To what extent can agricultural production be expanded?

van Keulen H., De Wit C.T.

Workshop agroecology

Paris : CIHEAM
Options Méditerranéennes : Série Etudes; n. 1984-I

1984
pages 55-76

TO WHAT EXTENT CAN AGRICULTURAL PRODUCTION BE EXPANDED?

H. van Keulen and C. T. de Wit
Centre for Agrobiological Research
P. O. Box 14
Wageningen, The Netherlands.

Key Words: Models, Crop Production, Environment, Inputs.

ABSTRACT

The objective of this paper is to discuss the capabilities of several agronomic models, their data requirements, and the possibilities for their use in predicting agricultural productivity. The models describe how crop production is affected by the physical environment and also consider the role of yield-increasing material inputs such as irrigation water and fertilizer. With these models it is possible to judge the capacity for expansion of agricultural production in a given environment. It is not likely that one can predict agricultural production capacity from knowledge of the rates for natural vegetation without detailed understanding of the factors influencing production.

RESUMEN

El objetivo de este informe, es la discusión de las capacidades de varios modelos agronómicos, los datos que se requieren y sus posibilidades de utilización en la predicción de la productividad agrícola. Los modelos describen cómo el medio ambiente físico afecta la producción de los cultivos e igualmente considera el papel de los inputs materiales para el incremento del rendimiento, tales como regadío y fertilización. Con estos modelos, es posible juzgar la capacidad de expansión de la producción agrícola en un medio ambiente dado. No es probable que se pueda predecir la capacidad de producción agrícola, a partir del conocimiento de las tasas de producción de la vegetación natural, sin una comprensión detallada de los factores que influyen en dicha producción.

INTRODUCTION

Agriculture may be defined as the human activity that produces useful organic material (food etc.) by means of plants and animals with the sun as the source of energy. The minimum resources needed are few in number: labour and land with some sun and rain. For many soils and climates, farming systems have developed that enable subsistence in food, clothing, shelter and fuel, provided sufficient land is available. Unless conditions are very favourable, these farming systems do not produce much more than bare necessities. However, man is an animal species that thrives on brick and concrete and the development of civilisation is very much intertwined with that of urban life. To maintain a substantial urban population, the productivity of the rural population has to be much higher than the subsistence level. This is only possible if the urban sector produces industrial means of production for the farmers within an economic structure that provides sufficient incentives for their use. Although a sharp distinction is not possible, these means of production may be classified as labour saving, yield increasing and yield protecting as with machines, fertilizers and pesticides. Only yield protecting inputs require little energy for their manufacture and use, although their development would hardly have occurred independent from the chemical industry. With some exaggeration modern agriculture could therefore as well be defined as the human activity that transforms inedible fossil energy (mineral oil and natural gas) into edible energy by means of plants, animals and the sun (Pimentel, this volume).

Agricultural production can be expanded in principle in two ways, either by expanding the area under cultivation or by increasing the yield per unit area. However, land which can be reclaimed by simple means within the social-economic framework of the family or the village is becoming scarce, so that Western technology is indispensable for further reclamation. Hence, to expand agricultural production, either more machinery has to be used to extend the surface under cultivation or more inputs like fertilizer to increase the yield per unit surface. Both venues require an open economy in which the farmer makes sufficient money for his agricultural products to pay for the necessary means of production. Too often the terms of trade are not so favourable, but claims that is possible to improve the food situation in the world substantially without these technical means are not justified in view of what is known about the agricultural production process.

The prospects for improvement of the food situation depend therefore also on the national and international political and economic dimensions. Policies at the international level that are aimed at stabilisation of the prices on the world market at a fair level and promote the opportunities of developing countries to penetrate the markets of the rich countries may create a more favourable position for developing and poor countries. These must then be complemented by national development strategies that enable farmers to increase their output and that improve in particular the production opportunities for the poor. This broad range of problems has been the focus of research undertaken by the Centre for World Food Studies in Amsterdam and Wageningen. For this purpose national economic models with the main emphasis on the agricultural sector have been developed and linked into a global model with the aim of analysing and improving policies of national governments and international agencies. These national economic models contain agricultural production modules that account for the possibilities of production differentiated with respect to region and commodity. The latter part of work of the Centre focusses on the physical and agronomic factors that determine agricultural production in technical terms and is the subject of this presentation.

THE METHOD OF ANALYSIS

In this paper the processes that govern the agricultural possibilities in a region are treated with an eye on making quantitative estimates of the yield levels of crops under various constraints and of the inputs that are needed for their realization.

