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Analysis of local limitations to maize yield under tropical conditions

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Abstract – A method for the diagnosis of yield limitation in maize was tested. The test was based on a survey carried out in west Burkina-Faso, with a total of 437 farmers, over a period of 3 years. Data on weather, soil, farm, maize (cultural practices, and, on two plots per field, components of yield) were recorded. The diagnosis is based on analysis of yield components, compared with their potential values. 'Realisation indices' for different phases of growth are defined to quantify local stresses, and to locate them in relation to time. A treatment is proposed which allows us to distinguish long-lasting stresses (such as fertility) from transient or random stresses. In our conditions, long-lasting stresses appeared to be the most frequent. They result more from cultural practices than from environmental factors. The intensity of the random stresses also appeared to depend on cropping techniques. The method provided a satisfactory analysis of the different types of situations encountered in the survey. The diagnosis is limited by data available on the abiotic factors which are sources of stress. (© Inra/Elsevier, Paris.)

maize / tropical agriculture / yield analysis / diagnosis / stress

Résumé – Analyse des limitations locales au rendement du maïs en conditions tropicales. On évalue une méthode de diagnostic des limitations au rendement du maïs. L'évaluation repose sur une enquête conduite dans l'Ouest du Burkina-Faso, chez 437 agriculteurs au total, et répartie sur trois ans. On a relevé des données du climat, du sol, de l'exploitation, du champ de maïs (événements culturaux, et, sur deux placettes par champ, composantes du rendement). Le diagnostic est fondé sur l'analyse des composantes du rendement, comparées à des valeurs potentielles. Des indices de réalisation des différentes phases du cycle sont définis pour quantifier les contraintes locales, et les situer dans le temps. On propose un traitement qui distingue des contraintes durables (de type fertilité), et des contraintes passagères (de type accidentel). Dans nos conditions, les contraintes durables étaient les plus fréquentes. Elles dépendent davanta-

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ge des techniques culturales que des facteurs environnementaux. L'intensité des contraintes accidentelles dépend aussi des pratiques culturales. La méthode permet une analyse satisfaisante des différents types de situations étudiées. Le diagnostic est limité par les données sur les facteurs abiotiques sources des contraintes.

maïs / agriculture tropicale / analyse du rendement / diagnostic / contraintes

1. INTRODUCTION

The yield of a maize (*Zea mays* L.) crop is attributable to the cultivar used, within defined regional conditions (radiation, temperature). It may be limited locally by environmental and cultural conditions (water, soil fertility, cultural practices, pests and diseases). These limitations are of a very diverse nature, appear at different stages of growth and affect different components of yield.

Tollenaar [24] showed the complexity of the processes accompanying the formation of yield components, which are unequally sensitive to stress in the course of their formation. The population density is determined very early, and is the component best controlled by the farmer. The number of ears per plant is more particularly affected by a stress occurring around flowering [21]. The number of grains per plant responds quickly and strongly during the 2 weeks following flowering [6, 19]. On the other hand, the powerful regulation which applies to the number of grains per plant, in relation to the availability of carbon reserves, makes the mean weight per grain sensitive to stress only at the end of grain formation [24, 25].

The variability of these components under the influence of growing conditions has been the subject of numerous experimental studies. Yamaguchi [26] showed that tropical maize grown under different climatic conditions (at lowland locations in various seasons, and at highland location), with non-limiting nutrition, gives better yields when temperatures are lowers, and the grain-filling period longer, grains being larger; the number of grains per square metre remains relatively constant, and is low compared with temperate maize. The differences in yield according to sowing date observed by Tanaka and Yamaguchi [23] are also mainly due to grain size, and are explained by the effect of temperature on the grain-filling period, and not by radiation intensity. On the other hand, Cirilo and Andrade [4, 5] found a decrease in ear numbers to be associated with a reduction in growth rate before flowering, whereas lower number and size of grains were associated with a lower growth after flowering, related to a decrease in the intensity of incident radiation.

Raising the population density may increase the yield up to a limit set by the cultivar, but has a strong negative effect on the number of grains per ear [9, 14, 27], and increases the inter-plant variability of the distribution of the organs formed [9]. At high densities, the number of sterile plants increases rapidly, leading to a bimodal distribution of the number of grains per ear in the population. The prolific cultivars are less susceptible to this effect. A comparison between cultivars [17] linked the sensitivity to shading during growth to the response to high densities. A negative effect of density on unit grain weight is sometimes found [8, 9, 23].

Shortage of nitrogen greatly affects the number of grains per ear [14, 16, 23], mainly owing to abortion of potential grains. Such a shortage may also affect to a lesser extent the weight per grain, and, when the deficiency occurs early, the fertility of the plants. It accentuates the competition effects of high densities or of defoliation. A single water stress period has very different effects depending on the growth stage of the maize. Like most determinate annual crops [2], maize is particularly sensitive to water shortage at the time of flowering. For a brief period of stress, the most marked effect on yield is observed when it occurs around the time of silk emergence. It then affects mainly the number of grains [6, 7, 13]. If applied more than 1 week before flowering, it affects mainly vegetative growth, with a limited effect on yield. Two weeks later, the effect is less, and applies to grain size. A stress beginning at tassel emergence [19] can, if prolonged, reduce the fertility of the plants by 75 %, and the number of grains on the remaining ears to the same extent. The authors cited noted a compensatory effect of grain size, of the order of 30 %.

A limitation of the source of assimilates, brought about by severe defoliation in the 2 weeks following silk emergence [26], has a very rapid and pronounced effect on grain number, and a significant but more limited one on unit grain weight, apparent only at the end of growth. Two weeks later, defoliation only really influences unit grain weight. Shading 45 % 2 weeks after flowering reduces unit grain weight [1]. The treatment does not affect the rate of grain-filling, but its duration. On the other hand, thinning out the plants has no effect on the number or size of grains.

The effects reported and the interactions are very variable, depending on the subjects chosen (varieties, treatments) and the other uncontrolled variables. Numerous observations indicate the sensitivity of yield components to stresses imposed by the environmental conditions, crop management or other possible setbacks.

The variation of yield components may therefore provide a basis for a diagnosis of the situation, as developed by Byerlee et al. [3]. Their use in the course of surveys in producers' fields is, however, complex, because the local information is generally more limited than for experiments, and the effects of several factors may be confounded. It should be based on experimentation and on an interpretive model [11, 16], and turns out to be easier when it is aimed at the analysis of a given technique [22].

