PHYSIOLOGICAL DIAGNOSIS — A GUIDE FOR IMPROVING MAIZE PRODUCTION BASED ON PRINCIPLES DEVELOPED FOR RUBBER TREES*

(Met opsomming in Afrikaans)

(Avec résumé en français)

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Abstract

Physiological diagnosis (PD) developed in Indochina for use in rubber tree cultivation has been adapted to maize production in southern Africa***.

Information obtained from experiments conducted over a wide area for five years has enabled established norms or 'reference data' to be drawn up which can be used directly to disclose and assess 'causes' of all kinds which are limiting yields in any particular area or site. The proposed techniques offer the advantage of direct and general application once the norms have been established for a given crop.

The established norms are concerned with 'causes' involved in cultivation, plant nutrition and environment. Physiological diagnosis as dealt with in this paper is, however, confined to the systematic determination of the status of the major nutrients N, P and K, as supplied by leaf analysis.

To facilitate this determination, a chart has been designed from which the status of these elements in the plant can be determined directly at any stage of the plant's growth. The interpretation of the results obtained by application of the chart must nevertheless take into account the various factors which might have an influence on the physiological functioning of the plant.

The norms established in southern Africa for N, P and K have been put to a critical test by applying them to a large number of experiments on maize published in the world literature. A number of examples of this test are given.

Graphs for each of the three elements N, P and K drawn from 21 536 observations recorded in various parts of the world relate yields to indices calculated directly from the standard chart. Each graph has been statistically analysed and it establishes the fact that the kind of relationship existing between yield and chemical composition of the plant's tissue is a manifestation of the Law of the Minimum. Highly significant relationships were found between yields and NPK — obtained irrespective of the experimental conditions.

One particular advantage of physiological diagnosis is that it is not affected by the usual masking factors of variability. By carrying out routine checks a diagnosis can be done directly at any time under any conditions thus allowing for a continuous picture to be obtained of the nutritional status within the plant. Problems can thus be studied whenever they occur.

Information collected from over 200 farms representing nearly 500 sites in southern Africa was recorded, processed and used for obtaining background information to assist with research work, and directly, for making field recommendations such as date of planting, row spacing, plant population . . . and of course, the nature and quantity of fertilizer to be applied.

The nature and quantity of nutrients to be applied have been determined with accuracy through successive approximations from routine controls.

Results and conclusions obtained from the 'classical field experiments' are reviewed and their limitations discussed. Improvements are suggested to increase the degree of reliability and to improve the limits of validity of field experiments. Other fundamental notions such as 'absolute' and 'relative' values, 'normal' and 'optimum' conditions are discussed in an author's note.

Physiological diagnosis, as partly presented in this paper, helps to set out the parameters of the problem, but it is not an automatic solution to the problem. Appropriate corrective action is not solely a function of the diagnosis, and subjective qualities such as knowledge, experience and perspicacity of the person who is to make the necessary recommendations are also required. Although the methodical aspect of physiological diagnosis is subject to personal interpretation, its intrinsic value is in no way diminished.

Improvements to the technique will come with more experience, but the tool can be advantageously used as it is. Practical application of PD to problems in maize culture has already confirmed its usefulness as a guide for research work, as well as for making recommendations to improve grain yields on farmers' lands.

If the ultimate purpose of fundamental agronomic experiments is to relate yields reliably to any sort of variable capable of being placed under man's control, then the conclusions reached in this work should be sufficient on their own to support the validity of the proposed principles.

Much of the knowledge acquired to date on PD is illustrated in an example in which it is applied on a large scale maize trial. Actual yields per morgen were brought during the first season from 28 bags up to 75 bags without irrigation.*

There appears to be no reason why these principles cannot be successfully adapted for use on other crops.

*One bag of maize grain weighs 200 lb.
One morgen = approximately 2.1 acres = 1.17 hectares.

Introduction

Historical

The concepts and principles of physiological diagnosis have been discussed in detail in various publications (Beaufils 1953, 1954, 1955, 1956, 1957, 1958, 1959, 1960) and have been originally presented by the writer as a thesis at the Sorbonne (Beaufils, 1961). The method was developed for rubber trees *(Hevea brasiliensis)* in Vietnam and Cambodia.

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***Physiological Diagnosis Chart for NPK maize has been patented in South Africa, Australia, New Zealand and South West Africa. Patent holder African Explosives and Chemical Industries Limited (Beaufils, 1968).

Profitable yield responses obtained by its application have amongst others been reported by Le Bras (1959); Le Bras (1960); Anon (1961); and Fallows (1963). In South Africa work on physiological diagnosis on maize was begun in 1965.

The principles appear to be simple in practice but certain problems present themselves, and confusion concerning fundamental aspects can arise. For example, Fallows (1960, 1961) tried to refute the suitability of the method for rubber trees in Malaya, and in order to prevent a similar situation occurring in maize, this point of controversy is discussed on page 27.

Diagnosis and remedy

According to the Shorter Oxford Dictionary (Little, Fowler & Coulson, 1959) a diagnosis can be defined as 'a formal, objective and reliable statement concerning a given situation.' This is also the aim of Physiological Diagnosis which is expected to supply and set out the parameters of the problem but not to solve it automatically.

Bridging of the gap between diagnosis and remedy is not always evident in the data and often depends on other factors. Many of these are subjective factors such as knowledge, experience and perspicacity of the specialist who makes the recommendation.

Objective of the investigation

The main objective of the investigation was to establish norms or reference data for maize and to show how these can be used as a tool for research in plant cultivation and for making recommendations, particularly fertilizer recommendations to improve maize yields on farmers' lands. In order to achieve this objective the investigation aimed at

(a) determining the influence of any factor suspected of having a possible action on the physiological functioning of the plant;

(b) defining physiological laws which govern plant growth, development and production;

(c) coding the relevant laws, using numerical data;

(d) relating such numerical data to yield, (PD norm);

(e) establishing norms or reference data whenever feasible;

(f) using those norms as a basis for making recommendations involving not only fertilizer requirements, but also any factor/s capable of increasing yield through physiological response.

Method

Sampling

Two thousand and twenty samples from different areas in southern Africa were taken. Only fully-formed, physiologically-active leaves were sampled. Sampling sites and the plants from which the samples were taken, were chosen at random, and specific data at sampling time was recorded as follows

(i) vegetative condition of plant sampled — general appearance, position of sample on the plant, age of the plant (expressed in number of days between date of planting and sampling), hour of sampling, colour, height, visual deficiency symptoms, disease and insect infestation;

(ii) weather conditions — rainfall, temperature, wind, light intensity;

(iii) cultivation practices — cultivar, date of planting, row spacing, plant population, details concerning usage of fertilizer, fungicides and weedkillers, history of the site;

(iv) soil analysis — chemical, physical and mechanical;

(v) grain analysis from samples taken at harvest time.

Leaf samples were taken at five different times during the growing season.

Leaf analysis

All samples were analysed for N, P, K, Ca, Mg, S, Cl, Mn, Zn, Fe and H_2O. Physiological diagnosis as dealt with in this paper, is however confined to the major nutrients N, P and K.

Recording of data

All the recorded information (including yields) was fed on to computer cards to give a comprehensive picture of each site sampled. The purpose of this was to divide all samples into two main categories viz

(a) non-abnormal plants ie plants which were not affected by abnormal conditions, and

(b) abnormal plants ie those which were affected by abnormal conditions.

By convention non-abnormal plants will be called 'normal plants.' (See author's note on page 27).

In this classification the vegetative condition of the sampled plants was mainly used and plants were scored on a five-point growth scale viz

Luxurious (L)
Luxurious to medium (LM)
Medium (M)
Medium to poor (MP)
Poor (P)

Of the L, LM and M classes, those sites which yielded 30 bags of grain per morgen (3 200 kg per hectare) or more were classified as non-abnormal. The analysis results of the non-abnormal group were then used as the basis for establishing physiological laws and norms or reference data.

Field experiments

It is a fact that the conclusions reached from an experiment, eg a fertilizer experiment, may be

(i) valueless because the experiment has been jeopardised by an accidental factor such as drought; or
(ii) misleading because of the existence of an unknown limiting masking factor (any kind of unapparent deficiency for instance); and
(iii) are usually limited to the particular conditions of the particular experimental site.

Extrapolations can sometimes be attempted but they always introduce one or more unknown factors of possible error.

The work undertaken under the designation of Physiological diagnosis has mainly been aimed at minimising the effects of the above three limitations viz

(i) Reducing influences due to factors such as drought. A provisional specification for a patent has been filed which claims that the effects of adverse climatic conditions can now be reduced whenever they may occur (Beaufils, 1970).
(ii) Reducing influences due to unknown masking factors. PD is mainly concerned with the disclosure and assessment of limiting factors of all kinds. It is an advantage that the proposed methods enable periodical routine controls of the experiment to be made as well as exceptional ones at any time as might be required. Periodical PD routine controls during a season for instance will give a continuous picture of the physiological development of the plant. This is preferable to a single

picture. Properly applied, PD should thus help — by disclosing and assessing limitations — to increase the degree of reliability of the results and conclusions of field experiments.

(iii) Reducing limitations at particular experimental sites.
The application of the extended scheme of experimentation suggested on page 24 should enlarge the limits of validity of the results and conclusions drawn from field experiments.
Thus the results given in this paper—which establish on a world-wide scale the relations between yields and tissue composition — are indeed the conclusions of a field experiment in which conditions are unlimited. If the ultimate purpose of fundamental agronomic experiments is to relate yield to any sort of variable capable of being placed under man's control, then the conclusions that follow should be considered as reasonably definite and their terms ready for profitable application.

Discussion of recorded data

Nutrient balances

From the analysis figures for N, P and K, nutrient ratios of N to K, N to P and K to P are worked out and it is these ratios which indicate whether one nutrient is in balance with another — after the norms have been established.

A balance between two nutrients is shown by means of a small horizontal arrow thus →. For example if nitrogen and phosphorus are in balance with each other the N to P ratio is written N/P→.

An imbalance between two nutrients is caused either by a relative excess of one nutrient or a relative deficiency of the other. This situation is shown by means of a perpendicular arrow pointing upwards to indicate an excess (↑) and downwards to indicate a deficiency (↓). If N is deficient relative to P then the N to P ratio is written N/P ↓. If N is in excess then the ratio is written N/P ↑.

The physiological diagnosis chart for NPK

The mineral ratios calculated for the normal plants were taken as norms using a method similar to that used for rubber trees (Beaufils 1953, 1954, 1955, 1956, 1957, 1958, 1959, 1961). The diagram in Figure 1 was statisically evolved from all the NPK analytical data of the normal plants. It is a three-way schematic presentation of the nutritional balances existing between N, P and K in terms of the ratios N/P, N/K and K/P.

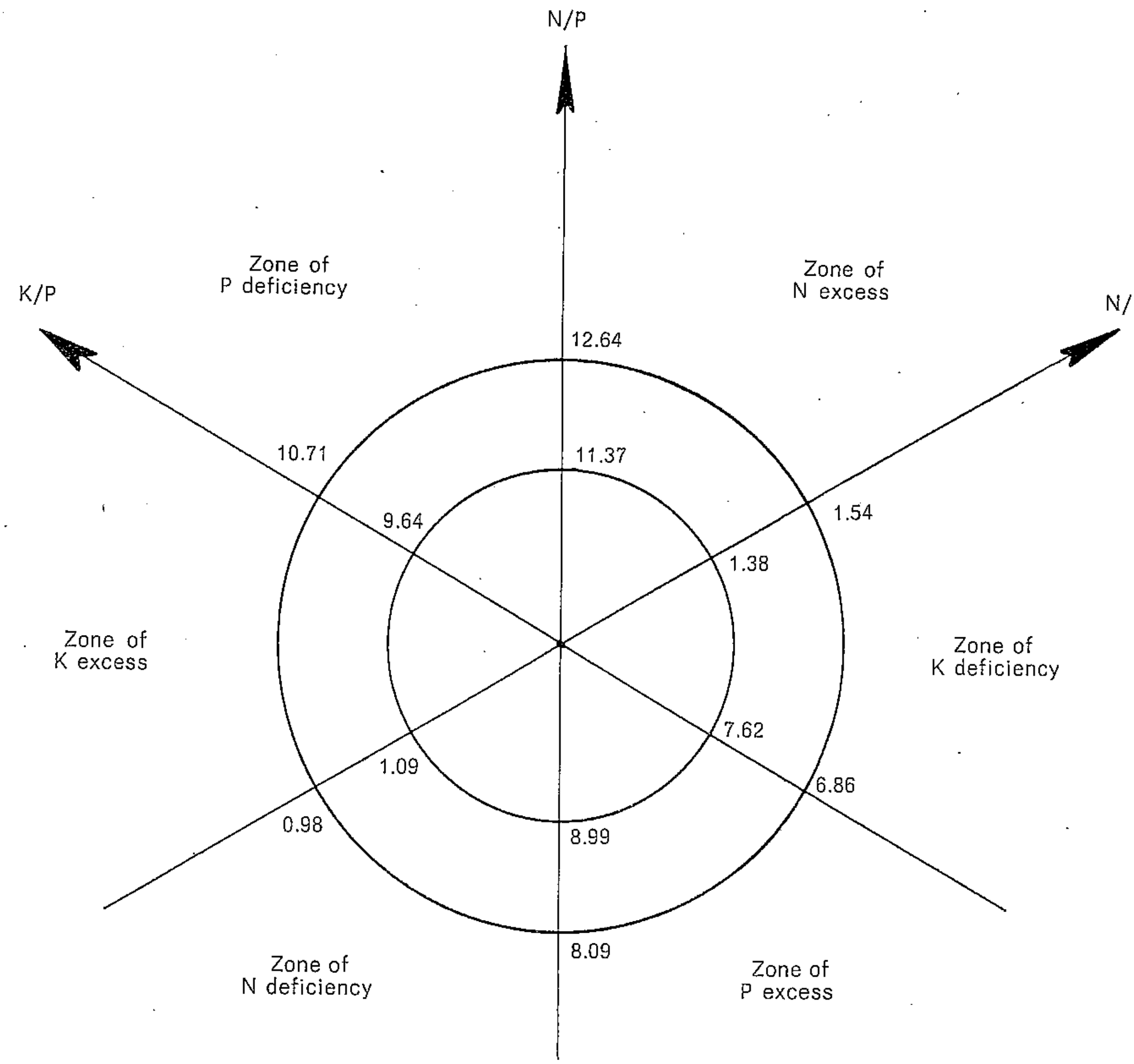

Fig 1 Physiological Diagnosis chart for direct determination of the N, P and K status in maize

Within the inner circle on the chart all three elements are considered to be in good balance (→). The zone between the inner and outer circles is a tendency zone, ie ratios tend towards imbalance. This situation is indicated by diagonal arrows (↘ ↗). Outside the outer circle is the zone of definite imbalance (↑↓).

An excess of one element corresponds to a deficiency of another. Thus for convenience the convention will be followed of taking only deficiences into account for the establishment of the diagnosis.

The following examples illustrate how to read the chart.

Example 1

Leaf analysis shows the following percentages of NPK expressed on a dry matter basis

2.28% N, 0.209% P and 2.91% K.

The mineral ratios calculated from these figures are

N/K = 0.784
N/P = 10.91
K/P = 13.93

which can now be interpreted in terms of the chart in Figure 1.

The N/K ratio of 0.784 on the N/K line lies outside the outer circle (0.98) which indicates a zone of N deficiency. This situation is expressed as N/K ↓.

The N/P ratio of 10.91 on the N/P line falls within the inner circle and is thus considered to be a balanced ratio. It is expressed as N/P→.

The K/P ratio of 13.93 on the K/P line indicates a P deficiency which is expressed as K/P ↑.

Considering only deficiencies the nutrient situation is expressed as follows

N/K ↓ = N ↓
K/P ↑ = P ↓

The relative NPK nutrient balance may therefore be written as

N ↓ P ↓ K→

Note that $\frac{N\downarrow}{P\downarrow} = \rightarrow$ which corresponds to N/P→. A balanced ratio only means that its terms are both situated in a similar position, (normal, déficient or excess).
Note also that the diagnosis

N ↓ P ↓ K→

is relatively the same as

N ↓↓ P ↓↓ K ↓ or
N ↓↓↓ P ↓↓↓ K ↓↓, the constant feature being that in all cases N and P are more serious limiting factors than K.

