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AGRICULTURAL ADAPTATION TO CLIMATE CHANGE IN THE SAHEL:

AN APPROACH TO CONDUCTING PHENOLOGICAL SCREENING

JULY 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)

JULY 2014

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ACRONYMS AND ABBREVIATIONS

ARCC	African and Latin American Resilience to Climate Change
CC	Climate Change
CIAT	International Center for Tropical Agriculture
CILSS	Comité permanent Inter-Etats de Lutte contre la Séchereses dans le Sahel
CMIP5	Coupled Model Intercomparison Project Phase 5
FAO	Food and Agriculture Organization of the United Nations
GIEWS	FAO Global Information and Early Warning System
GCM	Global Circulation Models
IPCC	Intergovernmental Panel on Climate Change
NCDC	National Climate Data Center
SRCVO	Section de Recherche sur les Cultures Vivrière et Oléagineuses
SREX	IPCC Special Report on Climate Extremes
USAID	United States Agency for International Development

ABOUT THIS SERIES

ABOUT 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 developed 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 to 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 Evaluating the Performance of Agricultural Practices, Profiles of Agricultural Management Practices, A Review of 15 Crops Cultivated in the Sahel, Expected Impacts on Pests and Diseases Afflicting Selected Crops, and Expected Impacts on Pests and Diseases Afflicting Livestock. Two documents produced under the Climate Change in Mali subseries also relate to this study: Organizational Survey and Focus Groups of Adaptive Practices and Impact Modeling of Selected Agricultural Adaptive Practices.

AN APPROACH TO CONDUCTING PHENOLOGICAL SCREENING

ARCC produced An Approach to Conducting Phenological Screening in response to a USAID request to develop and describe an approach to using phenological screening to better understand how changes in rainfall and temperature might affect crop productivity in the Sahel, and whether attaining specific thresholds would result in significant changes in productivity.

The implementation of the approach described in this paper depends upon the availability of a significant amount of site-specific data across several domains, such as soil characteristics, crop varieties, and current and projected climate. Time and resource constraints prohibited ARCC from executing this Sahel-wide screening approach. This report, nevertheless, constitutes a guide to institutions with the resources to conduct such a study, as well as elements for further ARCC work described below.

In addition to the present study, USAID requested ARCC to develop a companion document to develop an approach to enhance understanding of the effectiveness of adaptive measures currently being used by rural producers in the Sahel, as well as how this effectiveness may be affected by climate change. That document, An Approach to Evaluating the Performance of Agricultural Practices, draws on the present document. It proposes three basic components to an evaluation of adaptive practices: defining expected changes in climate; identifying the practices to be assessed and defining adaptation objectives; and conducting the evaluation of the defined practices. Additional ARCC West Africa Studies complete elements of the approaches described in these two papers. Of particular relevance are A Review of 15

Crops Cultivated in the Sahel, Profiles of Agricultural Management Practices, Organizational Survey and Focus Groups of Adaptive Practices, and Impact Modeling of Selected Agricultural Adaptive Practices.

EXECUTIVE SUMMARY

The present paper was drafted in response to a request on the part of USAID to develop options for conducting a phenological screening of the impact of climate change on the principal crops grown in the Sahel. The activity was carried out under the USAID African and Latin American Resilience to Climate Change (ARCC) project. Although the resources of the ARCC project did not allow for an application of the process described below, this document nevertheless serves to provide guidance to future researchers to the steps, necessary resources, and challenges of conducting such a screening.

Specifically, this paper presents an approach to evaluating the responses of crops to evolving trends in intra-seasonal weather patterns. As such, it contrasts with the more common approach of assessing the impacts resulting from inter-annual rainfall variations. Current understanding of climate change supports the argument that a shift in orientation to focus on the intra-seasonal occurrence of extreme weather events is critical, and that continued analysis based upon inter-annual precipitation averages will increasingly miss the realities of the intra-season distributional effects with which farmers must contend. The assessment of impacts of intra-seasonal trends is only now beginning to be explored; this represents the area with the greatest potential for new contribution from further analytic work.

In contrast to crop modeling approaches that focus on yields, the proposed approach produces results that describe the proximity of adaptive limits. This paper argues that this approach is particularly useful in environments such as the Sahel, where climate extremes are the norm and most crops are believed to be near the upper end of their adaptive range. The described phenological screening procedures offer the best approach to anticipating Climate Change (CC) impacts on rain-fed agriculture in the Sahel in the near-term (within the next 10 years).

The process includes the development of a phenotypic profile for each crop incorporating the norms of response to climate parameters; the definition of "rainfall years" for each crop under consideration; and the querying of climate records for the occurrence, timing, and magnitude of events breaching the thresholds defined by the profiles. Through this process, we learn about changes in the frequency of agronomically important weather events and what is likely to happen with regard to the proximity of these events and crop thresholds over the next decade.[1]

Knowledge of this "breathing room" would be valuable in aiding assistance programs to make informed investments in CC adaptation efforts over the near term. Depending on the dominant driver (temperature versus rainfall versus extreme events) and the crop concerned, different response pathways may be appropriate. Phenological screening results can alert policy makers to the potential loss (or gain) in revenues from major cash crops due to CC. It can also signal the need to begin investing in long-term research to develop new varieties tolerant to anticipated future conditions, so that there will be appropriate technical options available in 10–20 years when conditions materialize.

The proposed approach is designed as a tool in aiding country-specific and sub-regional investment decisions regarding needed CC adaptations through highlighting past and present climate features relevant to agriculture, how these are changing, and what new adaptive responses will be required in the future. Through focusing on the intra-season effects of CC, the approach draws varying degrees of attention to those climate features corresponding to farmers' principal management challenges. In

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1 The first of these three steps, the development of phenological profiles, has been conducted in conjunction with this paper, and results are presented in the companion paper in this subseries, A Review of 15 Crops Cultivated in the Sahel.

addition to signaling which crops (in specific locations) are at risk of exceeding their physiological thresholds, screening will highlight new information, some counter-intuitive, such as the potential of increase incidence of extreme rainfall events under drought conditions that demand new design considerations in moisture conserving technologies, that will be critical to incorporate in designing future response efforts.

A companion paper, An Approach to Evaluating the Performance of Agricultural Practices, presents a similar and complementary approach, outlining the steps to evaluating performance impacts of climate change on field-level farm practices.

1.0 FUNDAMENTALS OF THE APPROACH

1.1 THE IMPORTANCE OF INTRA-ANNUAL VARIATION

For the Sahel, adapting to within-season climate variations, especially timing of rainfall, constitutes a principle management challenge for farmers. For this reason, a critical decision in designing phenological screening is whether to focus analysis on annual trends or whether to include investigation of anticipated changes to intra-seasonal weather patterns. Consider these two examples of future rainfall distribution:

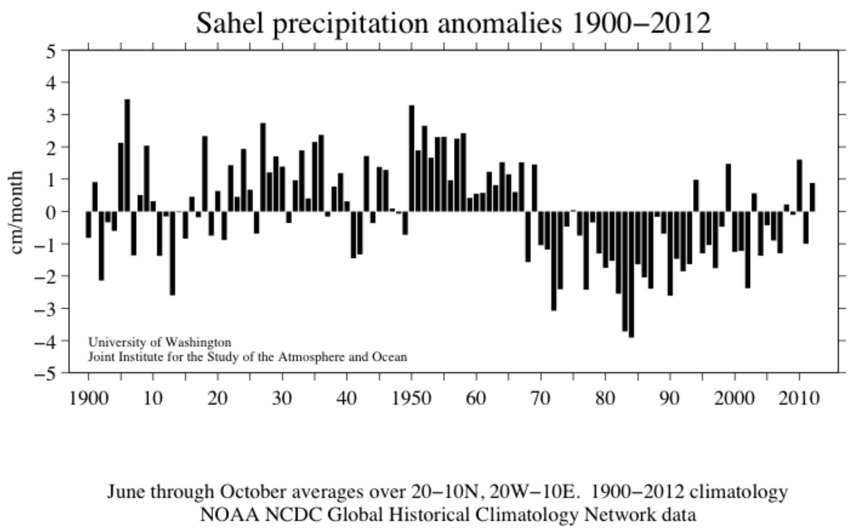
- Case 1: 600 mm of rain evenly distributed throughout the growing season in regular storm events of moderate size (20 mm).
- Case 2: 600 mm of rain, 30 percent of which falls out-of-season. During the season, gaps of over 10 days occur during germination and grain filling stages. Frequent rain events surpassing 50 mm lead to surface runoff of +50 percent.

