Past, Present and Future Criteria to Breed Crops for Water-Limited Environments in West Africa

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Abstract

Asia's Green Revolution of the 1960s and 70s has largely bypassed West Africa, and "modern" (high-yielding, input responsive) germplasm has found comparatively little adoption, except for the small proportion of systems that are irrigated. It is unlikely, however, that breeding traditional-type materials for better performance in subsistence systems would have been more successful. The authors thus identify systems caught in the agricultural transition from subsistence to intensified, market-oriented production as being promising targets for crop improvement, and provide examples of original breeding objectives for cowpea, sorghum and upland rice. In each of these cases, breeders, with the help of physiologists, have developed plant-type concepts that combine increased yield potential and input responsiveness with certain traditional crop characteristics that are thought to remain essential during the agricultural transition. In the case of cowpea, dual-purpose varieties were developed that produce a good grain yield due to an erect plant habit, then produce enough new leaves to enable a second harvest of green foliage. For upland rice systems that are limited by labour shortages (mainly needed to control a weed flora that abounds due to shortened fallow periods), a weed competitive, high-yielding plant type was developed from *Oryza sativa* x *O. glaberrima* crosses. Lastly, sorghum breeders who previously eliminated photoperiod sensitivity from improved materials are now re-inserting sensitivity into plants having "modern" architecture, in order to allow for flexible sowing dates while maintaining an agro-ecologically optimal flowering date near the end of the wet season. The perspectives of these plant types, as well as the problem of under-funding for their realisation, are discussed.

Keywords

Selection criteria, plant types, sorghum, cowpea, upland rice, dual purpose varieties, weed competition, stay-green, agricultural transition

1. Introduction

Genetic improvement of annual grain crops in West Africa has not met the same success in terms of adoption and economic impact as compared to Asia or South America (IRRI, 1997). A frequently-cited explanation for this is a difficult environment, such as highly variable climate (particularly, rainfall), pests and diseases, infertile or toxic soils, etc., but these or similar constraints affect cropping systems in other regions of the world as well, without having prevented the impact of genetic and technical innovation. For example, the Cerrados of Brazil were considered unsuited for cultivation only a generation ago and are now under highly intensive cultivation (Cirad, 2003), and semi-arid environments in Australia, although rather extensively cropped, are cultivated with modern genetic and cultural technologies (Turner, 2004). Why did the Green Revolution bypass much of West Africa?

The main answer is socio-economic: limited access of producers to markets and credit, small-scale holdings and land tenure issues, and political insecurity hampering investment. We will not elaborate these observations and instead raise the question how crop improvement objectives for major West African staples have responded to the challenge, what presumably went wrong (if it did), and what approaches appear to be promising for the future. We will thereby not focus specifically on drought and drought resistance, but on crop characteristics that breeders and agronomists consider key to profitable cropping in West African, rainfed production systems. In fact, the breeding programs highlighted in this paper generally do include screens for physiological drought tolerance, but also emphasise more indirect adaptations to water limitation, such as phenology-based escape mechanisms or competitiveness with a weed flora that is frequently more drought resistant than the crop.

We will limit the analysis to three crops, namely upland rice, cowpea and sorghum, which occupy different ecological niches and are part of different cropping systems in West Africa.

Upland rice is a main staple crop in the humid forest and moist savannah (Guinea savannah) and humid (forest) environments (>1200 mm annual rainfall) in the coastal countries of West Africa, particularly Guinea-Conacry, Sierra Leone, Liberia and Ivory Coast, yielding less than 1 t/ha on average (Mathieu, 2000) despite a potential near 4 t/ha (Dingkuhn et al., 1998). Although *Oryza glaberrima* Steud. cultivars were domesticated and cultivated in West Africa some 3000 years ago, *O. sativa* L. cultivars, first introduced by Portuguese traders 500 years ago, dominate today's systems. The crop's high susceptibility to drought, weed competition and fungal diseases (particularly under intensive cultivation) is offset by adaptation to the prevalent acid soils and growing domestic demand, particularly in the cities (Buddenhagen and Persley, 1997). Sustained varietal improvement for local upland conditions since the nineteen-sixties by French institutions, the International Institute of Tropical Agriculture (IITA) and the West Africa Rice Development Association (WARDA) has met limited adoption, in contrast to aquatic lowland systems where improved cultivars dominate. A recent breakthrough in crossing *O. glaberrima* and *O. sativa* (japonica) rices at WARDA ("Nerica" rices) appears to have partially reversed that trend at least in some countries, such as Guinea Conacry (refer to WARDA Annual Reports: www.warda.cgiar.org).

Cowpea [*Vigna unguiculata* (L.) Walp.] is important, particularly as an intercrop in cereal systems, in the drier regions of West Africa where rainfall is low and erratic and soils are sandy and of low fertility. Of the world total of about 14 million ha, West Africa alone accounts for about 9 million ha (Singh et al., 2003a). With >25% protein in seeds as well as in young leaves (dry weight basis), cowpea is a major source of protein, minerals and vitamins in daily diets and is equally important as nutritious fodder for livestock (Singh et al., 2003b). The mature pods are harvested and the haulms are cut while still green and rolled into small bundles containing the leaves and vines. These bundles are stored on roof-tops for use as feed supplement in the dry season, making cowpea a key factor for crop-livestock systems. Cowpea haulms fetch 50% or more of the grain price (dry weight basis) and therefore constitute an important source of income. Cowpea also improves soil fertility (Carsky et al., 2001) in various, low-rainfall cropping systems. Yields, however, are between 100 and 400 kg/ha despite a potential 5 times higher. This is partly attributed to shading by intercrops such as sorghum, a prostrate (weed-competitive, but low-yielding) architecture, and susceptibility to pests such as *Maruca* pod borers, root-parasitic weeds and nematodes (Henriet *et al*., 1997). Being primarily an African crop, few countries have cowpea improvement programs. IITA in Nigeria has a global mandate for cowpea research and development, and maintains a world collection of 16,000 lines.