The application of a model of yield formation to two kinds of tropical maize cultivars to a set of survey data has enabled us to define the upper limits or potential values of the different yield components other than plant population density (Siband et al., pers. comm.). The product of the potential values of the components multiplied by population density gives the potential yield for each type of cultivar, as a function of the population density. In the present paper, the basic hypothesis is that the differences between observed and potential values of the different yield components in local situations allow a diagnosis of the occurrence of stresses which affected the grain yield.

2. MATERIALS AND METHODS

2.1. Conditions of the study and data collected

The study was carried out in the maize-growing region of western Burkina-Faso (latitude 10–15°N). Annual rainfall is 800–1 000 mm, mean temperature for the growing season 27 °C, radiation 14–20 $MJ.m^{-2}.d^{-1}$. The maize consists of open-pollinated varieties, classified as local or selected, of fairly considerable height (3–3.50 m for local and 2.50–3 m for selected varieties). It is often fitted into a maize–cotton or maize–cotton–sorghum succession. Population densities range from 16 to 77 000 plants ha^{-1}; weed control is incomplete and levels of fertilisation are often very low, creating a set of situations of considerable diversity.

The study is based on 437 maize fields surveyed from 1989 to 1991. Weather conditions were fairly similar from site to site, and close to the mean for the last 20 years. The data set involved:

– the farm (geographical and topographical position, cultivated area, equipment available on the farm), cropping history and cultural techniques for the field surveyed (date and types of farming practices, sowing, fertilisation, weed control, harvest);

– the state of the crop (notes on weed infestation, lodging, *Striga*, viruses), number of plants at flowering (NP), number of ears at maturity (NE), yield of grain per hectare (Y), mean weight per grain (WG, on a representative sample of 1 000 grains from the harvest after shelling), on two plots (sampling areas) of 20–30 m^2 in each field. WG and Y are expressed at 15 % moisture content. The number of grains per hectare (NG) is obtained by dividing Y by WG; the mean number of ears per plant (NEP) by dividing NE by NP. The conditions of the survey did not allow a direct measurement of the number of fertile plants (i.e. plants with at least one ear larger than 10 cm). A frequency of fertile plants equal to NEP was defined if NEP was less than one; and equal to one if NEP was greater than one;

– radiation and temperature (which varied little spatially) recorded at Bobo Dioulasso; rainfall on a network of rain-gauges representing 300–400 km^2 areas; rough soil properties (depth, texture, proportion of gravel, pH).

The main parameters are divided into classes, the definition of which is shown in *table I*.

2.2. Approach

A method of yield analysis with four yield components will be used: population density, NP; frequency of fertile plants, FP; number of grains per fertile plant, NGFP; and unit grain weight, WG. The phases in which they are assumed to be determined are called vegetative (VEG); initiation-flowering, or pre-flowering (IFL); flowering-abortion limit stage, or simply flowering (FLA), and grain-filling and maturation (MAT). Thus we have:

Final grain yield observed:

$$Y_{OBS} = NP \times FP \times NGFP \times WG \quad (1)$$

Total growing period = VEG + IFL + FLA + MAT

The potential values are those considered to be allowed by the general conditions of the region investigated, and more specifically the radiation and the temperature (considered to be sufficiently homogeneous

Table I. Class distributions of the parameters used in the study.

Class	Abbreviation[3]	1	2	3	4	5
Topographical position		summit	high	medium	low	
Soil thickness (cm)		< 40	< 60	≤ 100	> 100	
% gravel		< 20	≤ 40	> 40		
Texture		sand	sandy clay	clayey sand		
pH H_2O (1:2.5)		< 4.8	< 5.5	≤ 6.5	> 6.5	
Previous crop		cotton	cereal	other		
Tillage	A	none	ridging	hoeing on the flat	animal draught	mechanised
Sowing: fortnights after 15 may	B	1	2	3	> 3	
Variety	C	local	other[4]	EV8822R		
Density ($\times 10^3$ pl.ha^{-1})	D	< 20	< 30	≤ 60	> 60	
NPK (kg.ha^{-1})	E	< 25	< 50	100	> 100	
Urea (kg.ha^{-1})	F	0	< 50	≤ 100	> 100	
Weeding (nb)	G	1	2	3	4	
Streak (% plants affected)[1]		0	< 5	≤ 10	> 10	
Striga plants/maize plant [2]		0	< 5	≤ 5	> 5	

[1] Counted on 15 × 10 m lengths of row; [2] counted on 10 m lengths of row; [3] used in the graphical representation of MCA; [4] various selected varieties, grown on by the farmer.

throughout the region and throughout the years as noted above). They are determined separately for each type of varieties.

Values lower than their potential level are considered to be due to local stresses (for a given site and a given year) associated with rainfall, soil, cropping techniques (soil preparation, fertilisation, weed control, etc.) and pests.

When a NP is established, the maximum (potential values) yield components can be calculated from empirical equations given in *table II*, and established separately for the two groups of cultivars studied (Siband et al., pers. comm.). These relations were obtained from boundary lines in plots of yield components versus population density in the same trials. The maximum possible yield for the density considered can be calculated as the product of NP and the potential values of other grain yield components.

2.3. Maximum yields at different phases of growth (updated potential yields)

The maximum yield which a variety can produce under the temperature and radiation conditions of the region, and in the absence of stresses during growth, will be called the radiation-limited yield (Y_{RAD}). This is the yield which can be expected at the moment of sowing.

It is generally admitted that most of the carbon source for maize grain-filling comes from photosynthesis occurring from the end of the establishment of the vegetative canopy until the end of grain-filling [15, 20]. Thus, Y_{RAD} can be defined as the weight of grain which the maize can produce with the energy intercepted between flowering and maturity. The largest yield, calculated from the relationships in *table II* allowing NP to vary, may be a good estimation for Y_{RAD} (Siband et al., pers. comm.). For the purposes of calculation, the lowest value of NP which enables Y_{RAD} to be reached is used. Beyond that density, yield no longer increases with NP.

In practice, the plants are submitted to various stresses and the yield components do not reach the potential value as defined above. Thus, each time a yield component is fixed by the plant, i.e. at the end of each of the phases taken into account, an updated value of the potential future grain yield can be calculated. These updated future yields are obtained by multiplying the real values of the components already determined by the potential values of those which will be determined in the subsequent phases. This corresponds to the yield which is still possible if the subsequent phases are completed without further stresses. The updated potential yield evolves from one phase to the next, remaining constant, or

Table II. Potential values of yield components, related to density of population.

