Chapter 19
Quantitative Land Evaluation for Agro-Ecological Characterization

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Introduction

Sufficient food, produced by agriculture, is an essential need of a community. Food shortages and their devastating effects are an integral part of human history. To judge whether shortages arise from excess demand or from incomplete exploitation of the inherent food-producing capacity of a region, the latter must be quantified and compared with the actual yield levels obtained. The actual level of yield at any location is determined on one hand by the agrotechnical possibilities and on the other by the socio-economic environment in which the farmer and his customers operate. Any analysis of the food and agricultural sector of a country or region, should therefore cover both aspects.

However, this paper, is concerned only with the physical and agronomic aspects of agricultural production systems. It presents a method for estimating yield potentials of crops, based on crop growth models that combine knowledge about crop characteristics and the environment in which they are grown. The method can identify the magnitude of the effects of principal constraints and estimate the effects on yield of lessening them.

Although the various elements which are important in determining growth and yield of crops are known to be interrelated, the actual quantitative relationships are in many cases only partially understood. To use this partial knowledge as efficiently as possible, a hierarchical sequence has been adopted in the method presented here. In this sequence, the number of factors that has to be taken into account to estimate crop yield at the highest hierarchical level, is substantially lessened by assuming that constraints, that can feasibly be removed, have indeed been eliminated. At the lower hierarchical levels considered subsequently, the factors taken into account at the higher levels remain fixed and the effects of the limiting factors, which are supposed to have been eliminated at the highest level, are successively taken into consideration.

In this presentation the method is elucidated with the help of a schematic presentation of the procedure employed, followed by a more detailed discussion of the most important elements and illustrated with some results.

General Outline

The procedure applied is schematically presented in Figure 1: the rectangles in the second row represent the factors that ultimately determine the agricultural yield potential. Climate and soil are fixed properties for a given location and, in combination with the level of reclamation of the land*, characterize the 'land quality level'. The characteristics of agricultural crops may be changed by selection and breeding; and the scope for improvements in this respect is reasonably well-defined at a particular time. For a given land quality level, the yield potential is therefore more or less fixed for the relevant period of time, and may be calculated with sufficient accuracy.

In the subsequent analysis, the objective is not to define a production function describing the relationship between yield and all possible combinations of inputs, but instead to establish a reasonable combination of inputs that will permit the crop to yield at a level which is acceptable given the land quality level. Therefore, the yield level is considered both as a dependent variable determined by crop characteristics and land quality

*"reclamation" includes all types of improvement of land for agricultural production.