Sorghum [*Sorghum bicolor* (L.) Moench] has been cultivated for millennia in West Africa, mainly in the Sudano-Guinean zone during the rainy season, which is monomodal with 800 to 1100 mm/year. Further north in the drier Sudan savannah, at 600-800 mm/year, sorghum is also cultivated although the rainy season is frequently too short to produce satisfactory yields. Often associated with other crops like cowpea, sorghum displays in the savannahs its greater drought resistance compared to maize and upland rice (which are found further south) and its higher yield potential compared to highly drought-resistant pearl millet (which is grown further north where rainfall is lower). Apart from rainfed upland cultivation, sorghum is traditionally also grown as a flood recession crop in the floodplains of the Sahel after the rainy season, temporarily as an aquatic crop (Chantereau and Nicou, 1994). Having a similar grain production as millet in West Africa, sorghum is the food staple of millions of people who traditionally consume the grain as stiff porridge (Toh) and couscous (steam cooked product) or as fermented beverages (Dolo, Chapalo), although sorghum foods are increasingly substituted with rice and maize (Debrah, 1993). Stalks are also a vital resource as animal feed, fencing material and fuel (National Research Council, 1996). From 1979-81 to 2001, sorghum production in West Africa increased from 5.1 to 13 millions tonnes but mean yields are stagnant (890 kg/ha in 1979-81, 780 kg/ha in 1992-94, 830 kg/ha in 2001) (FAO, 1997). Regional production continues to depend mainly on traditional cultivars characterised by hardiness, photoperiod sensitivity, long stalks, good grain quality and low harvest index.

In the following, we will discuss past breeding objectives for these three crop species, with particular emphasis on the underlying plant-type concepts and how they differ from the locally-available, traditional germplasm. We will then highlight some concepts for crop improvement that have evolved in the course of the past decade or so, and discuss whether or not we can expect from them a greater economic impact than has been achieved with the past approaches.

2. Past paradigms for varietal improvement and their impact

Although it is in the nature of any genetic improvement effort to change crop behaviour, it is striking how modern breeding products for West Africa differ from the available, traditional germplasm, selected by farmers over centuries. The "modern" germplasm is generally early maturing, has stable crop duration due to reduced photoperiod sensitivity, and has morphological features that enable a higher harvest index, indicating that priority was given to grain production, as opposed to other harvestable products such as stems or green foliage, even through these have multiple uses in traditional systems. These choices, when translated into selection criteria, have different morphological consequences depending on the species.

In rice, for example, reduced height of semidwarf materials is generally associated with higher tillering capacity, which multiplies the number of organs but reduces their size (e.g., leaf dimensions, stem diameter, grains per panicle) (Yoshida, 1981). In sorghum, however, dwarfing has mostly resulted in reduced internode length, increased stem diameter and reduced tillering while leaf size remained unchanged (Morgan and Finlayson, 2000). The leaves therefore are more densely stacked on a thicker axis. This remarkable difference between the two cereals is certainly related to different genetic dwarfing mechanisms used by breeders, but no comparative genetic and/or physiological study that explains this difference has come to our knowledge. In cowpea, the objective of increasing grain production has mainly reduced the creeping habit in favour of a more erect morphology, enabling improved light use efficiency over the season.

Breeding objectives for the three species were not limited to substituting a traditional with a modern architecture, but have always included quality traits and whatever resistances to biophysical stresses were required in the target environment, mostly selected for by exposing the materials to the stresses experimentally or at hotspots, and less frequently by selecting *in vitro* for associated morphological or molecular markers. Since the desired plant type and stress resistances rarely coincide naturally, stress resistances are introgressed from selected donors into materials that have the desired phenotype, phenology and general adaptation to the environment. We will in the following not further discuss such characters unless they are associated with the plant's morphology or phenology.

What is the reason for the generic phenological objectives (shorter and stable duration) in crops as diverse as cowpea, sorghum and rice, and for environments as diverse as the Sahel and the humid forest? And why, in the first place, are traditional cowpea and rice cultivars (case of *O. sativa*) rather late maturing? A comparative phenological study on diverse, introduced and traditional rices in West Africa gave a partial answer for that particular species (Dingkuhn and Asch, 1999). It turned out that mainly *O. sativa* rices, and among them those grown in rainfed environments (uplands and lowland swamps), had relatively long duration, whereas native *O. glaberrima* rices domesticated in the same environments had extremely short duration. The latter are highly weed competitive whereas most *O. sativa* materials are not (Dingkuhn et al., 1999), thus probably requiring a longer vegetative period to produce a satisfactory biomass. In fact, "modern", short-duration, japonica-type upland rices that have high yield potential, such as WAB56-104 (Johnson et al., 1998), are poor competitors and require a level of crop protection that is unaffordable to producers. Similar questions might be asked with respect to de-selection of creeping and long-duration ecotypes of cowpea, which are excellent weed competitors but produce little grain. This is not to conclude that "modern" (short-statured, short-duration, poorly weed competitive, high harvest index) cultivars have no place in West African production systems. They do have a place wherever traditional systems can be converted to market-oriented systems using external inputs, for example in association with input intensive cotton systems in northern Ivory Coast or in densely-populated environments such as northern Nigeria. Where weed control and inputs are available, short-duration materials can achieve their high yield potential.

Short crop duration also has potential advantages where the rainy season is short and/or the phenology of the crop has to fit into mixed cropping systems. Both sorghum and cowpea are commonly intercropped, frequently with each other, and both tend to venture north into drier habitats. Development of improved cultivars with increasingly shorter duration enables upland rice, maize and sorghum to be grown in shorter rainy seasons, and therefore further north. This phenomenon is difficult to evaluate, however, because decreasing rainfall totals in the past 40 years in the Sahel (Nicholson, 1986) have at the same time contributed to the opposite trend. But it is a fact that adoption of short-duration, photoperiod- insensitive sorghum materials is largely limited to the northern margin of their ecosystem, where the wet season is extremely short, whereas traditional, photoperiod-sensitive varieties still dominate in the traditional, more humid sorghum belt of West Africa (Kouressy et al., 1998). We will return to this phenomenon in the next section.

There is no point proving that improvement of grain crops for West Africa was insensitive to local needs and therefore achieved only limited adoption. In fact, it would be difficult to beat locally-adapted, traditional germplasm in areas where traditional cropping systems still function. Breeding therefore has to target cropping systems that are changing, driven by the demographic and economic upheaval and the collateral agroecological damage associated with the transition. Such systems, although ready for change, neither have good use for traditional production technologies (because they are not competitive) nor are they ready for “modern” germplasm and intensive management principles (because during the chaotic transition, impoverished producers are not able to invest in land and resource quality, a major condition for intensified production). It must be kept in mind that West Africa is not South-East Asia, where the green revolution, fuelled by an input-responsive rice plant type (Peng et al., 1994), could build on an existing culture of agricultural intensification, necessitated by high population density and high land value. The same demand for a “green revolution” type of crop is rare in West Africa, although it can be found, for example, in peri-urban and irrigated agriculture, or in cash crop/staple crop associations (example: cotton and cereals).