	FP	NP < 57 000 → FP = 1	NP >= 57 000 → FP = 57 000 / NP
Local varieties	NGFP	NP < 40 000 → NGFP = 690	NP >= 40 000 → NGFP = 2.8 10^4 / NP
	WG	(NP × NGFP) < 1.9 10^7 → WG 390	(NP × NGFP) >= 1.9 10^7 → WG = 7.3 10^2 / (NP × NGFP)
	FP	NP < 67 000 → FP = 1	NP >= 67 000 → FP = 67 000 / NP
Selected varieties	NGFP	NP < 48 000 → NGFP = 640	NP >= 48 000 → NGFP = 3.1 10^4 / NP
	WG	(NP × NGFP) < 2.2 10^7 → WG = 420	(NP × NGFP) >= 2.2 10^7 → WG = 9.5 10^2 / (NP × NGFP)

FP, frequency of fertile plants; NGFP, number of grains per fertile plant; NP, number of plants per hectare; WG, mean grain weight (mg).

declining. If the updated potential yields are noted Y with the suffix of the phase, we have:

$$Y_{RAD} \geq Y_{VEG} \geq Y_{IFL} \geq Y_{FLA} \geq Y_{MAT} \quad (2)$$

Note that Y_{MAT} corresponds to the final observed grain yield Y_{OBS}.

The model does not exclude compensation effects among components, but these may not exceed the strict compensation.

The expressions for successive maximum yields are therefore:

$$Y_{RAD} = NP_p \times FP_{pp} \times NGFP_{pp} \times WG_{ppp} \quad (3)$$

$$Y_{VEG} = NP \times FP_p \times NGFP_p \times WG_{pp} \quad (4)$$

$$Y_{IFL} = NP \times FP \times NGFP_p \times WG_{pp} \quad (5)$$

$$Y_{FLA} = NP \times FP \times NGFP \times WG_p \quad (6)$$

$$Y_{MAT} = NP \times FP \times NGFP \times WG \quad (7)$$

In these equations, a component that is still undetermined and therefore in potential form is given the suffix p, pp or ppp, if the other components that are or will be determined before the component considered (one, two or three phases earlier) are still themselves at their potential values.

It should be noted that FP and NGFP are assumed to be determined during two successive phases but independently depend on NP. This is why they can have the same number of p suffixes [equation (4)].

From this set of equations the evolution of the updated potential future yields during growth can be analysed to pinpoint the periods of stress having affected the crop, and provide a basis for a diagnosis.

2.4. Another expression of measured yield: realisation indices in successive phases

In the situations observed, these potentials are not completely reached. There is a gradual decrease in the values of the updated potential yields. For example, the density NP established is sometimes too low for the attainment of the radiation-limited yield. It follows that $Y_{VEG} < Y_{RAD}$. The part of the potential retained can be estimated by comparing the updated potential yields before and after the growth phase considered. Thus an index of realisation of potential is defined for each phase as the ratio of the potential retained at the end of this phase to that existing before the passage of the phase, i.e. at the end of the preceding phase. Four phase indices, I_{VEG}, I_{IFL}, I_{FLA}, I_{MAT}, are determined:

$$I_{VEG} = Y_{VEG} / Y_{RAD} \quad (8)$$

$$I_{IFL} = Y_{IFL} / Y_{VEG} \quad (9)$$

$$I_{FLA} = Y_{FLA} / Y_{IFL} \quad (10)$$

$$I_{MAT} = Y_{MAT} / Y_{FLA} \quad (11)$$

The product of indices is called the yield index, I_Y. The observed final yield will be written:

$$Y_{OBS} = Y_{MAT} = Y_{RAD} \times I_{VEG} \times I_{IFL} \times I_{FLA} \times I_{MAT} \quad (12)$$

or else:

$$Y_{OBS} = Y_{RAD} \times I_Y \quad (13)$$

This expression allows a clear separation of the effect of general conditions, Y_{RAD} – i.e. essentially the varietal and radiation parameters (temperature/radiation) – and that of local conditions, I_Y – parameters for rainfall, soil, cultural, pest factors: the realisation indices estimate the effects of the local stresses encountered. It should be noted that the indices are not the ratios of the real and potential values of the different components, but the ratios of the maximum yields which result from them: they take into account the possible readjustments of the potential values of the components formed during the following phases.

These indices can be used to represent the growing conditions throughout growth and identify the most limiting phase of growth in the different types of situation encountered.

2.5. Data interpretation

Large variations observed in data from farm surveys due to numerous interacting factors make interpretation difficult and limit us to the standard statistical tools.

Although some classical statistical analyses were used, an important part of the interpretation of data was based on a direct, visual interpretation of the different tables and graphs This gives more freedom to the interpretation by the authors, may allow more insight and makes possible the use of information otherwise difficult to take into account on studies of yields from survey data.

We are aware of the danger of subjectivism, but the use of a well-defined frame proposed for the analysis should hopefully guarantee the minimum of objectivity required of any scientific work.

2.5.1. Stress indice values

First, we examine directly the different realisation indices. Distribution of frequencies of values of yield realisation indices (I_Y) and phase indices were calculated, and a comparison of varieties (local versus selected, χ_2 test) and phases was made (*figures 1* and *2*).

To obtain more insight on the relative importance of the different phases of growth in terms of local stress affecting yield, we regrouped sites in classes according to values of I_Y. The relation of mean and standard deviation of the different phase indices with yield indice (*table IV*) was then discussed directly on the basis of visual examination of the table, and without further classical statistical analysis.