Similarly the diagnosis N→P→K→ could also be N ↓ P ↓ K ↓.

Additional information is required in order to decide which of the alternatives is applicable in a particular case.

Example 2

A maize leaf analysis of 1.29% N, 0.29% P and 1.69% K gives ratios of

N/K = 0.76
N/P = 4.45
K/P = 5.83

which interpreted from Figure 1 means that

N/K ↓ (0.76 < 0.98)
N/P ↓ (4.45 < 8.09)
K/P ↓ (5.83 < 6.86)

Thus the relative nutrient deficiencies are

If N/K ↓ then N ↓
If N/P ↓ then N ↓
If K/P ↓ then K ↓

N is deficient in two ratios while K is deficient in only one. The relative nutrient balance is written as

N ↓↓ P→ K ↓

It is important to know that nitrogen shows a relatively more intense deficiency than K. However before a fertilizer recommendation can be made, a knowledge of many other characteristics of the site is essential eg previous yields, cultivar, soil analysis and classification, history of fertilizer use, cultural practices for previous years, rainfall, temperature and status of other nutrients.

All such factors must be systematically recorded for each site and used whenever a recommendation is made. It is sometimes possible for sampling, analysis, recommendation and corrective action to be done in one growing season.

Example 3

A maize leaf analysis of 3.84% N, 0.49% P and 0.60% K gives ratios of

N/K = 6.40 ↑↑ (>2 x 1.54)
N/P = 7.84 ↓ (< 8.09)
K/P = 1.22 ↓↓ (< ½ x 6.86)
If N/K ↑↑ then K ↓↓
If N/P ↓ then N ↓
If K/P ↓↓ then K ↓↓
Therefore N ↓ P→ K ↓↓↓↓

Thus K is relatively much more deficient than N, which is still more deficient than P. The important point is to establish the order of limiting importance between the factors.

Relative distribution between non-abnormal and abnormal plants

Table 1 gives the reference data in tabular form.

TABLE 1 Basis for physiological diagnosis. Established norms for the interpretation of the nutrient balance in maize leaves (Proposed reference data)

Symbol	Interpretation class	Mineral ratio X/Y		
		N/K	N/P	K/P
↓↓	Severe deficiency	< 0.49	< 4.05	< 3.43
↓	Deficiency	0.49 — 0.97	4.05 — 8.08	3.43 — 6.85
↘	Tendency (deficiency)	0.98 — 1.08	8.09 — 8.98	6.86 — 7.61
→	Balanced (normal)	1.09 — 1.38	8.99 — 11.37	7.62 — 9.64
↗	Tendency (excess)	1.39 — 1.54	11.38 — 12.64	9.65 — 10.71
↑	Excess	1.55 — 3.08	12.65 — 25.28	10.72 — 21.42
↑↑	Severe excess	> 3.08	> 25.28	> 21.42
	Means for normal plants	1.23	10.11	8.57

Figure 2 shows typical distributions for the mineral ratio X/Y, for populations of abnormal and non-abnormal plants. The PD chart and its reference data are based on the distribution range represented by area A of the curve for non-abnormal plants. In this particular study the X/Y on the abcissa of Figure 2 can be either N/P, N/K or K/P.

The limits represented in Figure 2 are the same as those of Figure 1. Similar limits had first been pragmatically established for rubber trees (Beaufils, 1956) and their validity mathematically confirmed by Déjardin (1971).

In Figure 2, Ep refers to the 'probable range' of the non-abnormal population.

Probable range = Ep = $2/3\sigma$ (σ = standard deviation).

Range, m$\pm$ Ep = $4/3\sigma$ = 50 per cent of the total population

Range, m$\pm$ 2Ep = $8/3\sigma$ = 82 per cent of the total population.

The two narrowly-shaded areas each constitute nine per cent of the non-abnormal population, which might erroneously be interpreted to belong to the abnormal population. If the ordinates demarcating these two areas were moved further away from the mean m, the possibility of drawing an erroneous conclusion would be reduced. This apparent gain in precision would, however, be offset by the much greater resultant loss due to the increased possibility of regarding a specimen from the abnormal population (increased area A') as belonging to the non-abnormal population. See Figure 2 broadly-shaded areas B and C. At the nine per cent ordinates these gains and losses are in equilibrium.

Errors made by regarding non-abnormal specimens as abnormal are not serious since the nine per cent ordinates are far away from m and therefore such specimens are already marginal cases.

The seriousness of the possible errors is reduced by the fact that for each of the elements, N, P and K, there is a double reference; eg for N there is N/P and N/K, and even if N/P falls in the shaded area, N/K might not. If it does, the marginal status is confirmed.

The interpretation of the N, P and K status, based on a double reference, is somewhat quantified by calculating indices, thereby further minimising the possibility of erroneous interpretation. The indicated limits are not used in calculating indices. (See page 15).

The demarcation at nine per cent and 91 per cent of the non-abnormal population has been used for the N/P, N/K and K/P ratios and has been found to be effective in practice as a demarcation between imbalanced ratios (excess when > 91, deficiency when < 9) and balanced ratios.

At this stage the author proposes the hypothesis that the relative distribution between the two populations as shown in Figure 2, will most likely be found for any other crop.

Area A: distribution range for all plants growing under non-abnormal conditions. (Situation of X is identical to situation of Y; both normal)

Area A': same distribution range as for A, but plants growing under abnormal conditions. (Situation of X identical to situation of Y; both normal or both abnormal).

Areas B and C: distribution ranges for abnormal plants but distinct from A and for plants growing poorly and/or yielding low: Area B is the range where X < Y and area C the range where X > Y.

Influence of sampling conditions and other factors on the established norms for nutrient ratios

Table 2 summarises the mean data for NPK analyses, N/K, N/P, K/P ratios and dry matter, as well as weather and crop data recorded at the time of sampling normal plants. The term 'blank diagnosis' is analogous to a laboratory instrumental technique. The 'normal plants' should by definition and by application of the standard chart show no deficiency (or excess) whatever the non-unfavourable conditions might be.

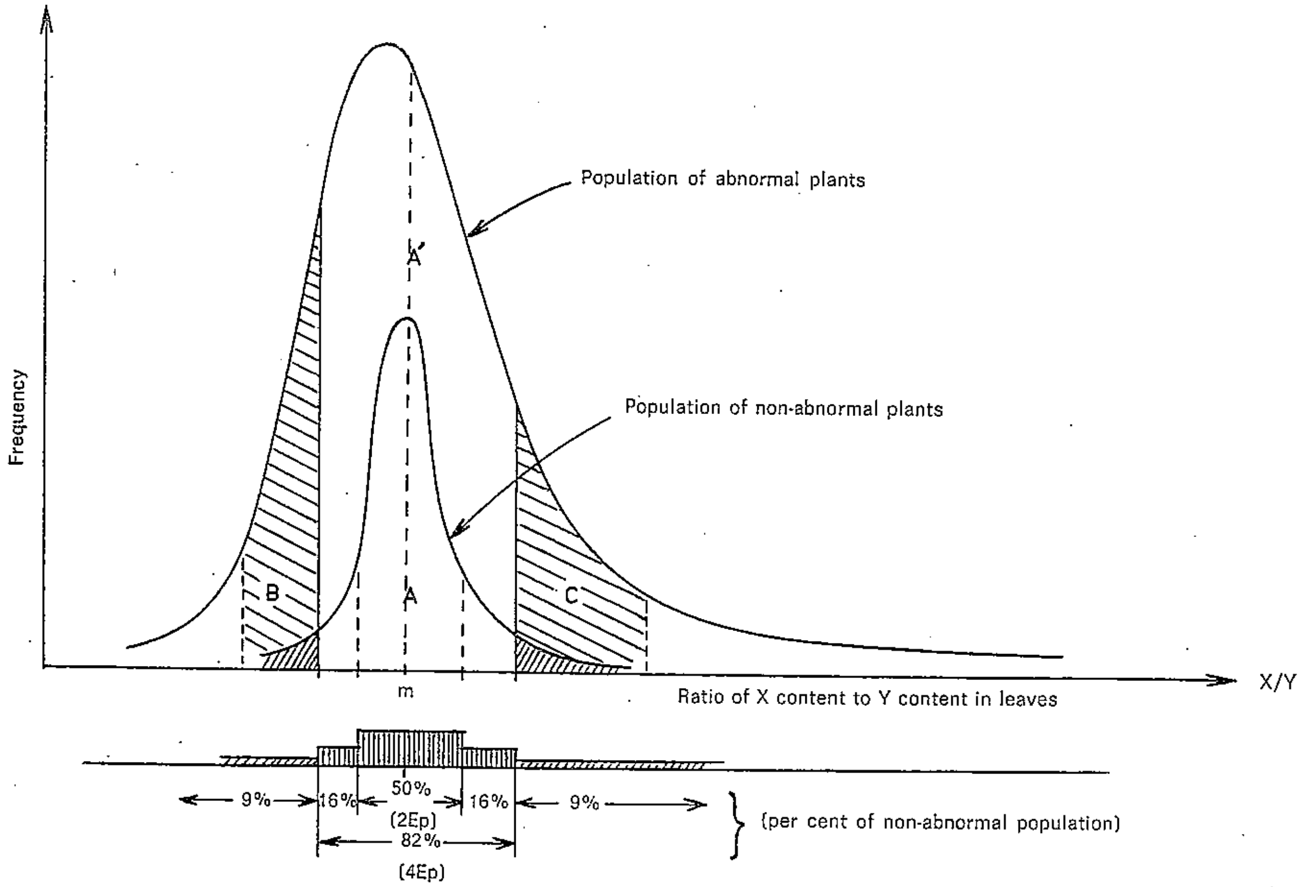

Fig 2 Relative distribution of mineral ratios in plant leaves (hypothetical example) Area A' includes area A. Areas B and C include both shaded areas on their respective sides

A study of Table 2 shows that although the elements N, P and K expressed on a dry matter basis vary widely under the influence of outside factors, the ratios between these three elements, and hence the resulting diagnosis, are always consistent. In other words the diagnosis is not influenced by time of sampling, weather conditions and cultivation practices as long as they are not unfavourable.

Table 3 gives a statistical evaluation of the influence of factors with regard to the way N, P and K are expressed.

TABLE 2 Application of the chart to healthy, good yielding plants ('blank diagnosis')

Designation of the factors	Specific influence	Number of samples	Leaf analysis on dry matter basis			Application of PD chart						Dry matter as percentage of fresh matter
			%N	%P	%K	N/K	N/P	K/P	N/K	N/P	K/P	
Position of the sample on the plant	upper level	258	2.87	0.29	2.41	1.23	9.93	8.35	→	→	→	24.6
	lower level	126	2.73	0.27	2.30	1.22	10.45	9.02	→	→	→	24.7
Months when sampled	November	7	3.45	0.31	2.77	1.32	11.32	9.16	→	→	→	19.1
	December	85	3.27	0.33	2.91	1.14	10.09	9.02	→	→	→	20.8
	January	201	2.74	0.28	2.38	1.18	10.01	8.75	→	→	→	24.7
	February	48	2.67	0.28	1.92	1.42	9.85	7.35	↗	→	↘	26.6
	March	48	2.47	0.24	1.82	1.39	10.62	8.21	↗	→	→	29.7
Time of sampling (hours)	Before 9 am	21	2.92	0.27	2.37	1.23	10.73	8.84	→	→	→	26.1
	9—10	48	2.90	0.31	2.41	1.24	9.67	8.25	→	→	→	22.9
	10—11	42	2.69	0.26	2.31	1.20	10.70	9.36	→	→	→	25.7
	11—12	53	2.75	0.28	2.51	1.13	10.15	9.27	→	→	→	23.8
	12—13	47	2.87	0.28	2.54	1.17	10.41	9.24	→	→	→	24.9
	13—14	29	2.82	0.29	2.48	1.15	9.71	8.61	→	→	→	23.2
	14—15	60	2.85	0.30	2.35	1.26	9.74	8.07	→	→	→	24.4
	15—16	44	2.80	0.28	2.19	1.33	9.90	7.75	→	→	→	25.1
	After 4 pm	43	2.90	0.29	2.22	1.35	10.25	7.95	→	→	→	26.1
Cloud density assessed from 0 to 4 0: no clouds 4: overcast	0	40	3.09	0.32	2.57	1.22	9.84	8.13	→	→	→	24.1
	1	21	2.78	0.26	2.20	1.29	10.77	8.88	→	→	→	28.4
	2	117	2.80	0.27	2.37	1.23	10.45	8.89	→	→	→	25.4
	3	55	2.81	0.28	2.38	1.22	10.12	8.59	→	→	→	23.9
	4	155	2.79	0.29	2.36	1.23	9.83	8.41	→	→	→	23.8
Wind intensity assessed from 0 to 4 0: no wind	0	118	2.81	0.29	2.43	1.19	9.78	8.45	→	→	→	24.3
	1	63	2.99	0.30	2.24	1.37	10.22	7.71	→	→	→	25.7
	2	184	2.79	0.28	2.36	1.23	10.18	8.69	→	→	→	24.6
	3	14	2.59	0.23	2.53	1.05	11.25	10.99	↘	→	↗	25.0
	4	10	2.94	0.29	2.82	1.07	10.32	9.84	↘	→	↗	18.8
Temperatures at sampling time (°C)	Up to 21°C	28	2.88	0.29	2.28	1.32	10.09	8.12	→	→	→	22.1
	22-24	55	2.70	0.27	2.35	1.21	10.04	8.75	→	→	→	24.8
	25-27	108	2.76	0.28	2.33	1.23	10.08	8.66	→	→	→	24.1
	28-30	97	2.84	0.28	2.39	1.22	10.47	8.93	→	→	→	24.6
	31-33	66	3.06	0.32	2.49	1.26	9.72	7.83	→	→	→	24.7
	Above 33	33	2.73	0.28	2.38	1.18	10.02	8.78	→	→	→	26.8

Table 2 (continued)

Designation of the factors	Specific influence	Number of samples	Leaf analysis on dry matter basis			Application of PD chart						Dry matter as percentage of fresh matter
			%N	%P	%K	N/K	N/P	K/P	N/K	N/P	K/P	
Number of days between sampling and the killing of the samples	0	12	2.51	0.26	2.24	1.12	9.71	8.69	→	→	→	NA
	1	75	2.64	0.27	2.31	1.16	9.99	8.88	→	→	→	NA
	2	42	2.80	0.28	2.21	1.29	10.42	8.25	→	→	→	NA
	3	42	2.73	0.28	2.20	1.27	10.40	8.72	→	→	→	NA
	4	26	2.76	0.28	2.06	1.39	10.31	7.93	↗	→	→	NA
	5	46	2.97	0.29	2.53	1.21	10.38	8.86	→	→	→	NA
	6	41	3.17	0.32	2.72	1.22	10.15	8.72	→	→	→	NA
	7	39	2.91	0.30	2.45	1.26	10.09	8.53	→	→	→	NA
	8	11	2.87	0.33	2.54	1.21	8.90	7.73	→	↘	→	NA
	9	12	3.09	0.30	2.81	1.15	10.71	9.76	→	→	↗	NA
	10-15	31	2.72	0.30	2.30	1.21	9.19	7.76	→	→	→	NA
	Over 15	3	3.04	0.29	2.30	1.34	10.65	8.15	→	→	→	NA
Hybrids	NPPK64R	33	2.75	0.25	2.25	1.28	11.07	9.00	→	→	→	25.8
	PPPK64R	20	3.12	0.30	2.59	1.24	10.80	8.97	→	→	→	22.9
	PPK64R	31	2.70	0.24	2.29	1.21	11.29	9.70	→	→	↗	26.5
	SA100	22	2.71	0.27	2.67	1.07	10.06	10.17	↘	→	↗	22.4
	SA9N	15	3.16	0.28	2.28	1.45	11.15	8.02	↗	→	→	23.9
	SR52	33	2.86	0.33	2.25	1.32	8.86	7.00	→	↘	↘	25.2
	SA4	77	2.79	0.27	2.49	1.15	10.49	9.45	→	→	→	25.6
Plant populations (per morgen)	Up to 15 000	88	2.86	0.29	2.32	1.28	10.29	8.37	→	→	→	24.5
	16-20 000	68	2.93	0.30	2.46	1.24	9.86	8.24	→	→	→	24.7
	21-25 000	58	2.72	0.29	2.35	1.23	9.60	8.55	→	→	→	24.4
	26-30 000	89	2.88	0.27	2.36	1.25	10.91	9.12	→	→	→	24.2
	31-35 000	20	2.63	0.28	2.33	1.15	9.56	8.55	→	→	→	26.5
	above 35.000	46	2.80	0.30	2.43	1.16	9.49	8.23	→	→	→	24.3