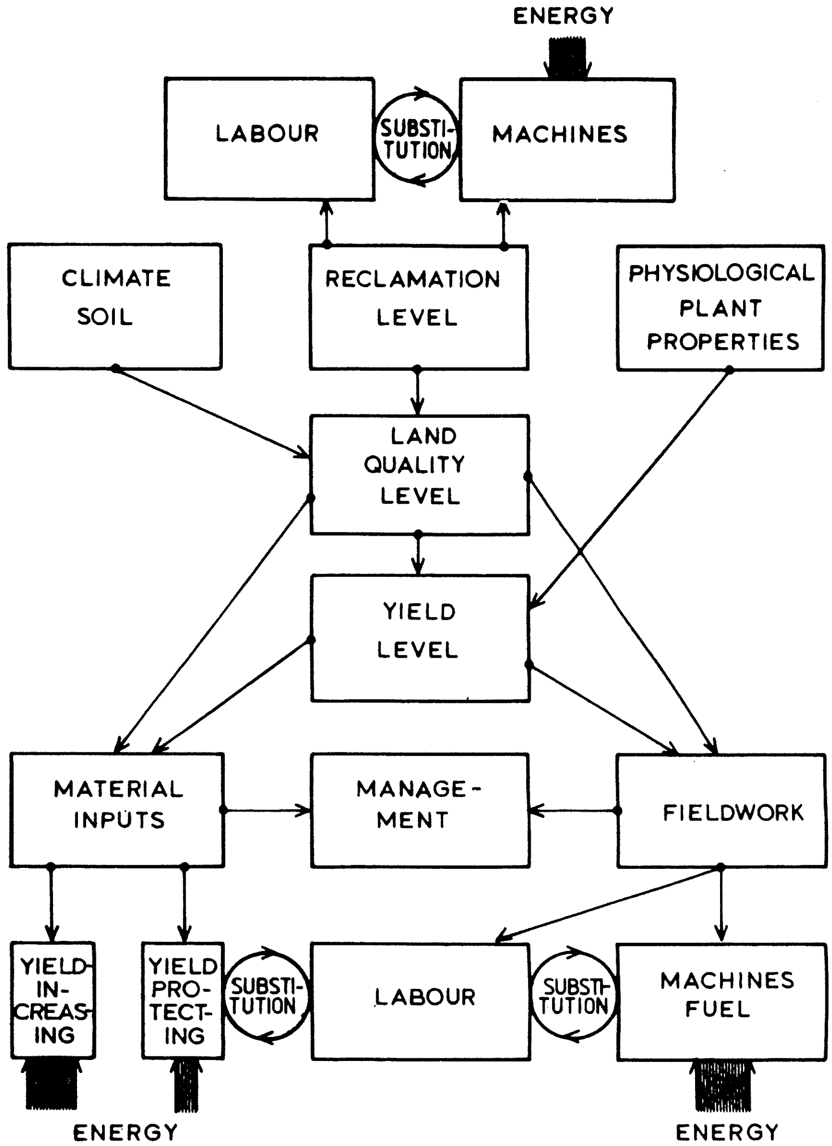

Fig. 1. Schematic presentation of the analysis for quantitative land evaluation.

level, and as an independent variable, dictating the combination of inputs needed to realize it. This definition is reflected in the direction of the arrows in Figure 1: they point towards the yield level in the upper part and away from it in the lower part.

With respect to the required inputs, a distinction is made between field work and material inputs. The necessary field work is described in physical terms: the requirements for ploughing, harrowing, weeding, the length of supply and transport lines, etc. The time required for these activities is to a large extent independent of the yield level. The total length of the period available to do the work depends strongly, however, on soil type and weather conditions. In performing the field work, considerable substitution is possible between manual labour and work done by heavy mechanical equipment with its associated requirements for fossil energy.

The material inputs are subdivided into yield-increasing inputs and yield-protecting inputs. The required amounts of yield-increasing inputs, such as water, nitrogen and mineral nutrients, are directly related to the required yield level, soil type and climatic conditions. Characteristically these inputs cannot be substituted by labour. In contrast labour can substitute (though perhaps less effectively and more expensively) for some yield-protecting inputs, e.g. labour-intensive hand weeding instead of herbicides, and manual eradication of insects instead of chemical control.

As indicated in Fig. 1 the land quality level is on the one hand determined by intrinsic soil properties and climatic conditions, and on the other by the level of reclamation. In our formal scheme, we distinguish four such levels. The lowest level refers to land covered with wild or even undisturbed vegetation used, at most, for no more than food gathering and extensive grazing. At the next level the land is cleared, so that it can be used to raise crops more permanently, with or without fallow periods. The water regime in that situation is fully dictated by weather conditions and local topography. Unintentional flooding is avoided, at most, by simple modifications of the topography or simple dams. The third level pertains to land where further improvements have been carried out, such as levelling, terracing and the construction of open drains to control excess water. The highest level refers to land which is continuously maintained in conditions favourable for crop growth: well-levelled, with complete control of water and the necessary physical infrastructure. Sufficient water is available to allow irrigation as required.

In addition to defining the present status of the land in a region, it is also important to quantify the reclamation activities required to bring the land to a higher level of quality. This applies especially to the amount of wild vegetation and stones to be removed, the quantity of soil to be moved and the infrastructure that must be developed. This aspect of the analysis is represented in the first row of the diagram in Fig. 1. Reclamation can be carried out with manual labour, but that is often only a hypothetical possibility, because most of the land that could easily be reclaimed is already in use for agriculture. At present, it is therefore almost inevitable that heavy mechanical equipment will be required. The reclamation activities are therefore defined for various technological levels expressed in terms of appropriate equipment.

A Hierarchy of Yield Calculations

In the actual analysis four hierarchically ordered production situations are distinguished (van Keulen and Wolf 1986). At the **highest hierarchical production situation** it is assumed that water, mineral nutrients, and nitrogen are in optimum supply, and that crop protection against weeds, pests and diseases is sufficient to eliminate any effects. Crop yield in that situation, referred to as potential yield, is determined only by the type of crop and its state at emergence or transplanting, the prevailing level of irradiance, and the temperature regime.

The basis for the calculation of dry matter production and yield is the gross rate of CO_2 assimilation of the crop, determined by the level of irradiance, the green area of the crop at any particular time capable of intercepting the incoming radiation, the photosynthetic characteristics of the crop species and the prevailing temperature. Part of the assimilates produced by the crop is used to maintain the existing structures. The remainder is available for increase in structural dry matter of the various plant organs: roots, leaves, stems and storage organs. The pattern of partitioning of the assimilates in the course of the growth cycle of the crop depends on the species and cultivar and is defined as a function of the physiological age of the crop, which in turn is a function of the prevailing temperature and daylength. The conversion efficiency of primary photosynthetic products into structural plant material depends on the chemical composition of the material and is defined for each organ separately.

For most regions, sufficient experimental data are available to judge the feasibility of cultivating the major crops and to define so-called cropping calendars, specifying among other things the most favourable times of sowing or transplanting. For crops or cultivars not cultivated in a region at present, sowing time may be determined using the model, in accordance with the length of the season, the desirable time of harvest and temperature and daylength requirements of the crop.