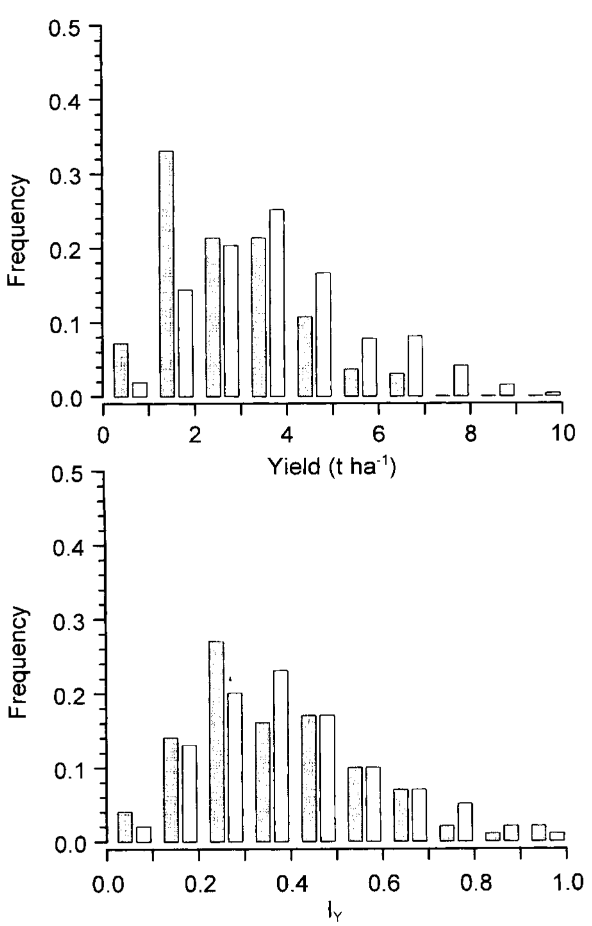

Figure 1. Comparative distribution of yield (Y) and yield index (I_Y) between varietal groups. Grey: local varieties; white: selected varieties. χ^2 test: no. classes = 10; *P* = probability not to be different. χ^2 (Y) = 43.97, $P = 4.96\ 10^{-6}$; χ^2 (I_Y) = 9.17, *P* = 0.42.

2.5.2. Stress profiles

The data were further analysed defining stress profiles as explained below.

The realisation index of a phase reflects the occurrence and importance of stresses during that phase. But, due to the lack of statistical analysis, the precision of the index is unknown. The value will only be used as an indication of the presence or absence of a stress, expressed as a stress value: zero if the index exceeds a threshold value, indicating that stress is negligible, and one if the index is below the threshold value.

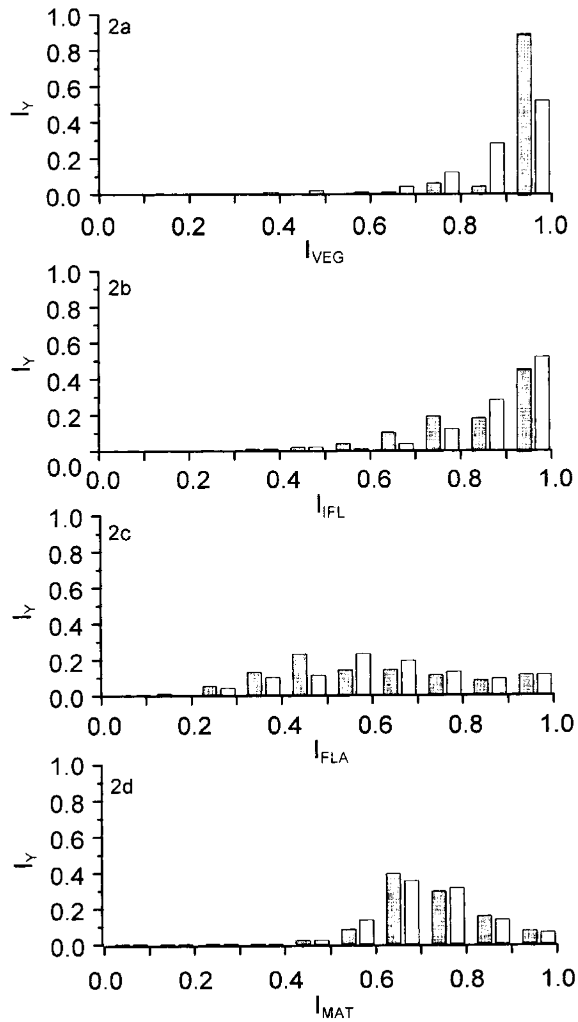

Figure 2. Frequency distribution of the different realisation indices of each growth phase. FLA = preflowering; IFL = flowering; MAT = maturation; VEG = vegetative phase. Grey: local varieties; white: selected varieties.

Table III. Mean and standard deviation of the yield index applicable to a group of supposedly stress-free plots, as a function of the threshold selected to define them.

Threshold	0.95	0.90	0.85	0.80
% of sites	0.46	1.37	2.75	4.33
Mean I_Y	0.977	0.945	0.886	0.841
S.D. I_Y	0.023	0.028	0.068	0.088

At the 0.85 threshold, the increase in the standard deviation indicates the inclusion of plots which have suffered a stress.

We considered stress to be negligible (stress value zero) when the realisation index was 0.85. This was determined by a trial and error procedure, based on a scatter diagram of yield for stress-free plots. The threshold was chosen to minimise the standard deviation (*table III*). It is assumed that, in this case, the difference between stress-free and stressed plots is statistically significant. This choice, made for I_Y, should be even more suitable for the indices of the individual growth phases, to which it was also applied.

Thus the stress values of the four successive phases for a plot will take the values a, b, c and d, each of which might be equal to zero or one. Those four values form a number with four digits that can be considered as the summary of crop history, and is called the stress profile.

As each phase can take either of two states (stress or no stress), a four-phase profile can take 2^4 different states: thus there exist 16 possible types of stress profile, whose frequency and determining factors can be analysed in different steps.

We examined the frequencies of stress profiles (*table V*), and the mean values of the yield and phase indices for each type of profile (*table VI*). To obtain a more indepth knowledge of the origin of the local stresses, we examined the relation of stress profiles to the technical variables (presented in *figure 3*), using multiple correspondence analysis [10], computed with XLSTAT (ad-in of Excel software).

2.5.3. The case of stresses localised within one phase

The objective is to determine plots which suffered a major stress during one particular phase. It was assumed that a major stress is applied during the course of a given phase when the value of its realisation index is lower than that of all the realisation indices of the other phases, thus playing a major role in determining the yield level obtained on the plot. A method has been adopted which uses a simple graphical representation:

if c is the phase most affected, and i, j and k are the three others, we have:

$$I_c < I_i, I_j, I_k \leq 1 \qquad (14)$$

This is verified particularly when:

$$I_c < I_i \times I_j \times I_k \leq 1 \qquad (15)$$

thus

$$I^2_c < I_Y \leq Ic, \text{ or more simply } I^2_c < I_Y \qquad (16)$$

In a graphical representation of the relationship between the realisation index attached to the phase c and the yield index I_Y, the points for the sites affected by a transitory stress during this phase are situated in the area between the parabola '$I_Y = I^2_c$' and the diagonal '$I_Y = I_c$'.