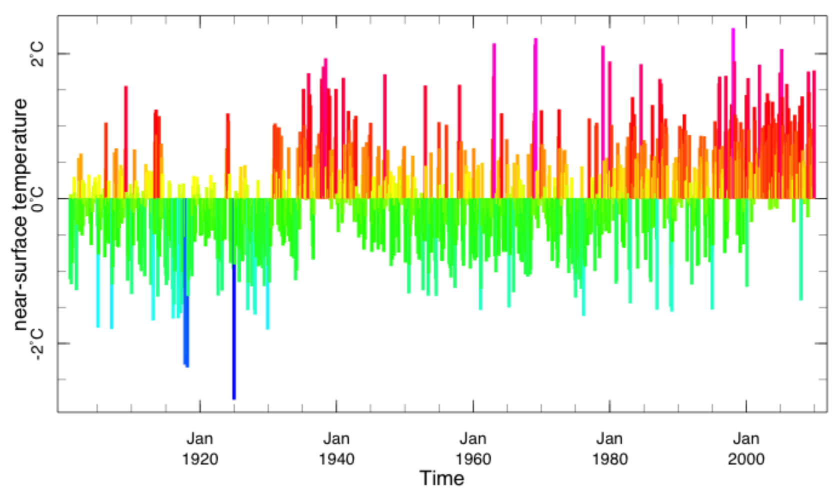
The effective agronomic rainfall would be 600 mm in Case 1 but, due to the timing and concentration of rain events, only about 270 mm in Case 2. Yet technical recommendations based on annual precipitation averages would be the same in both cases. These recommendations would consist of investments in moisture conservation and soil fertility enhancement practices, such as the installation of contouring plowing, ridging, and build-up of soil organic matter.

In Case 1, an analysis focusing on the inter-annual average would have been spot on; in Case 2, this kind of analysis would have been completely off-target. Not only would the technical response in Case 2 not have helped farmers to address the realities of their situation; but had farmers actually invested in the water harvesting techniques proposed, they would have been mal-adaptive and had effects counterintuitive in a context of overall declining rainfall. The increased frequency of large storm events would have led to water pooling up behind the ridges, which, when breached, could lead to a cascading effect and complete washout of ridges downslope. The cases are purposefully extreme, but research shows that such trends are in fact beginning to manifest themselves.

Every month since February 1985, average global temperatures have exceeded the previous climate period average (National Climate Data Center [NCDC], 2013), with growing season temperatures by 2100 projected to exceed the most extreme seasonal temperatures of the past century (Battisti & Naylor, 2009; Gourdji et al., 2013). It is known that warmer air holds more moisture. Recorded flood events have grown precipitously on every continent except Oceana since 1950 (Hassan et al., 2005). Recent research on the Sahel has shown that the partial rebound of rainfall levels in the 1990s and 2000s, unlike the prior wet period (1950s–1960s) (see Figure 1.1, next page), is composed of a similar frequency of rainy days as during the drought period (1970s–1980s), but a significant increase in the rainfall volumes per event (Giannini et al., 2013; Lebel & Ali, 2009), particularly toward the end of season (Figure 1.2, next page). The 2012 Intergovernmental Panel on Climate Change (IPCC) Special Report on Climate Extremes (SREX) cites an increased frequency of large storm events and heat waves in Africa since 1946–1965. The report projects that by 2081–2100, once-in-20-year events will be occurring once every 2 years (IPCC, 2012). Based on the evidence, a change in orientation to focus on changes in the intra-seasonal occurrence of extreme weather events is critical, whereas continued analysis based upon inter-annual precipitation averages will increasingly miss the realities of the intra-season distributional effects with which farmers must contend.

FIGURE 1.1. RAINFALL AND TEMPERATURE RECORD OF THE SAHEL (1900–PRESENT)

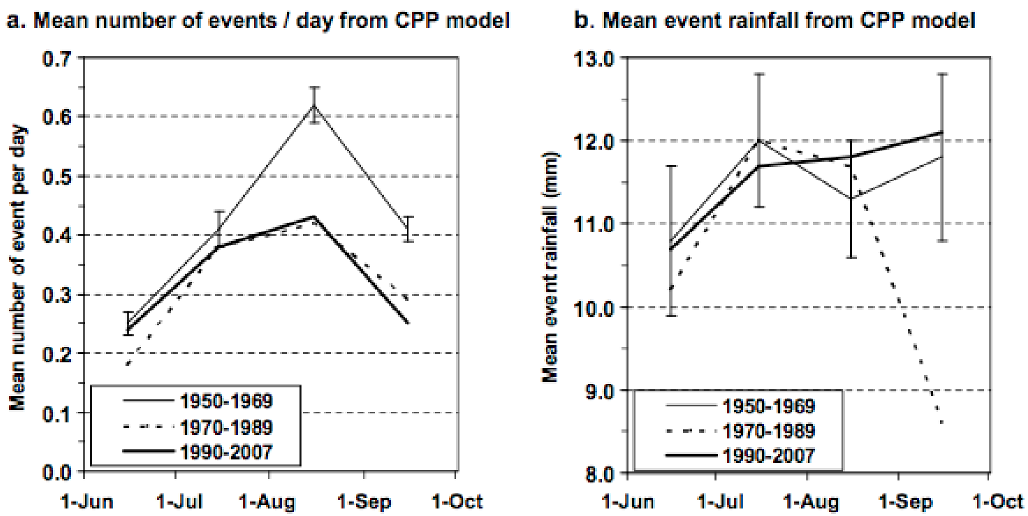




Source: Precipitation data accessed from: http://jisao.washington.edu/data/sahel/ (8/13); Temperature data accessed from: http://iridl.ldeo.columbia.edu/SOURCES/.UEA/.CRU/.TS3p1/.monthly/.tmp/ by Sylwia Trzaska (8/13).

In the Sahel, the farmers' decision regarding when to plant crops (perhaps the most critical decision they make each year) is based largely on their expectations regarding the onset and duration of the rainy season (Simpson, 1999). Farmers must await the arrival of consistent rainfall, because crops are most vulnerable to drought stress in their early stages and can be damaged by sporadic events early in the season. On the other hand, if farmers plant too late, crops miss an opportunity to receive nutrients. As initial rains moisten crop residues, manure, and any other organic matter found in fields, they release a burst of nutrients. This nutrient flush passes quickly, such that even a two-week delay in planting can result in significant yield losses, reaching 30 percent for peanuts and 60 percent for sorghum (Jaeger, 1986). Farmers who plant late also risk that the season will end before crops reach maturity. Analysis based on annual rainfall averages does not address these challenges related to seasonality; thus bypassing this most critical decision farmers face each year.

FIGURE 1.2. FREQUENCY OF EVENTS AND DAILY TOTAL RAINFALL ACROSS THREE EPOCHS (NIAMEY, NIGER)



Seasonal cycles of the parameters of the CPP model fitted to the daily series of observation at the synoptic Niamey station.

Source: Lebel and Ali, 2009

Basic climate change impact assessments of the major cereal and legume crops in West Africa have been conducted using annual parameters (Jalloh et al., 2013). The assessment of impacts of intra-seasonal trends is only now beginning to be explored; this represents the area with the greatest potential for new contribution from further analytic work.

