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In-field development of a conceptual crop functioning and management model: A case study on cotton in southern Mali

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Abstract

West African cotton production has increased rapidly in recent years. Cotton is being cropped under new ecological conditions by new cotton-producing farmers, but the cropping techniques recommended by developers have essentially remained the same. Methodologies are needed to generate a broad scope of recommendations on cropping techniques to deal with the increasing diversity concerning farmers and cropping conditions.

A conceptual model of a cotton field was developed that approaches a crop field as a biophysical system under the influence of a “technical system” (i.e. the combination of farmers’ practices implemented in the field). The system outputs were restricted to yield and the main yield components. A theoretical model was first designed on the basis of published data and expert knowledge on cotton physiology, local soil–climate conditions and farmers’ practices. It was based on five specific hypotheses on links between technical and biophysical systems. The hypotheses were tested in a local farmers’ network. Thirty “cropping situations” (soil–crop–technique combinations) were selected in farmers’ fields around Katogo village (Mali), a village that had been previously selected for a cotton crop management prototyping program. Homogeneous groups of situations were drawn up on the basis of the dynamics of crop aerial biomass accumulation. They were compared for their management and environment features. The initial conceptual model was then simplified, while taking the measured variability in its components and the sensitivity of the outputs to these components into account. This conceptual model is being evaluated in other villages, where we have partnerships with farmers, in order to develop a version adapted to a broad range of situations.

Keywords: West Africa; Cotton; Crop management; Yield; Conceptual model

1. Introduction

After decades of improvement, cottonseed yields are now decreasing in Mali (IER/CMDT/OHVN, 1998). The overall increase in Malian cotton production is exclusively due to the steep increase in planted area. Several explanations for the decreasing yield are proposed, but they have not been confirmed, nor have the constraints been classified. The proposed explanations include: soil mining by cropping systems prone to soil erosion and with unbalanced mineral budgets (van der Pol and Traoré, 1993); farmer’s lack of technical knowledge about cotton production or unwillingness to follow cropping recommendations (Fok et al., 1999); climatic change and the crisis in the rural credit system.

At the same time, the organization of the cotton technical and economic system in Mali is changing (Kebe et al., 1998). The formerly public-owned, centralized and integrated Compagnie Malienne de Développement des Textiles (CMDT), that dealt with technical production, marketing of chemical products, buying, processing and cotton marketing, is moving toward privatization. Therefore, the main economic stakeholders will soon change. Scientists will have new and more diversified partners, interested in local production problems with shorter timeframes. Prototyping of new cotton crop management systems tailored to this new set of constraints has been started in the region, in collaboration with farmers (Lançon et al., 2002; Lançon et al., 2004).

A methodology is needed to rank, under farmers’ field conditions, the main agronomic constraints of cotton production in small regions and to propose ways for focusing locally based research programs. This ranking should address the factors that limit crop functioning as well as their linkage with techniques

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in the way they are practiced by farmers or as they could be implemented in new crop management systems.

This agronomic diagnosis is frequently based on the statistical relationships between yield and a nonstructured set of explanatory factors combining pedoclimatic conditions and farmers' practices (Asadu et al., 2002; Kalivas and Kollias, 2001). Nevertheless, as the variables are often correlated, the real causes of yield losses are difficult to assess only by statistical methods and there is a risk of confusing the factors (Doré et al., 1997). To avoid this risk, Doré et al. (1997) proposed to measure a large set of state variables of the soil–plant system as intermediate variables between farmer's practices and yield. Yield determination models have been developed to reduce the number of measurements required and to quantify the impact of each factor on yield. They have frequently been formulated into computed growth and development models for crops or cropping systems (Calvino and Sadras, 2002; Meynard et al., 2001), but preexisting models have also been used (Affholder et al., 2003). Conceptual models, based mainly on existing knowledge, are useful for determining sound relationships between causes and consequences (Crozat et al., 1997).

Very few models of this type have been designed for cotton production (Baker et al., 1983; Lemmon, 1986), and none are calibrated for the West African environmental and cropping conditions. On the other hand, extensive technical knowledge has been accumulated through decades of applied research in West Africa on cotton growth and development (Hearn, 1972), cotton fertilization (Braud, 1987; Cretenet et al., 1994), climatic factors or weed influence on yield (Cretenet, 1980; Makan, 2001). Most of this knowledge was gathered on experimental stations, and is not directly applicable to the farmers' fields. On the other hand, farmers' practices have largely been documented through farmers' interviews, but usually with few measurements of state variables in their fields (Doucouré and Healy, 1999; Giraudy, 1993).

This study presents the design and evaluation of a conceptual model of cotton yield elaboration depending on the biotic and abiotic environment and on cropping techniques. It was designed on the basis of published results and expert knowledge and evaluated on 30 cropping situations (soil–crop–technique combinations), in farmers' fields around Katogo, Mali, in 2002.

2. Conceptual model of a cotton crop

In a systemic approach, a conceptual model is a representation of a system that is built to address specific questions. The system is defined by its limits, components, environment and the most relevant state variables and flows of mass and information within the system and exchanged with the environment (Walliser, 1977).

In a diagnostic approach to a crop system, one or several criteria have to be chosen from amongst the outputs of the system to evaluate its functioning. Yield is the criterion most commonly used in agronomic diagnosis (Doré et al., 1997) to evaluate crop performance. It was used in our study, but the approach could be extended to other outputs, e.g. the product quality, gross margin, or environmental impacts such as nitrate leaching (Cuny et al., 1998).

In order to identify the limiting factors of a crop system, we considered a crop to be a biophysical system influenced by the environment (climate) and by a "technical system" (Fig. 1). Depending on the objectives, the biophysical system is composed of a more or less complex set of compartments (cultivated plants, soil, weeds, diseases, pests), with each being represented by one or several state variables. The technical system is a combination of cropping techniques which act individually or interactively on the size of a compartment (e.g. plant thinning acting on stand density), on its state variables (e.g. fertilization acting on leaf area index (LAI)) or on flow between compartments (e.g. fertilization acting on mineral flows between the soil and plants).

The approach is primarily based on careful observation of the application of cropping techniques and their impacts in actual farms. Attainable improvements can thus be assessed according to farmers' technical potential and socioeconomic conditions.

Moreover, the quantification of relationships between components of the system (state variables, flows) could help to focus conceptual efforts in the main areas that actually drive the system, while disregarding other mechanisms that, although scientifically sound, do no help in explaining the observed variability of the system's performance.

This approach was found to be feasible and efficient when tested in a participatory program for prototyping food legume technical systems in farmers' fields in several regions of France (Metral and Wery, 2001).