In the next section, we will return to the specific plant type requirements for cropping systems caught in the agricultural transition in West Africa. Before closing the issue of the appropriateness of past varietal improvement objectives we would raise some questions regarding germplasm diversity and conservation, which are at the basis of any long term crop improvement strategy. Reorientation of breeding objectives in more recent times towards combining “traditional” with “modern” crop characteristics, for example in order to achieve better weed competitiveness (Jones et al., 1997; Dingkuhn et al., 1998 & 1999, Johnson et al., 1998) or timely maturity at the end of the wet season through photoperiod-sensitivity (Clerget et al., 2004), has called for the use of native donor materials. Unfortunately, at the time when native sorghum and African (*O. glaberrima*) rice germplasm was prospected and field-screened in West Africa in the 1960s and 1970s for future breeding purposes (Sapin, 1971?; Barrault et al. 1972?; Dobos, 1986), emphasis on the current agronomic selection criteria led to the de-selection and non-inclusion in germplasm banks of much of the exotic germplasm. This is particularly the case for West African sorghum landraces known as flood recession materials, which were grown in the Senegal river delta and valley (Durra types), the Niger inland delta (Durras and Guineas) and the floodplains associated with the tributaries of Lake Tchad (Durra-Caudatums, known as Muskwari and Babouri groups) (Chantereau, 2002). These materials have tall, massive stems and large leaves with good fodder quality, and are photoperiod-sensitive, cold- and drought-tolerant, and adapted to heavy clay soil and waterlogged conditions (Chantereau, 2002). In fact, the most extreme types found in the Niger inland delta, are sown or transplanted on residual moisture in the cool season (December), survive the scorching dry season and complete their growth cycle in the subsequent wet season, sometimes harvested by boat (Harlan and Pasquereau, 1969). These materials must possess remarkable phenotypic plasticity and a broad range of adaptations. Fortunately, at least for the flood-recession sorghums, *in situ* conservation through continuing cultivation seems to be working fairly well (Chantereau, unpublished), provided that climate change or river regulation does not dramatically affect the West African floodplains.

Oryza glaberrima germplasm, also mainly prospected during the 1970s, which shows a similarly wide range of environmental adaptation and originates from the same region and ecosystem as the flood-recession sorghums, has fared slightly better in terms of formal germplasm conservation, but the existing 3000-entry germplasm collection safeguarded by IITA (Nigeria) for WARDA has never been used for within-species breeding, and only recently for trait introgression into *O. sativa* backgrounds (Jones et al., 1997). Here, potential loss of biodiversity would probably be brought about by the continuing displacement of *O. glaberrima* by *O. sativa*. Least endangered among the three species discussed here is the biodiversity of cowpea, because long-standing breeding and conservation programs at IITA make broad use of it, and because cowpea, in contrast to *glaberrima* rices and flood-recession sorghums, plays an increasingly important economic role in diverse ecosystems and cropping systems in West Africa.

3. New breeding objectives – will they make a difference?

We will now briefly describe some more recent breeding strategies for cowpea, upland rice and sorghum that aim at morphological and phenological plant types developed for specific cropping systems and biophysical environments. These plant types generally combine local-traditional characters (providing key adaptations or features required by the cropping system) with certain modern characters (providing improved yield potential) in a way that can neither be found in local nor in introduced germplasm. In all three cases, the breeding strategy was driven by the realization that the West African agricultural transition from extensive to intensive systems requires crops that respond positively to intensification measures while taking into account that farmers have very limited means to control the crop environment (or may even degrade the natural resource base, thus aggravating biophysical constraints).

3.1 Dual purpose cowpea and sorghum crops

Cowpea continues to be a major source of both food and fodder in the dry savannas of West and Central Africa. Most farmers keep livestock and intercrop two types of cowpea varieties in alternate rows with millet and/or sorghum in the same field, one for grain and the other for fodder. Both are spreading (creeping) types, the grain type being early maturing (80-85 d) and the fodder type late maturing (100-120 d). Grain cowpea and millet are harvested late in the wet season (late August to early September) whereas the late maturing cowpea varieties are left in the field until the onset of dry season while making use of residual soil moisture (October – November). Farmers wait until the cowpea leaves show signs of wilting before they cut the cowpea plants at the base and roll the plants into bundles with all leaves still intact. Those bundles are kept on rooftops or in tree forks for drying and sold in the peak dry season when prices are high. If rains occur in October/November, the fodder-type cowpeas produce some grain as well (Mortimore *et al.* 1997; Singh and Tarawali, 1997).

Although this intricate system utilises rainfall from May to November, overall productivity is low because the grain-type varieties flower and pod under the shade of millet and the fodder-type varieties are often affected by terminal drought. Therefore, an ideal cowpea variety for this system would be a dual-purpose type with semi-determinate growth habit and intermediate maturity (85-95 days) so that it flowers in September when millet has been harvested and becomes ready for first picking at the onset of the dry season. Several such varieties (Fig.1C) have been developed at IITA which yield over 2 t/ha grain and 2 to 5 t/ha fodder (Table 1). They continue producing leaves after grain maturity, enabling harvesting the green plant tops 2-3 weeks after grain harvest. These cultivars derive their high productivity from an erect growth habit (Singh and Sharma, 1996) which distinguishes them from the flat and creeping traditional types, possibly to the detriment of competitiveness with weeds. On the other hand, this plant architecture makes the dual purpose cultivars responsive to plant population density, and therefore suitable for intensification (Table 1).

A similar concept of dual-purpose crop might in the future be applied to sorghum improvement in West Africa. Although sorghum is not an indeterminate plant such as cowpea, which is able to produce new leaves even after flowering, the stay-green phenomenon that has recently received much attention by breeders may be used. Stay-green is a trait originating from certain Ethiopian Durra sorghums and Nigerian Kaura sorghums (Mahalakshmi and Bidinger, 2002), enabling the plant to protect its photosynthetic appartus from destruction during grain filling and ensuring better quality forages to straw.

Surprisingly, this trait is compatible with high harvest index, indicating that the plant has an alternative (internal or external) source of nitrogen that can satisfy grain demand while protecting the leaves (Borrel and Hammer, 2000). Stay-green is associated with post-flowering drought resistance for unknown reasons. It also reduces the probability of lodging or stem collapse and stalk rot (*Macrophomina phaseolina*), which frequently occurs upon early senescence of the plant.