The state of the crop at the start of the calculations is characterized by measurable quantities, such as the weight of the above-ground plant parts, the weight of the roots, and the green area which is active in the assimilation process. These quantities are derived from the crop- and region-specific sowing rates, that have to be introduced as exogenous variables.

For the **second hierarchical production situation**, it is again assumed that the supply of nitrogen and

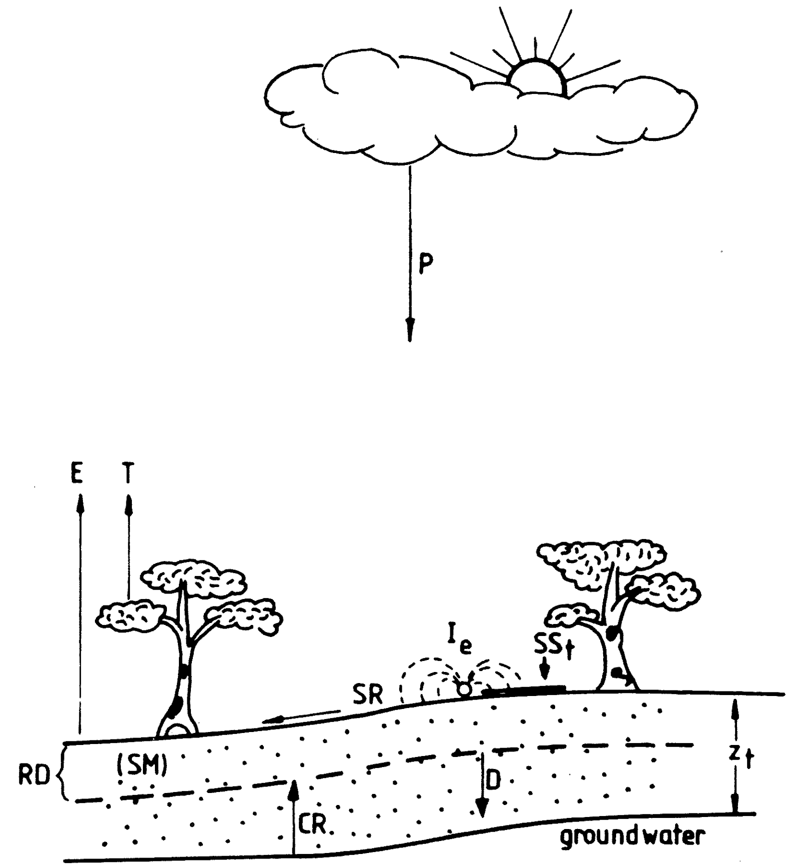

Fig. 2. Schematic representation of the terms of the water balance.

mineral nutrients is optimal: but now the influence of the supply and availability of water in the soil on the possible length of the growing season, and on transpiration and yield are taken into account. Potential transpiration, i.e. the rate at which water evaporates from the crop under conditions of unrestricted supply, is obtained from the prevailing weather conditions, so that the total water requirement can be calculated. The availability of water to the canopy depends on rainfall and sometimes on supplementary irrigation, on the local topography and on the physical properties of the soil. The rate at which water is actually transpired by the crop depends on the interaction between evaporative demand and soil water conditions. The water content in the root zone is calculated for each day during the growing season by means of a water balance. The terms of the balance are schematically presented in Figure 2. Incoming water comprises precipitation (P), effective irrigation (I_e) and capillary rise from the groundwater table (CR) where there is one. Water can be lost through deep drainage (D) from soil wetter than field capacity, surface run-off (SR), direct evaporation from the soil surface (E) or transpiration by the crop (T). Each of these terms is quantified according to soil physical principles. The change in water content in the root zone during a particular time interval is the difference between the income and loss of water, allowing for the effects of the penetration of roots into deeper layers of the profile. The course of the water balance indicates periods when water is in excess or deficit, both of which decrease growth rates compared to those in the highest hierarchical production situation. The model can also estimate the number of hours during which field work is possible, since they are determined mainly by the water content of the top layer of the soil.