1.2 SELECTING THE TIMEFRAME

In terms of our analysis, the second-most important decision influencing the quality and usefulness of projected impacts of CC on agriculture in the Sahel is the selection of time frames used in the analysis. The decision over what time steps to use should reflect the intended use of the analysis. Organizations making both short- to mid-term operational decisions and longer-term strategic investments require guidance at both these intervals. For "soft" interventions over the near- to mid-term (5–10 years), projections over shorter timeframes are most relevant; whereas investments in "hard" infrastructure and strategic research, meant to address anticipated conditions in the mid- to long-term future (20+ years), will obviously benefit from longer-term scenarios. Although somewhat arbitrary, the time steps of 2025 and 2050 represent reasonable intervals for CC-based analysis, and are consistent with the time steps used in other analyses. The 2025 period allows both lead-time and allowance for typical project cycles focusing on near-term adaptations. The latter provides guidance on more strategic, longer-term investments, such as crop breeding efforts targeting anticipated future conditions.

1.3 SELECTING THE APPROACH TO PROJECTING THE CLIMATE

After selecting appropriate timeframes for the analysis, the next critical decisions concern selection of appropriate analytic approaches for use at the different intervals. These include both approaches used in projecting future weather conditions and the assessment of crop responses to those conditions. These choices are co-dependent. Different approaches to projecting future weather conditions are best matched with different methods of assessing crop responses.

The choices for making climate projections are limited to using climate models or an extension of observed trends. However, the ability to downscale multiple Global Circulation Models (GCM) (e.g., Jalloh et. al., 2013), or GCM ensemble (e.g., Ramriez-Villegas et al., 2013) projections to the national level with enough precision to reflect agriculturally significant weather events sufficiently is currently not possible. In contrast, given what is known about the drivers of the West Africa climate system and decadal-like trends, a trend-projection approach can be selected with at least some confidence over the near-term, with far less effort. The empirical records of weather stations can be queried for trends in the frequency and magnitude of extreme weather events; trends (if they exist) can be extended forward over the next decade.

Over longer time periods, however, there is no basis for confidence that recent trends in precipitation will continue to 2050, while there is confidence that temperatures will continue to rise, with disagreement over the rate of increase. For estimating change to basic climate parameters (temperature and precipitation), use of modeled climate projections, as imperfect as they are, is the more appropriate approach, especially when applied to larger spatial scales (i.e., West Africa sub-region). The use of a modeling approach for the 2050 period would preclude the ability to assess changes to intra-annual weather events, but would be valuable in identifying central tendencies of the future climate useful in aiding long-term investment decisions, such as funding breeding programs of principal crops that will likely take several decades in developing new tolerant varieties.

1.4 SELECTING THE ANALYTICAL APPROACH: CROP MODELING OR SCREENING

After selection of an inter- or intra-annual orientation to the analysis, analytic time periods, and approach to projecting future weather conditions, a decision must be made as to the best way to capture important features of crop responses ("norms of reaction"). The choices are crop modeling and phenological screening.

Crop models fall into two general types: process-based and statistical models. Process or mechanistic crops models use algorithms and extensive data inputs to generate approximations of plant physiological responses to environmental factors. These models require field-level data and, with some exceptions, tend to focus on the major crops and dominant conditions of temperate zones. They typically are designed to accept weather data on a daily time-step, and thus may take into consideration intra-annual climatic variation when those data are available. In cases where weather data are missing or incomplete, or when future weather conditions are to be tested, as in CC scenarios, other models are used to generate or gap-fill key weather data inputs. Statistical models, in contrast, use extensive empirical datasets of crop yields under different environmental conditions as the basis for predicting crop response to target environments based on key environmental parameters. Assembling the database used in statistical crop models requires a great deal of effort; in most cases, it involves the extensive use of controlled trials involving irrigation and fertilizer inputs to establish a grid pattern of varying moisture and soil fertility regimes. When used in predicting future crop response to CC, research shows that statistical models perform better at larger (i.e., global and regional) spatial scales than at smaller scales, corresponding to the greater accuracy of larger-scale climate models (Lobell & Burke, 2010). It is generally acknowledged that at the extreme range of environmental conditions, often those being tested under CC scenarios, model accuracy (whether process-based or statistical) often breaks down and/or is not able to respond to more than one factor (e.g., extreme heat or drought). Part of this reflects the state of science, part reflects the original intended purposes for which the models were constructed and the availability of data that support them. A 2011 meta-study of 16 studies of potential impacts of climate change on crop yields in West Africa found that process based and statistical models give similar results for future yields. Overall, however, the studies examined produced a large dispersion of yield changes ranging from minus 50 percent to plus 90 percent. The median was a yield loss near 11 percent (Rodier, 2011)

If the interest is to project potential yields, the use of crop models is the only reasonable alternative, despite the fact that it is limited by accuracy and the availability of models for the specific crops. However, the effort required in generating the necessary weather data inputs, reflecting future conditions based on a sufficiently large collection of individual weather stations across the Sahel needed in using a crop modeling approach, would be an enormous and prohibitive challenge. This challenge would be further multiplied by the need to parameterize and enter the needed data into crop models for each of the main crops in the Sahel (or their proxies). Use of a regional climate model-generated dataset would eliminate the ability to monitor and assess the impacts of trends in intra-seasonal extreme weather events over the near-term.

In general terms, phenological screening is an effort to compare crop responses to current environmental conditions, with crop response to projected future environmental regimes. Crop breeders have long used elements of phenological testing in determining the ecological range of new varieties. Similarly, agronomists have used crop phenology in models to optimize management options and the design of field trials. Agro-climatologists have attempted to use statistical analysis of the timing of rainfall events to guide decisions on crop and variety choice (e.g., Sivakumar et al., 1993), as a general guide for farmers on planting decisions (Section de Recherche sur les Cultures Vivrière et Oléagineuses [SRCVO], 1992) and to analyze structural changes in the growing season (Lodoun, et al., 2013). The screening of crop phenology thresholds to predict crop-specific responses to CC is new (Mekong ARCC, 2013). Due to their ability to estimate crop yields, common practice to date has been to use crop models for exploring the potential impacts of CC on crop productivity. Crop models have been used particularly at global and regional scales, though work is increasingly being applied at sub-regional and national scales focusing on single or a limited number of crops (International Center for Tropical Agriculture [CIAT], 2011; Anton et al., 2012; Haggar & Schepp, 2011; Jassogne et al., 2013)

Phenological screening, while a "rougher tool" than crop modeling, lacking the ability to project yield responses, is potentially a more adapted approach for conducting first-order identification of likely CC impacts on agriculture, particularly in establishing thresholds of adaptability based on known crop and variety tolerances. In environments such as the Sahel (see Figure 1.1), where climate extremes are the norm and most crops are near the upper end of their adaptive range, phenological screening is particularly useful in identifying the proximity of adaptive limits. In screening crop-specific "norms of reaction" profiles against anticipated CC related stressors, use of the literature, including assumptions regarding physiological thresholds used in the major crop models, supplemented with expert opinion, will enable the identification of best-bet adaptive responses and future research needs.

In sum, weighing the evidence and intelligent use of phenological screening procedures, combined with an analysis of projected intra-seasonal weather trends, offers the best combined approach of anticipating CC impacts on rain-fed agriculture in the Sahel over the near-term. The output from such an analysis would be extremely valuable in aiding assistance programs in making informed investments in CC adaptation efforts over the 2025 time period. In contrast, the use of climate models (e.g., Coupled Model Intercomparison Project Phase 5 [CMIP5]) to generate a range of inter-annual climate conditions for use with crop models is more appropriate for assessing longer-term CC impacts (2050), and best used over larger areas. The high level of uncertainty over mid-century projections, and significant resources required to conduct an original analysis, must be carefully considered in deciding whether to invest in such an undertaking.

2.0 TECHNICAL ISSUES IN PHENOLOGICAL SCREENING

To conduct a screening, the limits of the study zone and the crops to be studied must first be determined, followed by the definition of the thresholds of crop genetic responses to key biophysical parameters. Both current and future environmental conditions, with special emphasis on those related to climate change, must also be determined. Thus, phenological screening requires the following four factors to be determined:

- The identification of the geographic location(s) of the study zone and crops to be considered (discussed below);
- A determination of norms of response profiles for each crop selected (norms for 15 crops are presented in a companion paper in this subseries);
- A definition of agronomically relevant climate parameters (discussed below); and
- A characterization of future climatic and environmental conditions, at specified intervals, using the same parameters as employed in defining the current climate (a characterization of future climatic and environmental conditions was conducted in conjunction with this paper).