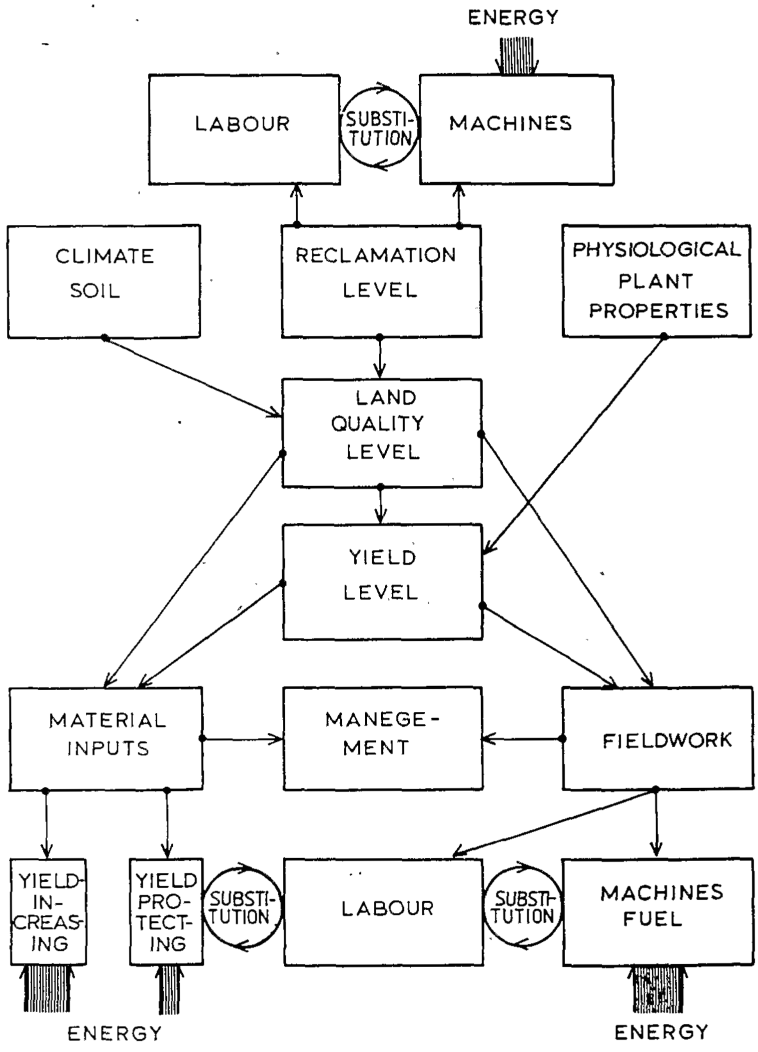
For this purpose, a hierarchical procedure is adopted which is schematically presented in Figure 1. The rectangles in the second row represent the factors that ultimately determine the production potential. Climate and soil are fixed properties for a given region and, in combination with the level of reclamation, characterize the land quality level. The characteristics of agricultural crops may be changed by breeding, the scope for improvements in this respect being reasonably well-defined. For a given land quality level, the yield potential is therefore fixed for a fairly long period of time, and it may be calculated with reasonable accuracy.

In the further analysis, the goal is not to define a production function describing the relationship between the yield and all possible combinations of growth factors, because, by the nature of the agricultural production process, no unique solution to such a production function exists. Instead, a reasonable combination of growth factors should be established that will result in the yield level that is plausible in view of the land quality level. Thus, the yield level is considered concurrently as a dependent variable, determined by crop characteristics and land quality level, and as an independent variable, dictating the required input combination for its realization. This is reflected by the direction of the arrows in Figure 1: towards the yield level as well as away from the yield level.

With respect to the required inputs, a distinction is made between field work and material inputs. The necessary field work can be described in physical terms, for example, the requirements for plowing, 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 as they are needed anyway. The total length of the period available to do the field work depends, however, strongly on soil type and weather conditions. In performing field work, considerable substitution is possible between manual labour and activities relying on heavy mechanical equipment and their associated fossil energy requirements.

The material inputs are further divided into yield-increasing materials, and yield-protecting materials. The required amounts of yield-increasing materials such as water, minerals and nitrogen, are directly influenced by the required yield level, soil type and weather conditions. Characteristic for these production materials is that they cannot be substituted by labour. This is in contrast to the yield protecting materials, biocides, for which alternatives are available, e. g.

Figure 1. Schematic representation of the hierarchical analysis procedure.



labour-intensive weeding versus the use of herbicides and manual insect eradication versus spray-killing.