This approach was applied to cotton crops and a conceptual model based on published results and local technical knowledge was initially proposed, focusing on the farmers' interventions as supposed causes of yield gaps. This conceptual model was not designed to be mechanistic or complete, but instead it stresses variables that could help in explaining observed differences in yield elaboration under specific local conditions. For example, although radiation and temperature are known to have important effects on shedding and boll filling (Guinn, 1998), these variables were not considered here, as the fields were all sown at approximately the same date. The relationships between radiation/temperature and LAI growth or biomass are thus not stressed, but they are indicated in the scheme for potential future development, since these parameters could be useful in explaining differences between experiments (different localities or different years), as shown in Fig. 1.

Cotton, and particularly the cotton varieties grown in West Africa, has an indeterminate growth habit. Flowering is thus continuous between its onset (first bloom) and the end of vegetative growth (cutout). In southern Mali, flowering begins around 50 days after emergence (DAE), whereas the cutout date is much more variable, as it depends on environmental stresses. The cotton seed yield is the result of two components, as indicated in Fig. 1, i.e. number of bolls per square meter and average boll weight. In turn, the number of bolls per square meter results from the stand density and the number of bolls per plant. The stand density is determined by the planting density, germina-

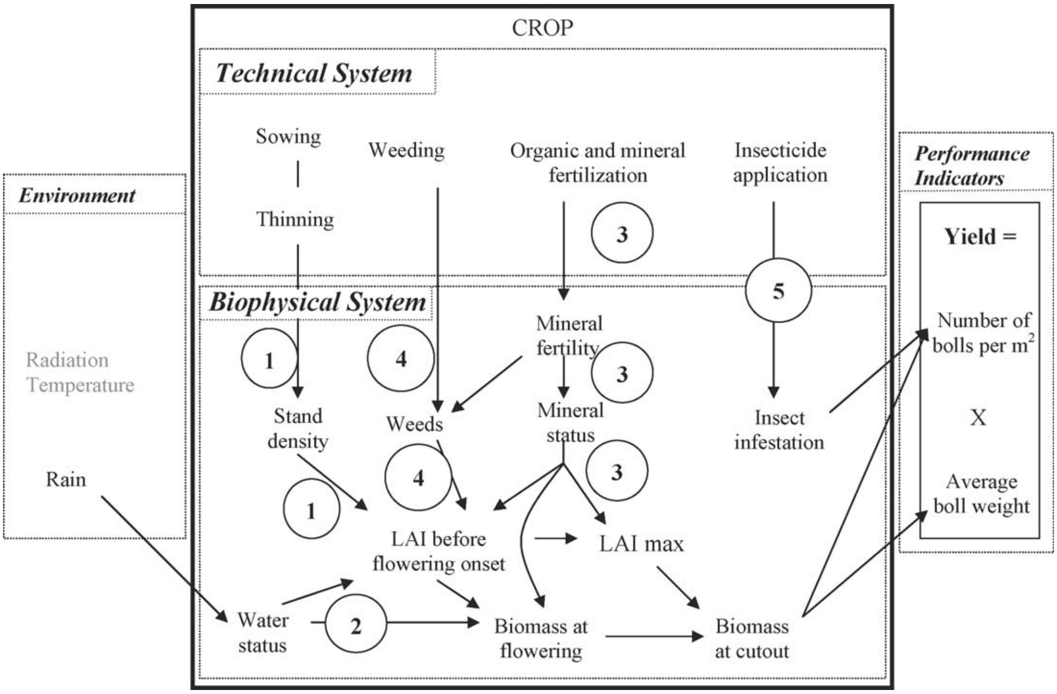

Fig. 1. The initial conceptual model for yield determination in cotton crops. This model was built on the basis of local expert knowledge and previously published results. Each number represents a hypothesis on the reasons underlying yield gaps in farmers' fields and they were tested in this study.

tion rate and thinning. Most fields are mechanically sown, plant densities are usually lower than recommended by the extension services and low densities are thought to be responsible for low yields (IER/CMDT/OHVN, 1998). The boll number per plant is considered to be the main yield determination factor (Lacape, 1998). The number of buds produced depends on the number of fruiting sites, i.e. on the vegetative growth of the plant at flowering. The LAI before the flowering onset seems very important in this regard, and its magnitude depends on the plant density, nutrient availability and water stress (Fig. 1).

Nevertheless, buds are usually produced in excess, and some shedding occurs, mainly as buds or young bolls (Cognée, 1968). This shedding has been widely studied. It depends on the internal ratio between carbohydrate sources and sinks, i.e. the previous boll load is known to affect future shedding (Guinn, 1998), and it also depends on the LAI during flowering (carbohydrates sources). This major yield component is therefore supposed to be controlled by the biomass accumulation, particularly between flowering and cutout. Nevertheless, this biomass must stay under an upper limit at both stages in order to limit shedding and competition between bolls and vegetative branches. Shedding also depends heavily on mineral and water stresses (Hearn, 1975), as well as pest infestation, mostly *Helicoverpa armigera* in southern Mali. The trophic relationships relating those stresses and boll number are included in our scheme (Fig. 1). Direct relationships between water or mineral stress and boll number are also possible.

The average boll weight does not seem to be as sensitive as boll number to direct stresses. It depends mostly on the photosynthetic capacity of the plants (Kennedy and Hutchinson, 1996), although elevated night temperatures have been related to poor boll filling (Zeiher et al., 1995).

The water status was included in the conceptual model, as it can be modified by human interventions, particularly with respect to water infiltration into the soil. Insect infestations were very low during this year and their chemical control was done properly. Nevertheless, they were included in the model as they could be an important component of the system to consider if insecticide utilization is restricted.

The causal relationships between technical interventions and yield elaboration elements upon which this study focused are indicated with numbers in Fig. 1. Each underlying hypothesis was tested with data collected in farmers' fields in order to evaluate and adapt the conceptual model.

3. Material and methods

3.1. Site

The village chosen for this study was Katogo (11°56N, 5°54W), located in the most long-standing cotton production area in southern Malil. Katogo is a small village with many years of experience in cotton production (over 30 years). The entire 450 ha of fertile and flat land is continuously cultivated by the 44 existing farmers. Cotton is grown on around 30% of the area. There is a close association between agriculture and livestock production (average of 22 heads of cattle per farm), and manure is applied on the fields in 98% of the farms. Animal traction, herbicides, mineral fertilizers and insecticides are widely used. Farmers have a good level of awareness on cotton cropping techniques, i.e. above the average for the Sikasso region (Togo, 2003).

There are ferruginous tropical soils with relatively low clay content in the upper 20 cm (11%), increasing to 30% toward the deepest horizons (110 cm). The average organic matter content is relatively high for the region ($12\,\mathrm{g\,kg^{-1}}$).