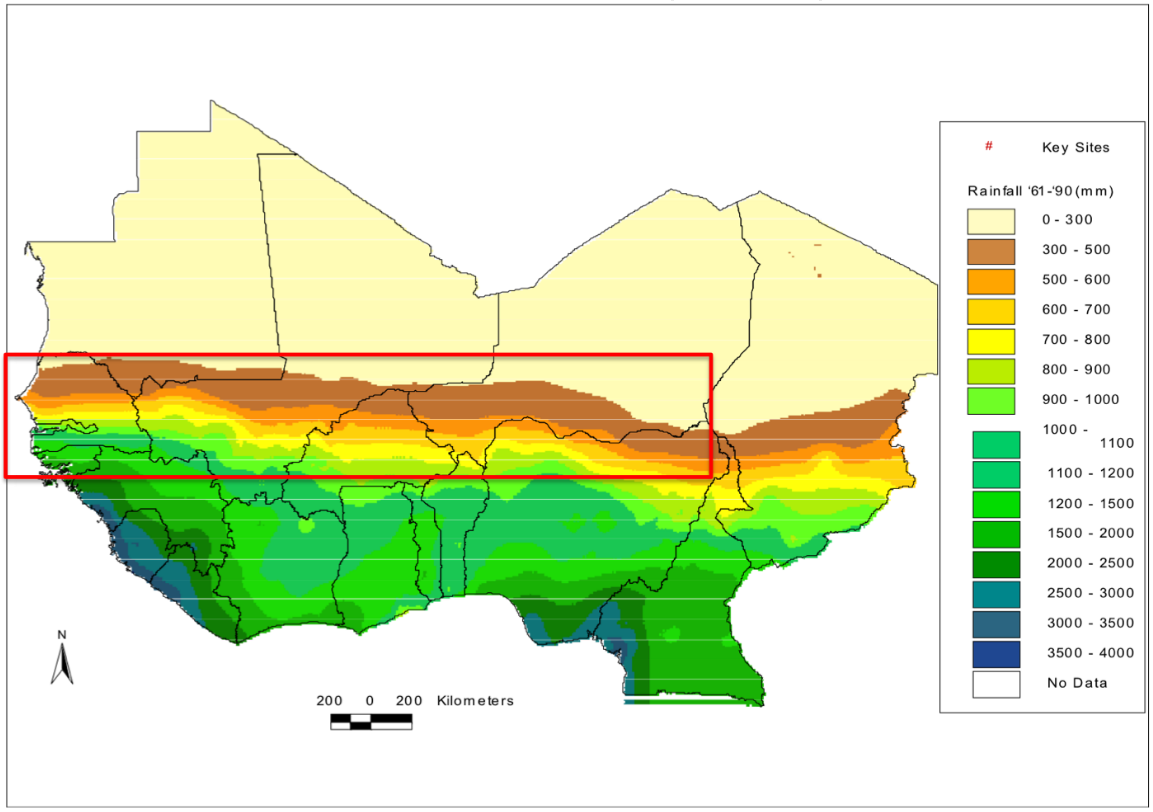
2.1 IDENTIFICATION OF THE STUDY ZONE AND CROPS

The Sahel climatic zone was first defined by precipitation parameters (250–600 mm of rainfall) by Chevailier (1900) (Lawson, 1986). Others have since applied alternative definitions (e.g., 250–500 mm by the Food and Agriculture Organization of the United Nations/Global Information and Early Warning System [FAO/GIEWS], 1998), as well as adding a sub-Sahelian zone, receiving 600–750 mm. Irrespective of the exact boundaries, defined this way the Sahel is not a fixed geographic location, rather its physical positioning shifts with the prevailing precipitation patterns of the reference climate period. Using this definition to frame the study, the assessment of impacts of CC on Sahelian agriculture would be limited to temperature change and frequency of extreme events within the 250–600 mm rainfall band. The more general intent, however, is in assessing the impacts of climate change on the people and agricultural systems in fixed locations of the semi-arid zone of West Africa. With this view in mind, the climatological practice of establishing a "box" of bounding lines of latitude and longitude, through which the Sahel climatic zone passes, is a more appropriate approach.

To capture the essence of a place-based and people-orientated assessment further, especially given the high levels of uncertainty over future rainfall trends, and historical decadal patterns, it is advisable to include at least the sub-Sahelian zone as well (600–750 mm). Many of the crops of high economic importance selected for West Africa (e.g., cotton, groundnut) are not grown in, or only in the southern portion of, the true Sahel.[2] Establishing a bounding box of roughly 11–17 degrees N, 18 W and 14 E would accommodate such a broader view (see Figure 2.1).

[2] An alternative would be to use the FAO Livelihood zones. The Pastoral and Agro-Pastoral Zones capture the target areas well (http://www.fao.org/nr/water/art/2008/flash/ruralmaps/gallery1.html)

FIGURE 2.1. LOCATING THE SAHEL WITH REFERENCE TO THE WEST AFRICA RAINFALL ISOHYETES (1960–1990)



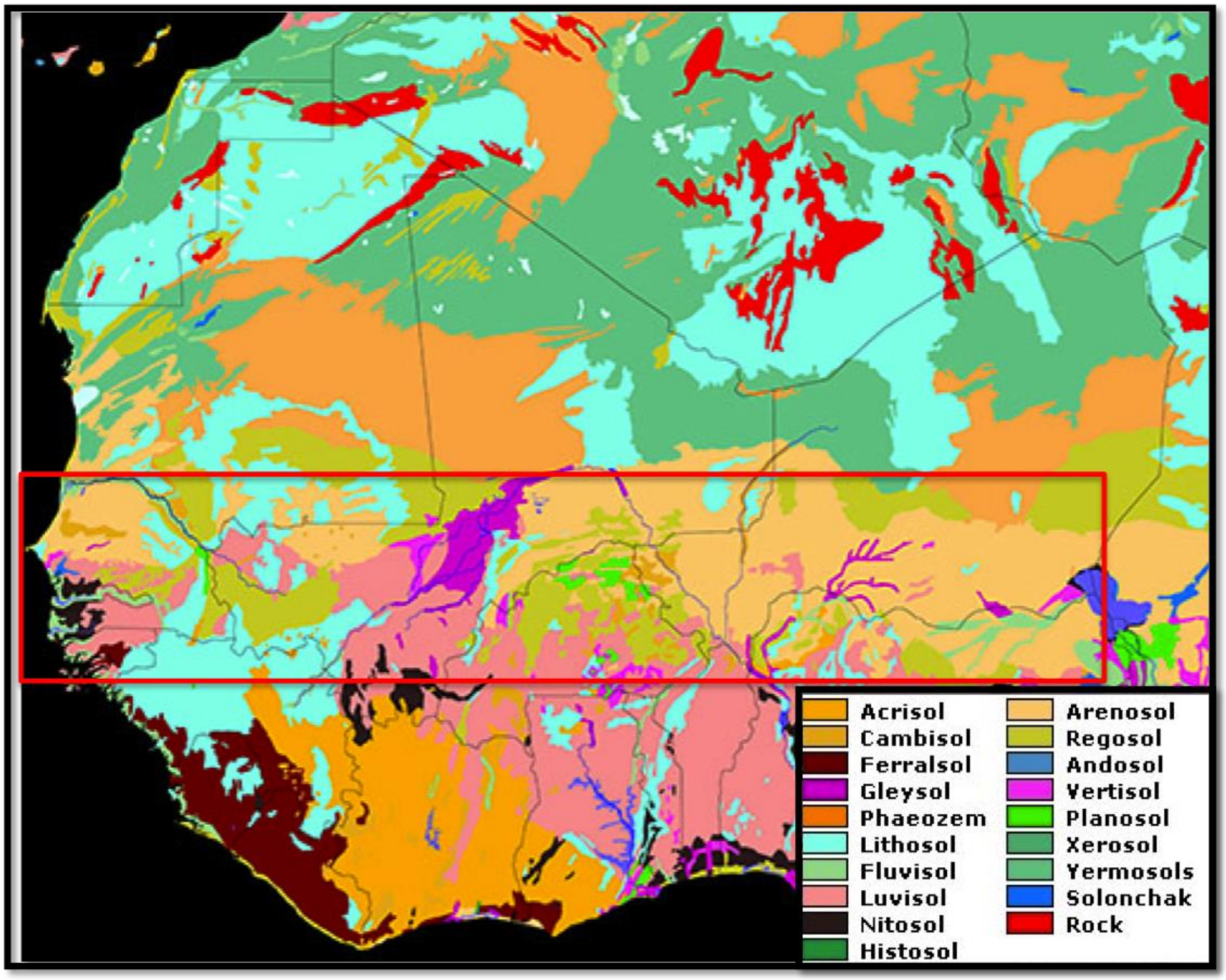
Source: International Crops Research Institute For The Semi-Arid Tropics (Icrisat), Sahelian Centre (1998).