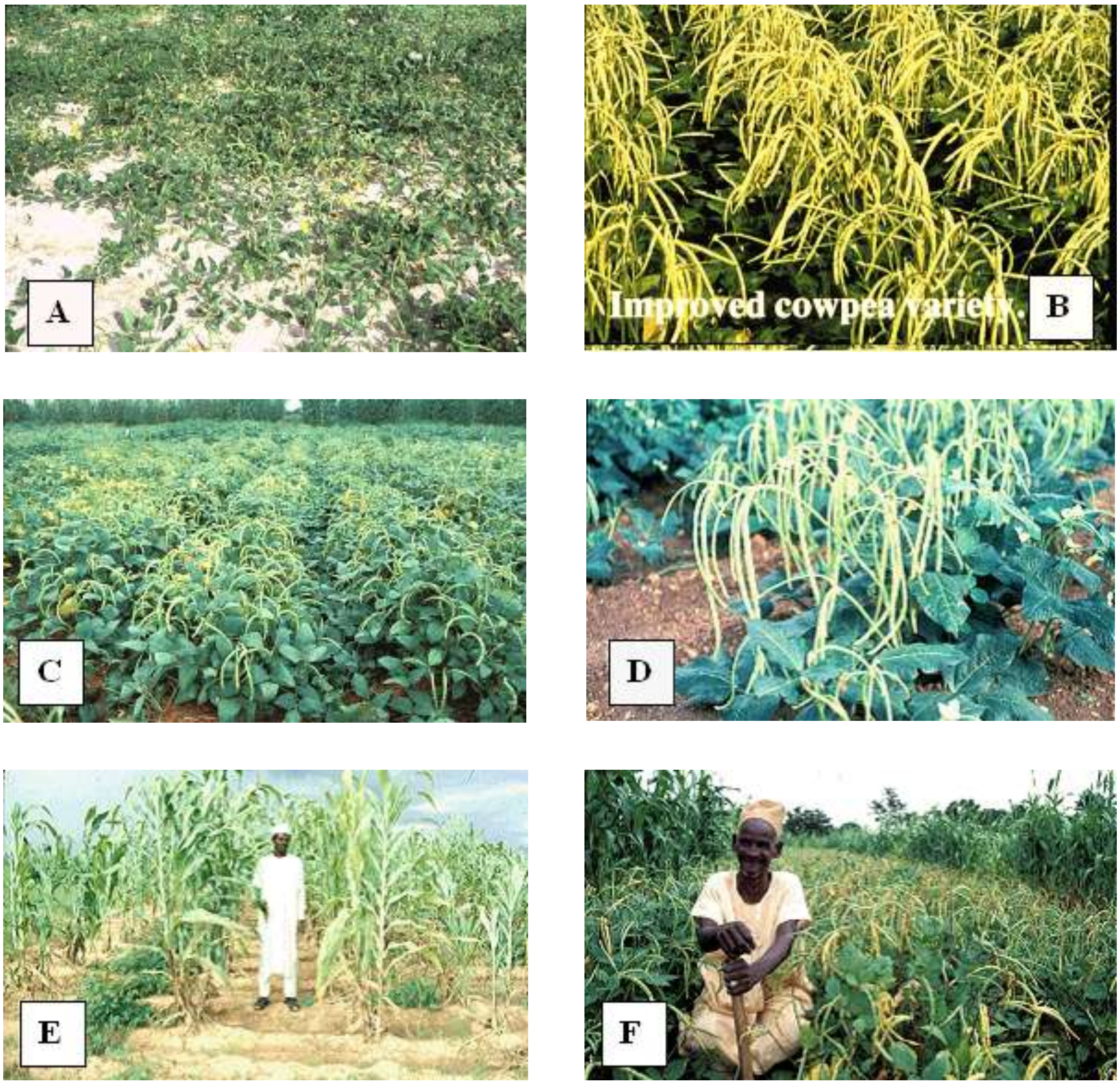

Fig. 1. Cowpea plant types and cropping systems in West Africa. A = local variety; B =early grain type; C = medium dual purpose; D = vegetable cowpea; E = Traditional intercrop; F = improved intercrop

Table 1. Performance (yield, kg/ha) of promising dual-purpose cowpea varieties in the Sudan savanna (Kano, Nigeria, 2002).

Variety	High population density)	Low population (farmer's practice

	Grain	Fodder	Grain	Fodder
IT98K-537-4	2346	2903	1559	1069
IT99K-213-13-1	2146	4481	1455	2416
IT99K-687	2008	3702	1270	1527
IT99K-23-1	1838	3424	1179	1944
IT99K-262	1788	5038	1018	3388
IT99K-7-21-2-2	1748	3674	1565	2291
IT99K-216-21-2	1679	3340	1016	2763
IT99K-216-24-2	1476	4064	1118	3124
IT99K-7-16-1	1578	4620	1268	2513
IAR-1696	913	5177	1330	3096
Kananado	1094	4147	878	3276
Borno Local	636	4481	598	1938
Mean of 25	1429	3838	1046	2320
SED	322	649	297	486

Stay-green is only in its early stages of characterization by sorghum breeders and physiologists in West Africa, for example at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) at Bamako, Mali, and the Regional Centre for Studies on the Improvement of the Adaptation of Plants to Drought (CERAAS) at Thi?s, Senegal. Its contribution to terminal drought resistance alone might improve attainable yields and yield stability considerably, but the prospect of developing dual-purpose fodder and grain sorghum for crop-livestock systems, combining stay-green with the sweet-sorghum trait, is particularly intriguing.

3.2 Combining weed competitiveness with yield potential in upland rice

A semi-quantitative “Delphi” analysis of production constraints and the potential impact of research on them conducted for West African upland rice at WARDA in 1996 (Fig. 2) indicated that weed competition is the most important yield reducing factor: on average, probably more important than drought and soil infertility combined (although these stresses are not independent and are all directly or indirectly aggravated by inappropriate intensification measures, such increased land cropping coefficients without soil conservation measures (Bognonkpe and Becker, 2003). Hand weeding is indeed the largest variable cost factor in upland rice production (WARDA, 1999). An innovative plant-type concept and breeding program were therefore initiated in the mid 1990s that aimed at (1) combining the superior weed competitiveness of *O. glaberrima* rices with the better yield potential of improved *O. sativa* tropical-japonica types, and (2) expressing the weed competitive morphology of *O. glaberrima* during vegetative growth (when the outcome of competition with weeds is decided) and the traits contributing to yield potential in subsequent phases of development (Jones et al., 1997). Methods to overcome the prohibitive sterility barrier between the two species, aided by the use of naturally comparatively-compatible parent combinations, had been developed a few years earlier.