*TABLE 3 Correlation coefficients (r), and degrees of dependance (Σr^2) for NPK (n = 350 results all belonging to healthy, good-yielding plants)**

			Dry matter basis			Water basis			Fresh matter basis			Plant basis			'Suitable element basis'		
	Factors of influence (at sampling time)	Dry matter as % of fresh matter	%N	%P	%K	%N	%P	%K	%N	%P	%K	N	P	K	N/K	N/P	K/P
r	Age (in days)	0.622	–0.639	–0.495	–0.742	0.215	0.169	0.001	0.086	0.047	–0.185	0.411	0.306	0.365	0.256	0.046	–0.117
	Hour of sampling	0.057	0.025	0.069	–0.092	–0.056	–0.057	–0.059	0.087	0.124	–0.054	–0.042	–0.049	–0.065	0.154	–0.062	–0.164
	Wind force	0.052	–0.050	–0.129	0.011	0.049	0.051	0.050	–0.097	–0.161	–0.082	0.028	–0.038	0.061	–0.012	0.133	0.148
	Cloud density	–0.126	–0.109	–0.012	–0.052	0.122	0.125	0.123	–0.195	–0.108	–0.167	0.160	0.172	0.214	–0.015	–0.069	–0.010
	Temperature	0.091	0.086	0.096	0.080	–0.088	–0.091	–0.087	0.163	0.171	0.203	–0.262	–0.194	–0.293	–0.044	–0.062	–0.044
	Plant population	–0.010	–0.091	–0.058	–0.034	0.008	0.010	0.010	–0.070	–0.066	–0.005	–0.284	–0.240	–0.289	–0.106	–0.061	–0.001
Σr^2	Estimate of the degree of dependence on these factors—(Σr^2)	0.417	0.439	0.279	0.569	0.074	0.058	0.029	0.094	0.089	0.113	0.346	0.165	0.356	0.103	0.036	0.065
	Number of days between sampling and killing		0.095	0.114	0.073										0.012	–0.066	–0.057
	Estimate of the degree of dependence on these factors —(Σr^2)		0.448	0.292	0.574										0.103	0.040	0.068

*Called 'normal' plants by convention

A study of Table 3 shows

(i) The age of the tissue (expressed in number of days between date of planting and date of sampling) is a factor of considerable importance. The dry matter content as well as N, P and K expressed as a percentage of dry matter are all highly significantly influenced by the age of the tissue whereas the ratios N/P, N/K and K/P are considerably less influenced by this factor. This is actually to be expected since

$$\frac{\%\ N\ \text{(dry basis)}}{\%\ P\ \text{(dry basis)}} = \frac{N}{P}$$

By calculating ratios on a 'suitable element' basis, dry matter — as a direct function of age — is therefore eliminated.

(ii) An estimate of the degree of dependence on the whole of the studied factors (sum of the r^2) shows a strong resulting influence on N, P and K expressed as a percentage of the dry matter, as well as expressed on a plant basis (total). This dependence is considerably minimised for the same elements if expressed on either a water, fresh matter or 'suitable element' basis. Preference has been given to a suitable element basis for using routine PD techniques because (a) the study of the relative distributions as explained from Figure 2 enables this choice and (b) moisture determinations are not necessary. It should be noted that the resulting degree of dependance on all non-unfavourable factors is represented by the range situated within the outer circle of Figure 1. This explains why general validity for the norms can be expected.

Practical application of the PD chart to field experiments

The proposed standard chart for maize (Figure 1) was applied to maize experiments conducted under a variety of conditions in various parts of the world. As examples of this application, the results of work undertaken by Thomas & Mack (1939) in Pennsylvania; Hanway & Dumenil (1966) in Iowa; Viets, Nelson & Crawford (1954) in Washington; Loué (1962) in France; Scott (1970) in Maseru (Lesotho) and Hyam, Clayton & Jarret (1967) in South Africa, together with the physiological diagnosis are given in Tables 4 to 15.

Example 1 Thomas & Mack (1939) *(See Table 4)*

TABLE 4 Application of PD chart to data of Thomas & Mack (1939) (*Table 3 of Thomas & Mack: Percentages of N, P_2O_5 and K_2O in the dried foliage for plants grown under different fertilizer treatments in tier 1.*)

From the literature									Application of the chart								
Treatments	Dates	Leaf composition					Yields		N/K	N/P	K/P	N/K	N/P	K/P	N	P	K
		%N	%P_2O_5	%K_2O	%P	%K	lb Grain per plot.	Bags per morgen (calculated)									
Control	July 6	2.960	0.307	2.387	0.135	1.981	165.4	14	1.49	21.93	14.67	↗	↑	↑	→	↓↓	↘
	July 21	2.210	0.305	2.515	0.134	2.087			1.06	16.49	15.57	↘	↑	↑	↘	↓↓	→
	Aug 8	1.800	0.230	1.841	0.101	1.528			1.18	17.82	15.13	→	↑	↑	→	↓↓	→
	Aug 25	2.010	0.316	1.608	0.139	1.335			1.51	14.46	9.60	↗	↑	→	→	↓	↘
	Means								1.31	17.68	13.74	→	↑	↑	→	↓↓	→
N	July 6	3.310	0.311	2.248	0.137	1.866	265.6	22	1.77	24.16	13.62	↑	↑	↑	→	↓↓	↓
	July 21	2.420	0.330	2.104	0.145	1.746			1.39	16.69	12.04	↗	↑	↑	→	↓↓	↘
	Aug 8	2.090	0.260	1.453	0.114	1.206			1.73	18.33	10.58	↑	↑	↗	→	↓↘	↓
	Aug 25	2.340	0.348	1.481	0.153	1.229			1.90	15.29	8.03	↑	↑	→	→	↓	↓
	Means								1.70	18.62	11.07	↑	↑	↑	→	↓↓	↓
P	July 6	3.210	0.656	1.019	0.289	0.846	371.2	31	3.79	11.11	2.93	↑↑	→	↓↓	→	→	↓↓↓↓
	July 21	2.260	0.841	0.756	0.370	0.627			3.60	6.11	1.69	↑↑	↓	↓↓	↓	→	↓↓↓↓
	Aug 8	2.060	0.602	0.794	0.265	0.659			3.13	7.77	2.49	↑↑	↓	↓↓	↓	→	↓↓↓↓
	Aug 25	2.100	0.678	0.911	0.298	0.756			2.78	7.05	2.54	↑	↓	↓↓	↓	→	↓↓↓
	Means								3.33	8.01	2.41	↑↑	↘	↓↓	↘	→	↓↓↓↓
K	July 6	2.980	0.301	3.984	0.132	3.307	298.4	25	0.90	22.58	25.05	↓	↑	↑↑	↓	↓↓↓	→
	July 21	2.280	0.263	4.000	0.116	3.320			0.69	19.66	28.62	↓	↑	↑↑	↓	↓↓↓	→
	Aug 8	2.320	0.270	3.901	0.119	3.238			0.72	19.50	27.21	↓	↑	↑↑	↓	↓↓↓	→
	Aug 25	2.020	0.392	2.480	0.172	2.058			0.98	11.74	11.97	↘	↗	↑	↘	↓↘	→
	Means								0.82	18.37	23.21	↓	↑	↑↑	↓	↓↓↓	→
NP	July 6	3.210	0.928	0.724	0.408	0.601	376.7	32	5.34	7.87	1.47	↑↑	↓	↓↓	↓	→	↓↓↓↓
	July 21	2.410	0.692	0.813	0.304	0.675			3.57	7.93	2.22	↑↑	↓	↓↓	↓	→	↓↓↓↓
	Aug 8	2.360	0.690	0.813	0.304	0.675			3.50	7.76	2.22	↑↑	↓	↓↓	↓	→	↓↓↓↓
	Aug 25	2.370	0.768	0.775	0.338	0.643			3.69	7.01	1.90	↑↑	↓	↓↓	↓	→	↓↓↓↓
	Means								4.03	7.64	1.95	↑↑	↓	↓↓	↓	→	↓↓↓↓
NK	July 6	3.040	0.336	4.031	0.148	3.346	263.5	22	0.91	20.54	22.61	↓	↑	↑↑	↓	↓↓↓	→
	July 21	2.390	0.280	4.209	0.123	3.493			0.68	19.43	28.40	↓	↑	↑↑	↓	↓↓↓	→
	Aug 8	2.000	0.262	3.081	0.115	2.557			0.78	17.39	22.23	↓	↑	↑↑	↓	↓↓↓	→
	Aug 25	2.380	0.376	2.763	0.165	2.293			1.04	14.42	13.90	↘	↑	↑	↘	↓↓	→
	Means								0.85	17.95	21.79	↓	↑	↑↑	↓	↓↓↓	→
PK	July 6	3.040	0.440	3.565	0.194	2.959	497.4	42	1.03	15.67	15.25	↘	↑	↑	↘	↓↓	→
	July 21	2.280	0.476	3.508	0.209	2.912			0.78	10.91	13.93	↓	→	↑	↓	↓	→
	Aug 8	1.960	0.420	2.887	0.185	2.396			0.82	10.59	12.95	↓	→	↑	↓	↓	→
	Aug 25	2.080	0.534	2.665	0.235	2.212			0.94	8.85	9.41	↓	↘	→	↓↘	→	→
	Means								0.89	11.51	12.89	↓	↗	↑	↓	↓↘	→
NPK	July 6	3.030	0.438	3.674	0.193	3.049	520.2	44	0.99	15.70	15.80	↘	↑	↑	↘	↓↓	→
	July 21	2.460	0.454	3.766	0.200	3.126			0.79	12.30	15.63	↓	↗	↑	↓	↓↘	→
	Aug 8	2.620	0.564	2.992	0.248	2.483			1.06	10.56	10.01	↘	→	↗	↘	↘	→
	Aug 25	2.540	0.626	2.879	0.275	2.390			1.06	9.24	8.69	↘	→	→	↘	→	→
	Means								0.98	11.95	12.53	↘	↗	↑	↘	↓↘	→

Leaf analysis of plants taken from the control plots and the subsequent physiological diagnosis indicates a relative phosphorus deficiency (P ↓↓. See Table 4). The correctness of this diagnosis is confirmed by the fact that the top yields in the experiment were all obtained from treatments which contained phosphorus viz P, NP, PK and NPK.

Some further observations are

* The application of N caused K to become relatively deficient (K ↓).
* The phosphorus treatment, while satisfying a P deficiency (P→; created a strong K imbalance (K ↓↓↓↓); and tended to create an N deficiency (N↘).
* The K treatment aggravated the P deficiency still further (P ↓↓↓); and caused a relative N deficiency (N↓);
* The NP, NK and PK treatments all resulted in relative imbalances while even the NPK treatment still showed relative tendencies of N and P deficiencies. This could indicate that the original diagnosis of the control plot is more likely N ↓ P↓↓↓ K ↓ than N→ P ↓↓ K→.
* A study of the diagnosis columns for N, P and K shows that the general picture is the same for all times of leaf analysis, although the concentrations of N, P and K might vary.
* In the P and NP treatments the correction of the P deficiency is apparent in the first sampling (July 6). Where however potassium is applied together with P (PK and NPK), the correction of P deficiency is delayed until the fourth sampling on August 25. The nutritional 'film' of plot

NPK shows particularly well the progression in the correction of the P deficiency: July 6 ↓↓, July 21 ↓↘, August 8 ↘, August 25→.

Example 2 Hanway & Dumenil (1966) *(See Table 5)*

It should be noted that in Table 5, two hypotheses are presented. Supplementary information is necessary to clear up the doubt.

The yields obtained from the experiment confirm the second hypothesis of diagnosis viz that there was a simultaneous deficiency of N. P and K.

The different treatments influenced the NPK balance towards a logical direction.

Thus

* N application corrected N deficiency and caused a reduction of P deficiency.
* P application corrected P deficiency and caused a reduction of N deficiency.
* K application corrected K and P deficiencies and reduced the N deficiency.
* NP application corrected both N and P deficiencies.
* NK application corrected only N deficiency.
* PK application corrected both P and K deficiencies and increased the N deficiency.
* NPK application corrected both N and P deficiencies.

A diagnosis of the NPK plot shows that an even higher yield might have been obtained had the application still been $N_1P_1K_1$ but that K_1 was more than 60 lb K_2O per acre.

TABLE 5 Application of PD chart to data of Hanway & Dumenil (1966) (Table 1 of Hanway & Dumenil: Effects of applied N, P_2O_5 and K_2O on leaf composition and yields)

From the literature					Application of the chart									Yields bags/morg calculated from bu/acre	Remarks
Fertilizer treatment*	Leaf analysis			Yields bushels per acre											
	%N	%P	%K		N/K	N/P	K/P	N/K	N/P	K/P	N	P	K		
None	1.9	0.20	1.6	46	1.19	9.50	8.00	→	→	→	**→**	→	→	27	First** hypothesis
None	1.9	0.20	1.6	46	1.19	9.50	8.00	→	→	→	**↓**	↓	↓	27	second hypothesis
N	2.6	0.22	1.5	65	1.73	11.82	6.82	↑	↗	↓	→	↘	↓↓	39	
P	1.8	0.22	1.5	47	1.20	8.18	6.82	→	↘	↓	↘	→	↓	28	
NP	2.6	0.28	1.3	76	2.00	9.29	4.64	↑	→	↓	→	→	↓↓	45	
K	1.9	0.20	1.8	47	1.06	9.50	9.00	↘	→	→	↘	→	→	28	
NK	2.6	0.22	1.8	65	1.44	11.82	8.18	↗	↗	→	→	↘	↘	39	
PK	1.6	0.20	1.9	38	0.84	8.00	9.50	↓	↓	→	↓↓	→	→	23	
NPK	2.5	0.27	1.6	88	1.56	9.26	5.93	↑	→	↓	→	→	↓↓	52	

*Amounts per acre were 60 pounds each of N, P_2O_5 and K_2O broadcast and ploughed under

**As mentioned previously, further information is necessary to clear up the doubt before hand

TABLE 6 Application of PD chart to data of Viets, Nelson & Crawford (1954) (Table 1 of Viets, Nelson & Crawford: Effect of three fertilizer elements on average grain yields, N content of grain and composition of second leaf below upper ear shoot sampled at silking)

From the literature							Application of the chart									Yields bags/morg calculated from bu/acre
Treatment			Leaf composition			Yields										
N lb/a	P_2O_5 lb/a	K_2O lb/a	%N	%P	%K	bushels per acre	N/K	N/P	K/P	N/K	N/P	K/P	N	P	K	
0	0	0	2.21	0.196	2.40	125.8	0.92	11.28	12.24	↓	→	↑	↓	↓	→	75
40	0	0	2.52	0.229	2.33	140.2	1.08	11.00	10.17	↘	→	↗	↘	↘	→	83
80	0	0	2.64	0.233	2.41	166.8	1.10	11.33	10.34	→	→	↗	→	↘	→	99
120	0	0	2.75	0.251	2.33	164.3	1.18	10.96	9.28	→	→	→	→	→	→	97
160	0	0	2.87	0.257	2.43	168.5	1.18	11.17	9.46	→	→	→	→	→	→	100
200	0	0	2.89	0.245	2.41	161.8	1.20	11.80	9.84	→	↗	↗	→	↘	→	96
120	60	0	2.79	0.274	2.36	161.1	1.18	10.18	8.61	→	→	→	→	→	→	95
120	60	80	2.80	0.282	2.40	172.1	1.17	9.93	8.51	→	→	→	→	→	→	102

Example 3 Viets, Nelson & Crawford (1954) *(See Tables 6, 7 and 8)*

Physiological diagnosis shows that although the yield on the control plot is high, deficiencies of both N and P are evident.