2.2 DETERMINATION OF CROP PROFILES

Crop physiology responds to a number of environmental factors and their interactions, although three standout: sunlight, moisture, and temperature. The level of potential sunlight is fixed by latitude and will not likely change appreciably for the Sahel under projected CC due to changes in cloud cover. Moisture and temperature are both expected to be directly affected by CC. Temperature and rainfall have differential effects on plant development and crop yields depending on their temporal occurrence. For instance, a 10-day gap in rainfall post-germination will lead to widespread die-off in most species, whereas the same gap occurring during vegetative growth may lead to stunting and some yield loss, but not widespread mortality. Flowering and grain-fill stages are others with particular sensitivity to rainfall gaps. To accommodate the temporal importance of different environmental effects, the appropriate segmentation of growth stages must be determined separately for each crop, along with the identification of key abiotic weather thresholds (where known) at each growth state.

A forth factor also warrants consideration: soil conditions, especially the inclusion of plant pH tolerance thresholds. The inclusion of pH tolerances will be most useful when spatializing (mapping) crop production domains across large-scale soil classes (see Figure 2.2) for the bounding effects that soil pH may have on limiting the expansion or movement of potential production areas for particular crops under CC (essentially preventing crops from migrating into non-suitable areas).

FIGURE 2.2. SOIL MAP OF SAHEL REGION



Source: FAO, Digital Soil Map of the World, Version 3.6

In preparing for the phenological screening, "norms of reaction" profiles for each crop (as well as major variety classes, such as early-, medium- and long-duration maturing varieties) must be compiled. These profiles will then be used to screen against anticipated changes in major environmental conditions: weather-based variables (temperature; precipitation; and frequency of extreme events, e.g., heat waves, flooding, and droughts) and a limited number of multipliers (increased potential evapotranspiration resulting from higher temperatures, limited infiltration of rainfall with extreme rainfall events, and the bounding effects of soil pH for major soil classes when mapping the change in potential production areas). When screening for the impact of climate change in the Sahel, the most important parameters of norms of reaction profiles are:

1. **Plant growth stages.** Determine the minimum number of plant growth stages that need to be considered to assess CC impacts for each species meaningfully. Plant growth stages should be expressed in terms of plant age, i.e., days from planting for annual crop species (a similar appropriate marker will need to be determined from perennial species). To avoid undue complexity, plant growth stages can be defined under the assumption that crop physiological development occurs normally from the time of germination as if under optimal (or normal/expected) climatic conditions.

This assumes no effect of climate on the delayed expression of developmental stages. To the extent possible, assumptions concerning the acceleration of crop maturation due to temperature increases may be included in the determination of plant development under CC.

2. **Climate change variables.** Determine the climate change variables that will be used in screening for all the crops. Basic agronomically important variables include:

   a. Daytime temperature min-max;

   b. Nighttime temperature min-max; and

   c. Precipitation.

   These are discussed at greater length below, in Section 2.3.

3. **Planting dates.** For each annual species, determine a weather-dependent set of conditions for establishing a planting date (e.g., "…that date after 1 May, when rainfall accumulated over 3 consecutive days is at least 20 mm and when no dry spell within the next 30 days exceeds 7 days") (Sivakumar et al., 1993).[3] Planting conditions will be expressed in terms of, or related to, a physical climate variable or combination of variables included in the climate data (discussed below).

4. **Thresholds.** For each crop, variety class (where relevant), and plant growth stage determine what constitutes preferred, tolerable, and threshold weather conditions, including:

   a. *Drought:* damaging gaps in rainfall expressed in days without rain, or periods with cumulative rainfall below a fixed value, e.g., <10 mm over 20 days;

   b. *Flood:* crops ability to withstand submersion or waterlogged conditions;

   c. *Heat wave:* damaging daytime high temperature threshold and duration of excessive heat period;

   d. *Cold spell:* damaging daytime/nighttime temperature thresholds; and

   e. *Minimum temperature requirements:* certain species require a minimum temperature regime during their maturation in order to reproduce, as well as night time lows that allow them to physiologically respire, without which their productivity is negatively affected.

Initial profiles of 15 major crops of the Sahel are presented in Agronomic Profiles of Fifteen Important Crops of the Sahel.

In addition to published literature, the assumptions included in the major crop models have been consulted in establishing crop growth stages and threshold profiles. Consultations with crop experts have also been conducted to validate the norms of reaction profiles and fill-in critical missing attributes.

2.3 DEFINING CLIMATE PARAMETERS

Digitized weather data is required to conduct an intra-seasonal analysis. Weekly reports, although less desirable, can be used for courser analysis. Such data allows for the fundamental analysis:

1. **Frequency of extreme events.** Trends in the increased prevalence of agronomically important extreme events in the Sahel over the past three decadal cycles. The time periods 1950–1970, 1971–1990, and 1991–2010 correspond to the Sahelian pre-drought, drought, and rebound periods,

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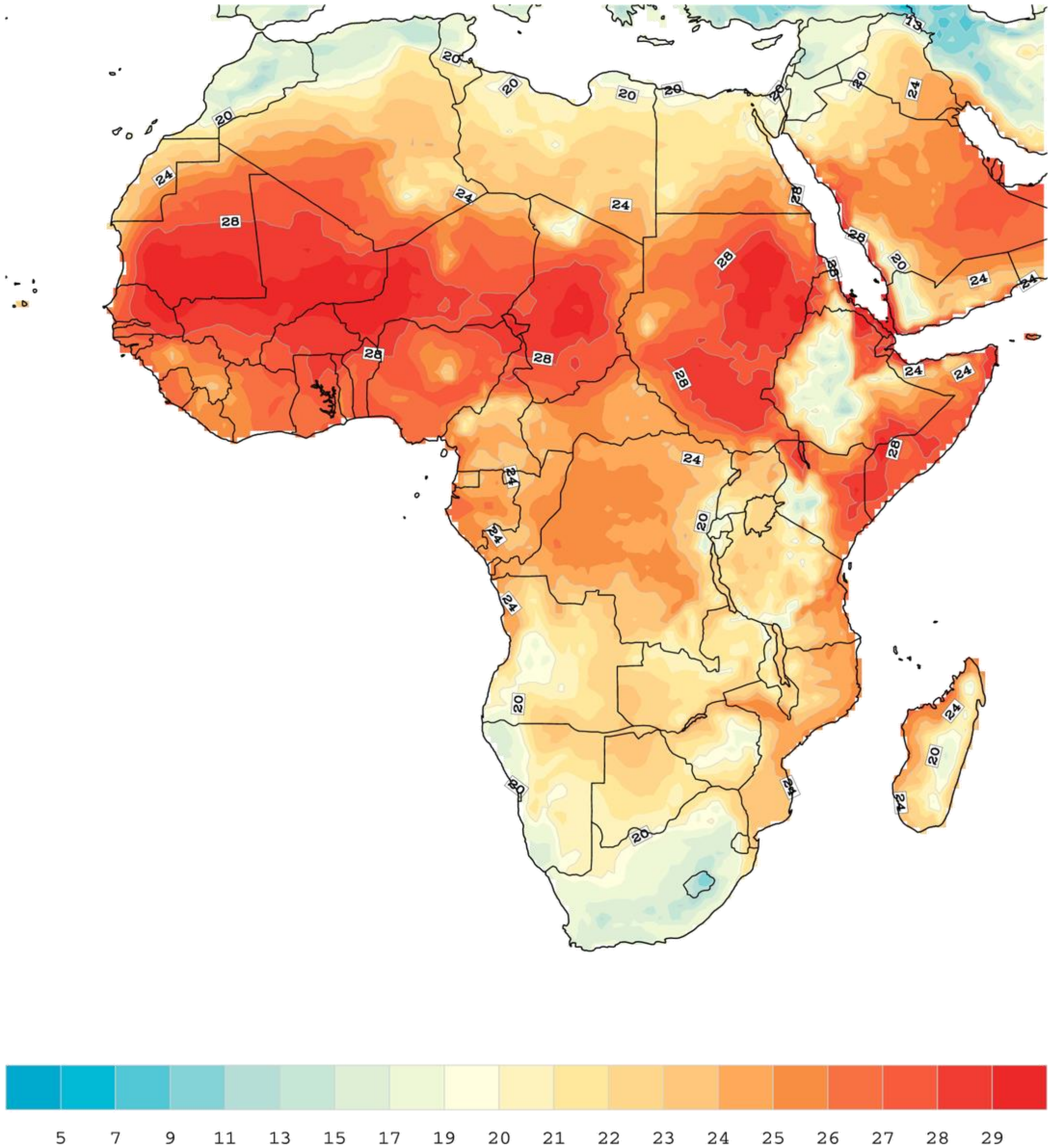
[3] For Mali, planting recommendations are based on dates established for each isohyet zone after which if there is 20 mm of rainfall in a single rainfall event, or two successive events each with 10 mm then planting should take place (Kouressy et al., 2002).