The climate of Katogo is hot and dry. The mean annual rainfall for the 1951–1989 period was around 1000 mm, while the rainfall for 2002 was low (722 mm). The mean temperature for the 2002 cropping season (June–November) was 26 °C, with peaks of up to 36 °C.

3.2. Field selection

Katogo farms were sorted in terms of total cultivated area, and one of each three farms was systematically selected (second, fifth, eighth, etc.) ensuring that about half of the fields received manure. Due to the late onset of the rainy season, all the farmers sowed their fields during the same week (between June 14 and June 21). As soil analysis and manure measurements had to be performed in the experimental fields before the onset of the rainy season, another criterion for field selection was the level of certainty shown by the farmer in the future allocation of the different crops in his fields. To account for these criteria, a subsample of 15 cotton fields on 10 farms, scattered in an area of about $12\,\mathrm{km^2}$, was selected.

Two plots (around 25 m × 10 rows) were tagged. These situations could not be considered as replications due to the inherent soil heterogeneity in the farmers' fields. They were treated as independent biophysical systems, under the influence of the same technical system. Two subplots (10 m × 4 rows) were selected in the plots to account for the residual heterogeneity, and considered as replicates. Measurements were taken independently in each subplot. The final set of data was thus measured on a set of 30 agronomic situations in 15 farmers' fields, with two replicates per agronomic situation.

3.3. Field measurements

3.3.1. Description of the technical system

For each field, the cropping interventions were recorded: manure application, soil tillage, sowing date, herbicide applications, weeding operations, mineral fertilization, insecticide operations (dates, products and doses) and date of first harvest. These data, except for manure application, were obtained from the person in charge of the farm operations and checked during the frequent visits to the fields.

Manure application was characterized after the manure was brought to the fields but before it was spread. One average heap was weighed in each plot and a subsample was brought to the laboratory for dry weight determination. The areas to be covered by this heap and two others were measured. A sample of manure applied in each field was obtained by mixing subsamples taken in three different heaps, and then sent to the laboratory for analysis (organic matter, N, P, K contents and pH).

3.3.2. Crop growth and yield

Date of emergence was measured in each field by counting the number of emerged plants during visits to the plots each 2 days. LAI and aerial biomass were measured in each subplot at four dates:

At 40, 60 and 90 days postemergence, plant height, node number and leaf number were measured in each subplot on 10 contiguous tagged plants in a central row. The same plants were observed at the different dates. As periodic observation of tagged plants may disturb their growth (Cahill et al., 2002), we took care to touch them or stamp around them as little as possible. Simultaneously, three plants outside the subplots were extracted in each field, the same data were recorded and the leaf and biomass dry weights were measured. The specific leaf area was measured by weighing leaf samples of a given area. A linear relationship was then established between height, number of leaves as independent variables and plant leaf area and aerial biomass as dependent variables, for each date, while pooling data from all fields. The squares of the correlation coefficient were always above 0.8, and usually more than 0.9. The regression coefficients were then applied to the 20 recorded plants of each plot, to compute their aerial biomass weight and leaf area. The aerial biomass of the subplot and LAI were then calculated by inclusion of the stand density at harvest.

At 70 days postemergence, three plants were extracted from each plot for N content measurement. They were oven dried at 60 °C, ground and analyzed in the laboratory. An index of N nutrition (INN) was calculated using the relationship published by Justes et al. (1997), that indicates the theoretical N content of a crop not limited by nitrogen, for a given biomass. INN was then calculated as the ratio between the actual and theoretical N content.

At harvest, the same 20 tagged plants were extracted for measurements. Cotton bolls located in the first fruiting position on the first five fruiting branches of the 20 plants were counted and weighed separately. The procedure was repeated for the fruiting branches 6–10, 11–15 and the last ones. Then the remaining cotton bolls (in the next fruiting position on all the fruiting branches and on the vegetative branches) were harvested and weighed. The leaves, carpels and stems of the 20 plants were dried and weighed. Cottonseed yields were measured on each whole subplot.

3.3.3. Typology of biomass dynamics

Biomass production is the key parameter of the conceptual model presented in Fig. 1. It has been shown in cotton that biomass accumulation dynamics are as important for yield determination as the final biomass itself (Hearn, 1972), due to substantial shedding. Therefore, the aerial biomass dynamics were characterized for each agronomic situation included in the study. Biomass accumulation during the vegetative cycle is assumed to follow a sigmoidal curve, according to the following equation:

$$\mathrm{Biom} = \frac{\mathrm{Biom_{max}}}{2}(1 + \tanh((x - I) \times P)) \tag{1}$$

where Biom is the aerial biomass measured in the plot ($\mathrm{g\,m^{-2}}$), $\mathrm{Biom_{max}}$ the maximal biomass attained, set as the asymptote of the fitted curve, x the number of days after emergence (DAE), I the abscissa of the inflexion point of the curve (DAE) and P is a slope factor.

For each situation, this curve was fitted to the measured values using the optimizing procedure included in Microsoft Excel to minimize the sum of square differences between measured and simulated values. Four parameters were used to characterize the curve fitted for each agronomic situation:

- Maximal slope of the curve ($a \tanh(P) \times \mathrm{Biom}_{\max}/2$);
- I, the abscissa of the inflexion point of the curve;
- $\mathrm{Biom}_{\max}$, ordinate of the asymptote of the curve;
- Difference between the maximal biomass and the biomass measured at harvest.

The latter value was added to the set because it was noted that some measured biomass curves did fall at the end of the cycle. This pattern could not be described by a sigmoidal curve.

An automatic classification by a *K*-means algorithm was then performed on the biomass dynamics data for the 30 agronomic situations (SPSS for Windows, version 10.0.5), in order to create six homogenous groups that served as a framework for the analysis of the relationships considered in the conceptual model.

3.3.4. LAI analysis

As for biomass, LAI dynamics were characterized using a polynomial curve of the third degree fitted to the measured values for each agronomic situation. The following values were determined on the basis of the equation of this curve for each situation: integral of the area under the LAI pattern curve from emergence until harvest (in LAI.day), first abscissa where the LAI reached 1 (DAE), the abscissa where LAI again reached 1 when diminishing, and the LAI max attained during the crop cycle.

3.3.5. Water availability

Soil water content was measured by the gravimetric method on August 26, September 18 and October 8 and 28. Samples were taken at 0–20, 20–40, 40–60 and 60–80. It was often not possible to reach deeper layers. A hole was made in each subplot, and the two soil core samples per plot were pooled, weighed, oven dried for 24 h at 105 °C and weighed again. The volumetric water content was then computed assuming an overall soil bulk density of 1.6, based on the density measured in the nearby experimental station of N'Tarla, as also confirmed at other locations with the same soil type in southern Mali. The soil texture was determined in the laboratory on the same samples as those used for water content measurements, whereas the soil water characteristics (wilting point and field capacity) were estimated from texture by using equations published by Saxton et al. (1986). The fraction of transpirable soil water (FTSW) was computed from the quotient between actual and maximum available water content by volume, as it was identified as a pertinent water status indicator for rainfed cotton crops in West Africa (Lacape, 1998; Lacape et al., 1998a).