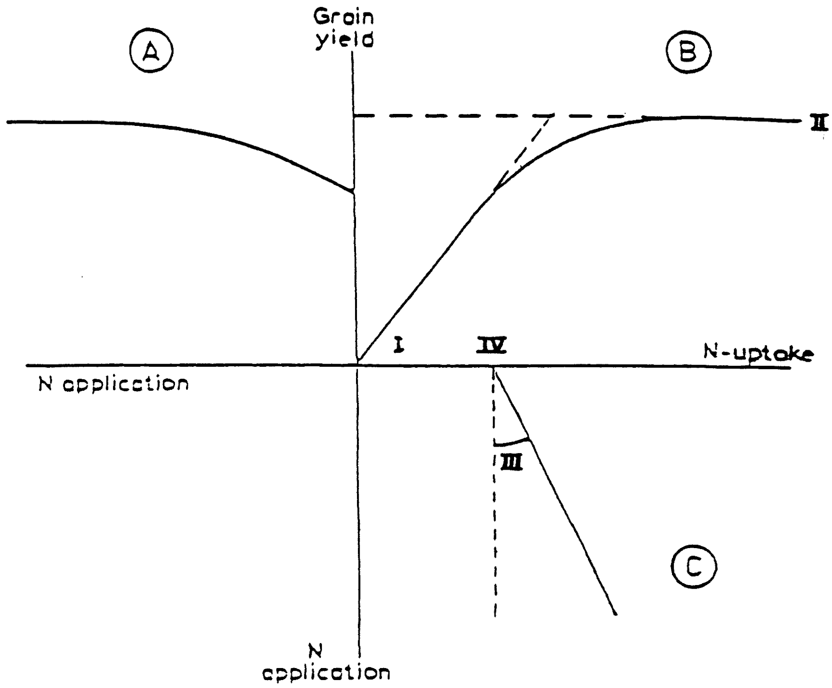

Fig. 3. The relation between yield and nutrient application (A), yield and nutrient uptake (B), and nutrient application and nutrient uptake (C).

In the **third hierarchical production situation**, lack of the plant nutrients nitrogen and phosphorus may at times limit growth. Nitrogen is particularly important because of the amounts required each year and because it is mobile in the soil-plant-atmosphere system. The effects of nitrogen availability on yield and the amount of nitrogen required to achieve the yield calculated for the second hierarchical production situation, are not treated in a dynamic way, as the present knowledge of the dynamics of nitrogen in the soil is hardly sufficient for such a treatment. Instead, the effects are quantified by considering separately the relation between the amount of nitrogen taken up by the crop and yield, and that between the amount of fertilizer applied and the amount which is taken up or recovered (Figure 3). The relation between yield and uptake (quadrant B) is of the well-known saturation type, but the relation between application and uptake is linear in the relevant range.

The problem of nitrogen nutrition can be separated into four partial problems, schematically indicated by roman numerals in Figure 3. The initial slope of the uptake-yield curve (I) is crop-specific and in most cases independent of soil type and weather conditions. For cereals, the value amounts to about 70 kg of grain per kg N absorbed by the crop, provided N is the factor limiting growth. The maximum yield level (II) with sufficient mineral nutrients and nitrogen, has been considered in the second production situation. The hierarchical structure of the analysis assumes that the nitrogen supply is independent of the water balance. This assumption is debatable, because the moisture regime in the soil affects both denitrification and leaching, and hence both the amount of nitrogen available from natural sources (the base uptake (IV)) and the recovery of the applied fertilizer (III). Conversely, if nutrient supply limits growth, the amount and rate of water use by the crop may be affected. Dynamic models describing the processes of nitrogen uptake by plants, mineralization and immobilization by soil microorganisms, leaching and denitrification are being developed at the moment.

The interaction between nitrogen supply and moisture regime is, however, difficult to disentangle and the dynamics of nitrogen in the soil are complex. In most cases quantitative treatment consequently requires too much detailed knowledge of the actual growing conditions. Therefore, estimation of the recovery of applied fertilizer, i.e. the fraction of the annual application which is accumulated by the crop in its above-ground parts, is to a large extent based on the results of local fertilizer experiments. Preferably, it should be deduced from experiments in which the same amounts of fertilizer have been applied for a number of years. The same also holds for the estimation of the base uptake of nitrogen from the soil. This amount is often so small, that a first approximation may be obtained from available yield data, using slope I combined with data on soil chemical composition, if available. For the time being, this is often more reliable than the use of existing models of nitrogen transformations in the soil.

Phosphorus is treated in a similar fashion. The recovery of phosphorus from fertilizer application depends, among other factors, on the presence or absence of soil constituents such as aluminium and calcium in forms that render phosphorus unavailable for the plants. Moreover, contrary to the case of nitrogen, the recovery fraction is often different for different application rates, and the transition from the nutrient-limited to the nutrient-saturated condition is generally more gradual for phosphorus.

The **fourth hierarchical production situation** pertains when hardly any external inputs are used, as in many forms of subsistence farming. A generalized treatment for this situation could be based on the concept that under such conditions any farming system moves towards an equilibrium level. The associated yield is then dictated by the balance between input and output of the main factor which limits growth. However, it is often difficult to identify that factor; and moreover in many cases growth is limited by a combination of several factors. That is one of the reasons why it is often impossible unequivocally to specify measures that will increase yield in a particular situation. In fact almost any improvement in agricultural practice may have that effect. The yield at the equilibrium level must be above a certain minimum to make the physical effort of farming worthwhile.