The land quality level is, on one hand, determined by intrinsic soil properties and the prevailing weather conditions and, on the other hand, by the level of reclamation. In a schematized set up, four levels of reclamation may be distinguished. The lowest level refers to land in an almost virgin condition where agricultural activities are limited to food gathering, fuel wood collection and extensive grazing. At the next level the land is cleared so that opportunities exist for more permanent agricultural use with or without fallow periods. The moisture regime is fully dictated by weather conditions. Flooding is avoided only if possible by simple modifications of the topography or by simple dams. The third level pertains to land improved by such measures as levelling, simple terracing and the construction of open ditches to control excess water. The final level refers to land in a favourable condition for crop growth, well levelled, with complete water control and the necessary infrastructure. Sufficient water is available to allow irrigation as required.

Apart from defining the present status of the land in a given region, it is also important to quantify the activities necessary to bring the land to a higher reclamation level. This applies especially to the amount of vegetation and stones to be removed, the amount of soil to be moved and the infrastructure that must be built. This aspect of the analysis is presented in the first row of the diagram in Figure 1. Reclamation can be carried out with manual labour, however it has been said already that this is often only a theoretical possibility, since most of the acreage that could easily be reclaimed has already been developed. The activities to be performed are therefore defined for various technological levels in terms of the available equipment.

In further analysis four hierarchically ordered production situations are distinguished. At the *highest hierarchical production situation* water, minerals, and nitrogen are in optimal supply. Crop yield is then only determined by the type of crop, the prevailing level of irradiance, and the temperature regime. For most regions, sufficient experimental data are available to judge the feasibility of growing the major crops and to define so-called cropping calendars, stipulating time of sowing, emergence, flowering, ripening, etc. Theoretical considerations and field data may be combined to apply models for the relevant crops, yielding the time course of dry matter production and transpiration, and economic yield as outputs.

For the *second hierarchical production situation,* it is also assumed that the supply of nitrogen and minerals is optimal, but the influence of moisture availability on transpiration and production of the crop is taken into account. Water supply to the canopy is dependent mainly on rainfall and sometimes on supplementary irrigation, whereas water consumption is mainly determined by environmental conditions. The physical properties of the soil and the climatic conditions are now of major importance. On the basis of these data, the water balance is calculated. This enables determination of periods with excess or shortage of water, resulting in reduced growth rates compared with those at the first hierarchical level. The models also enable the calculation of the number of workable hours in the field: an important parameter in the analysis of farming systems.

At the *third hierarchical production situation,* the plant nutrients nitrogen and phosphorus may at times limit growth, apart from water and irradiance. Special emphasis is given to nitrogen due to the amounts required each year, its costs and its mobility in the soil-plant-atmosphere system. The effect of nitrogen on production and the amount of nitrogen fertilizer required to achieve a higher hierarchical production level are determined by considering separately the relation between the amount of nitrogen that is taken up by the crop and the yield and that between this uptake and the amount of fertilizer applied, or its recovery. Phosphorus is treated in a similar fashion.

The recovery of nitrogen from fertilizer depends on the relative importance and the timing of the processes of uptake by the plants, mineralization from decomposing organic material, immobilization by soil-microbes, leaching and denitrification (formation of gaseous nitrogen). These processes are being modelled, but for the time being it is still necessary to rely on the results of fertilizer experiments. This holds also for the determination of the amount of nitrogen that is available from natural sources.The recovery of phosphorus from fertilizer depends among others on the presence of soil constituents as aluminium and calcium in forms that interact with that element, thus affecting its availability to the plants. The interaction between nitrogen and phosphorus fertilizer is treated by considering the P / N ratio in the plant tissue. Whether minerals like potassium, calcium and magnesium are in sufficient supply and the pH is in the proper range is most conveniently evaluated by means of soil analysis.

Subsistence farming may be treated as a fourth hierarchical production situation. Then hardly any external inputs are used. A generalized treatment may be based on the concept that under these conditions any farming system moves towards *an equilibrium for the input and ouput of the* main limiting growth factors. The yield level at this equilibrium must be above a certain minimum to make the effort of farming worthwhile. Plant nutrients and then especially nitrogen, limit ultimately the production in many cases. This implies that the effect of improved cultivation practices has to be judged on the basis of their temporal or permanent effects on the uptake of the limiting element. Since the possibilities to improve this uptake are very restricted under conditions of low soil fertility, the effects of improved crop husbandry practices other than fertilizer application, cannot be cumulative, whether this refers to improved varieties, better cultivation or pest and disease control.

At any production level pests, diseases and weeds may interfere. Their effect is treated by making a distinction between diseases that are of special importance in high yield situations and those in low yield situations. Different types of damage may be distinguished which are evaluated in terms of damage levels.