3.3.6. Weeds

Weed cover was recorded weekly in each plot on eight occasions beginning on June 25, using a scale based on the percentage of ground overgrown with weeds that was developed for tropical conditions (Marnotte, 1984).

3.3.7. Soil fertility measurements

Soil samples were taken in the upper 20 cm layer in each plot before onset of the rains. Three subsamples were taken and pooled to obtain a sample that was sent to an ISO 9002 certified laboratory (SOLTROP, CIRAD) for organic matter, N, P Olsen Dabin, exchangeable K contents and pH analysis.

3.3.8. Weather measurements

An automatic weather station was installed in Katogo during the rainy season. Five additional rain gauges were set up in different parts of the experimental area, and rainfall was recorded daily. The six rain gauges gave very similar results (standard deviations between gauges on 10-day accumulated rainfall were always less than 15 mm and averaged 7 mm). Average rains are plotted in Fig. 2. The dates of the soil water measurements are also shown, with the approximate phase of cotton development.

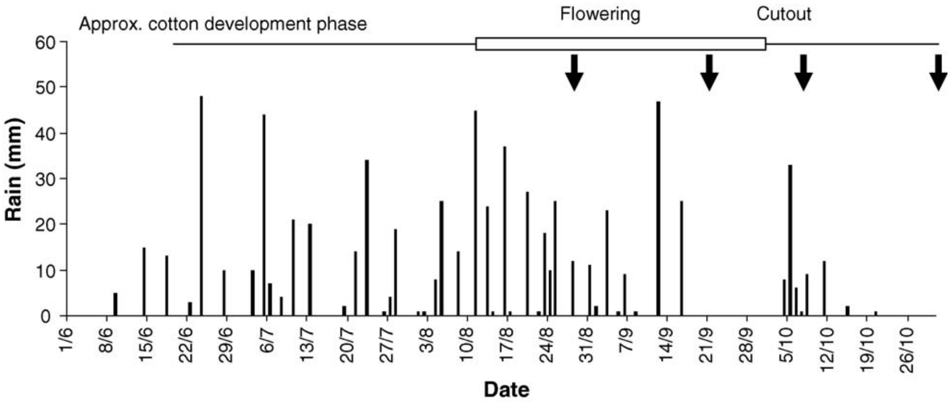

Fig. 2. Rainfall in Katogo during the 2002 season, cotton crop cycle and soil water content measurements. Each bar represents daily rainfall measured at six locations and averaged over the village. The horizontal line above the graph represents the approximate phase of cotton development and the box indicates the approximate flowering period. Arrows show the timing of the soil water content measurement.

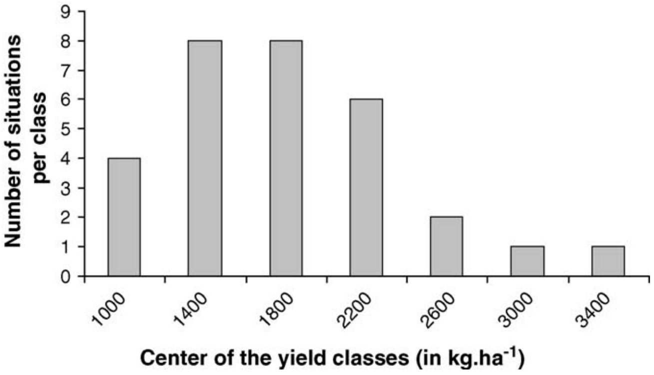

Fig. 3. Distribution of the system performance indicator (yield) for the 30 agronomic situations (2 plots in 15 fields). The data represent harvests of four rows 10 m long in each situation.

4. Results and discussion

4.1. Evaluation of the performance of the system: yields and yield components

Seed–cotton yields (Fig. 3) were extremely variable (890–3300 kg ha^{-1}) within the range of agronomic situations evaluated. The average (1780 kg ha^{-1}) was much higher than the Sikasso regional average (1200 kg ha^{-1}) or than the whole village average (1474 kg ha^{-1}, Togo, 2003). This could be attributed to the high percentage of selected fields that received manure, but probably also to the fact that farmers tend to make special efforts for the fields that they know will be observed by foreigners.

The observed yield variations were mainly related to boll number, as shown in Fig. 4. The average boll weight is not as variable as boll number. Although its relation with yield is highly significant, the boll number per square meter is the main determinant accounting for yield variations.

Yields are closely related to the number of bolls set at the first fruiting position of fruiting branches 11 to 15 ($r^2 = 0.73$). Unexpectedly, yields are negatively related to the number of bolls set at the beginning of flowering. Thus, boll number variations are mainly determined by the bolls set around the end of flowering (i.e. before cutout).

4.2. Biomass accumulation

Automatic classification of the 30 agronomic situations on the basis of the main characteristics of biomass accumulation yielded six classes (Table 1). The average yield of each class was then used to number the classes, as yield was not included as a factor in the classification. An example of biomass dynamics is presented for each class in Fig. 5. The 30 situations were clearly differentiated by biomass at harvest, giving the same ranking as that obtained with cottonseed yield measured on the same plants (Table 1). Nevertheless, the final biomasses were reached with different growth patterns (Fig. 5). For classes 3, 6 and, to a lesser extent 1, the maximal biomass was higher than the final biomass. Part of the cotton production potential, represented by early biomass production, was lost during the second part of the crop cycle. This is particularly clear for class 3, which had the earliest rise in biomass, as indicated by the lowest abscissa of the inflexion point (Table 1). Class 6 shows the same pattern, but with the lowest maximal slope and therefore the lowest final biomass. Classes 1 and 2 show very different biomass dynamics (Fig. 5), slower but sustained in class 2, and they achieved almost the same biomass at harvest and the same yield. Finally, class 5 shows sustained biomass accumulation but at a much lower level than class 2.

Biomass accumulation dynamics were therefore validated as the key element of the biophysical system in the conceptual model presented in Fig. 1, since it was found to be a good indicator of the performance of the crop system. The biomass classes will therefore be used as a framework to test the other hypotheses drawn from the conceptual model (Fig. 1).

4.3. LAI dynamics

Average values for LAI parameters are shown for each biomass class in Table 2.

