Chapter 19

Climate Prediction and Agriculture: What Is Different about Sudano-Sahelian West Africa?

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19.1
Introduction

Recurrent drought conditions that prevailed in the Sahel region of West Africa during the 1970s and 1980s have seriously challenged the resiliency of ecosystems and the adaptive capacity of human societies (IPCC 2001). This has triggered increased attention from the scientific community, resulting in a significant augmentation in climate-related publications and allowing for a better understanding of the complex regional and local climates.

Of prime importance is an improved appraisal of the variable nature of rainfall. When Hulme (2001) states that there is no such thing as 'normal' (mean) rainfall in the Sahel, he alludes to one of the most fundamental characteristics of the West African climate: its 'normality' is to be variable over a range of timescales. We first review the causes of this unique variability, then discuss its implications in terms of the prerequisites for beneficial use of forecasts (Hansen 2002), and the way forward in Sudano-Sahelian smallholder agriculture. Emphasis is put on the legacy of varietal adaptation as a powerful strategy for managing the stochasticity in climate – and further exploiting it in improved breeding programs, in parallel with rejuvenated early agrometeorological crop yield assessments.

19.2
The Context: Distinctive Climate Variability

19.2.1
A Variety of Forcings

A unique combination of external and internal forcings makes West Africa one of the most climatically sensitive regions of the world (Zeng 2003), and probably one of the most challenging to decipher, interpret and model (Jenkins et al. 2002) due to the superposition of numerous competing variability modes. Variability in rainfall results from location and astronomic forcings, which determine the seasonality of climate; oceanic-atmospheric large-scale forcings, which condition regional circulation and determine the season's potential; synoptic and sub-synoptic features, which control actual weather patterns and determine the realization of the season (Lister and Palutikof 2001). Interactions between these determinants are further complicated by land surface conditions which act as 'after-burners' of the regional climate engine (Traoré 2004).

19.2.1.1
Ocean and SST Forcings

There is still controversy over how SST and coupled ocean-atmosphere phenomena affect West Africa's climate. ENSO is known to influence the global summer monsoon system from China to West Africa through the Walker and Hadley circulations (Quan et al. 2003), but teleconnections with West African rainfall are less clear cut than for other regions of Africa (Nicholson and Kim 1997). More research on the modulating role of Atlantic SST variability (Camberlin et al. 2001; Janicot and Harzallah 1998) could help address the lack of consensus over ENSO's influence, drawn from apparent contradictory findings obtained over different timescales (Rowell 2001; Mason and Goddard 2001). There is growing agreement that Sahelian drought is not associated with a unique SST anomaly pattern, and that it results from the combined influences of the global SST anomaly field and interconnected individual oceanic contribution patterns (Folland et al. 1986; Giannini et al. 2003).

19.2.1.2
Synoptic Features

Similarly, current understanding of African convection remains deficient (CLIVAR 1999). African Easterly Waves (Cook 1999) provide a sound framework to explain the formation of squall lines and mesoscale convective systems through convective feedback loops on meteorological medium-range timescales (Landsea et al. 1999). They appear to be the key mechanism behind precipitation patterns during the core of the rainy season (Gu and Adler 2004) where the number of individual events explains most of rainfall variability (D'Amato and Lebel 1998; Le Barbé and Lebel 1997), but account for only a proportion of seasonal rainfall on the ground (Taleb and Druyan 2003). Further investigations are needed to understand processes that link synoptic events to regional and global circulation (e.g. MJO, Matthews 2004), tropospheric jets (Nicholson and Grist 2003), and land surface conditions (Fontaine and Philippon 2000).

19.2.1.3
Land Surface Forcings

It has long been suggested that degraded vegetation cover would result in decreased evapotranspiration, reduced precipitation and eventually further degraded cover, initiating an albedo-precipitation feedback cycle (Charney 1975). The lagged response of vegetation cover and soil moisture, which amplify low-frequency oceanic forcings (Giannini et al. 2003; Ward 1998) and buffer out high-frequency 'noise' appear required to closely simulate rainfall variations (Zeng et al. 1999). This conclusion should be no surprise owing to the unrivalled tropical landmass of northern Africa, but the transition from research on land-atmosphere modeling (Goutorbe et al. 1997; Dolman et al. 1997), causative mechanisms of climate change (Long and Entekhabi 2000; Xue et al. 2004) onto the operational implementation of dynamics land surface schemes in climate models remains incomplete in spite of the rapidly growing array of remote sensing observations.

