G., Jagtap, S.S. (1989).

GROUNDNUT				
Crop Model	**General Description of the Model**	**Type of Model**	**Phenological Parameters**	**References**
	the biomass accumulation, leaf area, phenology, and soil water balance of a groundnut crop, assuming no nutrient limitations.		• Expansion • Pod set • Pod filling	PNUTGRO v. 1.02. Peanut Crop Growth Simulation Model. User's Guide. Florida Agricultural Experiment Station Journal Series No. 8420. University of Florida: Gainesville, FL.
Cropping System Model (CSM)-CROPGRO-PEANUT	CSM-CROPGRO-Peanut is a crop model developed to evaluate yield performance and stability of peanut lines. It can be used for groundnut.	Process based	The model operates using the generic grain legume model, CROPGRO. CROPGRO is initiated at or prior to planting. The model considers: • Germination and emergence • First flower occurrence • First pod occurrence • First seed • Physiological maturity • Harvest	Suriharn, B., Patanothai, A., Pannangpetch, K., Jogloy, S., & Hoogenboom, G. (2006). Derivation of cultivar coefficients of peanut lines for breeding applications of the CSM-CROPGRO-Peanut model. *Crop Sci 47*, 605-619.

TABLE AVI.7 PHENOLOGICAL CHARACTERISTICS, COTTON

COTTON				
Crop Model	**General Description of the Model**	**Type of Model**	**Phenological Parameters**	**References**
SUCROS-Cotton	SUCROS-Cotton simulates development and growth of cotton under the influence of temperature and radiation.	Process based	SUCROS-Cotton considers: • Sowing to emergence • Emergence to flowering • Flowering to open boll in addition to: • Sowing to flowering • Sowing to open boll	Zhang, L., Van Der Werf, W., Cao, W., Li, B., Pan, X., Spiertz, J.H.J. (2008). Development and validation of SUCROS-Cotton: a potential crop growth simulation model for cotton. *NJAS - Wageningen Journal of Life Sciences 56 ½*, 59-83.
GOSSYM/COMAX	This cotton growth model simulates cotton growth given selected weather, soil, and management practices. Management options include fertilizer and irrigation strategies.	Process based	GOSSYM/COMAX describes the following phenological phases: • Plant emergence • Squaring • Flowering • Boll development	McKinion, J.M., Baker, D.N., Whisler, F.D., & Lambert, J.R. (1989). Application of GOSSYM/COMAX system to cotton crop management. *Agricultural Systems 31*, 55-65. Reddy, K.R., Kakani, V.G., McKinion, J.M., & Baker, D.N. (2002). Applications of a cotton simulation model, GOSSYM, for crop management, economic and policy decisions. In: L.R. Ahuja et al., editors, AgriculturalSystem Models in Field Research and Technology Transfer. CRC Press: Boca Raton, FL. p. 33–73.

COTTON				
Crop Model	**General Description of the Model**	**Type of Model**	**Phenological Parameters**	**References**
CROPGRO	CROPGRO is a process-based crop model that can simulate the main features of cotton growth and management.	Process based	CROPGRO is initiated at or prior to planting. The model considers: • Germination and emergence • First flower occurrence • First seed • Physiological maturity • Harvest	Gérardeaux, E., Sultan, B., Palai, O., Guiziou, C., Oettli, P., Naudin, K. (2013). Positive effect of climate change on cotton in 2050 by CO_2 enrichment and conservation agriculture in Cameroon. *Agronomy for sustainable development, 33*(3), 485-495. Messina, C., Ramkrishnan, P.B., Jones, J.W., Boote, K.J., Hoogenboom, G., Ritchie, J.T. (2004). A simulation model of cotton growth and development for CSM. In: Proc. Biological Systems Simulation Conference. University of Florida, Gainesville, FL, pp. 54–55.

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