Applications of 40 and 80 lb N per acre increased the yield and at the same time eliminated the N deficiency. The nitrogen from an application of 40 lb N also increased the P uptake as indicated by the change from P ↓ to P ↘.

A total correction of N deficiency resulted in a still higher yield from an application of 80 lb N, the P situation remaining at tendency.

Higher application of N alone did not effect the yields to any extent. These reached a plateau at around 100 bags per morgen where no strong imbalances remained.

A synergistic effect of N applications to P uptake is evident. This confirms a known phenomenon.

Further data from Viets, Nelson & Crawford (1954) are analysed in Tables 7 and 8.

A simultaneous N and P deficiency is apparent in the control treatment with a predominance for N deficiency.

This diagnosis is confirmed by the strong and progressive increase of yields for increasing applications of N in the form of ammonium sulphate or ammonium nitrate. The increase was also progressive but slightly weaker for the application of N as calcium nitrate.

In no case however was the imbalance corrected by the application of N. It is suggested that the application of N at the rate of 160 lb was still below the optimum amount. A supplementary application of P would probably have helped to obtain higher yields.

Physiological diagnosis shows a simultaneous N and P deficiency for the control treatment. (Table 8).

The application of 160 lb N and 60 lb P_2O_5 confirmed this diagnosis as it resulted in a large increase in yield.

The deficiencies of N and P were completely corrected by the application of 160 lb. N and 60 lb P_2O_5. A further increase of fertilizer up to 240 lb N and 120 lb P_2O_5 had no effect on the yields. Diagnosis shows that this further increase of fertilizer was not necessary.

TABLE 7 Application of PD chart to data of Viets, Nelson & Crawford (1954) (*Table* 2 *of Viets, Nelson & Crawford*: *Average grain yields, number of leaves showing N deficiency and mineral content of corn leaves as affected by N carriers applied at three rates*)

From the literature						Application of the chart									
Carrier	N applied lb/acre	Leaf composition %N	Leaf composition %P	Leaf composition %K	Yields bushels per acre	N/K	N/P	K/P	N/K	N/P	K/P	N	P	K	Yields bags/morg calculated from bu/acre
None	0	1.01	0.124	2.01	76.2	0.50	8.15	16.21	↓	↘	↑	↓↘	↓	→	45
$(NH_4)_2SO_4$	40	1.19	0.143	2.79	111.1	0.43	8.32	19.51	↓↓	↘	↑	↓↓↘	↓	→	66
	80	1.85	0.197	2.67	143.8	0.69	9.39	13.55	↓	→	↑	↓	↓	→	85
	160	2.13	0.261	2.71	159.8	0.79	8.16	10.38	↓	↘	↗	↓↘	↘	→	95
NH_4NO_3	40	1.31	0.145	2.45	107.1	0.53	9.03	16.90	↓	→	↑	↓	↓	→	63
	80	1.62	0.163	2.53	132.8	0.64	9.94	15.52	↓	→	↑	↓	↓	→	79
	160	1.94	0.242	2.42	155.5	0.80	8.02	10.00	↓	↓	↗	↓↓	↘	→	92
$Ca(NO_3)_2$	40	1.15	0.126	2.24	101.6	0.51	9.13	17.78	↓	→	↑	↓	↓	→	60
	80	1.31	0.136	2.13	112.4	0.62	9.63	15.66	↓	→	↑	↓	↓	→	67
	160	1.87	0.187	2.41	138.5	0.78	10.00	12.89	↓	→	↑	↓	↓	→	82

TABLE 8 *Application of PD chart to data of Viets, Nelson & Crawford* (1954) (*Table 5 of Viets, Nelson & Crawford: Mean yields and leaf composition from a crop rotation experiment fertilized with NH_4NO_3 and superphosphate*)

From the literature						Application of the chart									
Treatment N lb/a	Treatment P_2O_5 lb/a	Leaf composition %N	Leaf composition %P	Leaf composition %K	Yields bushels per acre	N/K	N/P	K/P	N/K	N/P	K/P	N	P	K	Yields bags/morgen calculated from bu/acre
0	0	1.74	0.171	2.05	72.1	0.85	10.18	11.99	↓	→	↑	↓	↓	→	43
80	0	1.98	0.180	1.91	83.3	1.04	11.00	10.61	↘	→	↗	↘	↘	→	49
80	60	1.93	0.184	1.90	96.2	1.02	10.49	10.33	↘	→	↗	↘	↘	→	57
160	60	2.19	0.209	2.01	112.8	1.09	10.48	9.62	→	→	→	→	→	→	67
160	120	2.22	0.223	1.99	113.1	1.12	9.96	8.92	→	→	→	→	→	→	67
240	120	2.41	0.234	1.98	112.9	1.22	10.30	8.46	→	→	→	→	→	→	67

TABLE 9 Application of PD chart to data of Loué (1962) (*Tables of Loué: Experiments carried out in France* 1954-1961)

From the literature							Application of the chart									Yields bags/morg calculated from Q/ha
Years and sites	Treatments		Foliar chemical analysis			Yields										
		Designation	%N	%P	%K	Quintaux per hectare	N/K	N/P	K/P	N/K	N/P	K/P	N	P	K	
1954 (Pau)	K0	A	3.84	0.49	0.60	23.6	6.40	7.84	1.22	↑↑	↓	↓↓	↓	→	↓↓↓↓	22
	K1	B	4.00	0.34	1.81	65.2	2.21	11.76	5.32	↑	↗	↓	↗	→	↓↓	62
	K2	C	3.99	0.33	2.29	70.8	1.74	12.09	6.94	↑	→	↘	→	→	↓↘	67
1955 No compost (Pau)	K0	D	3.44	0.39	0.96	43.8	3.58	8.82	2.46	↑↑	↘	↓↓	↘	→	↓↓↓↓	41
	K1	E	3.58	0.39	1.56	62.3	2.29	9.18	4.00	↑	→	↓	→	→	↓↓	59
	K2	F	3.56	0.39	1.94	65.1	1.84	9.13	4.97	↑	→	↓	→	→	↓↓	61
1955 With compost (Pau)	K0	G	3.56	0.39	1.41	62.2	2.52	9.13	3.62	↑	→	↓	→	→	↓↓	59
	K1	H	3.40	0.38	1.85	67.0	1.84	8.95	4.87	↑	↘	↓	↘	→	↓↓	63
	K2	I	3.51	0.41	1.93	70.8	1.82	8.56	4.71	↑	↘	↓	↘	→	↓↓	67
1956 No compost in 1955 (Pau)	K0	J	3.49	0.33	0.61	18.8	5.72	10.58	1.85	↑↑	→	↓↓	→	→	↓↓↓↓	18
	K1	K	3.51	0.28	1.57	51.9	2.24	12.54	5.61	↑	↗	↓	→	↘	↓↓	49
	K2	L	3.64	0.29	2.03	58.5	1.79	12.55	7.00	↑	↗	↘	→	↘	↓↘	55
1956 With compost in 1955 (Pau)	K0	M	3.45	0.29	0.97	45.0	3.56	11.90	3.34	↑↑	↗	↓	→	↘	↓↓↓	42
	K1	N	3.45	0.28	1.79	61.3	1.93	12.32	6.39	↑	↗	↓	→	↘	↓↓	58
	K2	O	3.66	0.28	2.04	60.7	1.79	13.07	7.29	↑	↑	↘	→	↓	↓↘	57
1955 (Pau)	K0	P	3.89	0.35	1.79	78.9	2.17	11.11	5.13	↑	→	↓	→	→	↓↓	74
	K1	Q	3.89	0.35	1.99	73.5	1.95	11.11	5.69	↑	→	↓	→	→	↓↓	69
	K2	R	3.82	0.34	2.05	81.3	1.86	11.24	6.03	↑	→	↓	→	→	↓↓	77
1956 (Pau)	K0	S	4.16	0.34	1.28	68.8	3.25	12.24	3.76	↑↑	↗	↓	→	↘	↓↓↓	65
	K1	T	4.18	0.35	1.99	65.6	2.10	11.94	5.69	↑	↗	↓	→	↘	↓↓	62
	K2	U	4.19	0.35	2.35	70.1	1.78	11.97	6.71	↑	↗	↓	→	↘	↓↓	66
1957 (Lalaque)	K0	V	3.84	0.30	1.57	46.1	2.45	12.80	5.23	↑	↑	↓	→	↓	↓↓	44
	K	W	4.00	0.31	1.92	51.4	2.08	12.90	6.19	↑	↑	↓	→	↓	↓↓	49
	KMg	X	3.88	0.33	1.90	52.5	2.04	11.76	5.76	↑	↗	↓	→	↘	↓↓	50
1961 (Ste-Martha)	K0	Y	3.39	0.30	1.12	39.1	3.03	11.30	3.73	↑	→	↓	→	→	↓↓	37
	K1	Z	3.38	0.29	1.33	42.0	2.54	11.66	4.59	↑	↗	↓	→	↘	↓↓	40
	K2	Z1	3.45	0.30	1.51	43.2	2.28	11.50	5.03	↑	↗	↓	→	↘	↓↓	41

Example 4 Loué (1962) *(See Table 9)*

Diagnosis shows that in all cases, the control K_0 was effected by potassium deficiency. This confirmed the diagnosis of the researcher who based his experiments on K applications.

The responses to K applications were irregular and sometimes very spectacular such as A, B, C or J, K, L where yields were trebled. At other times almost no response was shown eg P, Q, R or S, T, U.

In the cases of big responses to K application (ABC and JKL), the very strong K deficiency observed for the controls was reduced but never completely corrected.

In the other cases where the response was low or nonexistent, the diagnosis of the K_0 K_1 and K_2 treatments was almost identical. That is to say it was not sufficiently affected by the K applications even when the K content of the foliage expressed as a percentage of dry matter showed considerable increases —up to almost twice the concentration of the control in some instances (particularly STU).

The fact that in some cases no yield response was obtained from K application does not mean that the hypothesis (or diagnosis) was wrong. It means that some other factor of factors, known or unknown were more limiting. Such factors could be soil pH, clay content, Ca and Mg contents in the soil, and amount and/or form of K applied etc.

Example 5 Scott (1970) *(See Tables 10, 11, 12 and 13)*

A factorial experiment, N x P x Plant Population, was started in 1966 in Maseru at the Experiment Station of the Lesotho Department of Agriculture, and a physiological diagnosis applied during the 1968/69 season.

Table 10 reproduces the treatments and yields obtained in the 1966/67, 1967/68 and 1968/69 seasons.

TABLE 10 *Effect of nitrogen, phosphorus and spacing on maize yields (Scott* 1970)

Season	Treatments*	Yields (bags/acre)	LSD	Comments
1966/67	NO: 200 N1 : 400 N2 : 600	47.0 48.2 46.7	NS	Prior to the start of the trial, the field had been under lucerne for four years and had received single superphosphate at a rate of 250 lb per acre
	PO: 200 P1 : 400 P2 : 600	47.5 47.9 46.5	NS	
	SO: 3 ft x 9 in S1 : 3 ft x 11in S2 : 3 ft x 15in	51.9 50.0 40.0	±5.1	
1967/68	NO: 0 N1 : 200 N2 : 400	37.0 38.3 36.0	NS	Juvenile soil on riverine alluvium
	PO: Residual P1 : of P2 : 1966/67	37.2 38.9 35.2	NS	
	SO: Identical S1 : to S2 : 1966/67	39.4 38.8 33.0	±3.6	
1968/69	NO: 0 N1 : 200 N2 : 400	18.2 19.8 21.0	NS	Bad climatic season Varieties were also not suitable
	PO: Residual P1 : Residual P2 : 200	17.6 21.2 23.0	NS	

*lb/acre: N as limestone ammonium nitrate (26.1% N)
P as single superphosphate (8.7% total P)

The results of analysis made on the control plots in January 1969 are given in Table 11.

In the light of these results, alterations were made to the experiment in the 1969/70 season. More P was applied and K was used for the first time. The 1969/70 treatments and yields are given in Table 12.

In confirmation of the diagnosis, the K applications increased the yields linearly and significantly, while the N application, which was not desirable, actually reduced yields. Although the diagnosis shows P to be relatively low compared to N it was not limiting and the diagnosis given in Table 12 viz N→ P ↓ K ↓↓ is probably more of the order N ↑ P→ K ↓.

A second leaf analysis and diagnosis was made during the 1969/70 (28.1.1970) season which showed that 160 lb/acre KCl was still insufficient (Table 13).

TABLE 11 *Application of PD chart to data of Scott* (1970) *Leaf analysis results on first sampling*

Chemical analysis of foliage (dry basis)			Application of the PD chart					
%N	%P	%K	N/K	N/P	K/P	N	P	K
2.48	0.19	1.01	2.46 ↑	13.05 ↑	5.32 ↓	→	↓	↓↓
					or	↑	→	↓

TABLE 12 *Application of PD chart to data of Scott* (1970) *Alterations to treatments after a physiological diagnosis*

Season	Treatments lb/acre	Yields (bags/acre)	Comments
1969/70	NO: 0 N1 : 200 N2 : 400	28.4 29.3 NS 26.9	Rainfall over period =6.8 inches
	PO: residual P1 : 200 P2 : 400	27.2 28.2 NS 28.3	Four irrigations by sprinklers total 13.5 inches Date of planting 30/10/1969
	KO: 0 K1: 80 KCl K2: 160 KCl	25.9 — 27.9* 29.8**	Date of harvesting 16/4/1970 Variety SA4 Spacing 3 feet x 12in

LSD: $P = 0.05 \pm 1.98$*
$P = 0.01 \pm 2.73$**

TABLE 13 *Application of PD chart to data of Scott* (1970) *Leaf analysis results on second sampling*

Foliar chemical analysis of plot $N_0P_0K_2$			Application of the chart					
%N	%P	%K	N/K	N/P	K/P	N	P	K
2.33	0.22	1.41	1.65	10.59	6.41	→	→	↓↓

Note: Cases to diagnose are usually not as easy and simple as this one

Example 6 Hyam, Clayton & Jarret (1967) *(See Tables 14, 15 and Figure 3)*

This phosphatic fertilizer experiment which had been running for eight consecutive years on maize, showed no significant difference between treatments, all yields reaching a plateau at 20-30 bags per morgen.

A physiological diagnosis applied for the first time in January 1966 disclosed a simultaneous N and P deficiency for all treatments. N deficiency was more intense than P deficiency, although no deficiency symptoms could be seen.

The addition of 126 lb N as urea was given to all plots at the start of the 1966/67 season. This was correlated with an increase in yield for all P treatments and for the first time since the beginning of the experiment in 1958, differences were highly significant. This increase in yield was confirmed the following season (1967/68).