19.2.2

The Problem: A Notoriously Unpredictable Growing Season

19.2.2.1

From Rainfall Variability to Predictability: The Skill Issue

Meanwhile, regional climate prediction skill at various time scales remains modest (IPCC 2001). Contrasting SRES ensemble simulations for seasonal rainfall over Southern Africa (forecasting a likely decrease) and the West African hinterland (poorly specified forecast) further suggest that variability and predictability do not necessarily go hand in hand. Models' knowledge base originally tuned to maximize performance over the Pacific region on interannual timescales (CLIVAR 1999) and relying on a subset of mostly oceanic and atmospheric predictors works satisfactorily when ENSO wields a dominant control over regional climate (even when interannual variability is highest: Southern Africa) but fails when the distribution of forcings is widespread (e.g. West Africa). Sometimes simple statistical methods outperform dynamical models constrained by poor initialization of regional soil moisture and lack of dynamically prescribed vegetation (Garric et al. 2002). Low local skill levels dominate in spite of an understandable urge to demonstrate the value of seasonal forecasts through more attractive scores at the aggregate level. For example, 'high degrees of skill' for the JAS period (IRI 2005) should be carefully interpreted in terms of scale-compatible applications (such as large watershed management), because any space-time downscaling will irremediably result in a loss of skill as suggested by Gong et al. (2003). The inability of dynamic models to correctly reproduce the succession of sub-grid scale convective events severely limits their applicability in hydrology (Lebel et al. 2000) and even more so in smallholder agriculture.

19.2.2.2

From Climate to Agriculture: Limited Predictand Relevance

The scale mismatch issue becomes more challenging indeed when agricultural applications are at stake. In Sudano-Sahelian West Africa, proper understanding of intra-seasonal variability patterns is of critical importance because of the highly unstable onset of the rainy season and the frequence of dry spells (Ati et al. 2002; Dodd and Jolliffe 2001; Omotosho et al. 2000; Ward et al. 1999). The length of the growing period (LGP) is mainly a function of the date of the first rains (Sivakumar 1988), which is delayed with latitude and varies widely from year to year (Fig. 19.1a). This important relationship basically results from the independence between the onset and end dates of the rainy season (Fig. 19.1bc). The ability to predict seasonal rainfall is then relatively less important, with the exception of the northernmost desert margins, where LGP is 'invariably' very short and water availability – as opposed to water distribution – becomes the central issue (Ingram et al. 2002). In that marginal agricultural environment running from southern Mauritania to northern Burkina Faso, southern Niger and central Chad, there might be scope for the application of selected seasonal forecasts (e.g. JAS rainfall), for which reasonable skill is observed with short lead times (Neil Ward, IRI, New York, personal communication). However southwards across Sahelian, Sudanian and northern Guinean agro-ecologies, the relationship between