respectively. Recent climatological research (e.g., Lebel & Ali, 2009) has found that the partial "recovery" of annual rainfall levels in the 1991–2010 period, relative to pre-drought conditions (1950–1970), exhibits a higher frequency of large rainfall events. The trends in the frequency of agronomically important extreme events (see description of thresholds above) among these three climate periods will be important in establishing the 2025 rainfall year against which crop phenological responses will be screened.

2. **Agronomically useful rainfall.** Segregation of agronomically useful rainfall from rainfall totals. Here, two aspects are important: the elimination of rainfall outside of the growing period, too early or too late; and in terms of volume. With respect to the latter, research from the Sahel cites average rainfall infiltration rates of 10 mm/hour, but notes that 50 percent of the rainfall events exceed this threshold (Sivakumar, 1989). The predominant type of rainfall event, line squalls, typically last less than 2–2.5 hours (Cochemé & Franquin, 1967). By extrapolation, daily records with rainfall that exceeds 25 mm/day can effectively be reduced to 25 mm (a more conservative 30–50 mm threshold will be established), with the remainder lost to runoff (although potentially captured by soil conservation practices, an important adaptation measure).

3. **Evapotranspiration rates.** Increased potential evapotranspiration rates associated with higher temperatures. Rainfall volumes will be adjusted to reflect increased moisture loss due to evapotranspiration with increasing temperatures associated with CC.

FIGURE 2.3. AFRICA MEAN TEMPERATURES 1971–2000



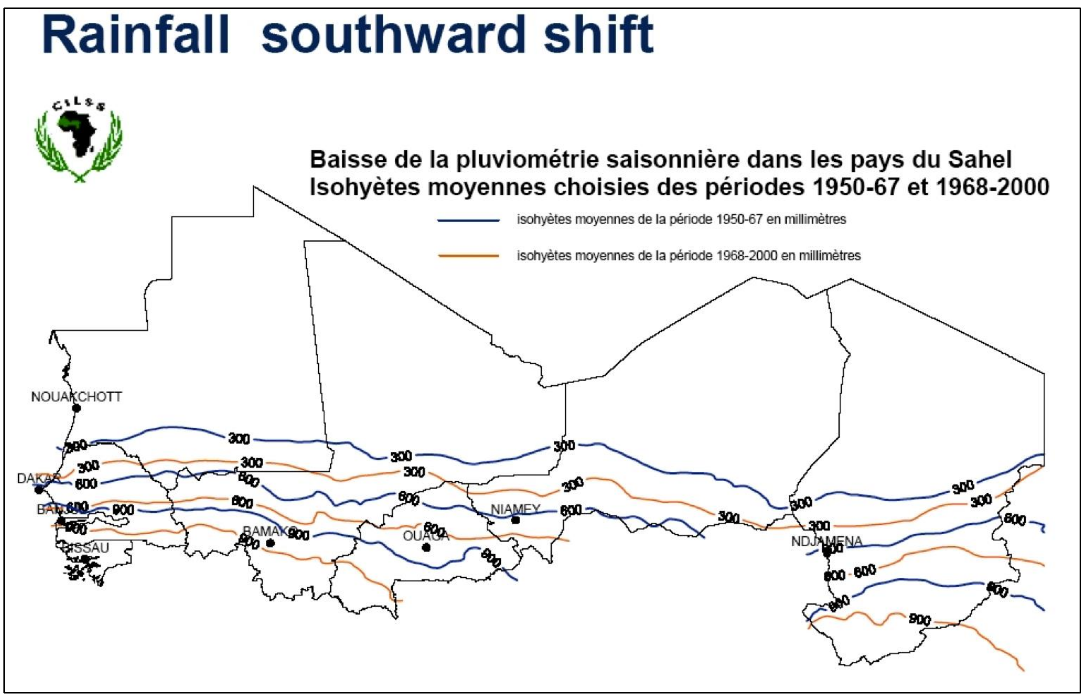
Source: Climatic Research Unit (CRU), 2010.

In general, if the region's precipitation increases and the frequency of extreme events does not increase, the rainfall isohyets will shift northwards, improving conditions across the zone. If rainfall declines outright or distribution changes significantly effectively reducing the quantity of rainfall available to crops, the isohyets (or production isohyet proxies based on the moisture actually available to plants) will move southwards. While there would be some decrease in productivity with a southward shift as cropping systems adjust to drier or more disrupted conditions (with maize production being replaced by sorghum, and sorghum by millet) the only zone to definitively lose out would be the most arid areas to the north where rain-fed agriculture would no longer be viable (see Figure 2.4, below). Unlike the steep north-south gradation in rainfall, temperatures across West Africa are much more uniform (although the data is very coarse). Regardless of what happens with rainfall, rising temperatures will ultimately force cultivation out of large areas of West Africa, starting in those areas under high levels of moisture stress.

2.4 CHARACTERIZING CLIMATE TRENDS

The climate period used to establish the production domain boundaries for the different crops and geo-location is critical. Use of the period 1960–1990, for example, should be avoided, as the sub-region went through a dramatic downturn in rainfall through the 1960s–1970s, after a relatively "wet" decade in the 1950s, and stayed low through the 1980s, 1990s, and early 2000s. There has been somewhat of a rebound in rainfall levels over the past 15 years, though precipitation is still below the pre-1970 average (see Fig. 1.1). A general rule of thumb used during the Sahelian droughts was that each 100 mm change in precipitation correlated to a 100 km shift (north or south) of the rainfall isohyets (Nicholson, 1982) (Figure 2.4). It has also been shown that each 5–10 km shift north-south correlates to a one-day change in the length of growing season (Franke & Chasin, 1980). Lodoun et al. (2013) show a 152 mm decrease in rainfall, 12-day delay in onset of rains and 26-day shortening of the rainy season in Burkina Faso Sahelian zone between pre-drought and drought/rebound periods (1941–1970; 1971–2008). Figure 2.5 shows the coefficient of variation[4] of the length of the rainy season in the Sahel: in the northern part of the Sahel, the length of rainy season can be reduced by over 50 percent.