TABLE 14 Application of PD chart to data of Hyam, Clayton & Jarret (1967) First sampling (Long-term effects of the application of different phosphatic fertilizers on maize)

	From the literature					Application of the chart								
Date of sampling	Treatments*	Leaf composition			Yields for 1965/66 season Bags per morgen	N/K	N/P	K/P	N/K	N/P	K/P	N	P	K
		%N	%P	%K										
20.1.1966	1 Monoammonium phosphate	2.21	0.26	3.03	14.8	0.73	8.50	11.65	↓	↘	↑	↓↘	↓	→
	2 Diammonium phosphate	2.20	0.26	2.54	14.2	0.87	8.46	9.77	↓	↘	↗	↓↘	↘	→
	3 Ammoniated double superphosphate	2.24	0.28	3.20	12.9	0.70	8.00	11.43	↓	↓	↑	↓↓	↓	→
	4 Ammoniated superphosphate	2.24	0.32	2.92	14.7	0.77	7.00	9.13	↓	↓	→	↓↓	→	→
	5 Double superphosphate	2.20	0.25	3.07	14.4	0.72	8.80	12.28	↓	↘	↑	↓↘	↓	→
	6 Superphosphate	2.17	0.28	2.97	12.8	0.73	7.75	10.61	↓	↓	↗	↓↓	↘	→
	7 High grade rock phosphate	2.25	0.23	3.07	16.4	0.73	9.78	13.35	↓	→	↑	↓	↓	→
	8 Control	2.29	0.18	2.88	15.6	0,80	12.72	16.00	↓	↑	↑	↓	↓↓	→
	Averages of the P treatments	2.22	0.27	2.97	14.3	0.75	8.25	11.06	↓	↘	↑	↓↘	↓	→
	Total average	2.23	0.26	2.96	14.5	0.75	8.64	11.50	↓	↘	↑	↓↘	↓	→

*P: Since 1958 each plot except control received 70 lb/P morgen
N: From 1958 to 1966 applications of N to equalise with diammonium phosphate
K: In 1966 the K applications to each plot were reduced from 166 to 69 lb K/morgen

TABLE 15 Application of PD chart to data of Hyam, et al (1968) Second sampling (Long-term effects of the application of different phosphatic fertilizers on maize)

	From the literature						Application of the chart								
Date of sampling	Treatments*	Leaf composition (dry basis)			Yields for 1966/67 season Bags per morgen	Yields for 1967/68 season Bags per morgen	N/K	N/P	K/P	N/K	N/P	K/P	N	P	K
		%N	%P	%K											
6.2.1968	1 Monoammonium phosphate	2.50	0.25	1.89	57.8	54.9	1.32	10.00	7.56	→	→	↘	→	→	↘
	2 Diammonium phosphate	2.55	0.26	1.76	54.5	53.9	1.45	9.81	6.77	↗	→	↓	→	→	↓↘
	3 Ammoniated double superphosphate	2.57	0.26	1.85	52.0	57.1	1.39	9.88	7.12	↗	→	↘	→	→	↘↘
	4 Ammoniated superphosphate	2.47	0.25	1.78	52.9	58.8	1.39	9.88	7.12	↗	→	↘	→	→	↘↘
	5 Double superphosphate	2.54	0.26	1.75	51.3	55.7	1.45	9.77	6.73	↗	→	↓	→	→	↘↘
	6 Superphosphate	2.51	0.25	1.84	52.7	59.3	1.36	10.00	7.36	→	→	↘	→	→	↘
	7 High grade rock phosphate	2.58	0.25	1.91	43.2	55.2	1.35	10.32	7.64	→	→	→	→	→	→
	8 Control	2.53	0.21	1.93	24.4	39.3	1.31	12.05	9.19	→	↗	→	→	↘	→
	Averages of the P treatments	2.53	0.25	1.83	52.1	56.4	1.39	9.95	7.18	↗	→	↘	→	→	↘↘
	Total average	2.53	0.25	1.84	48.6	54.2	1.38	10.18	7.39	↗	→	↘	→	→	↘↘

* Same as in Table 14 plus 126 lb N per morgen applied on 15.9.66 and 100 lb N applied on 21.9.67

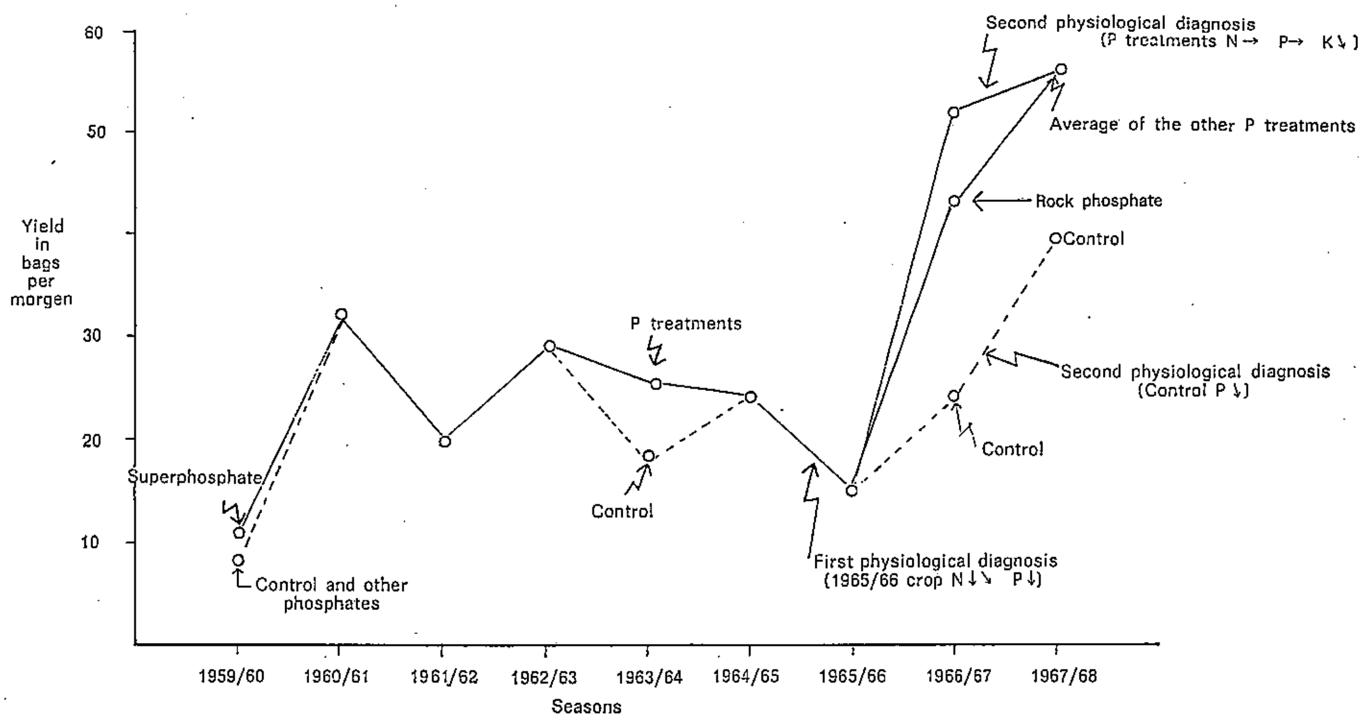

Fig 3 Application of PD chart to data of Hyam, Clayton & Jarrett (1967) Effect of corrective applications after physiological diagnosis

A PD control carried out in February 1968 showed

* complete disappearance of both N and P deficiencies on all P plots
* indication of a tendency towards a K deficiency
* the control plot, which received only N, still showed a tendency to P deficiency, which was however less than before the N application.

The improvement in the P situation on the control plot can be explained by the fact that nitrogen can help P uptake by the plant. This is illustrated by the diagnosis.

January 1966: P ↓↓
February 1968: P↘

Figure 3 shows the progress of this experiment, before and after physiological diagnosis.

General relationship between tissue composition and yield

Calculation of PD indices

In order to obtain a general, reliable and illustrative set of relations between yields and leaf analysis, the elements N, P and K have been expressed in the form of indices which are a measure of the equilibrium between one element and the other two. By means of these indices the qualitative diagnosis of the status of an element in terms of arrows is to a certain extent quantified. The index for each of N, P and K is given by the arithmetical mean value of functions of the two projected ratios including a given element. The ratios are projected on the bisector of the two axes representing the two ratios for which this element is included (Figure 4).

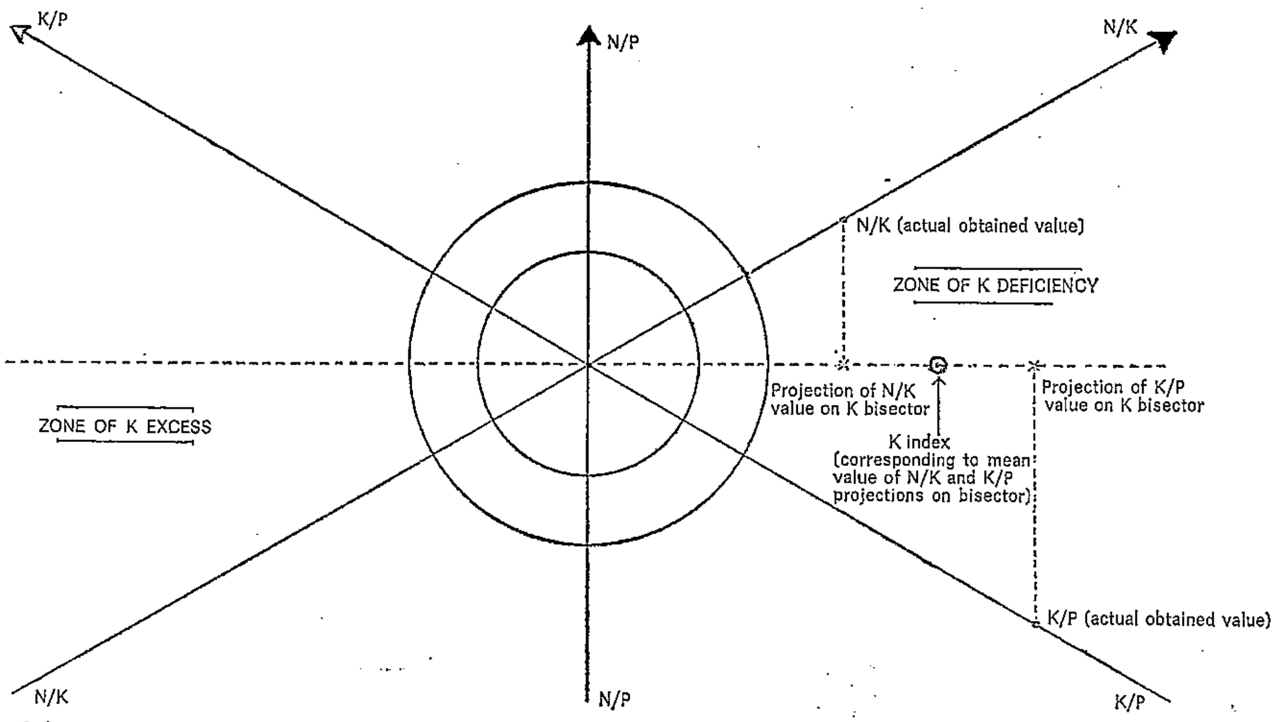

Fig 4 Schematic presentation of K index

Each bisector has been scaled in percentages of the general mean values obtained for the three ratios. The general mean values corresponding to the intersection point of the three axes have been found to be

1.23 for N/K
10.11 for N/P
8.57 for K/P

Thus these three indices are given by the following general formulae

$$\text{N index} = \frac{f(N/P) + f(N/K)}{2}$$

$$\text{P index} = -\frac{f(N/P) + f(K/P)}{2}$$

$$\text{K index} = \frac{f(K/P) - f(N/K)}{2}$$

$$\text{where } f(N/P) = \left(\frac{N/P}{10.11} \times 100\right) - 100 = \left(\frac{N/P}{10.11} - 1\right) 100$$

if the actual value found for N/P is higher than the general mean of 10.11; and where

$$f(N/P) = 100 - \frac{10\,000}{\dfrac{N/P}{10.11} \times 100} = \left(1 - \frac{10.11}{N/P}\right) 100$$

if the actual value for N/P is less than the general mean of 10.11.

f(N/P) is equal to nought when the actual value found for N/P is equal to the general mean value of 10.11.
f(N/K) and f(K/P) are derived in a similar way.
Note that the sum of the three indices must be zero.
Data taken from Table 9 is used as an example. From the K_0 treatment on the Pau site in 1954 leaf analysis was

3.84% K, 0.49% P and 0.60% K

giving ratios of

$N/K = 6.40\ (> 1.23)$
$N/P = 7.84\ (< 10.11)$
$K/P = 1.22\ (< 8.57)$

Expressed as a percentage of the general mean values

$$\frac{N/K}{1.23} = 520.4$$

$$\frac{N/P}{10.11} = 77.6$$

$$\frac{K/P}{8.57} = 14.2$$

$$f(N/K) = 520.4 - 100 = +420.4$$

$$f(N/P) = 100 - \frac{10\,000}{77.6} = -28.9$$

$$f(K/P) = 100 - \frac{10\,000}{14.2} = -602.5$$

$\text{N index} = \tfrac{1}{2}(-28.9 + 420.4) = +195.8$
is approximately equal to + 196
$\text{P index} = -\tfrac{1}{2}(-28.9 - 602.5) = +315.7$
is approximately equal to + 316
$\text{K index} = \tfrac{1}{2}(-602.5 - 420.4) = -511.5$
is approximately equal to − 512
$(+196 + 316 - 512 = 0)$

If these indices are compared with the more qualitative evaluation previously of N ↓ P→ K ↓↓↓↓, it now looks more like N ↑ P ↑↑ K ↓↓.

A direct reading of the indices can be obtained by appropriate scaling of the bisectors in Figure 4.

Graphs showing the general relationship between yield and PD indices

The graphs in Figures 5a, 5b, 6a, 6b and 7 illustrate the kind of relationship existing between yields and indices. Each graph has been drawn from 21 536 observations obtained from different parts of the world (Table 16).

Experimental data for N, P and K have been calculated from the chart into indices as explained previously.

Yields are reported as originally expressed by the different authors viz bushels per acre, bags per morgen and quintaux per hectare.

NOTE A small percentage of relatively low yields was found in the literature — presumably due to the authors' natural reluctance to publish non-interesting results. It is acknowledged that a consequent bias thus appears in the graphs at the lowest yield class intervals. The inclusion of such data would affect yield means in Tables 18-20, and improve the degrees of correlation in Table 17. Conclusions drawn would not be affected.

TABLE 16 Sources of information for plotting of Figures 5a, 5b 6a, 6b and 7

Continent	Country or State (and symbols used in the graphs)	Authors	* Number of observations
North America	▽		
	North Carolina	Baird (1958)	2 736
	North Carolina	Krantz & Chandler (1951)	264
	Illinois	Peck, Walker & Boone (1969)	4
	Iowa	Hanway & Dumenil (1966)	32
	Iowa	Powell (1968)	6 944
	Pennsylvania	Benton Jones Jnr (1959)	816
	Pennsylvania	Thomas & Mack (1939)	128
	West Virginia	Tyner & Webb (1946)	208
	Washington	Viets Jnr. et al (1954)	96
	Kansas	Ellis, Knauss & Smith (1956)	212
South America	▽		
	Brazil	Gallo, Coelho & de Miranda (1965) and Gallo, Coelho, Hiroce & de Miranda (1969)	720
	Columbia	Galiano (1968)	48
Europe	□		
	France	Loué (1962)	216
	France	Calmès (1965)	88
Asia	◆		
	India	Puntamker, Mehta & Sharma (1965)	128
Africa			
	Lebanon ◆	Soofi & Fuehring (1964)	128
	Western Nigeria ◆	Bromfield (1969)	4
	Egypt ◆	Fathi Amer, El Gabaly & Monem Balba (1969)	16
	South Africa O		
	Natal	Hahne (1965)	128
	Transvaal	Lintner (1958-1965)	540
	Natal, Orange Free State, Cape Province Transvaal and Lesotho	Beaufils (1965-1970)	8 080
		TOTAL ...	21 536

* Each point on each graph corresponds to four observations per sample viz N,P,K and yield.