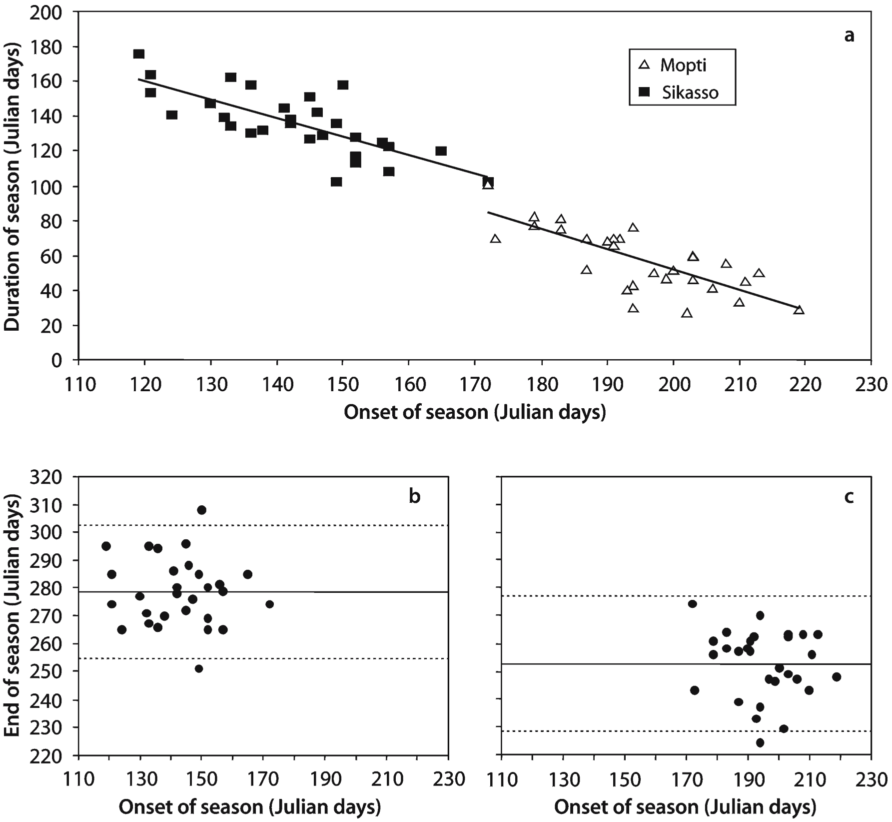


Fig. 19.1. a Duration of rainy season as a function of onset date in julian days for Sikasso (northern Guinea zone, 11°21' N) and Mopti (Sahelian zone, 14°31' N); normal period: 1971–2000; **b** relationship between onset and end dates for Sikasso; average end date is highlighted by *continuous line* with ±2 standard deviations (*dashed lines*); average end: 6 October, standard deviation: 12.0 days; average onset: 23 May, standard deviation: 12.9 days; **c** relationship between onset and end dates for Mopti; average end date is highlighted by *continuous line* with ±2 standard deviations (*dashed lines*); average end: 10 September, standard deviation: 12.2 days; average onset: 15 July, standard deviation: 11.9 days

3-monthly rainfall, soil water regimes and plant growth patterns is less clear cut: the relevance of seasonal products for agricultural applications therefore decreases.

19.2.2.3
Prospects for Temporal Downscaling: Disciplinary Divergences

Important ongoing work in the framework of the Multidisciplinary Analysis of the African Monsoon project (AMMA 2005) indicates that any potential application of downscaled seasonal forecasts will need to overcome a persistent dichotomy between climatologists and agriculturalists when it comes to farm decision-making advisories. The former advocate later sowing dates synchronous with an abrupt northward shift of the ICTZ, which they connect to monsoon onset, as opposed to the pre-onset (Sultan and Janicot 2003). The latter insist that the risk linked to delayed sowing (N leaching, lower radiation and temperatures, rainfall aggressivity on younger shoots, waterlogging, pest pressure and mostly competition from weeds) is considerably larger than the risk, associated with farmer earlier planting strategies, of losing 2–3 kg ha^{-1} of seeds (Vaksmann et al. 2005). Many of the biotic and abiotic stresses that impact final yield are not taken into account by water balance models (Sultan et al. 2005) and could explain these divergent views of what could be a safe 'agronomic' start to the cropping season.

19.2.3
What are the Options in the Face of Climate Variability?

19.2.3.1
Applicability of Response Farming

"Response farming springs from research on rainfall behavior and its predictability in a 'cropping systems design' project in Kenya […]" (Stewart 1988). In and of itself, this introductory sentence summarizes the tight association between climate forecasting (rainfall predictability) and "opportunity cropping" tactics (ibid.) promoted by response farming (RF). The fact that RF originated in a region characterized by a vulnerable population associated with a high rainfall variability and a fair level of ENSO-based predictability (Kenya) is likely not a product of chance and has probably contributed to a worldwide success story of pilot applications of seasonal climate forecasting in agriculture with Kenya (and notably the Machakos District) a popular benchmark area throughout the years (Rao and Okwach 2005; Hansen and Indeje 2004). In any case, the potential usefulness of seasonal forecasting should be embedded in a down-to-earth assessment of current practices and possibilities. In the Sudano-Sahelian region, considering such options as shifting crop mixes and response farming tends to assume far-fetched levels of farmer flexibility in a socio-economic context still marked by risk-adverse, conservative practices, and might thus be unrealistic (Abou Berthé, personal communication). This is not to say that vulnerability deprives farmers of responsiveness, rather that they will deliberately take the risk to respond to those signals that are unequivocal, and likely ignore those which are uncertain. This dichotomy was demonstrated in year 2000, when an unequivocal decrease in purchase prices by the cotton parastatal prompted a nationwide farmer strike with widespread changes in crop mixes in southern Mali. While illustrating clear independence from political power by non-subsidized farmers (contrary to developed countries), this does not imply that the same cotton farmers would be willing to risk their food security by responding to a seasonal forecast which, constrastingly, is largely uncertain.