The LAI max attained in the cotton fields were relatively low when compared with usual values for cotton fields in temperate countries. The LAI parameters were related with the biomass dynamics, particularly the LAI max with the max biomass slope ($r^2 = 0.80$) and the time when LAI dropped under 1, i.e. toward the end of the vegetative cycle, with the max biomass ($r^2 = 0.84$). These variables are clearly

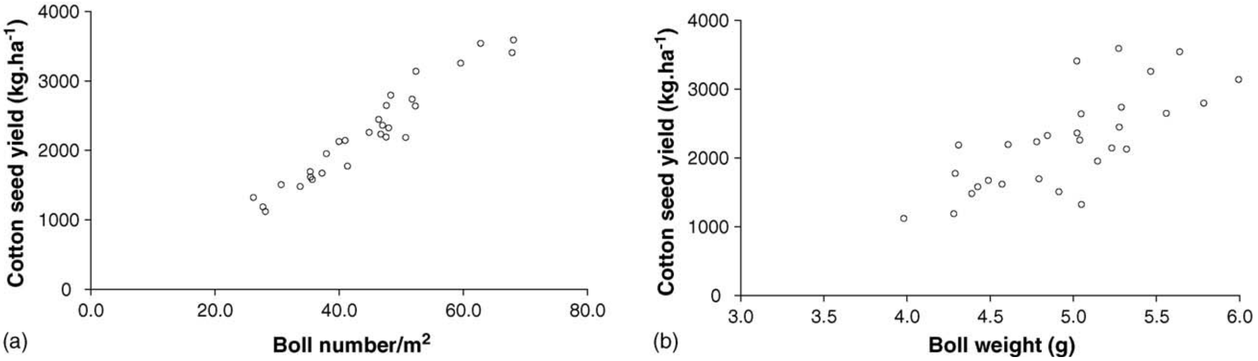

Fig. 4. Boll number and boll weight for the 30 agronomic situations. Yields, boll number and boll weight were calculated from the extrapolation of the data of two sets of 10 consecutive plants in the experimental plots.

Table 1
Average values of the parameters of the biomass accumulation curves, average biomass at harvest and cottonseed yield for the six classes of agronomic situations

Class	Number of situations in each class	Aerial biomass at harvest ($g\,m^{-2}$)	Evolution BM_{harv}–BM_{90DAE} ($g\,m^{-2}$)	Abscissa of the inflexion point (DAE)	Maximal slope ($g\,m^{-2}\,DAE^{-1}$)	Seed cotton yield ($kg\,ha^{-1}$)
1	3	807 a	−14 b	60 b	29.3 a	3270 a
2	5	762 a	122 a	67 a	17.9 b	3020 a
3	4	592 b	−129 c	53 b	28.4 a	2350 b
4	6	557 b	96 a	58 b	18.6 b	2290 b
5	8	389 c	79 a	59 b	10.5 c	1620 c
6	3	293 d	−51 b	58 b	10.3 c	1320 c

The classes were built by automatic classification (*K*-means algorithm) of the parameters of the biomass fitted curves. Yields were not used for the automatic classification. Values followed by the same letter in the same column are not significantly different (Snedecor–Newmann–Keuls at $p = 0.05$).

related mechanistically and this relationship is the basis of many of the crop models developed so far (Brisson et al., 2006).

The maximum LAI values were obtained for classes 3 and 1, i.e. those that also had the highest maximum biomass slopes. However, there were significant differences between these classes when considering the DAE when LAI dropped to 1. LAI remained higher for a longer time in class 1 and was only intermediate for class 3. For this parameter, class 3 was not significantly different from class 4, which reached a much lower LAI max.

The duration of the period when LAI remained at a high level could actually be related to the length of the active growth phase. It has been shown that under water stress the duration of this cycle is closely related to yield (Lacape et al., 1998b). We obtained a high correlation coefficient between this parameter and yield ($r^2 = 0.83$).

A theoretical hypothesis was put forward by Hearn (1972), whereby good transformation of biomass into yield would be related to good phasing between the supply of carbohydrates at the end of the cycle and the demand for these assimilates by growing bolls. This could be one explanation for the poor fulfillment of the biomass potential in class 3. The maximum photosynthesis capacity occurred too early and likely decreased before the maximum demand by the bolls occurred (Fig. 6). In contrast, the max LAI occurred much later in class 1, and the photosynthetic capacity remained at high levels during the boll filling period.

Table 2
Main features of LAI patterns for the biomass classes

Class	Green leaf area duration (Days.LAI)	DAE to reach LAI = 1	DAE to drop back to LAI < 1	LAI max
1	221 a	40 ab	126 a	3.2 a
2	157 b	43 ab	120 ab	2.3 b
3	202 a	37 b	113 bc	3.3 a
4	116 c	44 ab	104 cd	2.0 bc
5	75 d	48 a	85 e	1.3 d
6	90 cd	43 ab	95 de	1.6 cd

The parameters were calculated using the equation of a quadratic function fitted on the measured LAI for each agronomic situation, and then averaged over the biomass classes presented in Table 1. Values in a column followed by the same letters are not significantly different (Snedecor–Newmann–Keuls at $p = 0.05$).

Keeping both LAI and biomass in the conceptual model provides an efficient way to bridge the gap between the conceptual model and a numerical model that could be developed from this work. In the first step, LAI can be measured and used as an input variable in simple models of yield determination based on light interception and radiation use efficiency regulation via soil water deficit (Lacape and Wery, 1998; Wery and Lecoeur, 2000) and eventually leaf nitrogen content (Sinclair et al., 1997). In the second step, these LAI measurements can be used to parameterize, for local conditions, a more complex crop model which would be able to simulate LAI patterns (Affholder et al., 2003).

4.4. Stand density (hypothesis 1 in Fig. 1)

No relation was noted between stand density and the biomass class or seed–cotton yield (Table 3). No significant differences in plant density were found between classes, probably because of high intraclass variability. Moreover, the highest-producing situations (classes 1 and 2) had the lowest stand densities (although this was not confirmed for class 3). The range of actual stand densities explored was narrow (between 31,000 and 60,000 $pl\,ha^{-1}$) although it covers most of the range that is observed in the fields throughout the country. The arrow corresponding to hypothesis 1 in Fig. 1 could thus be deleted since stand density is not an essential variable in yield determination, provided it remains above the average value obtained for class 1 (3.4 $pl\,m^{-2}$), at row widths ranging from 0.7 to 1 m.

4.5. Water stress (hypothesis 2 in Fig. 1).

FTSW, calculated at four dates during the vegetative cycle (Table 4) was used here as an indicator of the soil water deficit

Table 3
Average stand densities for the biomass classes presented in Table 1

Class	Stand density ($pl\,m^{-2}$)	Seed cotton yield ($kg\,ha^{-1}$)
1	3.40	3270 a
2	3.93	3020 a
3	4.63	2350 b
4	4.13	2290 b
5	4.97	1620 c
6	4.83	1320 c

The cotton yields are shown for comparison. Values followed by the same letter are not significantly different (Snedecor–Newmann–Keuls at $p = 0.05$).