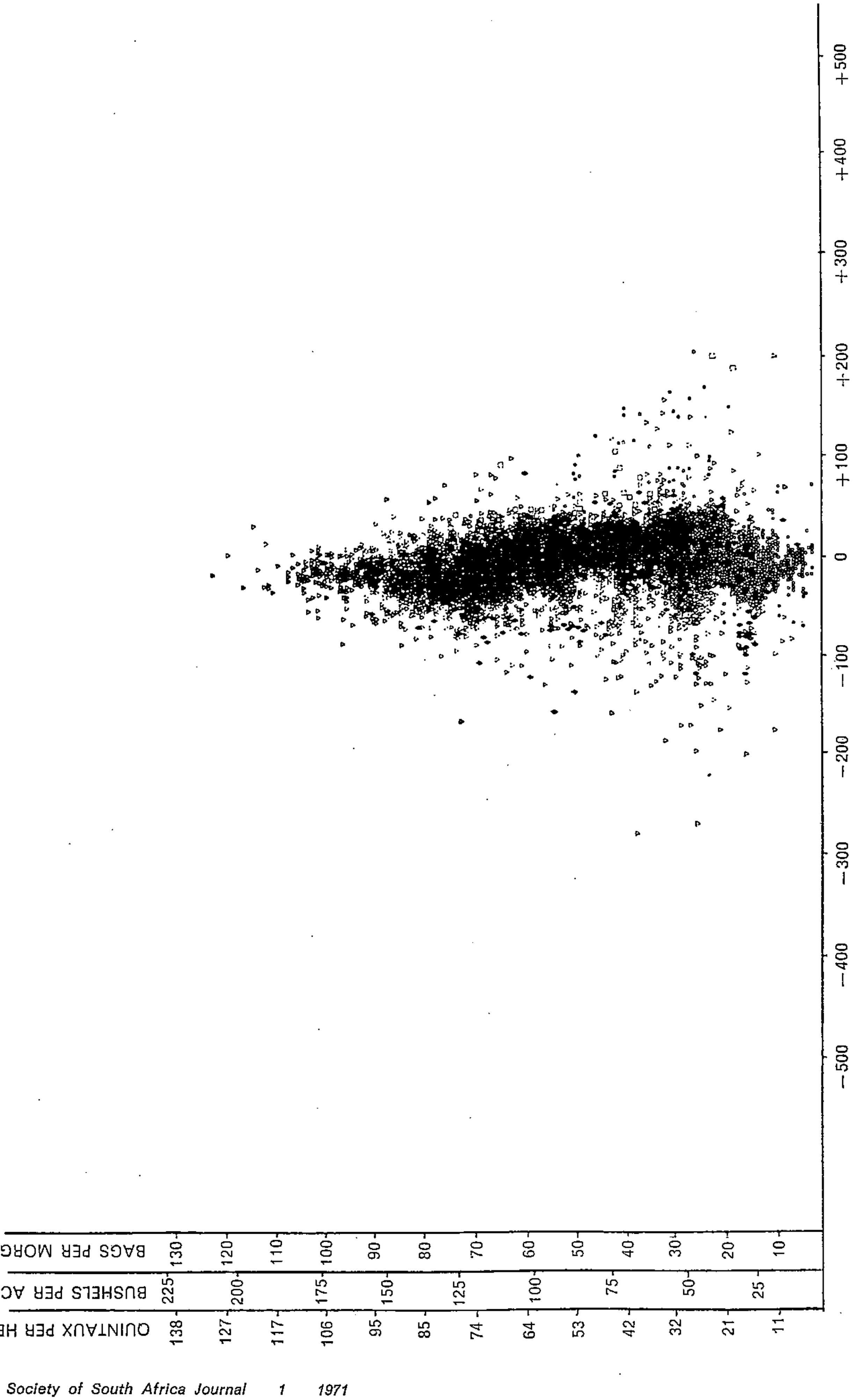

Fig 5a General relationship between yield and N index

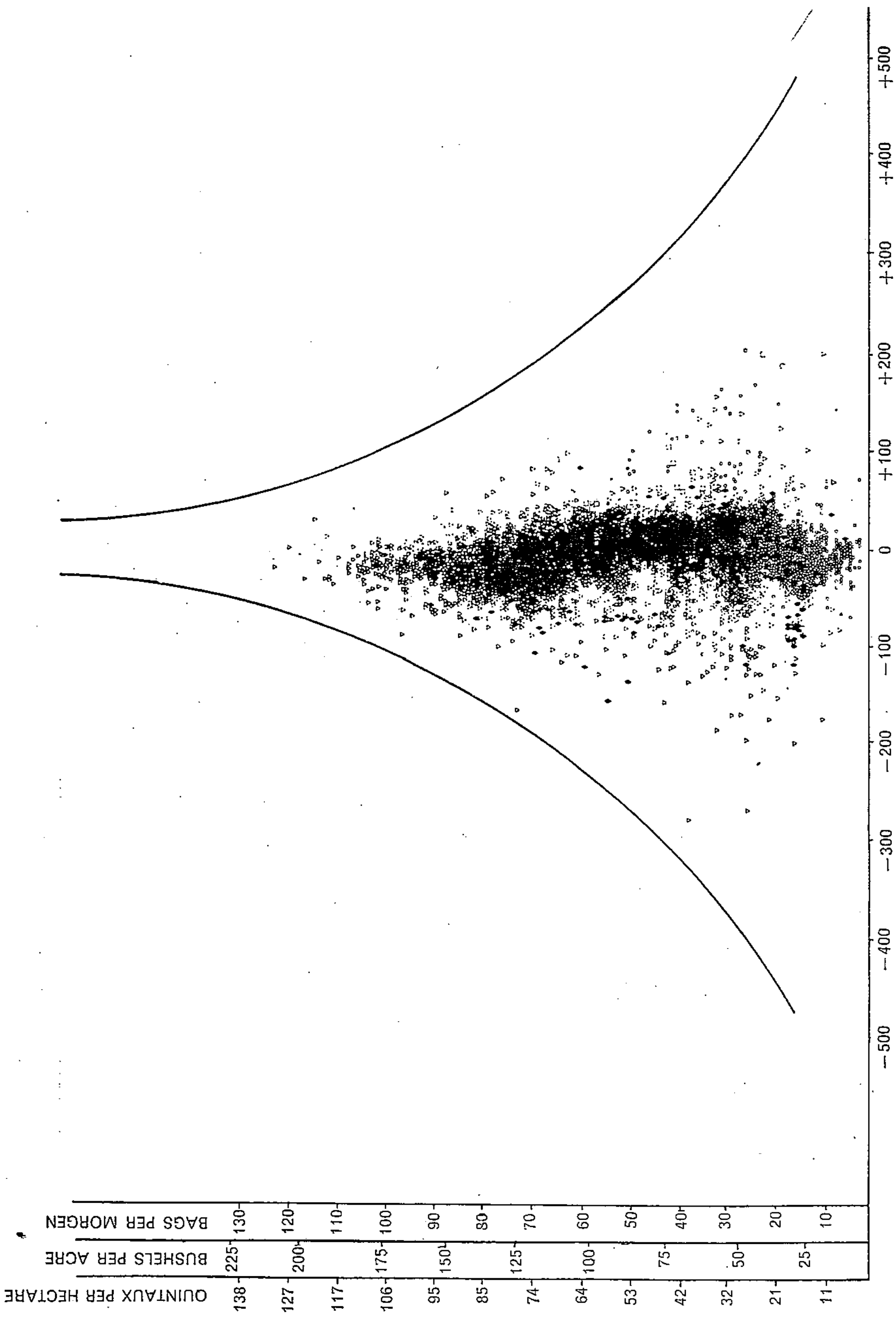

Fig 5b General relationship between yield and N index showing hypothetical limits

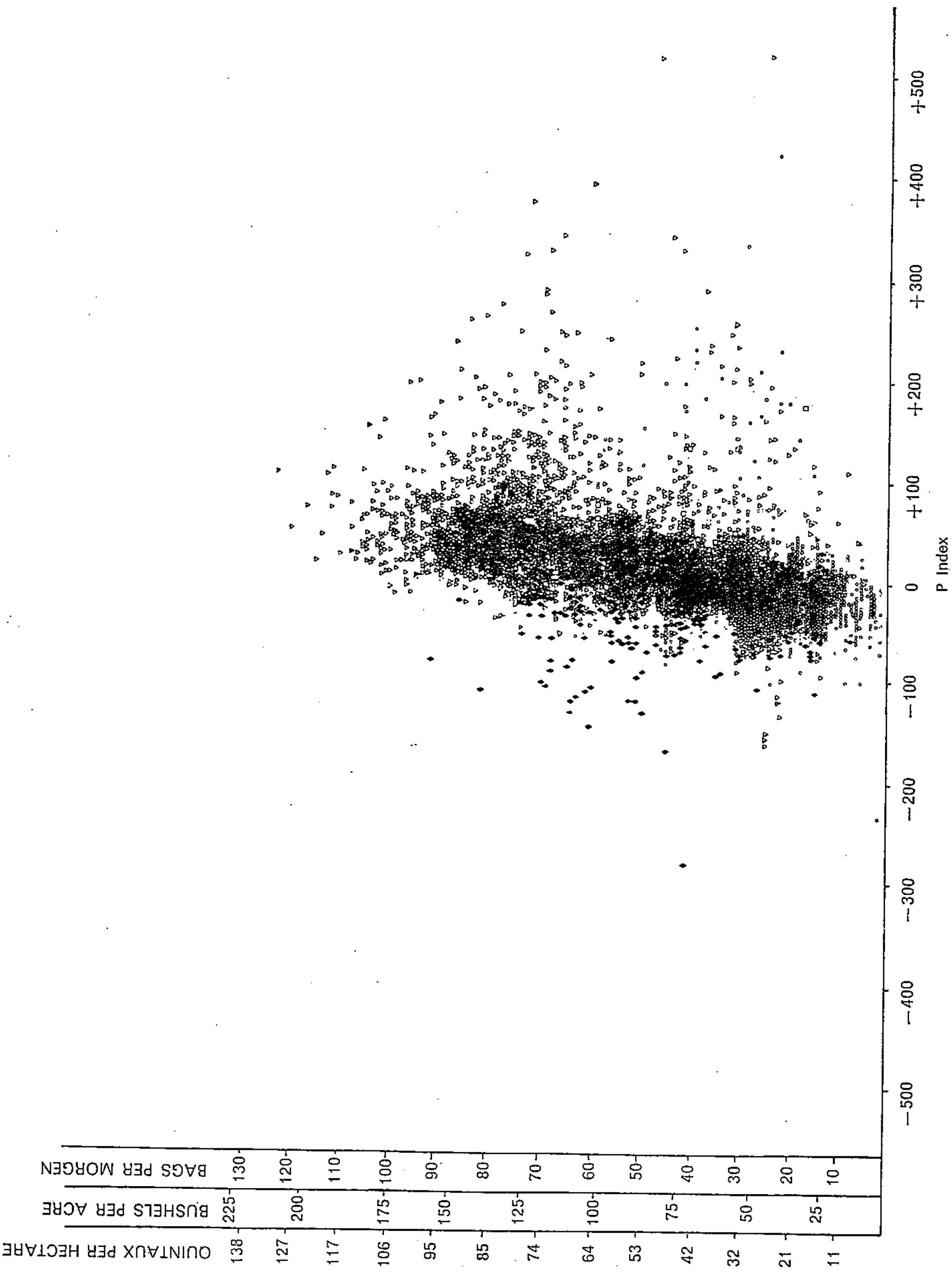

Fig 6a General relationship between yield and P index

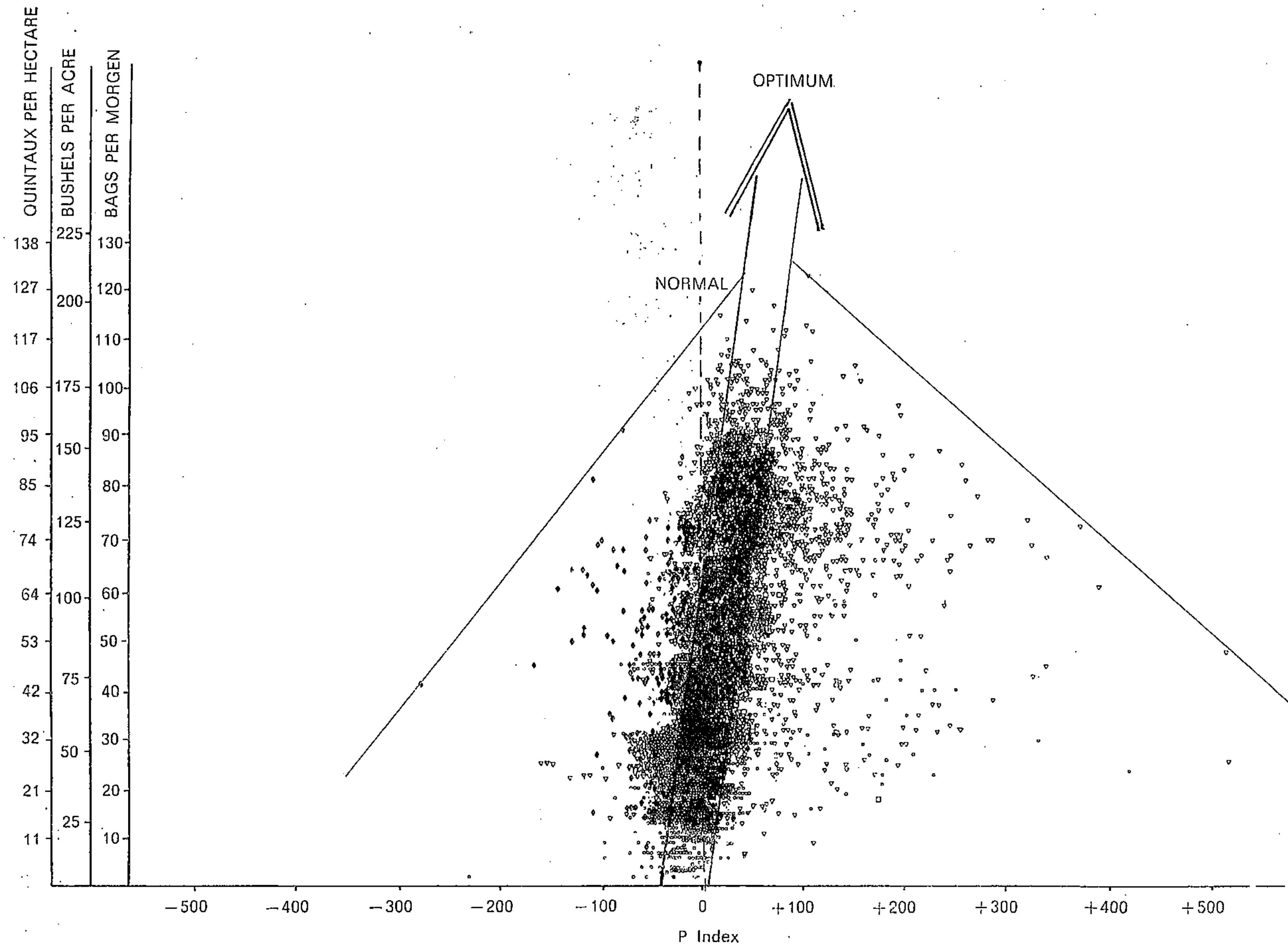

Fig 6b General relationship between yield and P index showing direction towards optimum (favourable imbalance)

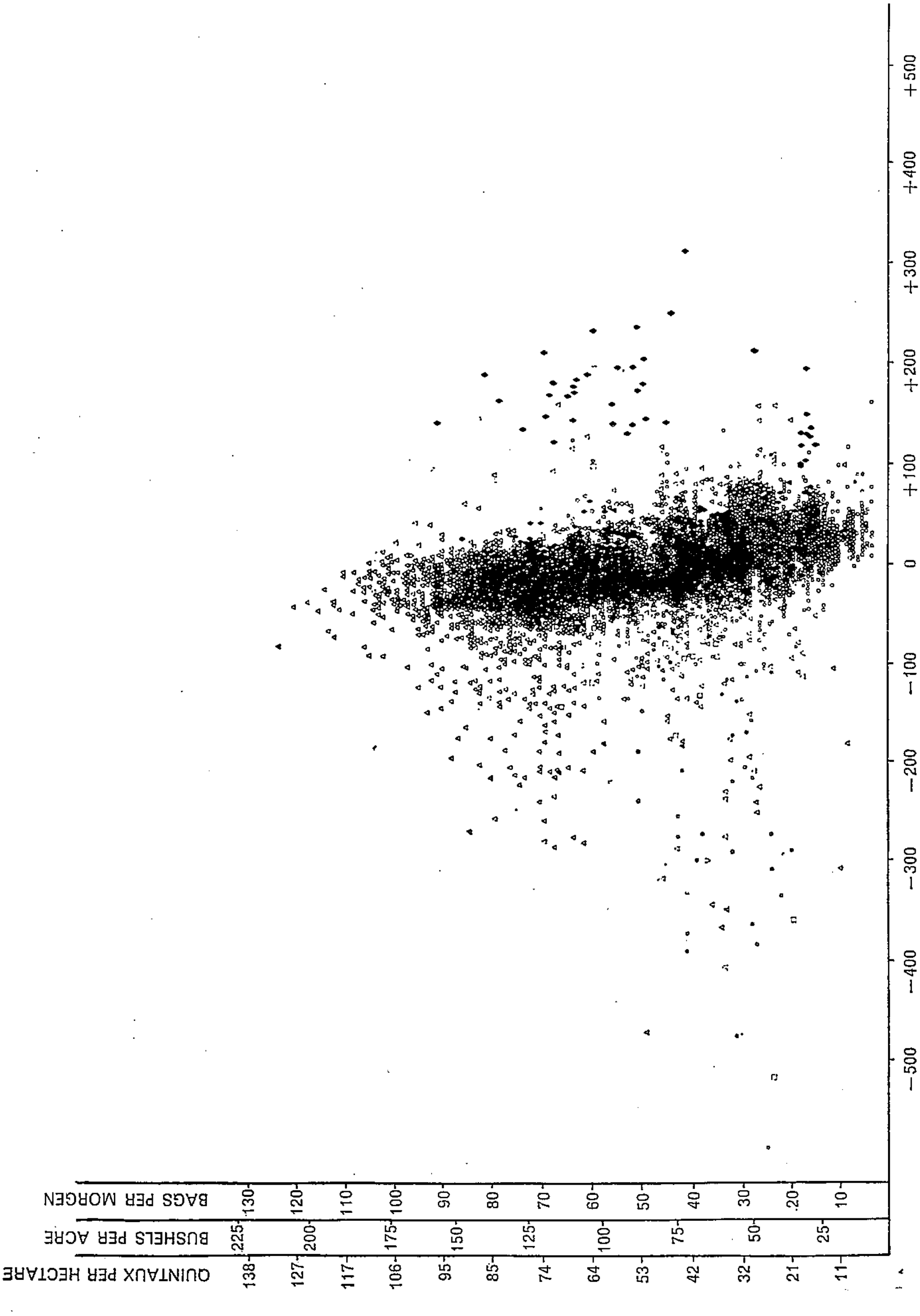

Fig 7 General relationship between yield and K index

In Figure 5b (yields versus N-index) two hypothetical assymptotic lines have been drawn which could also be drawn for K and P graphs.