THE ACTUAL CALCULATION PROCEDURE

Data requirements

In order to perform the calculations in a given region both the physical environment and the relevant crop have to be specified. The necessary data can be divided into site-specific data and crop-specific data.

a. Site-specific data

To apply the model for a specific site, information must be available on its exact location, on the prevailing weather conditions, and on the properties of the soil(s) on which the crops are grown. It should be noted, that a distinction has to be made between weather and climate, in the sense that for a comparison with actual field data in a specific crop year the actual metorological conditions of that year, the weather, must be known, whereas for more general purposes, such as estimation of the production potential of a region, long-term average values of meteorological conditions, the climate, may be used.

The necessary meteorological data consists of:

—Radiation: the amount of sun energy reaching the earth's surface. This characteristic is necessary for the calculation of both CO_2 assimilation and evapotranspiration.

—Air temperature: average daily air temperature is applied, obtained as the arithmetic average of measured maximum and minimum temperatures.

—Air humidity: the degree of water saturation of the atmosphere, especially important for the calculation of evapotranspiration. Various indicators can be used such as relative humidity, dew point temperature, or dry and wet bulb temperature.

—Wind speed: necessary for the calculation of evapotranspiration.

—Precipitation: necessary for the calculation of the water balance.

The soil is characterized by its physical as well as its chemical properties. The former are those properties that are related to storage and transport processes in the soil, such as storage and transport of water, of solutes and of heat. In the model they play mainly a role in the processes affecting the water balance.

—Soil moisture retention curve: this curve presents the relation between the volumetric moisture content in the soil and the force that must be exerted to remove moisture from the soil; with decreasing moisture content, the remaining water is held in pores of increasingly smaller size and is therefore more difficult to remove. The relation between moisture content and force is also referred to as the soil moisture characteristic, or the pF curve.

—Hydraulic conductivity of the soil: this characteristic describes the possibility for transport of moisture through the soil. Because of the same phenomenon described above, the conductivity is also a function of the soil moisture content.

The chemical properties of the soil, relevant to the model, are mainly related to plant nutrition such as the amount of the major elements nitrogen, phosphorus and potassium that can be supplied by the soil, the "natural fertility", and the mode and intensity of interaction between the soil and the nutrient elements applied as chemical fertilizers. In general, the results of routine soil chemical analyses, such as those carried out in the framework of, for instance, soil surveys, do not permit estimation of these properties. For that purpose, special analyses have to be carried out or existing ones must be interpreted in combination with results of fertilizer experiments, involving different crops. As a first approximation data deduced from past fertilizer experiments may be used, where necessary adapted for different crops.

b. Crop-specific data

It is obvious that important differences exist among agricultural crops: potatoes grow differently from paddy and cassava appears and behaves completely different from maize. Therefore, each crop must be presented by its own specific characteristics. The following ones are taken into account.

Assimilation characteristics: these refer to the properties of the plant with respect to the process of CO_2 fixation by green leaves in dependence of radiation and temperature. A distinction is made between crops possessing the C_3 type of photosynthetic pathway such as small grains, including rice, all leguminous crops etc., and those having the C_4 type of photosynthetic pathway, like maize, sorghum and sugarcane. Species having the C_4 photosynthetic pathway originate in general from tropical regions. They exhibit higher rates of CO_2 fixation, especially at high levels of radiation, but are also more sensitive to lower temperatures. In the last decade much research has been carried out to determine the photosynthetic pathway of various plant species, so that for virtually all agricultural crops this characteristic is known. Programs are available to calculate the crop assimilation rate from leaf-photosynthesis data, leaf area, leaf distribution and the amount and distribution of incoming radiation.

Respiration characteristics: plants, like all living organisms, respire to obtain energy for biological functioning. Hence, part of the energy fixed in the assimilation process is utilized for respiratory processes (Penning De Vries, 1974). Two main components can be distinguished:

Maintenance respiration, which provides energy for the maintenance of existing cell and organ structures and their functioning. The magnitude of total maintenance respiration is therefore proportional to total biomass and is influenced by the prevailing temperature conditions. The proportionality factor, the relative maintenance respiration rate, is dependent on the chemical composition of the structural plant material, which is not identical for all crops, nor for all organs of one crop. Therefore, specific values of the relative maintenance respiration rate are introduced per crop and per organ.

Growth respiration, associated with the conversion of primary photosynthates into structural plant material. Structural plant material consists of chemical compounds such as carbohydrates, proteins, lipids, etc. These are formed from primary assimilates, which are essentially a mixture of simple carbohydrates and amino-acids. During the chemical reactions involved in this conversion, weight losses are incurred. The magnitude of these losses depends on the chemical pathways followed and hence on the composition of the material being formed: oil and protein rich soybeans have a much lower conversion efficiency than potato tubers consisting for the major part of carbohydrates. Conversion efficiencies are introduced therefore in the model for each crop and crop organ.