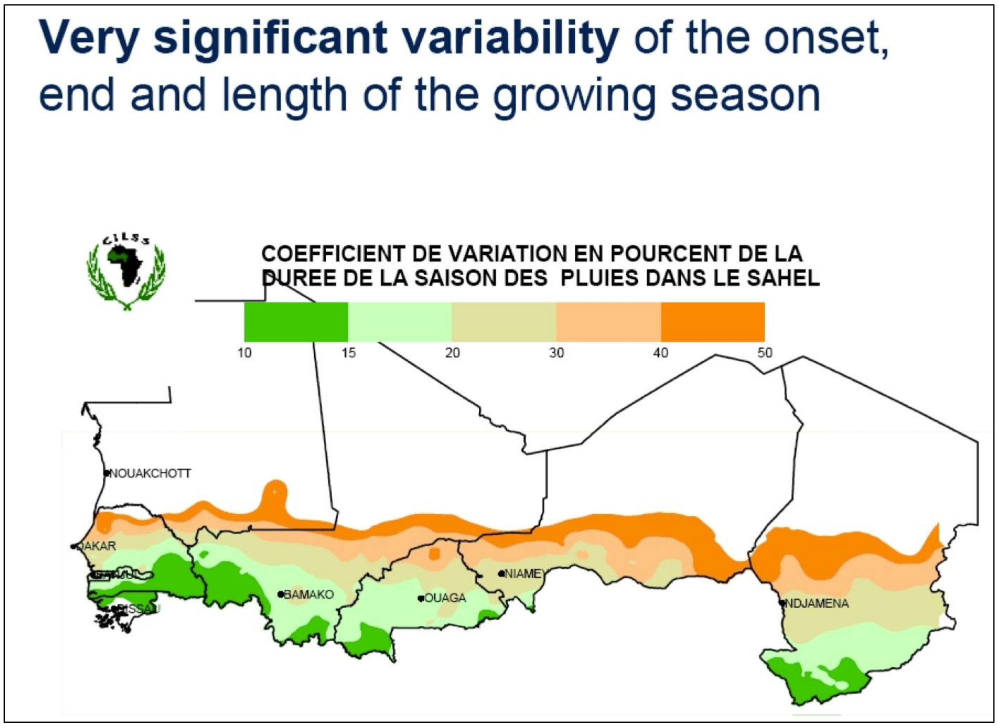
FIGURE 2.4. SHIFT IN RAINFALL ISOHYETES IN THE SAHEL (1950–1967 TO 1968–2000)



Source : Comité permanent Inter-Etats de Lutte contre la Sécheresses dans le Sahel (CILSS), n.d.

[4] The coefficient of variation is defined as the standard deviation of the values divided by the average value and is expressed as a percentage. A coefficient of variation of 30 percent means that 66 percent of all the values lie within a ± 30 percent interval around the average value and that 33 percent are even further from the average.

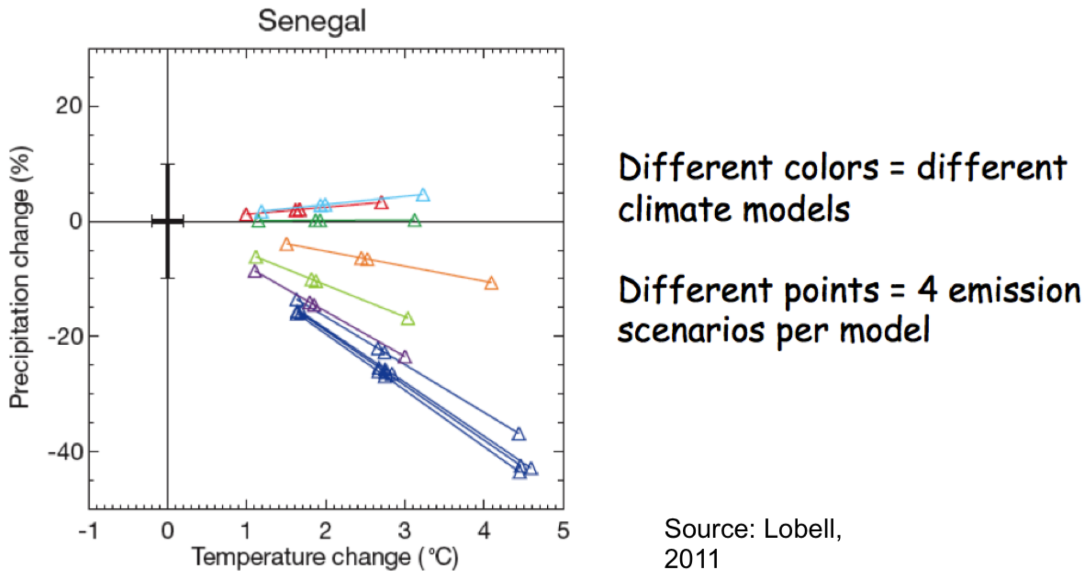
FIGURE 2.5. COEFFICIENT OF VARIATION IN SAHEL



Source: CILSS, n.d.

In general, future projections of the climate are in agreement over the increase in average temperatures, with disagreement over the magnitude and speed of onset, whereas predictions of precipitation changes range more widely, from slight increases to no change to significant decreases (see Figure 2.6). As mentioned previously, empirical records show increases in both extreme temperature and rainfall events, and models predict these trends to continue.

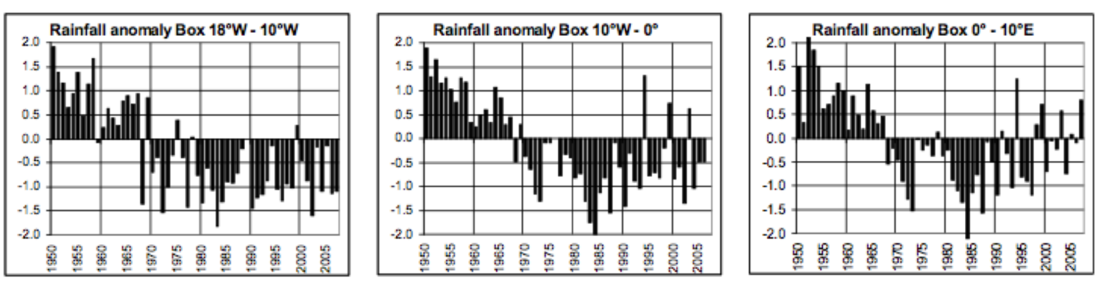
FIGURE 2.6. DIVERGENCE IN MODELED OUTCOMES (SENEGAL), 2050 RELATIVE TO 1960–1990



Source: Lobell, 2011

In estimating future climate conditions, it is important to note that the Sahel is not a uniform body. Across the East-West axis, the recent upturn in average annual rainfall levels show distinct differences between the eastern and western portions of the Sahel, with finer, but important differences, between the central and western parts (Figure 2.7). Regional averaging risks obscuring these important differences, with negative consequences for country-based program planning, thus partitioning the Sahel into East/West segments, or using country-based analysis is warranted.

FIGURE 2.7. HISTORICAL RAINFALL RECORD FOR EASTERN, CENTRAL, AND WESTERN SAHEL



Source: Lebel and Ali, 2009

2.5 CONDUCTING THE SCREENING

Building the preceding discussion, the following presents a rough outline of the steps involved in carrying out a phenological analysis in the Sahel.

2.5.1 Define Area of Analysis

- Select degrees of latitude that bound the countries of Senegal, Mali, Burkina, and Niger, and include the southern parts of Mauritania, western Chad, and northern Cameroon through which the 250–

750 mm isohyet band passes (Sahel and sub-Sahel), based on data from the agreed-upon climate period.

2.5.2 Selection of Weather Stations

Analysis should rely on *in-situ* daily measurements of rainfall. Remote-sensed or gridded data should not be used; the former because they tend to produce biased values and only date back to 1980s, the latter because in the process of gridding data extremes tend to be smoothed. The only dataset of *in-situ* observations spanning the region of interest exists at AGRHYMET. It is based on records provided by meteorological services of individual countries and has been compiled under the Comité permanent Inter-Etats de Lutte contre la Séchereses dans le Sahel (CILSS) mandate. However, the data remain exclusive property of individual metrological services and are not publicly accessible. Access needs to be granted by individual metrological services. In specific cases however, when the study directly benefits the region and involves AGRHYMET operating under its regional mandate, analyses can be performed on the data jointly with AGRHYMET.