At any production level weeds, pests, and diseases may interfere with crop production. Weeds, broadly defined as unwanted plants, compete with the crop for essential growth factors, such as solar energy, nutrients or water; and in dense stands they can substantially reduce crop yields. Some crop species are more competitive than others: uncontrolled weeds have smaller effects on their yields. As the competition between crop plants and weeds is dynamic, weeding has to be precisely timed to maximize the effect on yield. It is possible to specify for each crop a critical development stage or stages when the effects of weed competition are largest. The length of this critical period, relative to the total length of the growth cycle, determines the required intensity of weeding for unrestricted crop growth.

The influence of pests and diseases on crop yields varies strongly from location to location, and from season to season in relation, among other factors, to environmental conditions and management level. Consequently, any estimate of average losses can be no more than a very general approximation. In the analysis such approximations are used, however, for lack of more accurate detailed information.

Labour Requirements

In calculating yield levels in the second hierarchical production situation, the workability of the soil is also taken into account. This makes it possible to draw up crop calendars. It is usually relatively easy to indicate the activities that have to be carried out in the course of a crop growth cycle. The time required for these activities depends on the applied level of technique. Four such levels are distinguished: manual labour, animal traction, light mechanical equipment and complete mechanization.

Task-times for recurring mechanized operations are reasonably well established. However, agricultural research has given hardly any attention to manual labour and animal traction. Labour requirements are only very approximate. They probably vary substantially from place to place and year to year. They have had to be inferred from studies which were not originally intended for the purpose.

Labour requirements at the various levels of technique may vary considerably: 500 hours per ha for manual spading, 25 for ploughing with buffaloes, 15 for ploughing with a two-wheeled tractor and 5 for ploughing with a four-wheeled tractor. One weeding with a hoe takes about 100 hours per ha, but with herbicides and tractor-driven spray equipment only a few hours. Pest and disease control virtually always involves biocides. The major problem here is to estimate not the time requirements for control, but the yield loss without control, and to judge the necessity of the operation.

In summary, indicative task times are available at the four levels of technique, but the scatter in the basic data is such that without detailed local knowledge, it is not possible usefully to differentiate between various soil types, different levels of management and so on.

Results of the Analysis

The analysis described in the previous sections has been applied to assess the possibilities for the growth and yield of food crops in some African countries. As an example sorghum yields in Burkina Faso will be treated in this section. Only the first three hierarchical production levels are considered, as the local situation was not well enough known to allow useful analysis of the fourth production level.

Data base

Crop: The calculations assume a photo-insensitive sorghum cultivar with a total growth cycle between 90 and 140 days, depending on the prevailing temperature regime.

Climate: The country is divided into four agro-climatic zones based on average annual rainfall. These zones correspond closely to the classical vegetation belts of the West African savannah, i.e. Sahel, northern Sudan, southern Sudan and Guinea zones (Keay 1959). The climate is characterized by long term average monthly data. Rainfall is defined by the average monthly precipitation and the average number of rainy days. Rainfall distribution is derived from a random distribution of the rainfall events over the month. The model can also accommodate measured rainfall distribution, but such data are seldom available.

Soils. The classification of soils includes their geographical distribution and their chemical and physical properties. The classification is based on the soil map on a scale of 1:500 000 of the soil resources of Burkina Faso (Boulet 1976), supplemented by more detailed information from soil surveys and soil chemical analyses. Boulet's map, developed to classify agricultural suitability, distinguishes 15 main agronomic units, based on soil fertility factors, soil depth, soil texture and drainage class. The information provided on these factors is, however, not very detailed, so that the fertility status of the soil units and their physical characteristics had to be assessed subjectively.

Production calculations

Potential yields. As a first step in the analysis potential yield levels are calculated for a number of locations in the country. These yields are determined by the genetic characteristics of the crop and the prevailing climatic conditions, which govern the length of the growth period and the rate of assimilation. These calculations indicate a yield potential of 4.8 t dry matter ha^{-1} for a sorghum crop grown at Ouahigouya and emerging on July 1. The total growth cycle of this crop is 98 days and anthesis takes place 64 days after emergence. A crop emerging on June 1 at Bobo Dioulasso yields 4.7 t ha^{-1} under optimum conditions, with a total growth cycle of 131 days and anthesis 93 days after emergence. The difference in grain yield is small, despite the considerable difference in growth duration, because the lengths of the grain filling periods differ far less, 34 days for Ouahigoya versus 38 days for Bobo Dioulasso, and the longer pre-anthesis phase in Bobo Dioulasso produces much more vegetative material, the maintenance of which requires a substantial proportion of the post-anthesis assimilates. These phenomena are reflected in the harvest index values, 0.27 and 0.23 for Ouahigouya and Bobo Dioulasso, respectively.

Potential yields for the other climatic zones differ very little from those discussed above.

Water-limited yields: For the calculation of water-limited yields, the rainfall — amount and distribution — and the physical properties of the soil — maximum water holding capacity, water transport characteristics and rooting depth — are taken into account. In actual farming practice, the crop will be sown after the first effective rains, i.e. when the soil is wet enough to permit relatively easy working and ensure proper germination. In practice, these conditions vary from year to year, from place to place and also between soil types. In the present study a fixed sowing date has been assumed, coresponding to the average sowing date for a given climatic region. In addition, 2 cm of available water are assumed to be present in the soil at emergence.