Crop phenology: the development pattern of a growing crop is characterized by the rate and order of appearance of vegetative and reproductive plant organs. The order of appearance is a crop characteristic and is hardly variable. The rate of appearance of, for instance, leaves is strongly determined by environmental conditions, notably temperature and daylength. In the present model, daylength is not considered because in each region species and varieties with the proper daylength reaction are supposed to be available. Both the length of the period during which vegetative organs like leaves and stems are formed and the length of the period during which the storage organs are growing, are described in terms of heat sums. A heat sum is a certain number of day-degrees that have to be accumulated - for some crops counted above a non-zero base temperature - to complete a phase; e. g. a day with an average temperature of 15 °C contributes 15 day-degrees to the heat sum for a crop with a base temperature of 0 °C. These day-degrees are accumulated from the beginning of the growth cycle. The ratio of the actual heat sum at any point in time to that required for the completion of a certain phase, is a measure of the degree of maturity of the crop and is defined as the development stage. The heat sum requirements are not only different for various crops; different varieties or cultivars of the same species may also be characterized by different heat sum requirements (short duration cultivars vs. long duration cultivars).

Distribution pattern of dry matter: the dry matter formed during plant growth is utilized for the successive or parallel production of various plant organs, such as leaves, stems, roots and storage organs such as grains, pods and tubers. The distribution pattern varies among plant species and in time, and is therefore introduced as a dynamic crop characteristic. In the model this is achieved by defining the proportion of the total dry matter increase partitioned to each of the organs during a certain period, as a function of the development stage of the crop for various species.

Nutrient requirements: to realize its full yield potential, a growing crop must be well supplied with the necessary inorganic plant nutrients. If insufficient nutrients are available to the crop, the limited amount that can be taken up by its root system from the soil is utilized as efficiently as possible by producing plant material having a minimum concentration of the limiting element. These minimum concentrations are crop specific and vary among organs i. e. the minimum concentration in the leaves differs from that in the storage organs. Crop (or crop-group) specific minimum concentrations for the storage organs and the crop residues are defined for the macronutrients.

Some results

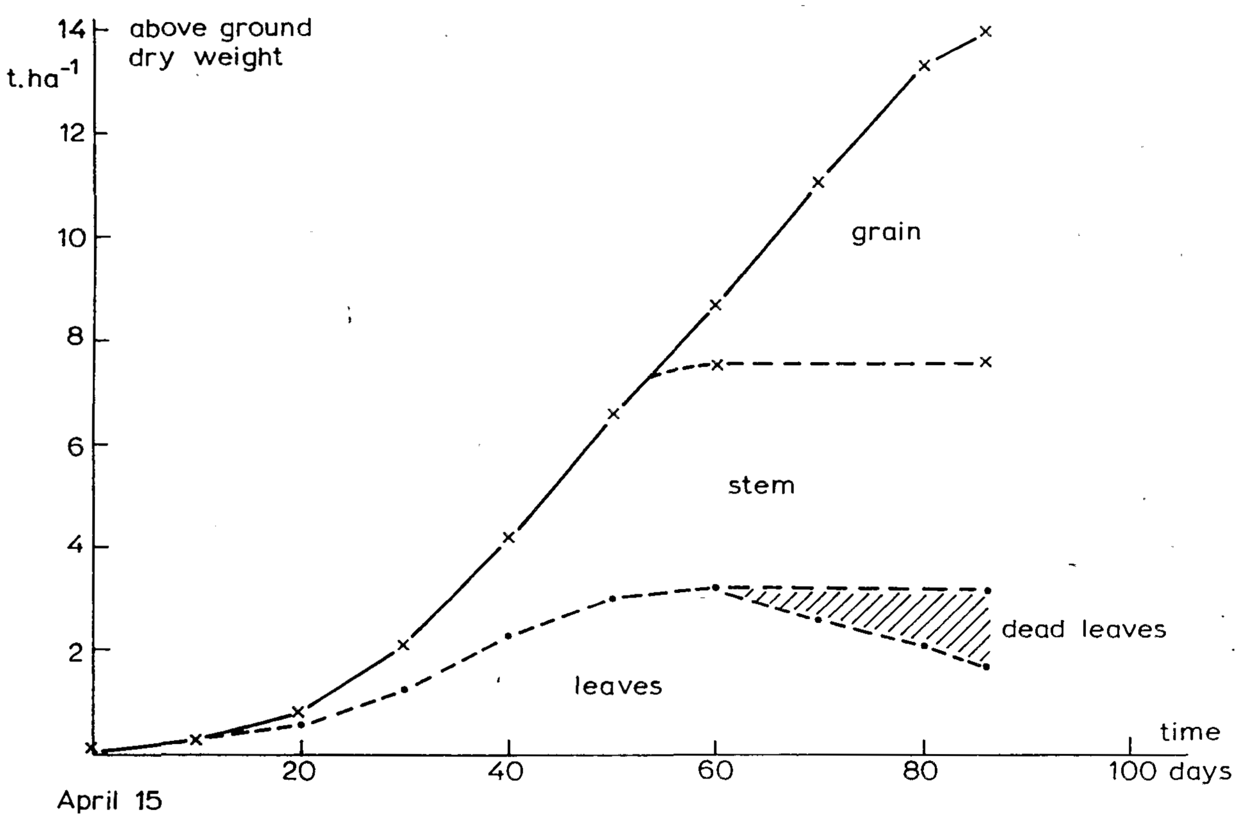
Bangladesh was one of the countries studied in the framework of the CWFS, therefore the examples refer to that country, the agrometeorological environment being characterized by long-term average climatic data. In the examples, those reported for Dhaka by the World Meteorological Organisation were used.