Traditional climate risk management practices by Sudano-Sahelian farmers include direct sowing, low planting densities, distribution of early and late maturing types throughout the landscape and spreading sowing dates (Ouattara et al. 1998). Potential innovations include contour ridge tillage cultivation, cover plants and mulching, zaï. Several of these have the potential to concurrently reduce climate risk and increase productivity (De Rouw 2004) in a 'conventional' response farming framework, provided reliable climate information is available. A large component of farmers management strategies however resides out of the response farming realm as it relates to specific adaptation traits engraved inside plant genetic resources.

19.2.3.2
Legacy from the Field: Plant Traits Encapsulate Variability Management

Traditional handling of plant genetic resources condenses most aspects of adaptation to climatic variability in subsistence agriculture and is known to contribute fundamentally to the development of sound production systems (WMO 2003). It is today slated for intense, conflicting questioning at the nexus of agricultural intensification processes, intervention policies and advances in biotechnology – before development and growth of agricultural income allow for a wider spectrum of response farming options. In continental West Africa, photoperiod (PP) sensitivity is required to best fit crop cycle to the probable duration of the season and is one example of the critical ingredients of environmental adaptation. It allows for grouped flowering at the end of the rainy season for a wide range of planting dates (Traoré et al. 2000) and is present in staple cereals (Mahalakshmi and Bidinger 1985) and other crops (Brink et al. 2000) with some of the highest recorded sensitivity levels worldwide. It helps minimize grain mold, insect and bird damage that affect early maturing varieties, and avoid incomplete grain filling, a problem for late maturing varieties faced with water shortage at the end of season (Cochemé and Franquin 1967; Curtis 1968; Kassam and Andrews 1975). Tillering is yet another example of unique adaptation trait, controlling the partitioning of biomass across plant organs.

It is tempting to make a parallel between contrasting levels of climate predictability and apparently marked differences in PP sensitivities observed between crops of West Africa and Southern Africa. It could be hypothesized that higher predictability of the length of growing period (LGP) in Southern Africa would favor the selection of a number of fixed maturity groups, best suited to the expected duration of the cropping season. Conversely, uncertainty associated with LGP in continental West Africa would logically tend to eliminate PP-insensitive material. Further investigation will show whether landrace PP sensitivity can be trusted as a good indicator of climate unpredictability.

19.3
Forecasts for Smallholder Food Security: Which Way Forward?

19.3.1
Where Do We Stand Now?

A few exploratory studies have confirmed Sudano-Sahelian farmers' expected interest in climate forecasts, and the determinants of potential response strategies (Ingram et al. 2002; Roncoli et al. 2004). Conclusions substantiate farmers' understanding of uncertainty, risk and opportunities associated with the use of predictions, but also highlight the inadequacy of forecasts which (regardless of skill) do not fulfill their need for estimates of season onset and end dates, time distribution and total amount of rainfall (in decreasing order of priority). Interestingly enough, these studies do not mention the widespread use of PP-sensitive cereals as one central, ingenious and sophisticated strategy to ensure food security even in the most erratic of seasons (National Research Council 1996), and how that practice would interact (or interfere) with the prospective use of seasonal forecasts. This contrasts with the increasing number of promising applications elsewhere, even though most successful cases are confined to regions facing open oceans and displaying high predictability levels such as Australia, Argentina, Florida, Kenya or Southern Africa (Hammer et al. 2001). The difficult challenges of seasonal predictability and agricultural resilience in Sudano-Sahelian West Africa might also explain the local dominance of health-related applications in the Africa Regional Program implemented by IRI and its partners.