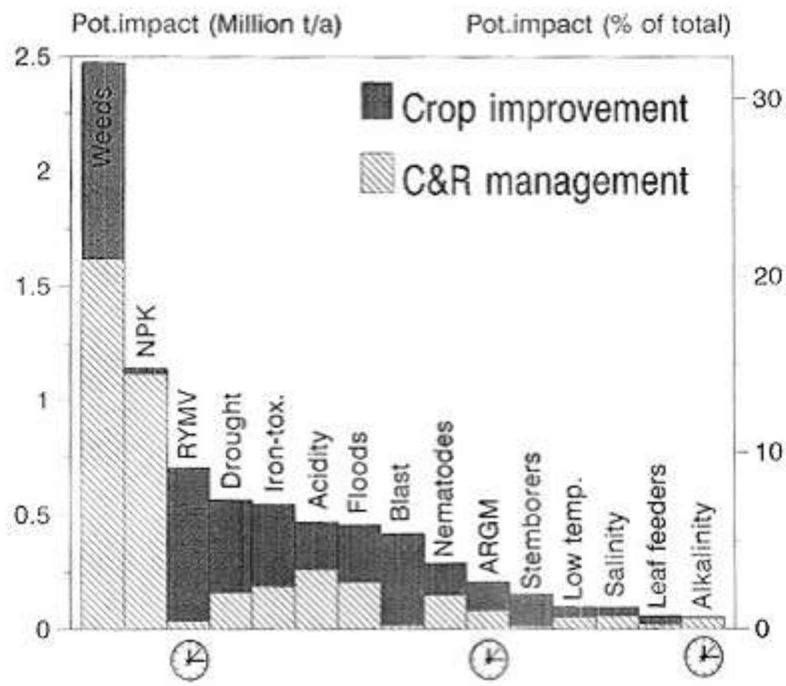

Fig. 2. Summary result of a Delphi type ex-ante impact analysis conducted at WARDA in 1997 for research on rice and rice systems in West Africa, specified by the bio-physical constraints addressed by research and by type of research (crop improvement or crop and resource management). All ecosystems confounded. Weeds appear as the most important constraint.

The plant type concept called for thin (high specific leaf area, SLA), droopy leaves enabling rapid ground cover and light interception early in development, as well as the opposite features (wide, thick, erect leaves) during reproductive growth in order to maximise radiation use efficiency (RUE) (Dingkuhn et al., 1998, Johnson et al., 1998). Although civil unrest in Ivory Coast led to the suspension of breeding activities at WARDA's headquarters at Bouak? in recent years, the inter-specific "Nerica" rices became synonymous with upland rice improvement for Africa and indeed are apparently successful in Guinea and other humid, weed-prone production environments (refer to WARDA Annual Reports: www.warda.cgiar.org). The schematic diagram in Figure 3 illustrates the "metamorphic" concept behind the Nericas, which emulates the droopy and leafy appearance of *O. glaberrima* during vegetative growth and the erect and dark green appearance of the plant towards flowering, inherited from *O. sativa*.

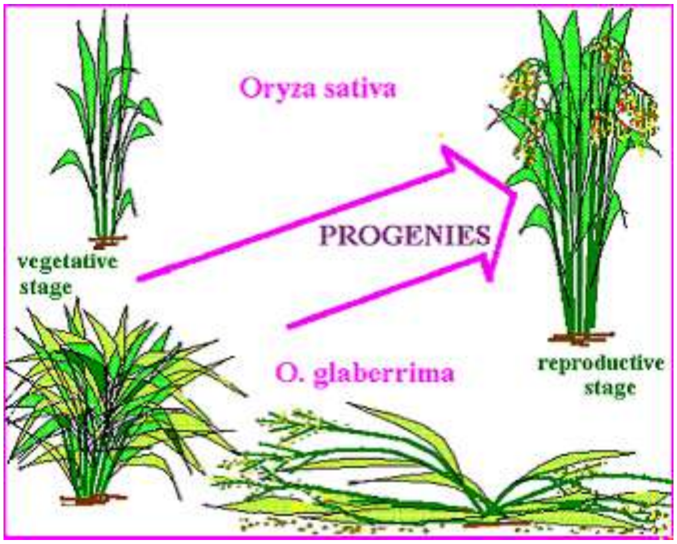

Fig. 3. Schematic diagram illustrating the juvile (left) and mature (right) habitus of O. sativa (top) and O. glaberrima (bottom) upland rices. The arrow indicates the inter-specific breeding strategy, which aims at realising a weed competitive architecture initially and a more erect, high-yielding architecture during reproductive stages. Adapted from WARDA Annual Reports.

Field selection for the dynamic expression of morphological traits as called for by the Nerica concept is not simple and at present not fully implemented, although a good theoretical basis exists. Mass selection for specific leaf area (SLA), in this case required for at least two growth stages, would be impractical if based on destructive sampling and laboratory analyses. Measurements of associated crop parameters such as high leaf area at early stages (frequently a result of high SLA and sought after anyway), followed by selection during reproductive development for high leaf nitrogen or chlorophyll content on a leaf area basis (e.g., measured non-destructively by SPAD; Chapman and Barreto, 1997) to select for low SLA, is one possible example of how the dynamic plant-type concept might be inexpensively selected. Currently-available Nericas, selected with less sophisticated screens, have excellent yield potential and overall adaptation but are also as weed competitive as *O. glaberrima* (Dingkuhn et al., 1999). An irrefutable proof-of-concept therefore remains to be produced for this interesting plant type, and at this point it is still possible that the Nerica success story reflects mainly the selection of good short-duration upland rices, combined with effective marketing of an appealing concept.

The concept might also be transported to aquatic rice ecosystems. An impressive array of genetically-stable, vigorous and high-yielding *O. glaberrima* x *O. sativa* indica materials has been developed since the late 1990s at WARDA's Ndiaye station in Senegal (K. Miezan, pers. communication, 2002) but weed competitiveness could not be related to the same morphological traits as those found for upland rice, and might therefore require a different concept.

3.3 Combining photoperiod sensitivity with improved yield potential in sorghum

The direct application of classical crop improvement concepts to sorghum in West Africa, as we have seen, had little success in the core climatic zones of sorghum cultivation (800-1100 mm/year, roughly 14-9? N). The photoperiod-insensitive materials, when planted after the first major rains of the season, would frequently flower too early and sometimes too late, resulting in plant health or drought problems, respectively. In fact, the duration of the Sahelian wet season is closely linked to the earliness of its onset, which is highly variable, whereas the rains terminate during a fairly constant period (Fig. 4). If one accepts that sorghum sowing should be done upon the first major rains of the season, and not at a particular calendar date, photoperiod-sensitivity is essential to ensure flowering near the end of the rains. The same reasoning applies to millet, a cereal that occupies the same climatic environment as sorghum but extends further north due to its greater drought resistance.