The analysis should be performed on all the stations in the region available at AGRHYMET after quality control and discarding those with insufficient records. According to Lebel & Ali (2009), the operational network of the countries of interest totals 650 rain gauges, but only 266 of these have less than 20 percent of missing data over the period 1950–2006 and only 96 have been operated continuously over that period. It is expected that the data set would be equivalent to that of Lebel & Ali (2009), updated to 2013. Researchers should also check for spatial homogeneity of the distribution and discard stations where the density will be particularly high, to keep the results valid Sahel-wide and not strongly biased by local characteristics.

For this type of analysis to be robust, data from a large number of stations are usually pooled together. However, rationale for dividing data into sub-regions exists: Lebel & Ali (2009), for example, divide the region into western and eastern portions based on the fact that rainfall recovery seems different in those sub-regions. Division into northern (<400 mm) and southern zones (>400–750 mm), based on water requirements for different crops (e.g., maize vs. sorghum) is another possibility. In order to preserve statistical robustness of the analysis, the availability of the data will strongly influence final pooling decisions.

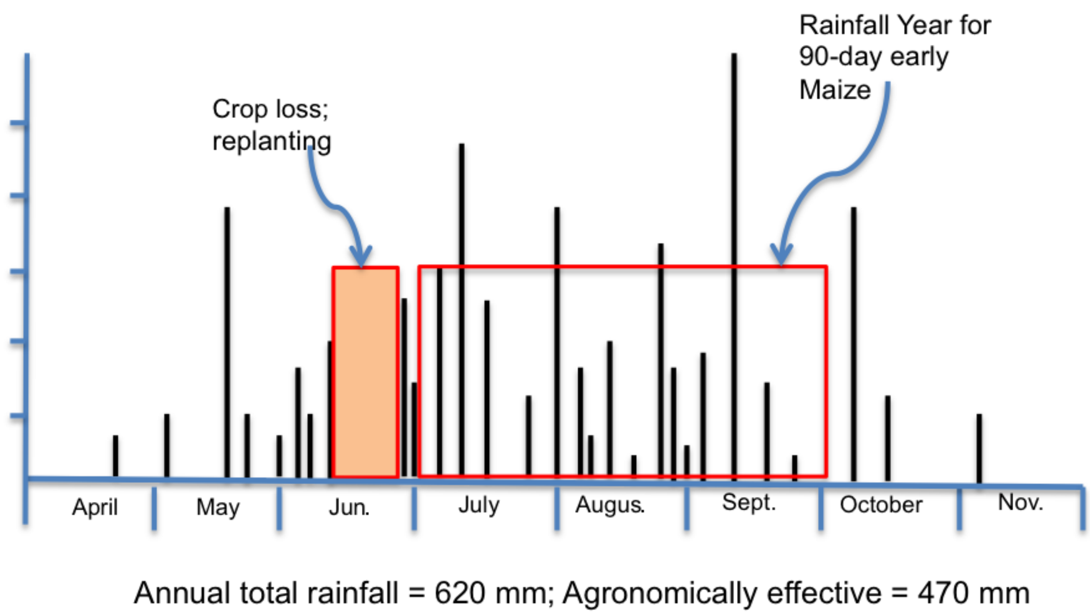
2.5.3 Screening Procedures

- As detailed above, a phenotypic profile for each crop, and where relevant variety classes (e.g., short, medium, or long duration) will be developed, to include: (1) establishing the minimum number of plant growth stages, expressed in terms of days from the start of the growing season (i.e., planting); and (2) the norms of response to climate parameters in terms of both the general tolerances and, where available, tolerances within each growth stage. Values to be included for each crop include: ideal conditions, tolerances, and terminal thresholds for min/max temperature effecting reproduction and growth; ideal conditions and thresholds for min precipitation levels; and definition of agronomic tolerances to extreme events (drought, heat waves, inundation).

- Determine the agronomic "rainfall year" for each crop by: (1) establishing a decision rule for determining when the agricultural season has started for each crop (e.g., planting is assumed to occur after XX mm of rainfall, within a YY day period after ZZ date); (2) setting the end-date of the growing season for each crop based on the crop and, where relevant, crop variety class requirements (e.g., days to harvest for extra-early-, early-, medium-, and late-maturing varieties of maize); and (3) eliminating rainfall volumes that (a) occur before the calendar date established for that "rainfall year" (see adjustments below), (b) occur after the harvest period for that crop, and (c) are above a single/day event threshold level (e.g., above 30 mm/day) (Figure 2.8).

- Adjustment: to account for the common occurrence of needing to replant, a decision rule will be established to determine when replanting is required (e.g., if a gap in rainfall of at least XX days occurs during the crop's first 20 days post-germination, defined as YY days after the start of the "rainfall year," with less than ZZ mm of rainfall, then assume total loss of the crop and need to replant). In such cases, the decision rule used to determine the start of season for that crop initially would be re-applied to establish a new "start" to that season.

FIGURE 2.8. RAINFALL YEAR SCHEMATA FOR EARLY MAIZE



- Once the crop "rainfall year" is established, the pooled records will be queried for occurrence, timing, and magnitude of extreme events, as well as a limited set of other perimeters. The trends (if any) in these statistics will be plotted and used in projection of the weather pattern for the 2025 crop rainfall year, which will be screened against the crop phenological profiles to establish the CC impacts for each crop. Basic statistics will be collected from the intra-annual processing, including: change in frequency and volumes of "out of season" rainfall, both prior to and after the established rainfall year; shift in starting dates of crop rainfall years; change in frequency and volume of extreme rainfall events (total and within the rainfall year period); change in frequency of crop defined "droughts" within the rainfall year and relative to key phases of crop development; frequency of replanting required due to early season drought; change in frequency of heat waves, total and relative to key reproductive stages; changes in nighttime low temperatures effecting respiration and reproduction; and frequency of cold days during the dry season potentially effecting off-season irrigated crop production.
  - Adjustment: the increase in potential evapotranspiration rates associated future higher temperatures will be applied to the 2025 rainfall year to correct for the moisture actually available to crops over the current conditions.
- In applying the crop phenotypic profiles to weather records, once the "rainfall year" is established, an example query would look like:

- Find periods of 10 consecutive days, or more, with cumulative rainfall of less than 10 mm, from 0 to 20 days after the start of the rainfall year (e.g., corresponding to crop germination and early plant establishment).

- The summation of the frequency of these events, by year, across the reference period (e.g., 1992–2012) and various spatial scales (country, region) will establish the trend that can be projected, with confidence intervals, over the next decade in establishing the 2025 rainfall year record. We learn three important lessons by doing this: (1) what has happened within the Sahelian region with regard to the frequency of agronomically important weather events; (2) following these trends, what will likely happen over the next decade (providing operational guidance as to what adaptive responses, if any, are needed); and (3) by comparing the results with trends in inter-annual parameters (temperature and precipitation), the importance (or not) of looking at the intra-annual impacts of climate change is verified, which if positive, will exert a forcing influence on the science community in further strengthening and refining procedures intra-annual analysis.

2.6 USE OF PHENOLOGICAL SCREENING ANALYSIS

Knowledge of how close current climatic conditions are to important thresholds of crop physiology and whether and when (with CC) these thresholds will be surpassed essentially define the "breathing room" until agricultural productivity is negatively affected in different locations. Depending on the dominant driver, temperature versus rainfall versus extreme events, and the crop(s) concerned, different response pathways may be appropriate. For example: investments in rainfall harvesting technologies and land management options that conserve soil moisture may be most appropriate if the limiting factor is the decrease in rainfall, versus efforts to promote switching crops to those that are more tolerant of higher temperatures, if daytime highs the principal driver.

Phenological screening results can alert policy makers to the potential loss (or gain) in revenues from major cash crops due to CC. It can also signal the need to begin investing in long-term research to develop new varieties tolerant of anticipated future conditions now, so that there will be appropriate technical options available when conditions materialize in 10–20 years. Having a clearer understanding of the proximity to crop-based thresholds, especially those associated with intra-annual trends, is critical in terms of gauging the urgency of developing new technologies/practices. Currently there is no such understanding.

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