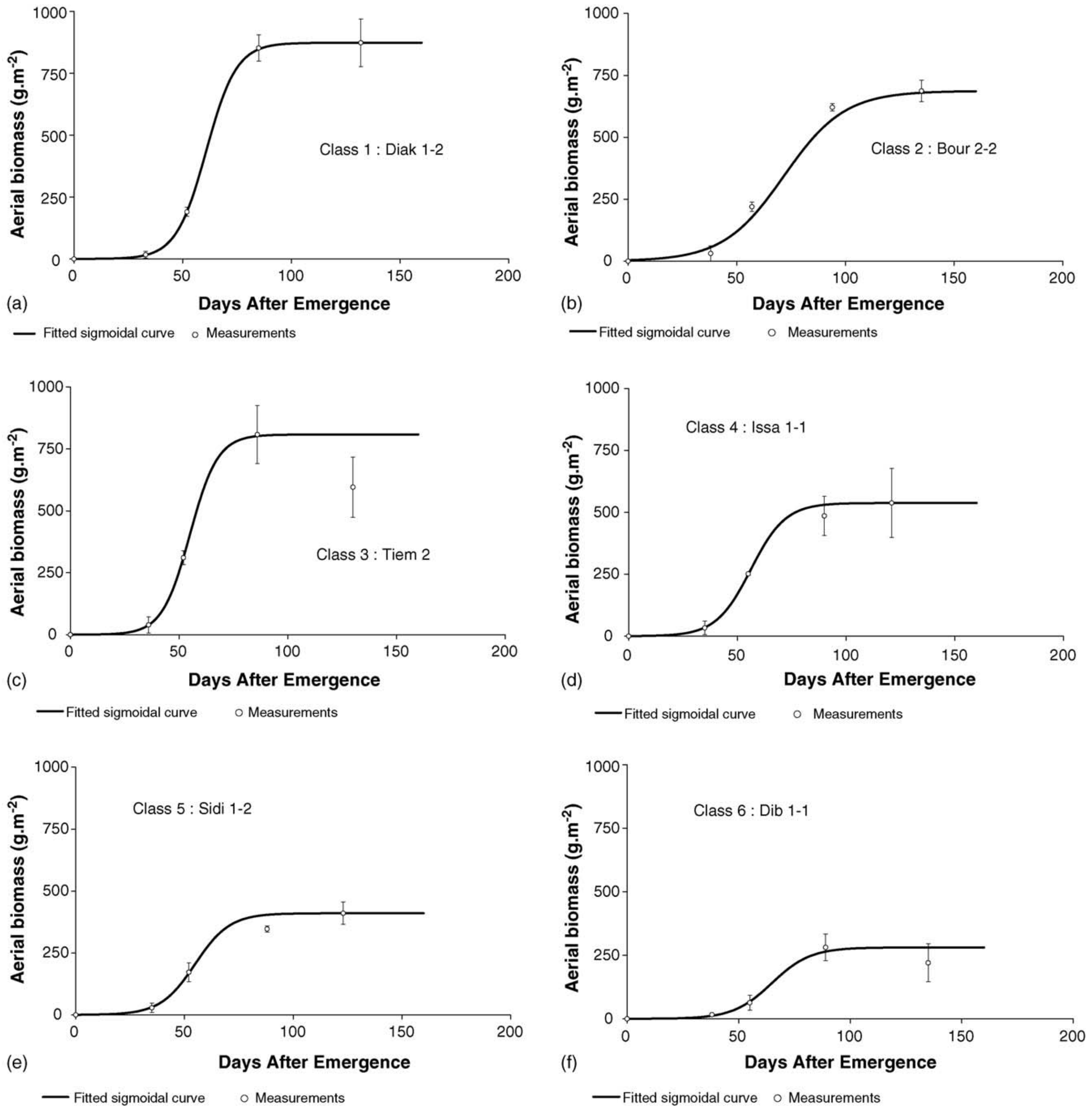

Fig. 5. Typical examples of biomass accumulation curves characterizing each biomass class. The data were derived by extrapolation of nondestructive measurements on two sets of 10 consecutive plants in the experimental plots. The plants were the same throughout the season. The error bars on each side of the points are standard deviations calculated on the basis of the two sets. The sigmoidal curves (equation 1) were fitted by optimization procedures on three parameters: maximal biomass (ordinate of the asymptote of the curve), *I*, abscissa of the inflexion point and *P*, the slope factor.

affecting the cotton crop (Lacape et al., 1998a). The only time at which the classes were differentiated was 88 DAE. At this date, the cotton crop was supposed to be sensitive to water stress, and some water shortage was actually observed. For the other dates, the rains were regular and no deficit was expected (65 DAE) or the measurement corresponded to the phase when the cotton crop phase was no longer sensitive to water stress (108 and 128 DAE).

At 88 DAE, soil water availability (FTSW) was significantly lower for class 6, which also showed the shortest vegetative cycle and the lowest yield and biomass. Classes 1 and 2, which had the highest FTSW values, were also the highest yielding classes. It has been shown, in West African experimental conditions, that the main effect of water stress is shortening of the cotton productive cycle, and that this shortening is responsible for much lower yields (Lacape et al., 1998b). FTSW measured at 88 DAE in each agronomic situation is correlated with boll weight ($r^2 = 0.30$) and boll number above fruiting branch 5 ($r^2 = 0.38$), suggesting that water stress also had a direct effect on shedding.

Despite the rainfall homogeneity in this small area, marked differences in soil water deficit were observed between and within classes. This variation cannot be related to different levels

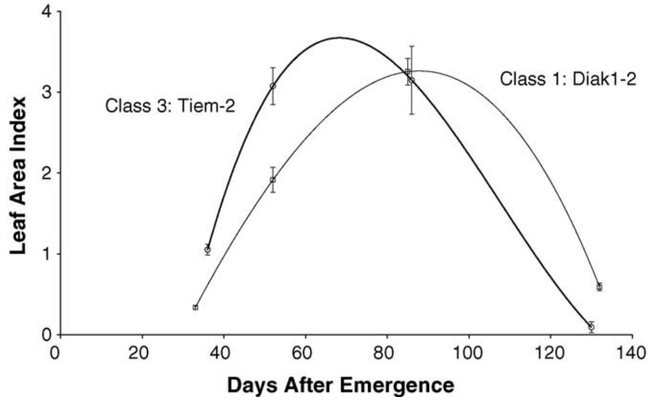

Fig. 6. Examples of LAI dynamics for two agronomic situations of classes 1 and 3. The data were derived by extrapolation of nondestructive measurements on two sets of 10 consecutive plants in the experimental plots. The plants were the same throughout the season. The error bars on each side of the points are standard deviations calculated on the basis of the two sets. The fitted curve is a quadratic function of third degree, optimized over the four parameters.

of water consumption by the crop since the highest availability coincided with the most developed stands, which should have the highest water use. Therefore, it was assumed that these variations were essentially related to heterogeneity in water infiltration and runoff between and within fields. This was clearly observed in the fields some time after the rains. The slope heterogeneity caused the soil to dry quicly in some places and to accumulate water in others. Water stress that occurred in some agronomic situations could probably have been avoided by proper cropping practices, e.g. plowing along the contour line (Gigou et al., 1997).