All the graphs have been subjected to statistical analysis as follows

(a) The behaviour of the NPK indices has been studied according to different yield class-intervals (Table 17)

(b) The behaviour of the yields has been studied according to different indices class-intervals (Tables 18, 19 and 20).

TABLE 17 Means and standard deviations σ for NPK indices at different yield class-intervals

Yield class intervals expressed in bags/morgen	No of samples per class	N indices		P indices		K indices	
		means	σ	means	σ	means	σ
0 to 29	1 568	–7.9	34.6	–6.7	42.5	14.9	48.9
30 to 39	708	–4.3	38.0	11.2	43.3	–7.1	58.4
40 to 49	719	–1.6	32.4	12.1	49.0	–10.0	61.4
50 to 59	532	–6.4	31.0	19.7	40.1	–12.9	44.2
60 to 69	572	–9.0	30.5	33.6	57.4	–23.6	58.1
70 to 79	589	–16.9	26.4	45.0	55.3	–27.6	46.6
80 to 89	481	–15.1	20.8	44.7	43.0	–29.4	38.8
90 to 99	155	–18.5	17.8	43.0	38.8	–29.9	34.7
100 & above	60	–19.5	16.4	52.1	33.4	–32.4	24.8

From these figures the following correlations have been obtained

a Yields/indices' means
N: $r = -0.841$ $P < 0.01$
P: $r = +0.965$ $P < 0.001$
K: $r = -0.934$ $P < 0.001$

b Yields/indices' standard deviations
N: $r = -0.927$ $P < 0.001$
P: $r = -0.287$ NS
K: $r = -0.781$ $P < 0.02$ (for $P = 0.01$, $r = 0.797$)

The conclusions from the interpretation of this experiment under unlimited conditions are represented in Figures 5a, 5b, 6a, 6b and 7 and analysed in Tables 17, 18, 19 and 20. They show that

* There is a single, general phenomenon relating tissue composition to yield under a high number of dissimilar conditions.

* The indices calculated from the PD chart enable the phenomenon to be observed. This indicates the general validity of the chart and reference data.

* The aforementioned phenomenon is merely a manifestation of Liebig's Law of the Minimum (Mitscherlich, 1909).

* A significant bias exists between yields and indices' means.

These facts indicate that low yield can frequently be obtained for an index situated in the vicinity of zero (good balance) because another factor or factors might limit this yield. It is on the other hand exceptional to obtain a relatively high yield for an index situated either in a position of severe excess or in a position of severe deficiency.

Although a deficiency may be corrected by the application of the deficient element (or elements), the resulting yield might not necessarily be increased. This is particularly the case if another unfavourable factor (or factors) is, or becomes more limiting.

On the other hand, although a yield may be increased by the application of the deficient limiting element (or elements) the resulting index need not necessarily be improved. If for example the amount of the element applied is insufficient the index might still show a deficiency indicating that a further application is still required.

Except for very high yielders (favourable imbalance*), the further an index lies from the centre of the bisector

* See author's note on page 27

TABLE 18 *Average yields for N indices at different indices class-intervals (t-test for significance)*

Number of samples	N indices class-intervals in increasing order for yields	Yield means in bags per morgen	Difference % from (A)	Degree of significance	Difference % from B	Degree of significance	Difference % from C	Degree of significance	Variances (of the data)
163	A	33.24							218.0355
161	B	37.02	+11.4%	N.S.					415.3062
1 934	C	42.43	+27.6%	P<0.001	+14.6%	P<0.01			419.0852
3 126	D	49.98	+50.4%	P<0.001	+35.0%	P<0.001	+17.8%	P<0.001	684.0000

A: all N indices found to be + 51 and above
B: all N indices found to be —76 and less
C: all N indices found to be +1 to + 50
D: all N indices found to be 0 to —75

TABLE 19 *Average yields for P indices at different indices class-intervals (t-test for significance)*

Number of samples	P indices class-intervals in increasing order for yields	Yield means in bags per morgen	Difference % from A	Degree of significance	Difference % from B	Degree of significance	Difference % from C	Degree of significance	Difference % from D	Degree of significance	Variances (of the data)
220	A	29.29									363.5681
1 942	B	35.81	+22.3%	P<0.001							366.5537
2 370	C	51.25	+75.0%	P<0.001	+43.1%	P<0.001					570.6162
336	D	57.10	+94.9%	P<0.001	+59.5%	P<0.001	+11.4%	P<0.001			475.8237
516	E	64.01	+118.5%	P<0.001	+78.7%	P<0.001	+24.9%	P<0.001	+12.1%	P<0.001	466.9126

A: all P indices found to be —51 and less
B: all P indices found to be —1 to —50
C: all P indices found to be 0 to +50
D: all P indices found to be +101 and above
E: all P indices found to be +51 to + 100

TABLE 20 *Average yields for K indices at different indices class-intervals (t-test for significance)*

Number of samples	K indices class-intervals in increasing order for yields	Yields means in bags per morgen	Difference % from A	Degree of significance	Difference % from B	Degree of significance	Difference % from C	Degree of significance	Variances (of the data)
457	A	27.75							287.0669
1 898	B	35.47	+27.8%	P < 0.001					426.1160
247	C	48.94	+76.4%	P < 0.001	+38.0%	P < 0.001			529.6067
2 782	D	56.65	+104.1%	P < 0.001	+59.7%	P < 0.001	+15.8%	P < 0.001	523.3315

A: all K indices found to be +51 and above
B: all K indices found to be +1 to +50
C: all K indices found to be —101 and less
D: all K indices found to be 0 to —100

(Figure 4), the less chance there is that the yields will be high. In other words, the index to a certain extent, appears to be proportional to the degree of imbalance or deficiency of the element it represents.

Indices can be used to determine the relative severity of deficiencies (or excesses).

The significant correlation observed for all three elements, N, P and K, between the index averages and the yields is to be expected since by postulate and for convenience the method is based on 'normal' conditions and not 'optimum' conditions. In the light of the graphs it would now become possible, if considered necessary, to determine these optimum values and conditions. The validity of the chart can in no way be affected since from a PD point of view these 'optimum' values are considered 'favourable imbalances.'

Such 'provisional optimum' conditions for NPK maize, appear in Table 17. They would correspond — according to the proposed standard chart — to a diagnosis in the form of

N↓ P→ K↓

or more precisely in this particular case

N→ P↑ K→ (see Figure 6b)

obtained under the necessary simultaneous conditions that the well developed corresponding plants are not unfavourably affected — according to our present knowledge — by limiting factor(s) of any kind.

Note that all the specific advantages of PD still apply and that a diagnosis of 'favourable imbalances' could be made at any time, under any condition. The corresponding values for this diagnosis would then at this stage, approximately become (see Table 17)

index N = −20
index P = +52
index K = −32

or N/P = 7.0, N/K = 1.3 and K/P = 5.4 for which, the actual values for % N, % P and % K (dry matter basis) would vary according to age and/or any other non-unfavourable and/or favourable factor, particularly plant dynamism. (Beaufils, 1955b, 1957, 1961).

An examination of Figure 6b shows that the particular consideration of these calculated 'favourable imbalances' would nevertheless be of no use or even misleading whenever the plant yield potential is below 70 bags per morgen (approximately 75 Q/ha or 125 Bu/a).

The converse nevertheless is valid and a profitable diagnosis using the normal reference data should still be established for plants yielding 70 bags/morgen and above. Indeed, whenever 'stimulating' P uptake (in order to promote yield increase towards optimum).N and K need to be corrected according to the diagnosis

N↓ P→ K↓

The graphs reported in the paper show what is the general direction taken by the NPK balance towards the optimum.

Logical consequences in field experimentation

As the concept of general reference data illustrated in the previous experiment can be advanced for a particular crop, it means that the traditional basis of field experimentation could be complemented by giving consideration to an extended and more general form.

This consideration is largely motivated by the fact that the conclusions obtained by the conventional experimentation in agronomy are limited to a considerable extent to the particular conditions obtaining at a particular site.

A suggestion for a general scheme of experimentation could be where

* the sites — which are the actual components of the system — could be considered analogous to the replications of a traditional experiment, unlimited in their sufficiently large number, and located anywhere at random.
* the treatment based on various references could represent any kind of information derived from controlled observations for which the conditions have or have not been deliberately provoked. (The term 'controlled observations' is understood in its larger meaning).
The conclusions obtained would enable the determination of presumptions of causality — which anyway is usually the case with the traditional field experiment — on a larger and more general concept.
Field experiments (factorial or some other design) could then allow general conclusions to be obtained which would or would not be limited to a given type of soil, variety, rainfall, etc throughout a whole area, region, country or continent.

An example of the use of indices in the Northern Transvaal

The following data are extracted from an experiment conducted at Warmbaths in the Northern Transvaal (Hyam, 1969) for which a P deficiency had been found using the described method.

A standard application of 91.5 lb P per morgen was given using four different types of fertilizers.
Superphosphate: 8.7% total P
Saaifos: 8.5% total P
Double superphosphate: 20.6% total P
Saaifos 24: 20.0% total P
(Saaifos and Saaifos 24 are ammoniated superphosphates).

The N differences in the fertilizers used were adjusted to a standard application of 212.5 lb N per morgen.

Including an unfertilized control, the design of the experiment consisted of five treatments each at two plant population levels (15 000 and 25 000 plants per morgen).

In Tables 21 to 23, the P indices show the variation in P uptake from the different types of fertilizer for the two densities of population.

The P indices in this case are all negative. It should be noted that the lower the values, the stronger the deficiency, since all other factors have been kept similar.

TABLE 21 *Influence of fertilizer on P deficiencies for* 15 000 *plants per morgen*

Treatments in increasing order	Actual P deficiencies (P indices)	Difference % to control	Degree of significance
Control ...	—41.50		
Saaifos ...	—33.50	+24%	*
Double super	—29.00	+44%	**
Saaifos 24...	—28.50	+46%	**
Superphosphate	—26.75	+55%	**

TABLE 22 *Influence of fertilizer on P deficiencies for* 25 000 *plants/morgen*

Treatments in increasing order	Actual P deficiencies (P indices)	Difference % to control	Degree of significance
Control	—55.00		
Saaifos	—44.25	+24%	*
Superphosphate	—38.25	+44%	**
Saaifos 24	—36.75	+50%	**
Double super	—32.50	+69%	**

TABLE 23 Influence of fertilizer on P deficiencies as affected by plant population

Treatments in increasing order		Actual P deficiencies (P indices)	Difference % 25 000 plants/ morgen	Degree of significance
Control	25 000	—55.00	—	
	15 000	—41.50	+33%	**
Saaifos	25 000	—44.25	—	
	15 000	—33.50	+32%	**
Super-phosphate	25 000	—38.25	—	
	15 000	—26.75	+43%	**
Saaifos 24	25 000	—36.75	—	
	15 000	—28.50	+29%	**
Double super	25 000	—32.50	—	
	15 000	—29.00	+12%	NS

* 5% level of significance
** 1% level of significance

Among the many observations which can be made from Tables 21 to 23, is one that shows that 91.5 lb P per morgen applied in this experiment was insufficient to correct the P deficiency completely.

Important Although it is shown that to a certain extent a proportionality exists between the value of an index and a degree of deficiency or excess, indices should only be compared when all other variables are also comparable (Figures 5a, 5b, 6a, 6b and 7, which illustrate the Law of Minimum, support this).
For example an index of −300 indicates a greater deficiency than an index of −100, only if the other factors are comparable.

Integrated treatments

The following is an illustration of what can be achieved by full and correct application of PD to maize grown under dryland conditions, ie without irrigation. In the example quoted, the specific advantages of Physiological Diagnosis have been fully utilised. As physiological checks can be made at any stage of the plant's growth, this enables a systematic use of a repeated treat-and-check technique for which actual controls exist within the limits of the treated plot itself. One or more treatments based on these successive checks can then be applied — concurrently if need be — hence the term 'integrated treatments'.

The exercise consisted of two fertilized plots and a pilot plot viz First fertilized plot (120 morgen):
usual farmer's practices

Second fertilized plot (1 morgen):
usual farmer's practices altered in only one specific aspect by PD recommendation namely date of planting

Pilot plot (1 morgen):

recommendations and treatments based on a repeated check-and-treat PD system throughout the season.

Details of the farmer's usual practices per morgen were

Variety	Sabi 3
Planting date . .	about November 20
Plant population .	28 000 plants/morgen
Row spacing . .	7 ft
Lime	dolomitic lime: 2 tons
Fertilizer before planting . . .	Limestone ammonium nitrate: 100 lb (52 lb N) Calmafos: 300 lb (24 lb P) double superphosphate: 300 lb (60 lb P) potassium chloride: 100 lb (50 lb K) zinc fertilizing material: 20 lb (4 lb Zn)
side-dressed . .	urea: 200 lb (92 lb N) potassium chloride: 100 lb (50lb K)

The second fertilized plot was identical to the first plot except for date of planting, which, according to PD norms, was advanced to 30th October.

Details of the Pilot plot were

Variety	unchanged
Planting date . .	October 30
Plant population .	36 000 plants/morgen
Row spacing . .	2 ft 6 inches
Lime	dolomitic lime: 7.5 tons
Fertilizer before planting . . .	double superphosphate: 500 lb (100 lb P) potassium chloride: 250 lb (125 lb K) urea: 500 lb (230 lb N)
Band-placed . .	double superphosphate: 100 lb (20 lb P)
at planting . .	zinc fertilizing material: 40 lb (8 lb Zn)
Side-dressed on 13th January 1970 .	double superphosphate: 200 lb (40 lb P) potassium chloride: 200 lb (100 lb K) urea: 200 lb (92 lb N)
on 3rd February 1970	potassium chloride: 200 lb (100 lb K) double superphosphate: 100 lb (20 lb P)

Results of the first season were (see also Plates 1 and 2)

First plot: 28 bags/morgen (47 bu/acre or 30 Q/ha)

Second plot: 46 bags/morgen (78 bu/acre or 49 Q/ha)

Pilot plot: 75 bags/morgen (127 bu/acre or 80 Q/ha)

Note 1 A yield of 28 bags/morgen is considered reasonably good for the area.