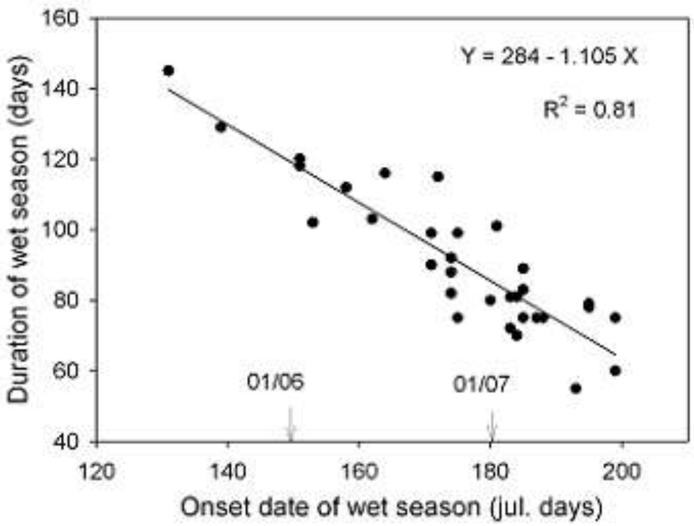

Fig. 4. Relationship between the duration of the wet season and its onset date for 1960-1990 at S?gou, Mali. The monsoon rains in the strict sense, which are associated with much greater reliability of rains than the ??pre-season??, begin roughly on 170 jul. days.

Why is it so important (and traditional practice ever since) that sorghum be sown at the earliest possible date? In fact, from a purely climatic and hydrological point of view it does not make sense. Recent studies indicated that the "true" rainy season in terms of the summer monsoon, which is associated with a sudden northwards jump of the inter-tropical conversion zone (ITCZ), begins at a very constant date (23 June). The highly irregular rain storms occurring prior to the onset of the monsoon can be called a pre-rainy season, constituting only 10% of total seasonal rainfall on average (site of Niamey) (Sultan and Janicot, 2003; Sultan et al., 2003). According to crop simulations for a photoperiod- insensitive crop of appropriate duration, driven by climate and soil hydrology only, the highest and most stable yields can be expected for sowing dates around the onset of the summer monsoon, whereas quite erratic results are obtained with earlier sowing dates during the 'pre-rainy' season (Sultan et al., 2004) (Fig. 5).

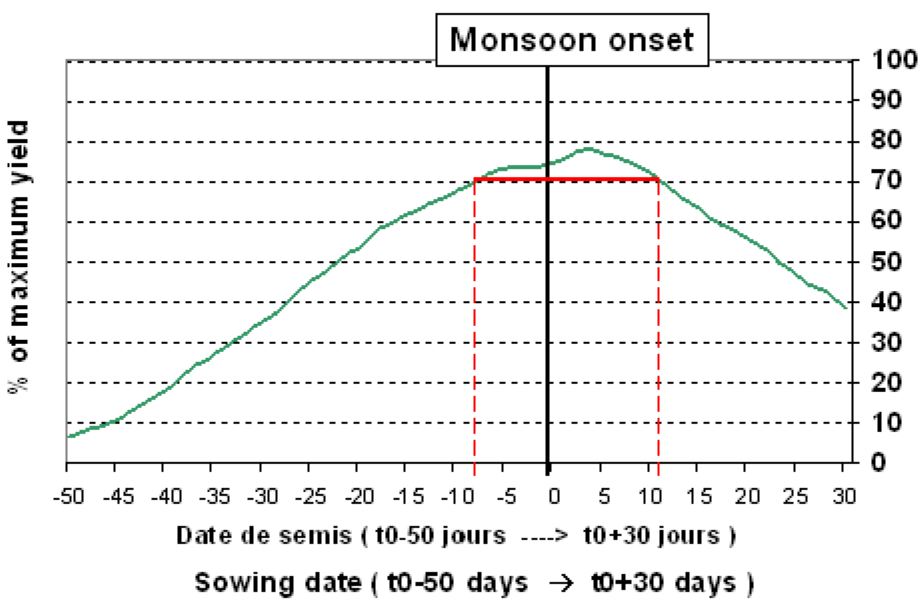

Fig. 5. Relationship between relative, attainable yield simulated with the crop model SARRAH for a 90-day millet crop at Niamey, Rep. Niger, and the sowing date (expressed relative to the onset data of monsoon rains, typically around 23 June).

Cereal farmers in the Sahel and Sudan savannah apparently accept a high risk of failure of crop establishment, resulting in repeated sowing if seed and manpower are sufficiently available, in order to avoid other problems associated with the later, hydrologically-safer sowing date. These problems are related to soil fertility and weed pressure: the early rains cause nitrate leaching and trigger a flush of gaseous nitrogen losses caused by de-nitrification of nitrate stored in the soil during the dry season (Blondel, 1971abc), and at the same time initiate the annual cycle of weed growth (Stoop et al., 1981; Vaksmann et al., 1996). A crop sown late in the wet season therefore misses some of the potentially-available nitrogen resources (which are relevant because no chemical fertilizer is applied in most cases), and the farmer also has to use scarce labour to remove an established weed flora. In short, the hydrologically- and climatically-ideal sowing date may be of relevance to future, intensified systems that use sufficient mineral inputs and soil/weed management, but as long as systems are extensively managed, farmers are forced to sow at variable dates and use photoperiod-sensitive cultivars.

In view of these findings, Vaksmann et al. (1996) proposed developing cultivars that combine a “modern” architecture (reduced height, reduced tillering and thicker stems enabling higher harvest index) with photoperiod sensitivity. This concept has stimulated a large number of ongoing ecophysiological and genetic studies because it is far from simple. The main difficulties reside in (1) strong effects of photoperiod on plant morphology and architecture in photoperiod-sensitive materials, (2) the extraordinary complexity of photoperiodic responses in sorghum, and (3), apparently, limited sink capacity in panicles resulting in suboptimal use of stored assimilates in the stems. We will in the following provide some detail on these three problems.

The problem of photoperiod-dependent architecture is mainly related to variable leaf number per culm and the phenological timing of internode elongation (Singh and Rana, 1997). Depending on sowing date, photoperiod-sensitive cultivars produce canopies between 1.5 and 5 m tall, with between 12 and 41 leaves on the main stems (Fig. 6). Internode elongation is triggered by panicle initiation when floral induction is early, or happens spontaneously after the initiation of about 23 leaves. Stem elongation is a very costly process in terms of assimilates and competes with panicle development when leaf number and area are too small to provide sufficient assimilates for both (Clerget, 2004).