Table 4
Average fraction of transpirable soil water (FTSW) values for each biomass class

Class	Approximate dates[a]			
	65 DAE	88 DAE	108 DAE	128 DAE
1	0.51	0.42 ab	0.27	0.01
2	0.38	0.49 a	0.25	0.02
3	0.36	0.37 ab	0.24	0.04
4	0.36	0.39 ab	0.25	0.05
5	0.32	0.36 ab	0.25	0.06
6	0.47	0.29 b	0.24	0.00

Water contents were measured by gravimetric methods and FTSW calculated from soil characteristics over a depth of 80 cm. Values followed by the same letters are not significantly different (Snedecor–Newmann–Keuls at $p = 0.05$).

[a] DAE were averaged over the different fields (sowing dates varied between June 14 and June 22).

Table 6
Average values for the initial soil chemical analysis by biomass classes as presented in Table 1

Class	Organic matter (%)	Total N (‰)	P Olsen-Dabin (mg P kg^{-1})	Exchangeable K (meq/100 g)
1	1.4	0.60 ab	11.1	0.61
2	1.5	0.67 a	6.9	0.43
3	1.3	0.54 ab	6.7	0.43
4	1.1	0.47 ab	8.6	0.34
5	1.0	0.46 ab	9.4	0.28
6	0.9	0.41 b	10.2	0.30

Only the top 20 cm were sampled in each agronomic situation. Values followed by the same letters are not significantly different (Snedecor–Newmann–Keuls at $p = 0.05$).

We therefore validated the hypothesis of an effect of water deficit on yield elaboration (hypothesis 2 in Fig. 1, but we also add an environmental component in the water status pathway (runoff) and a cropping technique in the technical system (plowing techniques) (Fig. 7). These will be included in the prototyping phase (Lançon et al., 2004).

4.6. Mineral nutrition (hypothesis 3 in Fig. 1)

All the cotton fields under study received mineral fertilization. The fertilization dates proposed by CMTD were generally adopted by farmers, as indicated in Table 5. All farmers used the same fertilizer containing 14% N, 22% P_2O_5 and 12% K_2O. Ten agronomic situations received manure, applied by the farmers at very high doses before plowing (42 t DM ha^{-1} on average). These high manure doses are common in West Africa on small areas within fields (Kanté, 2001).

The initial soil chemical fertility level (Table 6) differentiated the biomass classes into two groups: classes 1, 2 and 3 had relatively higher organic matter, N and K contents, although the differences were not always significant. The situation differed for the P content and classes 1, 5 and 6 showed the highest contents.

The total amounts of N, P and K brought by mineral and organic fertilization are indicated in Table 7. The data show high variability between and within groups due to the concentration of manure applied in some fields. Nevertheless, there were differences between biomass classes. In particular, classes 3 on one side and 1 and 5 on the other side received significantly different levels of fertilization. Manure is often applied by farmers to correct an assumed deficit in their fields (Kanté, 2001). This trend seemed to apply in our study, except for two classes: class

Table 5
Mineral fertilization used by farmers compared with the CMDT recommendations

	Complex fertilizer doses (kg ha^{-1})	Date of fertilizer application (DAS[a])	Urea doses (kg ha^{-1})	Date of urea application (DAS)
Farmers	126 (29)[b]	24 (5.6)	47 (13)	40 (7.6)
CMDT recommendation	200	15	50	45

The fertilizer complex was NPK 14–22–12. Both complex and urea were applied on the soil before a manual weeding.

[a] DAS: days after sowing.

[b] Standard deviation around the mean is indicated in brackets.

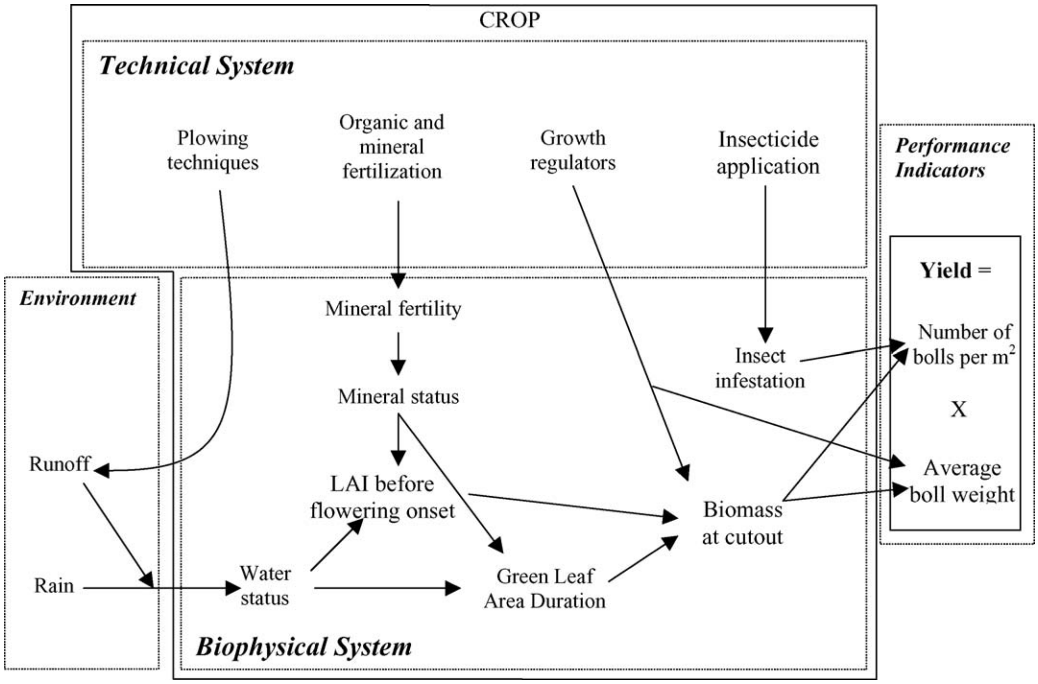

Fig. 7. The modified conceptual model for yield elaboration. This model is valid only for Katogo village, and for a stand density greater than 3.4 pl m^{-2}. It was simplified from the initial conceptual model, according to the results of this study.