a. Production situation 1: potential production

The production in production situation 1 is defined as the production of a certain crop, characterized by its genetic and physiolocial properties, growing in a well-defined environment, under optimum growing conditions. Such conditions imply complete control of the water supply so that neither shortage nor excess moisture occurs, a well-balanced supply with nutrient elements avoiding periods of deficiency, no influence of competition by weeds through efficient weed control and complete control of pests and diseases.

Under such conditions the rate of accumulation of dry matter is completely determined by the amount of solar energy that can be utilized by the vegetation for the conversion of CO_2 into carbohydrates, the basis for structural plant material. The amount of energy that can be utilized is a function of the energy availability and the green area of the crop, mainly leaves, capable of intercepting and utilizing that energy. In the potential production situation, the green surface area reaches in general within a relatively short time after establishment of the crop a level that is sufficiently high to intercept all available energy, so that the crop from then on

Figure 2. Time course of total above ground dry weight and dry weight of various plant organs under optimum growing conditions for bunded rice transplanted April 15 in Dhaka, Bangladesh.

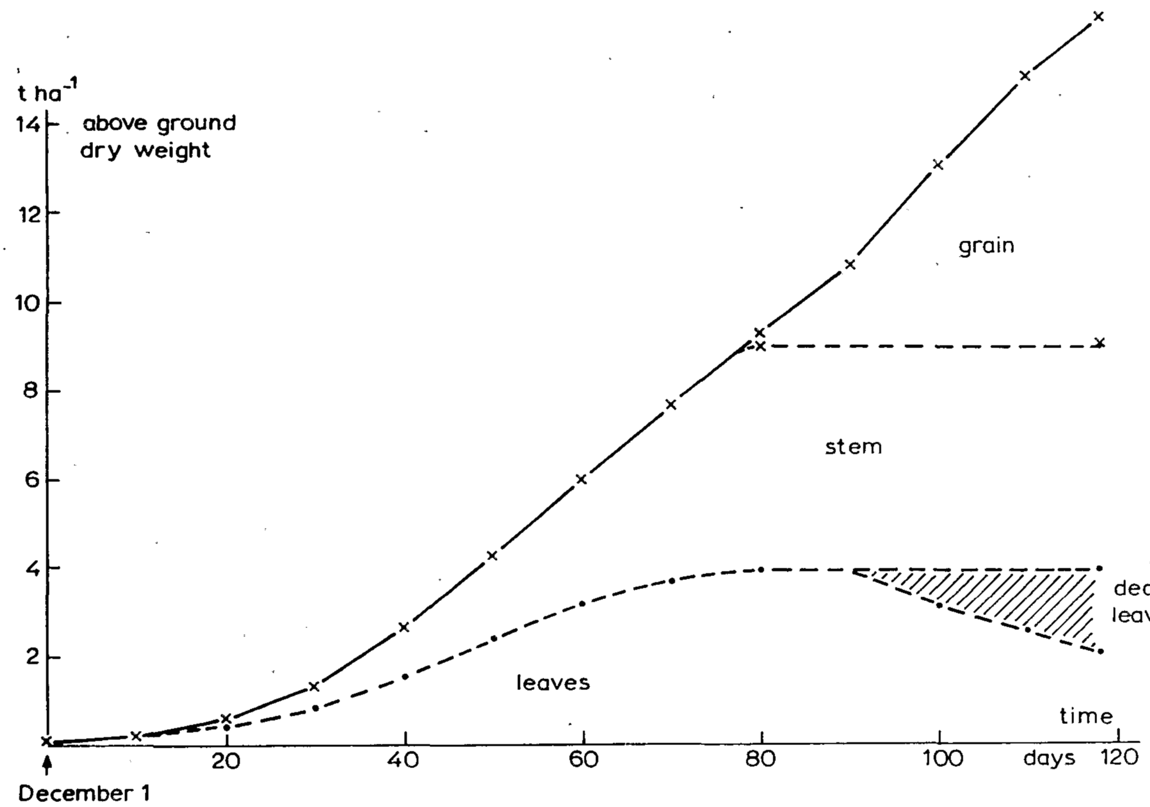


maintains the radiation-determined potential growth rate provided that extreme temperatures do not occur. The total amount of dry matter accumulated at maturity is then mainly determined by the length of the period during which this potential growth rate can be maintained. The length of that period is on one hand governed by genetic crop characteristics (short duration versus long duration crop species or crop varieties), and on the other hand by environmental conditions, especially temperature. At higher temperatures, the phenological development of crops proceeds at a higher rate, and consequently, the crop growth cycle shortens. Crop yield, which comprises