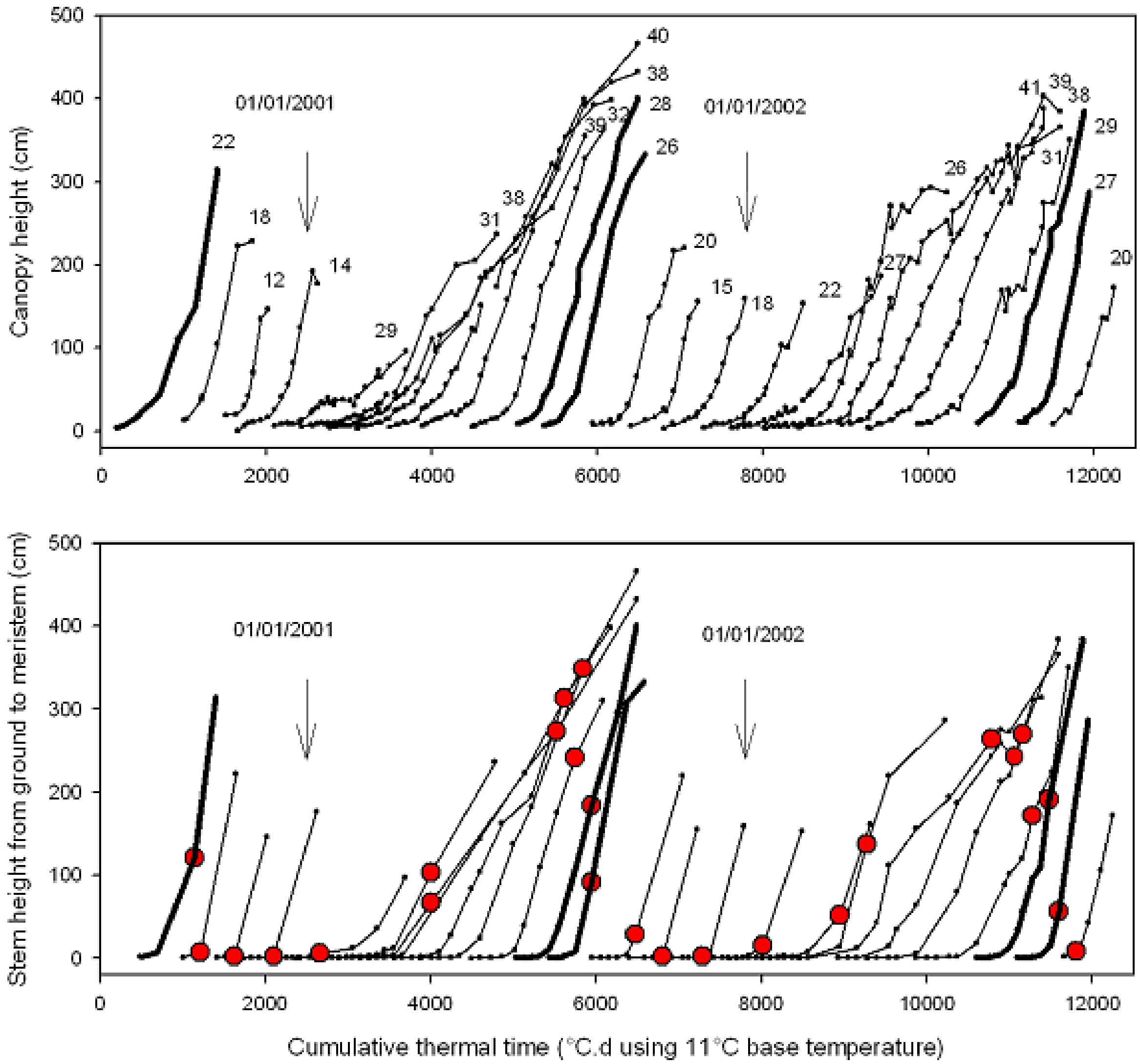

Fig. 6. Development of canopy height (top) and stem length from ground to the apical meristem (bottom) for the photoperiod-sensitive sorghum cultivar CSM 335, sown at Bamako, Mali, on 26 consecutive months in 2000-2002. Crops were irrigated during dry periods. Bold lines indicate crops sown according to farmers' practice in mid June and mid July. Inserted numbers (top graph) indicate total leaf number produced on main stems. Circular symbols indicate panicle initiation observed by dissection.

In sorghum, photoperiod not only influences the time of panicle initiation but also leaf initiation and appearance rate, resulting in poor leaf area development and low yields when plants are sown late in the season (August or September, period of decreasing day length; Clerget, 2004). The simple model of thermal and genetic determination of plastochron (Rickman and Klepper, 1995) is therefore inaccurate in this case. Moreover, the photoperiodic signal(s) sensed by the plant seem not only to include absolute daylength at a given time, but also its rate of day-to-day change and light quality (Clerget et al., 2004). As a combined result, the effects of sowing date on the duration of phenological phases are complex and differ even among photoperiod-sensitive genotypes (Fig. 7).

In contrast to other cereals such as rice (Kropff et al., 1994), panicle size and spikelet number in African sorghum cultivars are not strongly linked with crop growth rate before heading. Consequently yield potential is comparatively insensitive to resources (Clerget, 2004).

These observations suggest that photoperiod-sensitive sorghums have extreme phenotypic plasticity, which may convey excellent adaptation to variable environments, but make it difficult to develop plant types combining photoperiod sensitivity with desirable agronomic traits such as short stature and high harvest index. More research needs to be conducted before innovative breeding strategies can be devised. Interesting, intermediate breeding products have recently been developed in Mali (Vaksmann, pers. comm.), but they have not yet been studied thoroughly.