5 had a relatively low chemical fertility level, and received little fertilization. On the other hand, class 3 had a high initial fertility and the fields benefitted from high fertilization.

The effects of N fertility and fertilization on the cotton crop were evaluated with the INN indicator at 70 DAE and the results are given in Table 7. Plants with values above 0.8 are considered to be non-N-stressed (Justes et al., 1997). Class 5 clearly appeared to be N stressed. In contrast, class 3 showed a very high N index, indicating probable excessive N nutrition, which could likely be explained by excessive manure application and N fertilization. It induced an excessive LAI development (Table 2), which did not allow the crop to fulfill its yield potential (Table 1).

The crop nitrogen status was therefore kept as an important variable in the conceptual model, and it is under the control of soil fertility, manure application and N fertilization. An optimal level of this variable is required to reach the LAI and biomass required for high yield. Under current cropping techniques, excess nitrogen leads to high LAI and biomass, but fails to convert part of this vegetative biomass into seed–cotton yield.

Table 7
Nutrient doses applied to the fields (mineral fertilizer and manure cumulated) and indicator of nitrogen nutrition of the cotton crop (INN) in each agronomic situation, averaged over the biomass classes presented in Table 1

Class	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})	N (kg ha^{-1})	INN
1	19 b	10 b	57 b	0.83 b
2	62 ab	139 ab	165 ab	0.78 b
3	179 a	530 a	419 a	1.19 a
4	89 ab	179 ab	165 ab	0.82 b
5	53 b	98 b	121 ab	0.60 c
6	185 a	411 ab	239 ab	0.74 bc

INN is calculated at 70 JAE from N content of the aerial parts, corrected by the aerial biomass to take the dilution factor into account (Justes et al., 1997). Values followed by the same letters are not significantly different (Snedecor–Newmann–Keuls at $p = 0.05$).

4.7. Weed control (hypothesis 4 in Fig. 1)

Technical characteristics of weed control and consequences on the biophysical system are presented in Table 8. None of the variables could differentiate the biomass classes. The weeding intensity, indicated by the number of weed control interventions, was not related to the weeding grade, nor was the weeding grade related to cotton biomass at early stages. No significant difference in weeding grades at early stages was found between fields that had received herbicide treatments after sowing and fields that had not.

Weeds are often considered to be a major constraint to cotton production in West Africa (Jallas et al., 1990; Makan, 2001). The absence of any weed effect in our study indicates a good weed control efficacy, wich could be explained both by good technical control by farmers and by the late and abrupt onset of the rainy season (Fig. 2); the time between the first rain and the cotton sowing date was very short, thus hampering weed emergence.

Taking weed cover into account would not provide any additional explanations for yield elaboration patterns in our conceptual model. This component was therefore eliminated from the model. This removal is however only valid in Katogo for the year of study and was the result of good cropping practices and favorable ecological conditions. Furthermore, the conclusions could have been different if the system performance indicators would have included variables other than yield, e.g. labor opportunity costs during weeding periods.

Table 8
Comparison between biomass classes for the weed control interventions performed by the farmers and for weed presence in the sampled fields

Class	First mechanical weed control (DAS)	Number of weed controls	Maximum interval between weed controls (days)	Maximum weed grade	Average weed grade
1	28.3	3.3	28.3	4.3	2.3
2	20.6	3.6	21.0	4.3	2.4
3	23.0	3.5	23.0	3.3	1.9
4	25.0	3.3	26.5	4.3	2.1
5	20.4	3.4	23.3	3.8	2.0
6	21.7	3.3	21.7	3.2	1.6

The weed presence was assessed by a visual method developed for tropical conditions by (Marnotte, 1984). The differences between biomass classes were not significant (Snedecor–Newmann–Keuls at $p = 0.05$).

5. Conclusion

The initial conceptual model proposed to assess the main effects of cropping interventions on yield elaboration in cotton crops was helpful as an initial framework. This model could be modified and simplified on the basis of the results obtained in this study (Fig. 7).

Concerning the core of the model, the biomass accumulation model has shown its relevance. LAI, and particularly its rapid increase at the beginning of the cycle, yielding different LAI at first bloom, is a key element of biomass accumulation. The duration of the period during which the photosynthetic apparatus works at high level, characterized by the green leaf area duration, is also an important feature of biomass dynamics. The core model was modified to stress this issue.

Other modifications were made to the initial model as follows:

- Stand density and weed effect were removed, as no relation with final yield was observed.
- Water status hypothesis was modified, by inclusion of plowing techniques in the technical system and runoff as an important factor of the environment.
- Growth regulator applications were added as a possible technical intervention, as situations were detected in which biomass accumulation was too rapid and not well converted into bolls. Therefore, those applications will be tested in the prototyping phase.

Mineral status is certainly a major issue for cotton production in Katogo. The connection between this status and the fertilization techniques was not clear in this study. The initial fertility of the plots seemed to be the key determinant of the mineral status. The addition of mineral or organic fertilizers is a means to maintain this fertility but does not compensate the effect of the initial soil fertility.

The effect of insects on boll retention was not assessed in this study. The hypothesis is therefore retained in the modified conceptual model.

This conceptual model is fundamentally different from a more mechanistic model for the simulation of development and growth of crops, like GOSSYM (Baker et al., 1983) or APSIM (Keating et al., 2003). Both kinds of models are complementary in the process of conceiving innovative cropping system.

The model presented here aims at integrating the knowledge gained in this particular place. Being primarily empirical, it may need adaptations when transposed to another place. However, the core of the model may remain stable, i.e. the assumption that the biomass dynamics is the central part of the cotton production process. The model was mainly build as a framework to help in focusing on research areas and to gain understanding on the functioning of the local cotton based cropping system. Its simplicity makes it a suitable tool for developing new cropping technique combinations in a systemic and participatory approach, in response to local constraints.

More mechanistic models are also needed in this conception process. In Western Africa, the climate vaiability hampers the validity of any new cropping option that might be experimented. If adequately parametrized, a mechanistic model is a very useful tool to assess the impact of climate variability. Validated mechanistic models could also be used for adjusting decision rules in any cropping system, e.g. the fertilization timing and doses depending on the environment. Such work is under way in Mali. Nevertheless, the efforts needed to develop or to adjust an existing model should not be underestimated.

The development and evaluation of a conceptual model on the basis of farmer's field is therefore proposed as an initial step in a model-assisted participatory research when mechanistics models are not available, not properly parametrized or not able to simulate some of the key aspects of the cropping systems.

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