19.3.2
Develop Dynamic Land Surface Schemes in Climate Models (Long-Term)

However distant from smallholders livelihoods (and agricultural research) this priority may appear, abundant literature points to the need to improve the representation of land forcing in climate models, if higher predictability of local and regional climates is to be attained. The implementation of this consensual effort has possibly been delayed by the lack of extensive satellite time series but is quickly picking up as the climate science community now strongly acknowledges the role of 'new and/or better existing observational networks as the drivers of model improvement and thus of improved climate anomaly predictions' (Grassl 2005). Differing results by Wang et al. (2004) and Crucifix et al. (2005) on the impact of vegetation dynamics on rainfall variability ('memory' or 'after-burner' effect) provide encouraging signs that significant progress is underway, with important breakthroughs possible in the coming years.

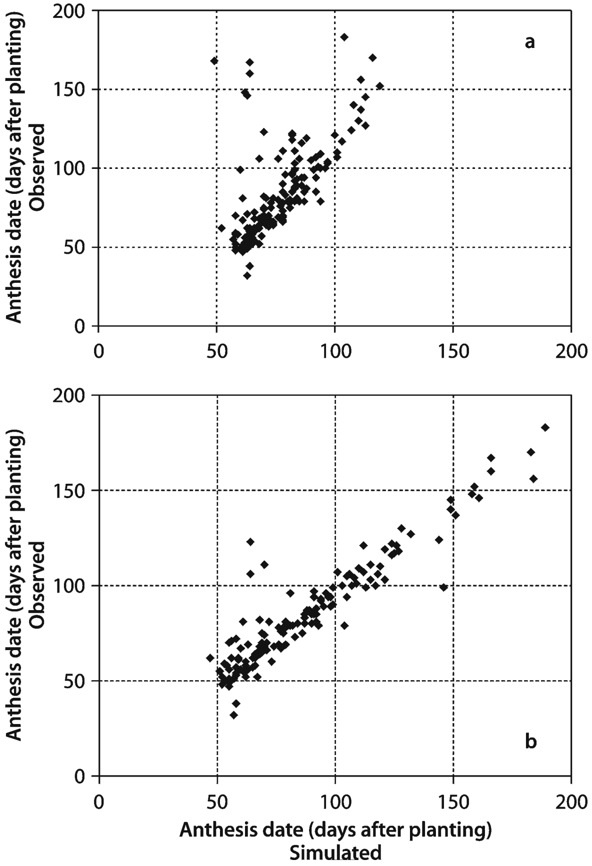
19.3.3
Adapt Crop Models (Short-Term)

A more immediate prerequisite to the successful identification of profitable tactical management decisions based on seasonal forecasts is that crop simulation models must first be able to effectively reproduce the characteristics of local cropping systems (Phillips et al. 1998). This presents difficult challenges for a range of models available for use in West Africa, because of such peculiarities as surface crusting, low planting densities and heterogenous canopies, etc. Critical advances were however made, e.g. in the adaptation of PP response in the CERES-Sorghum and -Millet modules of the DSSAT-Century cropping systems model. In its original form, a linear photothermal response resulted in underestimates of crop cycle duration for late-maturing landraces (Fig. 19.2a). A threshold-hyperbolic function was shown to simulate cycle duration (Fig. 19.2b) for both PP-sensitive and PP-insensitive material (Folliard et al. 2004). This work allowed to revisit the popular, but incorrect photothermal approach widely used in modeling crop development (Robertson 1973). Other ongoing work seeks to improve models poor ability to simulate yield components because of flaws in the timing of stem elongation (occurring after panicle initiation in CERES) and the inadequate partitioning of assimilates resulting in inflated harvest indices for Sudano-Sahelian landraces.

19.3.4
Apply GIS and Crop Models to Target Breeding Strategies (Medium-Term)

A popular misconception argues that landrace rusticity traits related to development (e.g. photoperiod sensitivity) and growth (e.g. tillering) are incompatible with pro-