The actual distribution of rainfall has considerable influence on the production potential, especially under these semi-arid conditions, since it determines how precipitation is partitioned between surface run-off and infiltration on one hand, and percolation, evaporation from the soil surface and transpiration on the other.

As explained earlier, the rainfall regime is characterized in the model by the average monthly precipitation, and the average number of rainy days per month. At one extreme one could assume that all showers are of equal size, spaced uniformly through the month. At the other, rainfall could be taken to be concentrated in

Table 1. Calculated water-limited sorghum yields for different soil types located in the Ouahigouya area, Burkina Faso.

Soil texture	Maximum rooting depth (cm)	Grain yield ($t\ ha^{-1}$)	Harvest index
sand/sandy clay	20	2.1	0.19
id.	70	4.0	0.23
id.	120	4.5	0.26
sand/clayey sand	20	2.8	0.19
id.	70	3.7	0.22
id.	120	4.3	0.25
clay loam	120	4.9	0.30

as short a period as possible, in the middle of the month or at the beginning or the end.

In the model the assumed 'actual' rainfall distribution is determined by applying a random number generator. To account partly for the stochastic effect, the reported yields are the averages of a variable number of runs (mostly between 4 and 10) with different rainfall distribution patterns.

In Table 1 calculated yields, limited by water only, are given for soils with different properties, located in the Ouahigouya region, with an average rainfall during the growing season of 542 mm. The main factor affecting the yield decrease through water stress is the potential rooting depth. In shallow soils (rooting depth 20 cm), so little water can be stored, that a substantial proportion of the annual precipitation is lost by percolation, leading to prolonged periods of water stress and yield decreases of up to 40 percent of the potential. In soils permitting rooting to a depth of 70 cm, yield decreases hardly exceed 20 percent, and in deep soils the decrease is generally less than 10 percent. In this area the shallow soils occupy less than 15 percent of the total area, so that water shortage decreases sorghum production in the region to a modest extent only. This may seem surprizing, but the sorghum cultivars used in the region are adapted to the 'average' climatic conditions.

It is interesting that on the deep clay loam soil (Table 1) the yield under natural rainfall exceeds the 'potential' yield. In this case mild water stress during the pre-anthesis phase limits vegetative growth, but not sufficently to decrease the interception of light. The smaller vegetative biomass requires less assimilate for maintenance in the post-anthesis phase, so that more assimilate is available for grain filling, and the harvest index is larger. A converse phenomenon is well-known in fertilizer experiments on cereals under semi-arid conditions: fertilizers — particularly nitrogen fertilizer — may increase vegetative growth, and consequently the rate of water use. The result may then be that water becomes deficient in the post-anthesis phase so that both harvest index and grain yield are dramatically lessened.

Water-limited yields for sorghum have been calculated for the whole of Burkina Faso, taking into account climatic zonation and spatial distribution of soil types. The results of this analysis are illustrated in Figure 4.

Some of the consequences of using average monthly precipitation, and an average number of rainy days, instead of measured rainfall distribution could be tested with a 22-year set of rainfall data available from Niamey, Niger. The model was run both with generated rainfall patterns (for 50 years) and with the 22 years of measured rainfall for the same sorghum cultivar used in the Burkina Faso study. For the generated rainfall pattern the average calculated yield was 2335 $\pm$ 618 kg ha^{-1}. The 22-year measured rainfall data led to a yield of 2348 $\pm$ 1328 kg ha^{-1}. The estimated average yields are thus very similar, but the variability was much greater for the measured rainfall patterns. The extreme values were also more variable: using the 22-year measured rainfall maximum and minimum yields were 4381 and 105 kg ha^{-1}, respectively, and with the generated rainfall pattern 3664 and 1195 kg ha^{-1}. Thus, the generated rainfall pattern only partly represents the erratic nature of rainfall in semi-arid regions.

Nutrient-limited production: In addition to water and carbon dioxide, plants need inorganic elements to produce biomass and yield. Shortage of nitrogen or mineral nutrients affects the assimilatory capacity of the green plants, the distribution of assimilates between the various plant organs (shoot/root ratio), the conversion of primary photosynthates into structural plant material ('growth'), and consequently the yield.

108 BFSORGH2 Sorghum (water lim.) BFASO

					coverage	
		0	. . .	6507 cells		54.2%
1	1111	1	no dry matter production	114 cells	0.9%	
2	2222	2	1-150 kg/ha	1 cells	0.0%	
3	3333	6	1075-1650 kg/ha	18 cells	0.2%	
4	4444	7	1650-2300 kg/ha	1585 cells	13.2%	
5	5555	8	2300-3525 kg/ha	1568 cells	13.1%	
6	6666	9	¨3525 kg/ha	2207 cells	18.4%	

Fig. 4. Calculated water-limited sorghum yields for Burkina Faso.