Table IV. Mean values (and standard deviations) of phase realisation for increasing yield indices, for ten classes of 41 individual plots.

I_Y	0.12	0.20	0.25	0.28	0.34	0.38	0.44	0.50	0.60	0.77
I_{VEG}	0.96	0.95	0.95	0.98	0.97	0.97	0.98	0.99	1.00	1.00
	(0.08)	(0.10)	(0.10)	(0.06)	(0.06)	(0.07)	(0.05)	(0.04)	(0.02)	(0.00)
I_{IFL}	0.65	0.78	0.81	0.85	0.90	0.90	0.90	0.94	0.94	0.99
	(0.18)	(0.14)	(0.12)	(0.12)	(0.09)	(0.09)	(0.10)	(0.07)	(0.09)	(0.03)
I_{FLA}	0.33	0.44	0.49	0.52	0.56	0.64	0.68	0.74	0.82	0.94
	(0.10)	(0.08)	(0.08)	(0.09)	(0.10)	(0.11)	(0.10)	(0.09)	(0.12)	(0.09)
I_{MAT}	0.61	0.65	0.68	0.68	0.71	0.72	0.74	0.73	0.79	0.83
	(0.10)	(0.11)	(0.11)	(0.09)	(0.09)	(0.12)	(0.10)	(0.09)	(0.13)	(0.10)

The realisation index of a phase is the ratio of yield still possible after and before this phase.
Phases: FLA, flowering; IFL, pre-flowering; MAT, maturation; VEG, vegetative.

Table V. List of stress profiles and frequencies.

Profile (no.)	Number	Profile (no.)	Number
0000 (1)	12	1 000 (9)	0
0001 (2)	41	1 001 (10)	3
0010 (3)	24	1 010 (11)	2
0011 (4)	174	1 011 (12)	14
0100 (5)	2	1 100 (13)	0
0101 (6)	6	1 101 (14)	0
0110 (7)	10	1 110 (15)	1
0111 (8)	136	1 111 (16)	12
Total	405	Total	32

The stress profile is a number in which each digit provides information about one phase of growth. If the phase index is greater than 0.85, it is assumed that there was no stress, and the corresponding digit is zero. If the index is less than 0.85, it is assumed that there was stress, and the digit is one. Sixteen profiles are possible.

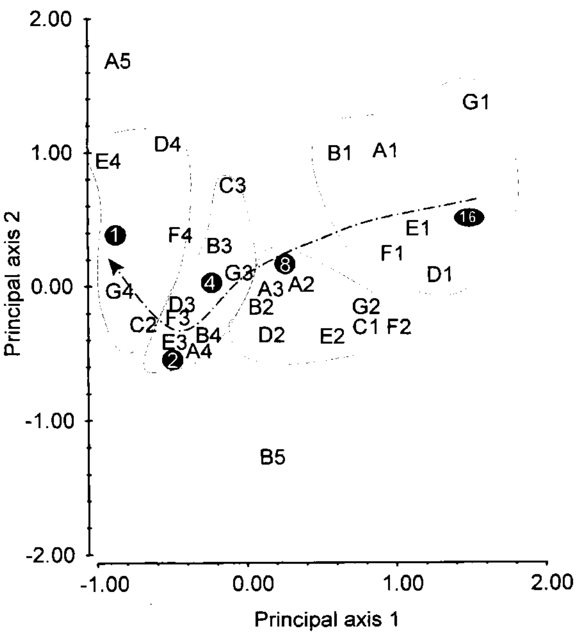

Figure 3. Multiple correspondance analysis for the technical variables (see *table I*). One letter symbolises one variable: A = soil preparation; B = earliness of sowing; C = variety; D = population density; E = NPK fertilisation; F = urea application; G = weedings. They are divided into classes from 1 to 3, 4 or 5, either chronologically (B) or in order of increasing level of intensity (others). The levels of long-lasting stress (appearing earlier and earlier: profiles numbers 1, 2, 4, 8, 16 refer to the list in *table V*) are supplementary variables.

Table VI. Mean index by profile type.

Profile (no.)	Number	I_{VEG}	I_{IFL}	I_{FLA}	I_{MAT}	I_{RDT}
0000 (1)	12	1.00	0.98	1.00	0.91	0.89
0001 (2)	41	1.00	0.99	0.95	0.72	0.68
0011 (4)	174	0.99	0.94	0.59	0.69	0.38
0111 (8)	136	0.99	0.71	0.51	0.67	0.24
1111 (16)	12	0.76	0.75	0.44	0.71	0.18
Total/mean	375	0.98	0.86	0.61	0.69	0.35
Whole sample	437	0.97	0.87	0.62	0.71	0.39

Phases: FLA, flowering; IFL, pre-flowering; MAT, maturation; VEG, vegetative.
The profile numbers refer to the list in *table V*.

By applying this representation successively to the four phases of the cycle, it is possible to locate the affected sites and to evaluate the stress value attributed to each one.

3. RESULTS AND DISCUSSION

3.1. Yield analysis

3.1.1. Yield and yield index (figure 1)

For yield (= Y_{OBS}) (*figure 1a*) the varietal groups behave quite differently: the local cultivars are found mostly among the plots with the lowest yields, and are not represented in the high yield classes.

For the index I_Y (*figure 1b*) most of the difference between varieties has disappeared (χ_2 not significant), and only a minor difference between the modes remains.

I_Y of the class with highest frequency is 0.2–0.3 and 0.3–0.4 for local and selected varieties, respectively. Thus both groups of varieties suffered to the same extent from stresses due to the local conditions proper to each site.

*3.1.2. Distribution of the phase index values (**figure 2**)*

There are no clear differences between the two groups of cultivars. Both seem to suffer equally from stress preventing them from reaching their own yield potential. Comparison of phases shows less stress in vegetative phase VEG (*figure 2a*). The pre-flowering phase IFL (*figure 2b*) is more affected, being only completed satisfactorily (index > 0.85) for one case out of two, and the loss of yield can reach 40 %, and even exceptionally 80 % on some plots of local maize. It is the flowering phase FLA (*figure 2c*) which exhibits the greatest variation in the index, losses varying from 0 to more than 80 %. Finally, although the end of growth – MAT (*figure 2d*) – is quantitatively slightly less affected than the previous one, the number of sites where conditions were satisfactory is even lower here (one case in 20).