Fig. 19.2. Days to anthesis computed over a sample size of 146 from planting date experiments conducted between 1992 and 2003 in six locations (Cinzana, Koporo-Pen, Katibougou, Samanko, Sikasso, Sotuba) covering a latitudinal gradient in Mali. Participating sorghum and millet varieties: CSM219, CSM388, Jebana, M9D3, Nazongala, Sanioba-03, Sanioba-B, Surukuku, W33, Wasulu. PP response; **a** cumulative linear (CERES original), $R^2 = 0.37$, $RMSE = 25.7$; **b** threshold hyperbolic (Folliard et al. 2004), $R^2 = 0.88$, $RMSE = 11.6$



ductivity traits. This simply is not the case, and the preservation of stability is a central paradigm in breeding for productivity (Dingkuhn et al. 2005). Photoperiod sensitivity is positively correlated with productivity as it allows for longer vegetative phases, increased production of biomass (Reyniers et al. 1998) and augmentation of yield components such as seed number per panicle (Vaksmann et al. 1998). Major dwarf genes can be mobilized to shorten stems and augment harvest indices in photoperiod sensitive sorghum (Kouressy et al. 1998). Tillering is compatible with high yields (Lafarge et al. 2002) and helps early stand development and rapid canopy closure to limit weed invasion and soil erosion. Figure 19.3 illustrates the potential use of models and GIS to investigate genotype × environmental interactions in a spatially explicit manner over the CILSS region of West Africa. Here, a large amount of learning from indigenous knowledge, mechanistic crop modeling and sensitivity analyses is synthesized to map varietal adaptation based on a phenological criterion which seeks to align (as do farmers and plants) flowering dates on the end of rains – instead of relying on the misleading average ('normal') length of growing season (LGP). Next steps for improved targeting of breeding programs will involve higher level mapping to represent