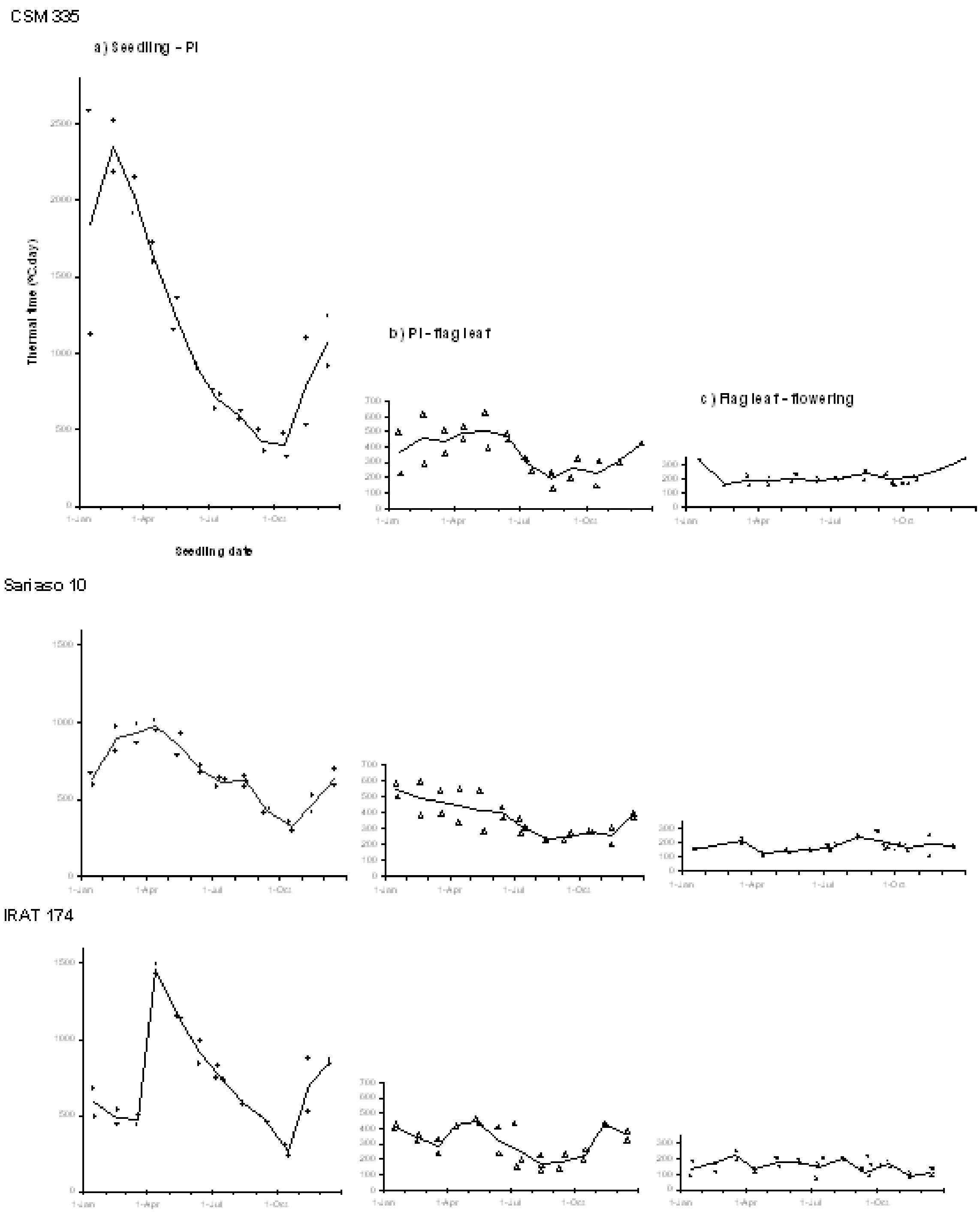

Fig. 7: Thermal duration of three consecutive phenological phases (from emergence to panicle initiation (PI) (left), from PI to flag leaf exertion (centre), and from flag leaf exertion to flowering (right); as a function of sowing date, observed on three sorghum cultivars at Bamako, Mali. Lines join the monthly averages of the 2 years' records.

4. Outlook

In this paper we have described past breeding objectives and their underlying plant type concepts, and noted that in many situations the results have met with only limited adoption because they frequently addressed intensive production systems that are not yet reality in much of West Africa. We have also suggested that trying to improve genetic materials for traditional systems would probably be futile because existing, traditional germplasm is already well adapted and the traditional systems as we know them will probably largely disappear in the course of demographic growth. Lastly, we discussed some more recent and original breeding concepts that address more specifically the agricultural transition in which much of West Africa is currently caught, endangering ecological equilibria and degrading natural resources, shifting the labour force from the countryside to the cities, thus calling for agricultural intensification strategies that replace what the crop removes from the soil with external inputs. The fact that current intensification largely lacks external inputs suggests that crops for the transition should: (1) reward the use of such inputs by being responsive to them, (2) tolerate or escape the constraints brought about or aggravated by “wild” intensification (essentially, increasing cropping coefficients by eliminating fallow periods), such as weed competition, and (3) suit the multiple objectives traditionally associated with the crop, such as grain and fodder production.

These are ambitious objectives, but the example of dual purpose cowpea cultivars at IITA demonstrates that innovative and viable solutions can be achieved. In the case of dual-purpose (grain/fodder) sorghum, modern but photoperiod sensitive sorghum and weed-competitive upland rice, the concepts are underpinned by a solid theoretical basis and can draw from well characterised source germplasm, but whether these plant types will eventually fulfil their promise is not yet proven. Much will depend on the resources made available for this research, which is multi-disciplinary and thus expensive. Creating a new plant type designed with specific agroecological adaptations and agronomically-useful traits requires a broad-based breeding program backstopped by disciplines ranging from socio-economics and cropping systems agronomy to physiology and molecular genetics to be successful. The trend is such that integrated research is increasingly difficult to fund, particularly for the long periods of time it takes to develop a new crop. Both the Nerica (WARDA) and photoperiod-sensitive sorghum (CIRAD, ICRISAT and the Institut d’Economie Rurale (IER) in Mali) breeding programs are undersized, and require more multi-disciplinary input to meet their respective challenges. In particular, such innovative and promising breeding approaches should make greater use of molecular tools and advances in functional and structural genomics. Rice, being a “model crop”, happens to be on the frontline of genomics research and sorghum is likely to become a model crop for studying the genomics of C_4-type cereals, principally because of its comparatively small genome. If the Consultative Group for International Agricultural Research (CGIAR) and other research entities would rigorously invest in Africa’s agriculture, we might in the near future see real progress in areas where breeding can potentially make a huge difference: drought-resistant, high harvest index, stay-green sorghums, flowering at the right time; dual-purpose, grain/fodder cowpeas, peanuts and sorghums; and high-yielding, weed-competitive upland rices (and sorghums, cowpea and other African crops).

This outlook would not be complete without asking the question: how long will the agricultural transition in Africa last? Will systems in the not-so-distant future “modernise” and have the same technical and varietal needs as any other intensified agricultural system elsewhere in the world? Is it worth breeding varieties for a transition period? There is no sure answer to this question, but if it is true that the Green Revolution failed in Africa because of lack of political stability (discouraging investment) and the predominance of subsistence agriculture (predominant in sparsely populated areas, lacking the stimulus exerted by markets), as speculated in the opening remarks, it should not be difficult to identify regions on the continent that are rewarding targets for innovative breeding efforts. To this extent, the new revolution could be ‘green’ in the modern sustainable sense, as well as in the original sense of increased production.

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