only the economically relevant plant parts and which is thus only a fraction of the total dry matter, is co-determined by the distribution of dry matter between the various plant organs. The distribution pattern is again to some extent a genetic property: plant breeding has resulted in so-called improved varieties or cultivars that tend to invest a larger proportion of their total biomass in the economic plant parts. For these varieties the ratio of economic yield to total dry matter yield, the *harvest index* is in general superior to that of traditional varieties.

On the basis of the processes outlined so far a model is developed describing potential production. The procedure followed for such a calculation is given in detail by Van Keulen (1984a).

As a first example the results are given for a rice crop grown under floodirrigation, transplanted on April 15. In Figure 2, the time course of total above ground dry matter is presented, as well as the distribution between the various plant organs. In the first ten days only leaf blades are formed, from then on gradually more of the dry matter is invested in stem tissue until anthesis, i. e. the moment of fertilization when growth of the grains can start. After anthesis, all available assimilates are diverted to the growing grains, while concurrently part of the leaves deteriorate due to senescence. The rice variety simulated here has a total growth duration from transplanting till maturity of 86 days under the prevailing environmental conditions, anthesis taking place just prior to day 60. The calculated grain yield refers to brown rice (how grain is defined depends on the definition of the partitioning factors). At maturity the grain weight equals 6,350 kg of dry matter per ha, which is equivalent to a yield of 7.3 t ha^{-1} at a moisture

Figure 3. Time course of total above ground dry weight and dry weight of various plant organs under optimum growing conditions for bunded rice transplanted December 1 in Dhaka, Bangladesh.



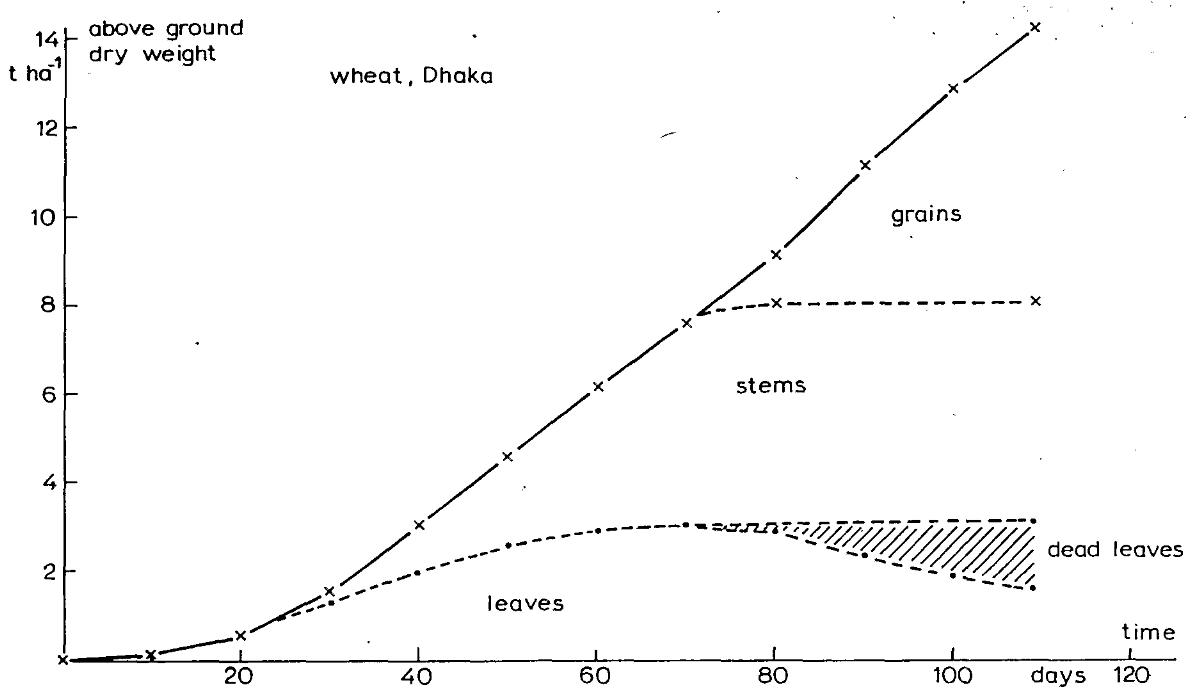
content of 0.14 H_2O per kg dry matter, a value normally used in yield reports.