Note 2 The important influence of planting date on maize physiology as affecting resulting yields is well marked in this trial.

Note 3 PD checks on the pilot plot have shown that not only have the treatments increased the yields, but that they simultaneously improved the soil fertility level. It is clear that having once brought the fertility level of the soil to its 'optimum', the fertilizer requirements would drop to a 'plateau of maintenance' level.

Note 4 PD checks also showed rapid correlative corrections of imbalances after application of the corresponding nutrients during the course of the experiment (and particularly on the 13th January 1970 and 3rd February 1970).

Plate 1 Second fertilized plot: yield 46 bags per morgen (photograph taken 80 days after planting) planted: 30 October 1969

Plate 2 Pilot plot: Check-and-treat system: yield 75 bags per morgen (photograph taken 80 days after planting) planted: 30 October 1969

Problems in the application of the PD technique

In order to avoid possible mis-interpretation of the PD principles an instance is cited where Fallows (1960, 1961) claimed that PD reference data developed by Beaufils for rubber trees in Vietnam was not suitable for use on Malayan rubber trees. See also Holland (1966).

Fallows used an alternative method of selecting healthy plants, since only a little work had been done in Malaya on leaves selected on a healthy/unhealthy basis (as described earlier in this paper for maize).

Since agreement was found between N/P ratios determined in Malaya and Beaufils' reference data for 'normal' N/P ratios in rubber trees, the latter were accepted as a sole criterion for selecting healthy trees. Fallows assumed that the corresponding sampled leaves could be used to determine the other mineral ratios for Malayan conditions. All leaves with N/P ratios within Beaufils' limits for 'normal' trees were therefore assumed to come from healthy rubber trees. This assumption is not valid as leaves from 'abnormal' trees may have similar mineral ratios as explained earlier in this paper.

The confusion comes from the fact that it is never possible from the consideration of a single ratio to determine whether it belongs to the 'healthy population' — as Fallows did in order to reach his conclusions. Consequently his 'alternative selection' contains an undefined number of unsuitable cases.

Conclusions

Physiological Diagnosis is neither a doctrine nor a dogma. Postulates had to be selected and rules followed only because this is necessary to make progress.

The terms, methods, systems and techniques have sometimes been retained for clarity and to emphasize the distinction which has to be made between
the objective part of this work: production of a diagnosis by application of a method
and
the non-objective part: personal interpretation of the diagnosis leading usually to a recommendation and appropriate corrective action.
The border between the two aspects does not always appear obvious.

Experimental results obtained from pre-selected postulates and rules must validate such postulates and rules. This appears to be the case in this study.

Author's note

Without wanting to move into the area of semantics, the author feels that some clarification on the use of certain terms is warranted. This will ensure that the reader's understanding of these terms is the same as his own.

Normal and optimum

According to the Shorter Oxford Dictionary, normal means "usual" whereas optimum means the "best or most favourable". Taken as such, the best or most favourable conditions and their parameters constitute one of the ultimate steps of research and progress. The question is how can such conditions be identified with certainty as being definitely the best ones in the dynamics of a natural evolution; they appear to be quite 'unseizable' and too much dependant on particular conditions.

In the development of the PD principles, two main phases have been considered (Beaufils, 1957). The first phase involves the establishment of a reliable system enabling the correction of soil and plant deficiencies and imbalances. The second phase aims at optimum yields once the environment has been normalised.

Maximum yields are obtainable through what can be called a favourable imbalance which for a period can be considered analogous to "relative optimum" conditions. (Beaufils, 1957).

It has been found convenient to consider normal conditions and their parameters as a basis for this work because

- they satisfy the notion of balance
- being usual, they are commonly known and therefore easy to define and select
- they enable the establishment of physiological laws by the particular study of the population of plants not unfavourably affected by abnormal conditions (normal plants)
- they do not discard but, on the contrary, are expected to prepare — whenever possible and necessary — the establishment of what could be considered as optimum references.

Absolute and relative values

At the outset, no preference was given to ratios between elements or any other modes of expression. It was found however, that expressing a given element in terms of another element, submitted normally to a similar set of laws, enables the establishment of a reliable diagnosis by eliminating to a large extent the masking factors of influence. In the case of NPK, a double reference is used, eg N is expressed in terms of P and K at the same time.

What is usually called "optimum level" and even "absolute level of nutrient" (Fallows, 1963), is in fact the concentration of a given element in the dry matter. In the case of N for example, it is expressed as %N on a dry matter basis, which is the same as

$$\frac{\text{amount of N(g)}}{\text{amount of dry matter(g)}} \times \frac{100}{1} \text{ in other words,}$$

a ratio multiplied by a constant which is still a ratio between two variables and not an absolute value.

In this case (%N dry matter), the element N is made dependent through a single reference to a variable (dry matter) for which the variations through a season are known to be tremendous; it normally is a direct function of the age of the tissues and can largely be affected by numerous factors particularly adverse climatic conditions.

Physiological diagnosis uses as supplementary information, graphs representing concentrations versus ages of the tissues, which if considered alone have been found insufficient.

Absolute is given as "independent, existing without relation to any other being" (Little, et al, 1959). Does this really occur in plant physiology?

The author invites correspondence on any aspect of his paper.

Opsomming

FISIOLOGIESE DIAGNOSE — 'N GIDS VIR DIE VERBETERING VAN MIELIEPRODUKSIE GEBASEER OP 'N TEGNIEK ONTWIKKEL VIR RUBBERBOME

Die fisiologiese diagnosemetode wat in Indo-sjina ontwikkel is vir die verbouing van rubberbome is vir mielieproduksie in suidelike Afrika aangepas.

Uit inligting verkry uit proewe wat oor 'n wye gebied gedurende 'n periode van vyf jaar uitgevoer is, is norme of ‚verwysingsdata' vasgestel wat regstreeks gebruik kan word om allerhande opbrengsbeperkende ‚oorsake' in 'n spesifieke gebied of plek aan die lig te bring. Hierdie metode het die voordeel dat dit direk en algemeen toegepas kan word sodra norme vir 'n betrokke gewas vasgestel is.

Die vasgestelde norme het te doen met ‚oorsake' in die verbouing, plantvoeding en omgewing, maar fisiologiese diagnose soos in hierdie artikel behandel word beperk tot die sistematiese bepaling van die status van die hoofvoedingstowwe, N, P en K.

Om hierdie bepaling te vergemaklik, is 'n kaart opgestel met behulp waarvan die status van die elemente in die plant regstreeks bepaal kan word op enige groeistadium. By die interpretasie van resultate verkry deur toepassing van die kaart moet nietemin verskeie faktore wat 'n invloed op die fisiologiese funksionering van die plant kan hê, in aanmerking geneem word, en dit is hier waar die plantfisioloog 'n rol speel.

Die norme wat vir N, P en K vasgestel is, is aan 'n kritiese toets onderwerp deur dit op 'n groot aantal eksperimente met mielies, soos in wêreldliteratuur gepubliseer, toe te pas. 'n Aantal voorbeelde van hierdie toets word gegee.

In grafieke vir elk van die drie elemente, N, P en K saamgestel uit 21 536 waarnemings uit verskillende dele van die wêreld, word opbrengs in verband gebring met indekse wat regstreeks van die standaard kaart bereken is. Elke grafiek is statisties ontleed en bevestig die feit dat die verwantskap tussen opbrengs en die chemiese samestelling van plantweefsel 'n manifestasie van die Wet van Minimum is. 'n Hoogs betekenisvolle verband tussen opbrengs en N, P en K is verkry—onafhanklik van die eksperimentele toestande.

Een besondere voordeel van die fisiologiese diagnosetegniek, is dat dit nie deur die gewone bedekende veranderlike faktore beïnvloed word nie. Dit bring mee dat die metode regstreeks te enige tyd en onder alle omstandighede gebruik kan word, bv 'n aaneenlopende prentjie van plantvoeding kan verkry word, en die moontlikheid om roetine kontrole uit te voer, bestaan.

Inligting is van meer as 200 plase verkry, wat bykans 500 plekke in suidelike Afrika verteenwoordig, opgeskryf, verwerk en gebruik in die verkryging van agtergrond inligting vir navorsingswerk en vir die regstreekse maak van veldaanbevelings soos plantdatum, spasiëring, plantbevolking, en natuurlik die aard en hoeveelheid kunsmis wat toegedien moet word.

Die aard en hoeveelheid voedingstowwe wat toegedien behoort te word, is akkuraat bepaal deur die tegniek van opeenvolgende benaderings uit roetine kontroles.

'n Oorsig van resultate en gevolgtrekkings van ‚konvensionele veldproewe' word gegee en hulle tekortkomings bespreek. Ten einde die graad van betroubaarheid te verhoog en die geldigheidsgrense van veldproewe uit te brei, is verbeterings voorgestel.

Fisiologiese diagnose (PD), soos deels in hierdie artikel weergegee, is 'n metode om 'n probleem se parameters uiteen te sit, maar bied geen outomatiese oplossing van die probleem nie. Toepaslike regstellingsmaatreëls is nie slegs 'n funksie van diagnose nie, en subjektiewe hoedanighede soos kennis, ondervinding en die insig en skerpsinnigheid van die persoon wat die nodige aanbevelings moet maak, is ook nodig. Hoewel die metode dus aan persoonlike interpretasie onderworpe is, word sy intrinsieke waarde nie verminder nie.

Verbeterings aan die metode sal met meer ondervinding kom, maar dit kan alreeds met voordeel gebruik word. Die praktiese toepassing van fisiologiese diagnose in mielieverbouingsprobleme het reeds die nuttigheid daarvan as 'n gids vir navorsing bevestig, asook vir aanbevelings om graanopbrengste op boere se lande te verbeter.

Indien dit aanvaar word dat die uiteindelike doel met akkerboukundige proewe is om opbrengs met enige soort veranderlike wat deur die mens beheer kan word, in verband te bring, dan behoort die gevolgtrekkings in hierdie werk voldoende te wees om die geldigheid van die beginsels te bewys.

'n Groot gedeelte van die kennis wat tot dusver met fisiologiese diagnose verkry is, is geïllustreer in 'n voorbeeld waarin fisiologiese diagnose op 'n grootskaalse kommersiële proef toegepas is. Werklike opbrengs is gedurende die eerste seisoen van 28 sak tot 75 sak per morg verhoog sonder besproeiing.

Daar skyn geen rede te wees waarom die fisiologiese diagnosetegniek nie suksesvol aangepas kan word vir gebruik op ander gewasse nie.

RÉSUMÉ

LE DIAGNOSTIC PHYSIOLOGIQUE — UN GUIDE PERMETTANT D'AMÉLIORER LE RENDEMENT DU MAÏS, BASÉ SUR DES PRINCIPES DÉVELOPÉS POUR L'HEVEA.

La Diagnostic Physiologique développé en Indochine pour être employé dans les plantations de caoutchouc a été adapté dans la partie sud de l'Afrique à la culture du maïs. Les informations provenant d'expériences poursuivies pendant cinq ans sur une grande échelle ont permis, l'établissement de normes ou "données de référence" — Ces normes peuvent être employées directement pour déceler et préciser les "causes" de toute nature qui limitent la production, quelles que soient les conditions particulères du cas étudié. Un avantage de la méthode est d'être d'application directe et générale une fois les normes établies pour une culture donnée. Les normes établies permettent de déceler et de préciser les "causes limitantes" provenant des méthodes culturelles, de la nutrition ou des conditions d'environnement de la plante.*

La partie du Diagnostic Physiologique qui a été traitée dans ce rapport sera néanmoins restreinte à la seule détermination méthodique de la situation des éléments nutritifs majeurs N, P et K. Pour faciliter cette évaluation, une clé a été imaginée qui permet de déterminer directement la situation de ces éléments dans la plante, quel que soit son stade de développement. L'interprétation des résultats obtenus par application de la clé doit cependant tenir compte des divers facteurs susceptibles d'avoir une influence sur le fonctionnement physiologique de la plante.

Les normes établies dans le sud de l'Afrique pour N, P et K ont été éprouvées sur un nombre considérable d'expériences portant sur la maïs et publiées dans la littérature mondiale. Un certain nombre d'exemples de ce test sont analysés dans ce rapport.

Des graphiques relient les éléments N, P, K, exprimés en indices calculés directement à partir de la clé standard, aux productions correspondantes de maïs pour chacun des 21 536 observations enregistrées dans diverses régions du globe. Chaque graphique, soumis au calcul des probabilités, permet d'établir que la nature des relations éxistant entre production de maïs et composition chimique des tissus de la plante est une manifestation de la Loi du Minimum.

Des relations hautement significatives ont été établies entre N, P, K et productions, obtenues indépendammet des conditions expérimentales.

Un avantage particulier des techniques du Diagnostic Physiologique est qu'elles éliminent les facteurs masquants habituels de variabilité. Celà permet de les appliquer dans n'importe quelles conditions (obtention du "film" de la nutrition, possibilité de contrôles routiniers . . . par exemple).

Les informations détaillées en provenance de plus de 200 exploitants agricoles et correspondant à environ 500 parcelles expérimentales industrielles dans le sud de l'Afrique ont été enrigstrées, interprétées et utilisées en vue d'établir, en premier lieu, les normes appliquées dans la poursuite des recherches, puis pour l'obtention des préconisations au profit des agriculteurs.

Ces préconisations portent notamment sur la date de semis, l'espace entre rangées, la densité de population, . . . et, évidement, la nature et la quantité des engrais à employer. Ces deux derniers facteurs ont été déterminés avec la précision nécessaire grâce à des séries d'approximations successives provenant des contrôles routiniers.

Les resultats et conclusions tirées des "expériences classiques" en champs sont analysées et leurs limitations discutées. Des améliorations sont suggérées qui permettent d'augumenter le degré de fidélité et d'étendre les limites de validité des expériences en champs. D'autres notions fondamentales telles que: valeurs "absolues" et "relatives," conditions "normales" et "optimales" sont discutées dans une note de l'auteur.

Le Diagnostic Physiologique (D.P.) présenté partiellement dans ce rapport constitue un ensemble da techniques qui permettent de poser les données du problème; elles ne fournissent pas automatiquement la solution de tous les problèmes posées. L'établissement de l'intervention la plus appropriée n'est pas uniquement fonction du diagnostic; des qualités personnelles telles que connaissances et expérience de la personne qui effectue la préconisation sont également requises. Bien que la méthode soit sujette à des interprétations personelles, sa valeur intrinsèque une fois établie demeure hors de cause.

Des améliorations sont attendues avec l'expérience mais l'outil tel qu'il est peut déjà être utilisé avantageusement.

L'application pratique du D.P. aux problèmes posés par la culture du maïs a déjà confirmé son utilité en tant que guide dans la poursuite de recherches académiques, aussi bien que dans l'établissement des préconisations visant à augmenter les rendements des exploitations agricoles.

Si le but ultime des expériences en matière de recherches agronomiques est d'établir un lien fidèle entre le rendement et toute variable quelconque susceptible d'être placée sous contrôle humain, alors les conclusions établies dans cette études devraient être suffisantes à elles seules à accréditer la validité de la méthode.

La majeure partie des connaissances acquises à ce jour sur le D.P. du maïs est illustrée dans un exemple utilisant cette méthode sur une large parcelle industrielle (Transvaal Oriental): les rendements effectifs à l'hectare ont été élevés en une saison, de 30 quintaux à 80 quintax, sans irrigation.

Il n'y a, semble-t-il, pas d'objection majeure à ce que cette méthode et ses techniques ne puissent également être employées avec succès sur des cultures autres qui maïs ou hevea.

* *La technique du "Diagnostic Physiologique" appliquée au maïs a été brevetée en Afrique du sud profit de African Explosives and Chemical Industries Limited. (Beaufils 1968).*

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