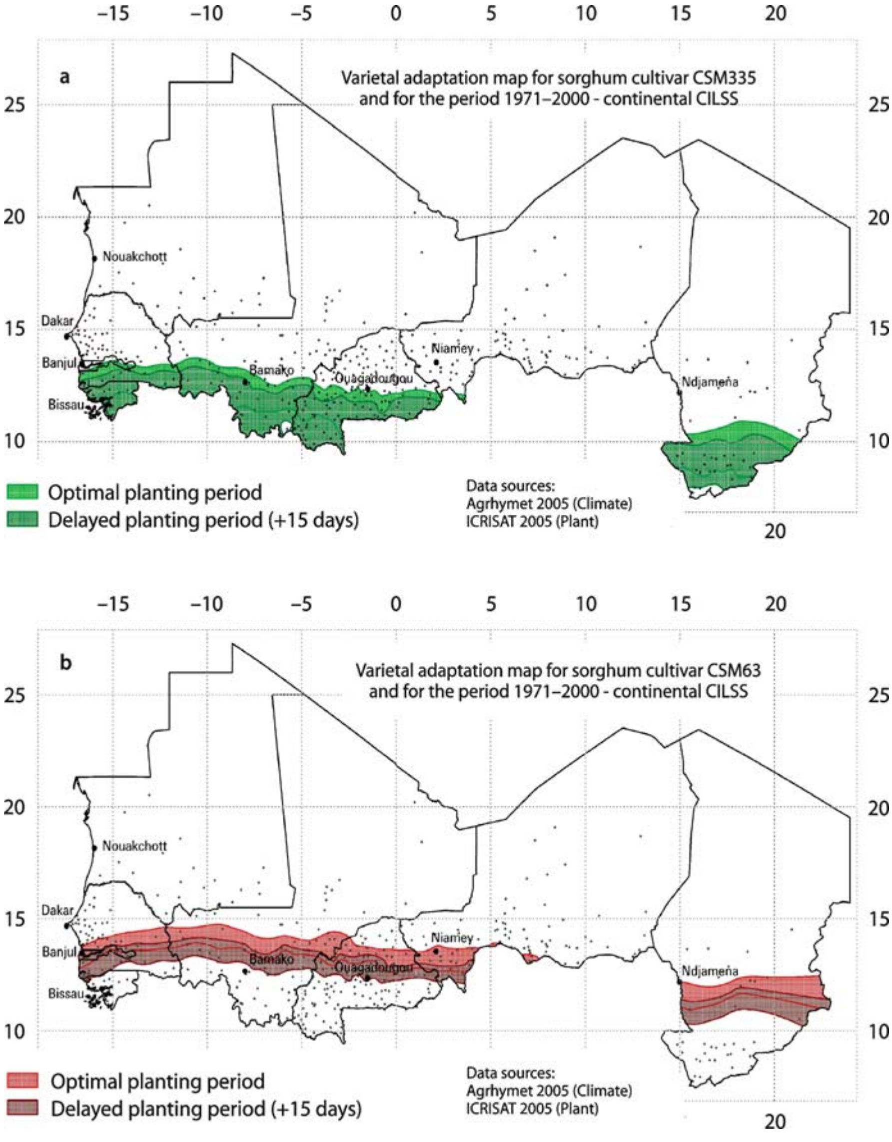


Fig. 19.3. Varietal adaptation maps for cultivars CSM335 (**a**) and CSM63 (**b**) and for the 1971–2000 period (continental CILSS countries). Here, adaptation is defined based on phenology, i.e. when the average flowering date occurs 20 (±10) days before end of season. End of season occurs when a moving 10-day average of daily rainfall drops below the ETP line (~end of humid period, adapted from Cochemé and Franquin 1967). The two planting periods, optimal (shortly after onset of humid period) and delayed, reflect the traditional spread of sowing dates. The adaptation strip for early-maturing, non-PP sensitive CSM63 is thinner than that of late-maturing, PP-sensitive CSM335 on any given date. It rapidly migrates southwards for delayed sowing, with relatively small latitudinal overlap for a 15-day delay, in contrast to CSM335. CSM63 can be seen as a variety of large geographic adaptation if, and only if, there is a shift in sowing dates. CSM335 demonstrates both large temporal adaptation (small latitudinal shift, large overlap) and large geographic coverage. PP-insensitive germplasm (like CSM63) is more likely to benefit from improved climate forecasts, but PP-sensitive cultivars could remain very competitive

the larger spectrum of abiotic, biotic, and socio-economic constraints to varietal adaptation.

19.3.5
Revisit Early Crop Yield Assessment Techniques (Medium-Term)

The suggestion to incorporate rusticity traits in breeding strategies as a way to temporarily or durably 'hard-code' variability management should not be seen as a pessimistic attempt to downplay potential tactical uses of seasonal forecasts in Sudano-Sahelian agriculture or (even worse!) underrate the critical importance of agroclimatic risk analyses. Rather, we believe that before forecasting skill and smallholder endowment improve, there is room for a parallel and renewed effort in the agrometeorological early estimation of crop production. A much larger array of data sources (from climate models and remote sensing), finer understanding of crop growth and development (from process-based models) and stochastic data assimilation (DA) techniques now allow a more operational 'invigoration' of probabilistic agroclimatology by looking at 'weather within climate' (Hansen et al. 2005) in the context of facilitating investment in rainfed agriculture (Cooper et al. 2005). Predictability at intermediate intra-seasonal (~20–60 day) timescales has been somehow neglected in favor of more fashionable seasonal products, but holds promise in the short term as it will benefit from enhanced representation of continental forcings (Céron 2004) and ongoing projects such as AMMA (2005). Experimental hybrid monthly forecasts are routinely published by ECMWF since October 2004 with the objective to bridge the gap between extended weather and seasonal timescales, a priority focus area from a climate science perspective (Grassl 2005). Figure 19.4 proposes a schematic procedure to improve final model yield estimates using such in-season rainfall forecasts and bi-weekly satellite biomass observations (from ASTER) in a sequential DA framework. Sequential DA is computationally more efficient than variational DA recently tested for crop yield estimation (Guérif and Duke 2000; Bach and Mauser 2003). It can accommodate a wider range of uncertainty as Monte Carlo ensemble generation allows for any statistical form of time/space correlation in error structure (Crow and Wood 2003), and can propagate the full probabilistic climate information into yield estimates along with measurement and model uncertainties (Jones et al. 2006). It is better suited for near-real time applications oriented towards the prediction of future system states that is key to early warning systems.

19.4
Conclusions

In 2003 we started a START-funded project entitled 'Bytes for Bites: Translating Climate Forecasts into Enhanced Food Security for the Sahel' carried by a sense of 'environmental urgency' (Raynaut et al. 1997). Little did we realize then that Sudano-Sahelian farmers (and their crops) still are, in many ways, experts in resilience (Batterbury and Warren 2001; National Research Council 1996) and that our early assumption of *human vulnerability* could be challenged by generations of trusted kinship networks (Roncoli et al. 2001) and sophisticated practices including the selective management of plant genetic resources.