The minor influence of the early stages in the determination of maize yield, and the major importance of the period around flowering, agree well with the literature [19, 21, 24]. In particular, one plot in two may lose half its yield potential at around the time of flowering, and, for three plots out of four, a quarter of the potential is lost during grain-filling.

3.1.3. Relative importance of the different phases of growth

Sites were regrouped into classes of equal frequencies according to the values of I_Y and the mean values and standard deviation of the phase indices for each class were calculated (*table IV*). This allows a descriptive analysis of the relations of phase realisation indices with I_Y, and therefore of the part that stress in each given phase played in the achievement of I_Y and yield.

This shows, at the first analysis, that:

– the four indices show very distinct variations in relation to I_Y, and therefore yield;

– the lowest yield indices correspond to hazardous conditions at nearly all phases of growth (class 1), except the vegetative phase, but the effects are particularly marked at flowering.

– with slightly higher yields, the different indices increase, especially the pre-flowering index (classes 2–5);

– in classes with still higher I_Y values, the stresses remain, with flowering and grain-filling having equal importance (classes 6–9);

– the plots in the upper class (10) still frequently exhibit plants with incomplete grain-filling.

Thus, the more pronounced the stress conditions in one phase, the more pronounced they are in the other phases: they are not independent. When I_Y or yield increases, the phase indices approach their maximum approximately in chronological order of the phases (I_{FLA} is lower than I_{MAT} in the first seven classes, but it increases and reaches its maximum more rapidly); the drop in yield of a plot is greater when that plot was subjected to earlier stress.

The standard deviation of the indices for the two last phases (I_{FLA} and I_{MAT}) is of the same order of magnitude for both phases and fairly constant for the whole yield range. Standard deviation of I_{VEG} is of the same order for low yields, but it falls rapidly. For I_{IFL}, it also falls quickly as yields increase, but starts from higher values, being particularly high for the lowest yields: the most variable conditions in early growth (VEG; IFL) are associated with the lowest yield indices.

3.2. Stress profiles

3.2.1. Examination of the profiles

The 16 possible profiles are present in very unequal numbers (*table V*): 93 % of the plots were sown at densities which do not preclude the achievement of Y_{RAD} (first digit in profiles is zero). Among them, a third (136) show a stress in the three last phases of growth; three quarters in the two last phases (174 + 136), and nearly nine out of ten in the last phase. Conversely, the occurrence of a limiting stress during an intermediate phase only applies to 6 % of cases, these being mainly at flowering. In most situations, once one phase has been affected, the following phases are also affected. These effects may indicate lasting dominant conditions of stress, which can result from different types of factors: long-lasting factors, or factors with a long-lasting after-effect, or a continuous series of different successive factors. A low I_{VEG} (right-hand column), which depends on plant population, a factor largely under the farmer's control, is associated four times out of five with stresses in two or three of the last phases, and is never observed at sites which have not suffered stresses during the other phases (sites with profile code 1 000).

Table VI shows the mean indices for sites grouped according to stress profile for the five most common types of profile: they include 86 % of the plots studied, and represent groups of sites without stress, those where a stress state existed only in the final phase, the two last phases, the last three or the entire growth period, respectively. In every case the stress, having appeared, persisted until maturity.

It appears that the more a plot has been stressed at an earlier stage, the more the index of each later phase is, on average, severely affected. This reinforces the hypothesis of the existence of lasting conditions of stress, which are more pronounced when they set earlier.

A low population (i.e. a profile with first digit equal to 1, corresponding to profile 16 in *table VI*) which on average accounts for a quarter of the possible yield, does not reduce the effects of stresses arising during the three last phases, shown by the values of phase indices: it contributes to the low yield index, and does not seem to result from a choice of sowing density by the farmer for growing conditions which he knows must be hazardous, and whose effects he hopes to mitigate. It indicates an additional stress on the crop.

The most favourable profile (1) also shows a mean I_{MAT} index numerically lower than the indices for the preceding phases.

3.2.2. Origin of local stresses

In the case of lasting conditions of stress, the origin of local stresses must be sought in lasting or even permanent factors, such as soil characteristics, topographical position of the plot, features of the farms, technical level of the farmer and the crop management programme followed. These variables have been assigned to classes with size, the validity of which has been checked by a series of chi-squared tests. A series of multiple correspondence analyses (MCA) was carried out on the 437 individual plots investigated. Variables taken into account were the technical variables given in the caption of *figure 3*, plus the parameters of the analysed environment and of the preceding crop. These latter two parameters proved to be of little importance in the analysis, and were discarded. The stress profile associated with each plot was regarded as a supplementary variable. The quality of the representation in the 1–2 plane of the MCA is poor, but nevertheless acceptable (cumulative inertia of 18 %) as is the projection on this same plane of the stress profiles. The graph (*figure 3*) locates the variables against axis one (determined to some extent by all the technical decisions) and two (determined essentially by the sowing date, i.e. variable B). We distinguished four groups of variables corresponding to the levels of intensification of crop management: variables with the same subscript, indicating the intensity, are grouped together.

Organising the data according to axis 2 shows that sowing is early (B1) in simple cropping situations, where no prior tillage operation (A1) delays it, or on better equipped (mechanised) farms A5, where the reduction in working time per unit area permits early sowing. It appears that the long-lasting situations of stress (profiles 16, 8, 4, 2 and 1, which are found along axis 1 become apparent earlier in growth when the intensification level of the crop is lower (profile 16 is in the same group as variables with low intensification subscript; profile 1 is in the opposite group).

Thus, most of the individual plots of the sample surveyed seem to be classifiable according to the magnitude of the long-lasting conditions of stress, which appear to be classified with the level of the techniques used by the farmer (method of soil preparation, choice of variety, sowing density, fertilisation and weeding). Insofar as this technical level is associated with farm characteristics, and is repeatedly applied to a field which has a definite status within the farm (related to its situation and characteristics), it is probable that its effect on the crop would be reinforced by its repetitive nature during the recent history of the field. The long-lasting condition of stress should then correspond to a low intensification, and therefore eventually to a low level of acquired fertility. It seems normal that the more marked a stress is, the earlier is the growth stage at which its effect appears.