In many parts of the world the supply of nitrogen and phosphorus from natural sources is so small that uptake and yield are severely restricted, even where only a limited amount of moisture is available (Penning de Vries and Djitèye 1982, van Keulen 1975). To quantify these effects, it is first necessary to estimate the amounts of the elements available for uptake by the crop, and secondly to quantify the 'utilization efficiencies' of the elements, i.e. the ratio between the quantities taken up and the yield. As has been explained, the latter relation is linear with a slope specific to each species if the availabilities of the elements are small. The slope departs from linearity as availabilities, the concentrations of the elements in the tissue, and the yields increase. With further increases in supply, the element ceases to limit yield, and concentrations increase without affecting the yield level. These relations are relatively easy to quantify from existing experimental data (cf. van Keulen and van Heemst 1982, van Keulen 1977).

To estimate the amounts of the elements available for uptake by the crop from natural sources ('base uptake') is thus of prime importance for reliable yield estimates in unimproved systems and for quantifying the effects of fertilizer application. In spite of more than a century of work by plant nutritionists and soil chemists, there are still no objective criteria, such as generally applicable soil chemical analyses, for estimating the 'natural fertility' of a soil.

In the present study the nitrogen and phosphorus-supplying capacity of the more widespread soils in Burkina Faso have been estimated by a 'combination and analogy' method. This method employs both chemical analyses — albeit in a very complex way — and the results of fertilizer experiments (Smaling and Janssen 1986, Janssen, Guiking, van der Eijk, Smaling, and van Reuler 1986, Guiking, Janssen and van der Eijk 1982). The results of this analysis are presented in Table 2, calibrated for a maize crop. As the processes which determine the availability of nutrients to the crop proceed at a more or less constant rate, the total amounts are approximately proportional to the length of the crop growth cycle. As the 'average' growth cycle of sorghum is about similar to that of the local maize cultivars, the same data may be applied.

In Burkina Faso, where the soils are generally chemically poor, soil fertility classes (Table 2) E1 and E2 are prevalent, covering about 75 percent of the arable area, with the remainder divided about equally between D and E3.

To convert nutrient uptake to yield, an estimate has to be made of the harvest index of the crop, i.e. the ratio between weight of marketable product and total above-ground dry weight at harvest, and of the limiting nutrient concentrations in the harvested product. For sorghum in Burkina Faso an average harvest index of 0.30 is assumed (grain/stover ratio 0.43). The absolute minimum concentrations of nitrogen and phosphorus in the harvested product for sorghum are about equal to those for other cereals, i.e. about 0.01 kg kg^{-1} in the grain and 0.004 kg kg^{-1} in the stover for nitrogen and about 0.0011 and 0.0005 for phosphorus, respectively (van Keulen and van Heemst 1982). However, under field conditions, especially when water may be deficient during part of the growing period these minimum values are seldom reached. For the calculations, values of 0.015 kg kg^{-1} for N and 0.0017 kg kg^{-1} for P in the grain, and of 0.006 kg kg^{-1} for N and 0.0008 kg kg^{-1} for P in the stover, have been assumed. Combining these numbers with the harvest index leads to a 'utilization efficiency' of 34.5 kg of grain per kg nitrogen taken up, and 280 kg of grain per kg phosphorus taken up.

When these values are combined with the nutrient supplying capacity of the soils in Burkina Faso (Table 2) it follows that the nutrient-determined yield levels are 1035 (D, N-limited), 760 (E1, N-limited), 518 (E2, N-limited) and 276 (E3, N-limited) kg ha^{-1}, respectively. The most important limiting factor is thus the nitrogen supply, but because the availability of phosphorus is also very small, only very small increases in yield are likely if nitrogen fertilizer is given without concurrent application of phosphorus (Penning de Vries and Djitèye 1982).

Comparing the nutrient-limited yields with the water-limited yields (Table 1) leads to the conclusion that under practically all conditions the natural soil fertility is the constraining factor for sorghum production in Burkina Faso. Similar conclusions were also reached for millet and cassava in the country, and for food crops in other African countries, such as Ghana and Kenya. This analysis thus confirms the conclusion drawn from detailed analyses of the growth of natural rangeland in West Africa, that despite low and erratic rainfall, the main constraint on crop production is the extremely poor fertility of the soil. Attempts to improve food output under these conditions, without a considerable increase in the availability of plant nutrients, seem certain to fail.

Table 2. Soil fertility classes, corresponding nutrient availability levels for N, P and K, and indicative values for nutrient uptake by maize, Burkina Faso.