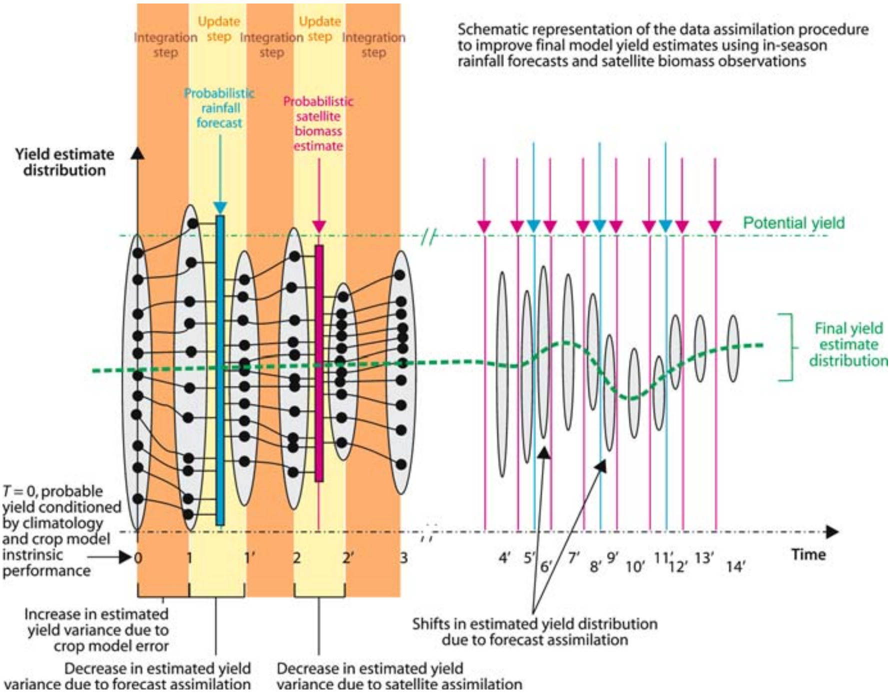


Fig. 19.4. Schematic representation of a data assimilation procedure to improve final model yield estimates using in-season rainfall forecasts and satellite biomass observations. At $T = 0$, a crop model (mechanistic or empirical) is initialized with an ensemble of equally likely conditions (using a Monte Carlo technique). The model is then propagated forward in time with each realization of the ensemble. When estimates of system states (e.g. biomass), model parameters (crop type, sowing date, …) or boundary conditions (cumulative rainfall) become available an Ensemble Kalman Filter (EnKF) updates these and the measures of uncertainty thereof. EnKF has improved early estimates of system states in physical oceanography, meteorology, air pollution monitoring, hydrological streamflow forecasting, petroleum engineering, fish stock assessment, and more recently carbon sequestration studies (Jones et al. 2006)

A thorough review of current knowledge on regional climate revealed that in Sudano-Sahelian West Africa, *climate predictability* remains limited and very likely constrains the beneficial use of current forecasts in the region. This problematic setting combines with a context of low endowment of smallscale farmers and still deficient information systems to hamper *decision capacity* at multiple scales by reducing the array of options available to take advantage of developing seasonal forecasting opportunities.

With this, the successful application of seasonal forecasts in Sudano-Sahelian smallholder agriculture appears today premature, contrasting with several other regions of Africa and the world, some even close (Adiku and Stone 1995) with more immediate potential.

This will change over the next decade, as progress on the implementation of retroactive land-atmosphere interactions in dynamic climate models yields tolerable uncertainty levels for uptake by Sudano-Sahelian farmers, and production systems intensify under growing population pressure, increase in sedentary agriculture and fallow reduction. Meanwhile, a range of preparatory activities can be pursued with benefits in the shorter term: the ongoing adaptation of crop models to simulate local crops and farming systems (Folliard et al. 2004), their coupling with GIS technologies to target regional breeding programs (Soumaré et al. 2005), and a 'rejuvenation' of early agrometeorological crop yield assessment techniques using the latest stochastic data assimilation approaches within the rapidly expanding spectrum of data sources (Traoré 2005). The latter offers timely prospects for the use of within-season, intermediate timescale forecasts in operational early warning systems and, possibly, selective response farming by Sudano-Sahelian smallholders. In a few years, progress achieved on these fronts will combine with improved predictability of climate variability trends to investigate agricultural impacts of global and regional change, and specifically the sustainability of existing and alternate patterns of adaptation (Sivakumar et al. 2005).

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