3.3. Stress in one phase (transient stresses)

Figure 4 shows the relationships between phase index and yield index, for each of the four phases. Note that when one stress affects a site in one phase in particular (pronounced transitory stress), the point representing it is situated between the diagonal and the parabola.

*3.3.1. First phase VEG (***figure 4a***)*

There are no points above the parabola. The choice of a low density never seems to be associated with good growing conditions.

*3.3.2. For the second phase IFL (***figure 4b***)*

There are nine sites with marked localised stress (located on or above the parabola). Most are for crops of local varieties. The four most strongly affected are near the bottom of a valley, and the points rank very well according to their topographical position, suggesting risks of temporary waterlogging, related to heavy and frequent rainfall and poor external drainage.

*3.3.3. In the flowering phase FLA (***figure 4c***)*

Half the surveyed sites are affected, being localised above the parabola. The lower value of the index I_{FLA} falls to 0.2, and the higher values do not exceed 0.8. Most of the points representing these

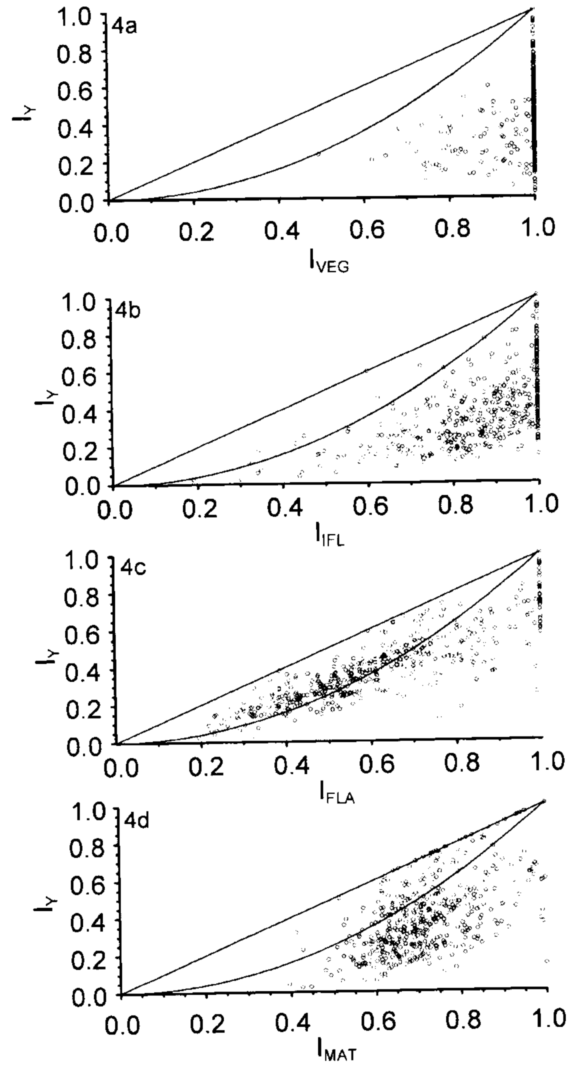

Figure 4. Graphical identification of sites which suffered severe stress during one of the four growth phases. FLA = pre-flowering; IFL = flowering; MAT = maturation; VEG = vegetative phase.

sites are located near the parabola, indicating that this pronounced transitory stress is often associated with additional yield limitations occurring at other growth phases. Only at a few sites (about ten) is yield loss occurring entirely in this phase (points near the diagonal).

The sites affected are situated largely in areas where practices are the least intensive, the farms on which they are located being often less mechanised than the average of the region. However, compared with the whole sample, the averages for size of holding and the use of urea are relatively very high (*table VII*).

The analysis of the sub-sample of sites exhibiting transient stress on this phase shows that the intensity of its effect is associated with other parameters as in the following.

– The lowest indices are for 15 sites where the soil is often shallow (risk of drought). In contrast to the average, the farms are small and cultivation by hand represents 87 % of cases. The cultural choices are non-intensive (high-yielding varieties rare, infrequent weeding, little urea). The high incidence of *Striga* suggests a long period of cultivation and probably, in this context, a limited fertility.

– In sites with an index above 0.3, the presence of *Striga* diminishes progressively, the number of weedings increases, more urea is applied and use of the improved variety (EV84222SR) becomes more common. Mechanisation increases. In the best cases, the farms are larger.

The transitory nature of this stress and its pronounced effect seem to indicate that it is linked to climatic factors. The availability of data on rainfall, soil depth and texture, and timing of the growth period, allows a simulation of the water balance which was carried out according to Franquin and Forest [12]. Only a few instances of water deficit were found during the whole growing period, and they did not figure particularly in the group of stress situations during the flowering phase. The available information is too inaccurate to envisage a diagnosis over short periods, and the difficulty in precisely locating flowering for an open-pollinated variety prevents the clear identification of a water stress event associated with FLA phase. It can be stated, however, that:

– a stress during this phase frequently occurs in this region;

– its incidence is heavily dependent on the fertility and techniques used. This suggests that the state of the crop stand at the time when the stress occurs could determine the outcome, but even in the best cases, this stress seriously affects the yield, reducing it by at least 20 %;

– it appears rarely to be the only stress during the growing period.

3.3.4. Grain-filling phase MAT (figure 4d)

More than one site out five appear to be affected by a transitory stress. Most of the sites concerned are situated in an area of intensive cropping (*table VIII*). The points are mostly aligned along the diagonal (*figure 4d*), therefore indicating that the

Table VII. Magnitude of a stress confined to the flowering phase (I_{FLA} index) as related to selected parameters of the cropping and farming system.

I_{FLA}		0.3	0.4	0.5	0.6	0.7	Mean	Whole population
n = 229	15	41	59	52	41	21	–	437
% Soil[1] thickness < 60 cm	47	25	29	10	19	24	23	24
% Presence of *Striga*[1]	70	47	35	46	16	19	37	39
Mean number of weeding[2]	1.37	1.81	1.87	1.93	2.17	2.21	1.93	1.94
Urea used[2] ($kg.ha^{-1}$)	13	46	60	71	73	81	61	41
% Var. EV8422SR[1,3]	20	17	19	36	42	62	30	31
% Mechanisation[1]	13	37	38	53	54	71	45	50
% Farms > 7.5 ha[1]	7	27	19	30	34	42	27	15

[1] Class frequency; [2] class mean; [3] highest yielding selected variety.
The first five columns represent classes of increasing value of the index I_{FLA}. The sixth gives the mean frequency[1] or mean value[2] for those plots which suffered a stress during the phase. The last gives the corresponding means for the whole sample studied.