Fertility class	Availability level[1)]			Nutrient uptake (kg ha^{-1}		
	N	P	K	N	P	K
A	1	1 or 2	1	130	12.3	140
B	2	2	1	95	8.0	120
C	2	2 or 3	2	75	5.3	70
D	3 or 4	3	2 or 3	30	4.5	40
E1	4	3	3	22	3.5	35
E2	4	4	3	15	2.5	30
E3	4	4	4	8	2.0	20

1) For each nutrient four availability levels are distinguished, corresponding to maize yields of more than 5, 2.5–5, 1.25–2.5, and less than 1.25 t ha^{-1}.

Output of the Analysis

After calculating the various yield levels attainable under well-defined constraints, as explained in the preceding section, the analysis continues with an evaluation of the inputs required to achieve these yields (Figure 1).

An example of the type of information generated in this process is given in Table 3. This table refers again to sorghum cultivation in Burkina Faso. This table is not a formal computer output, but has been constructed as an example.

The activity codes refer to growth of a specific crop (or cultivar), cultivated on a specific land type (or land unit), under specific climatic conditions, with a specific sowing date, in this case at three management levels, i.e. I with complete irrigation and fertilizer application, II without irrigation and with moderate fertilizer application to achieve water-limited yields, and III under unimproved conditions. Because these data are intended for further use in an agricultural supply model (LP model), the outputs have a negative sign, i.e. YIELD (grain) and STYLD (stover), while the required inputs have a positive sign.

Table 3. Example of output of the model, giving yield and required farm and non-farm inputs for given production situations.

Resource code	Activity code CXIWL2	Activity code CXIIWL2	Activity code CXIIIWL2
1. YIELD	−4757.0	−2773.0	−760.0
2. STYLD	−12974.0	−11393.0	−3796.0
3. FERTILN	86.0	194.0	0.0
4. FERTILP	10.0	91.0	0.0
5. FERTCP	1.0	1.0	0.0
6. WEEDCT1	1.0	1.0	1.0
7. WEEDCT2	1.0	1.0	1.0
8. IRRCAP	1.0	0.0	0.0
9. LODGPREV	1.0	1.0	0.0
10. PDCRCAP	0.0	1.0	0.0
11. PRPRCAP	1.0	1.0	1.0
12. SGSDCAP	1.0	1.0	1.0
13. HCARCT	1.0	1.0	1.0
14. HCWRCT	4757.0	2773.0	760.0
15. HCSRCT	12974.0	11393.0	3796.0

Table 4. Coefficients to create 'fertilizer capacity' at three levels of technique.

Resource code	T1	T2	T3
HOURMAN	35.0	2.0	2.0
HOURANIM	0.0	2.0	0.0
HOURLTRC	0.0	0.0	2.0
FUEL	0.0	0.0	2.5
HFERTEQ	0.0	2.0	2.0
HCARTS	0.0	2.0	2.0
FERTCP	−1.0	−1.0	−1.0

FERTILN and FERTILP specify the amounts of nitrogenous and phosphorus fertilizers required to achieve the yields. They were calculated on the basis of the yield-uptake relation treated in the preceding section, using fertilizer uptake efficiencies (recovery fractions) of 0.3 and 0.07 for nitrogen and phosphorus fertilizers, respectively.

The resource codes 5−13, having either a 0 (if not used) or 1 (if used) refer to 'capacities', such as 'capacity for fertilizer application' (FERTCP) or 'capacity for weeding' (WEEDCT). These coefficients are further transferred to a file that contains labour coefficients etc. for specific agricultural activities. As an example the 'capacity for fertilizer application' coefficients are given in Table 4, for either broadcast application by hand (T1), requiring 35 man-hours ha^{-1}, or for using animal-drawn equipment, requiring 2 man-hours and 2 animal-hours ha^{-1}, in addition to spreading equipment (T2), or for using light mechanization, requiring also two hours ha^{-1} but in addition 2.5 l of fuel per operating hour (T3).

Hence, after transposition of the relevant coefficients, yield possibilities are generated with required physical inputs both in material terms and in labour. These data can then be used for further economic analyses or for estimating possibilities for regional development.

Conclusions

The method presented in this paper represents a coherent framework for quantitative land evaluation, in which the properties of crops, soils, and weather are combined in such a way that estimates of the yield potentials can be made. These estimates permit evaluation of the major constraints in any particular situation and of the requirements for eliminating these constraints.

By combining the results of these calculations on a regional or a country scale, agro-ecological zones (in whatever way they may be defined) can be specified.

It must be concluded, however, based on operating this system for some time, that the availability and quality of data are the principal limitations on accurate predictions of yield.

It should be realized of course that the accuracy of yield predictions is also limited by the unpredictable and erratic nature of the weather, not incorporated explicitly in the model. This further limits the accuracy of predictions of the ways in which actual farming systems are likely to develop in a region.

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ACRONYMS

ORSTOM	Office de Recherche Scientifique et Technique Outremer (France)
PUDOC	Centre for Agricultural Publishing and Documentation (The Netherlands)