Table VIII. Magnitude of a stress confined to the grain-filling phase (I_{MAT}) as related to selected parameters of the cropping and farming system.

I_{MAT}		0.6	0.7	0.8	Mean	Whole population
$n = 97$	9	41	31	16	–	437
% Soil thickness < 60 cm[1]	32	29	43	40	36	24
% Sowings > 20 days later than the first date[1,3]	78	54	53	53	56	24
Mean number of weedings[2]	1.67	1.98	2.26	2.27	2.08	1.94
Urea used[2] (kg.ha^{-1})	26	40	55	120	57	41
% Var. EV8422SR[1,4]	44	42	46	47	44	31
% Mechanisation[1]	22	53	74	95	64	50
% Farms > 7.5 ha[1]	0	19	50	66	35	15

[1] Class frequency; [2] class mean; [3] the first favourable sowing date is after a 20 mm fall of rain following a seasonal total of 30 mm; [4] highest yielding selected variety.
The first four columns represent classes of increasing value of the index I_{MAT}. The fifth gives the mean frequency[1] or mean value[2] for those plots which suffered a stress during the phase. The last gives the corresponding means for the whole sample studied.

yield loss took place exclusively during this phase. The yield range concerned is high (above 40 % of the maximum possible). The crop has lost up to half its yield updated potential during this phase. By comparison with the whole population of sites (*table VIII*), the stress arose on farms that were larger and better equipped than average, under good growing conditions (e.g. weeding, urea use and varietal choice), but it was frequently associated with late sowing and, in a third of the cases, with shallow soil; these two last factors suggest that water stress during this phase could be possible.

However, the nine most affected sites (index below 0.6) constitute a very special group of small, mainly hand-cultivated farms, where farmers make little use of urea, weed rarely and sow particularly late, whilst readily adopting the best variety (somewhat shorter-term than others).

In other cases, mainly the largest cotton farms, intensive growing conditions reduce the effect of the stress. Its very localised nature within the growing period when the index exceeds 0.8 (points on the diagonal) attests to the very good growing conditions.

The maturation problems are clearly related to the sowing date, which exposes grain-filling to the risk of early cessation of rainfall, and thus occurs under the following types of extreme situations:

– on some small poorly producing farms, where maize is sown particularly late, perhaps together with limited technical means, and on soils with a low water-holding capacity; in this case, poor grain-filling is associated with other stresses which contribute to a low yield;

– on farms of good technical capability, where maize sowing is not a priority. The yield loss is a lesser evil which the farmer tolerates in the interest of his work routine. It does not prevent the achievement of yields which are among the best. The strong dependence of yields on cultural practices gives hope for possibilities of improving production.

4. CONCLUSION

Survey data of farmers' fields display large variations which make classical statistical analysis and interpretation difficult. The lack of information on the detailed history of the crops makes the analysis still more difficult. Our method allows a structuration of the data, a reconstruction a posteriori of the history of the crop, in terms of presence or absence of stresses having affected a local specific field in the survey (local stress). It is based on analysis of the sequential determination of yield through the yield components, and the comparison through realisation indices of final observed grain yield to successive updated estimations of the potential future yield, calculated at the end of each phase. The realisation indices are then submitted to different presentations in the form of tables and graphs which are analysed, partly through classical statistical analysis, but to a larger extent through a direct visual examination giving a large freedom of interpretation. This approach, which could be qualified as semi-quantitative, may have obvious limitations, and presents the danger of a greater subjectivism, but it has also its rigour and allows us to obtain practical results, which do not appear without value.

Indeed, the method has brought out a number of consistent features: a very general importance of long-lasting stresses, related to the fertility level of the field, and probably more to its history than to its intrinsic soil properties; the occurrence of very marked transitory stresses, the effects of which may be superimposed on those of long-lasting stresses. This is the case in the flowering phase for many of the sites and during maturation for the less productive sites, and also even applies to stresses occurring under good cultural conditions and resulting simply from late sowing. In every case, it may be possible to interpret the response of yield to the local stress in term of technical factors and, behind the technical choices made by farmers, in terms of the importance of the resources available to them.

However, the approach does not always allow a clear identification of the factors responsible for the local stresses detected. But, also, yield loss under sub-optimal growing conditions is rarely dependent on a single factor, but depends rather on a set of interacting factors, and these can be taken into account globally through the use of the indices proposed. Nevertheless the difficulty in finding a clear causal relationships between techniques and results remains. One of the reasons is that a farmer's decisions are as much a consequence of the judgement he makes on the production possibilities of a field, as the effect of the underlying causes of these.

The method allows an identification of the occurrence of local stresses and, to estimate to some extent their importance, it draws the attention to the relation with the technical decisions. Even though the origin of the stresses might not always be clearly identified, appropriate technical decisions can have large positive effects. The method offers elements for the analysis of situations, which could give an useful diagnosis, provided that sufficient relevant site information is available.

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List of abbreviations:

1) Yield components:

FP	frequency of fertile plants
NE	number of ears per unit ground area
NEP	number of ears per plant
NGFP	number of grains per fertile plant
NP	number of plants per unit ground area
WG	mean grain weight
Y	yield
p,pp,ppp	subscript indicating the potential value of these components without subscript: value observed at final harvest

2) Development phases:

FLA	flowering-abortion limit of grains (flowering)
IFL	initiation-flowering (preflowering)
MAT	grain-filling (maturation)
VEG	vegetative phase

3) Potential yields:

expressions for the potential yield at the end of each phase (updated potential yield), taking into account the limitations on yield components due to previous local stresses

Y_{FLA}	updated potential yield at the end of phase FLA

Y_{IFL}	updated potential yield at the end of phase IFL
Y_{MAT}	updated potential yield at the end of phase MAT (corresponding to Y_{OBS})
Y_{OBS}	yield observed
Y_{RAD}	radiation-limited yield
Y_{VEG}	updated potential yield at the end of phase VEG

4) Realisation indices for each growth phase:

I_{FLA}	FLA phase
I_{IFL}	IFL phase
I_{MAT}	MAT phase
I_{VEG}	VEG phase
I_{Y}	yield realisation index (product of the phase indices)