To illustrate the effect of environmental conditions, another simulation run was executed with the same rice variety, now transplanted at the beginning of December when average daily air temperatures drop to values as low as 18.5 °C. The results are presented in Figure 3: it now takes this same variety 118 days from transplanting to maturity, so that it requires 30 days more to accumulate the same heat sum than during the summer season. The radiation level during winter is, however, substantially lower, and with it the energy for assimilation. The early growth of the crop is therefore much slower in winter as illustrated by the fact that 60 days after transplanting the "winter crop" has accumulated only 6,000 kg dry matter ha^{-1} compared to 8,700 for the crop transplanted in April. The much longer growing period of the former crop, however, under increasingly favourable conditions, results in a final dry matter yield of 16,300 kg ha^{-1} and an associated grain yield of 8.5 t ha^{-1} (at 14 % moisture content) which is higher than for the crop transplanted in April. When the average rate of dry matter accumulation, the growth rate, over the full growing season is calculated for both crops, the December crop yields a value of 138 kg ha^{-1} d^{-1} compared to 161 kg ha^{-1} d^{-1} for the crop transplanted in April, hence substantially lower.

In contrast an upland crop is considered, for which wheat is chosen as an example. In summer the temperatures are so high, that wheat can hardly be grown. Firstly, these high temperatures would lead to very short growing periods, and secondly there is also a risk that tillering and fertilization may be unfavourably affected. In the calculation it was assumed therefore that wheat was sown at the end of October and emerged November 5. The calculated course of dry matter accumulation, partitioned over the various organs (Figure 4), shows that the length of the growing period for this cultivar is 109 days, between emergence and maturity, anthesis taking place at day 70, so that the grain filling period lasts 39 days. Total above ground dry matter at maturity reaches 14,200 kg ha^{-1} and grain yield 7,100 kg ha^{-1} (at 14 % moisture content).

The calculated production and the yields presented in this section may seem high, when compared

Figure 4. Time course of total above ground dry weight and dry weight of various plant organs under optimum growing conditions fow wheat emerging November 5 in Dhaka, Bangladesh.



to actual yields, presently achieved. It should be realized, however, that these calculations are based on the assumption that the conditions for crop growth are *optimal* throughout the entire crop growth cycle. Such situations are difficult to realize, even under experimental conditions, let alone under farmer's conditions. This may be illustrated by wheat yields in the Netherlands, which are potentially around 10,000 kg ha^{-1}. Even on the best soils and an optimum supply with water and nutrients, this level is only rarely achieved, because of the effects of so-called ripening diseases, which are especially active during the final stages of grain filling and are very difficult to control, and may therefore result in yield losses of up to 10-15 %. Even if optimum control is possible from a biological point of view, it needs careful consideration to decide whether complete control is worthwhile from an economic point of view, taking into account the costs that are involved, both in physical and financial terms. This is one reason why potential yields are not pursued in practice. They are however important as a yardstick to indicate the scope for further improvements.

b. Production situation 2: influence of moisture supply

The process of assimilation, underlying dry matter production of green plants, requires an open connection of plants with the atmosphere through which CO_2 can enter. These passages are provided by the stomata. The walls of these stomata are covered with water and because the atmosphere is normally not saturated with water vapour, open stomata result in diffusion of water to the atmosphere. The assimilation process is thus inevitably accompanied by loss of water from the leaves, called transpiration. This loss of water is replenished by uptake from the soil, if sufficient moisture is available. If there is a shortage of water in the soil, the suction applied by the plant roots is insufficient to replenish all the water lost by transpiration. The plant reacts by closing of the stomata in an effort to curtail water loss. This leads to a higher resistance for the entrance of CO_2 and hence to reduced assimilation. If water stress persists, the plants will wilt and eventually die of dehydration. It is therefore essential for the realization of the yield potential of crops that at all times sufficient moisture is available in the rooted volume of the soil. However, under natural conditions periods may occur where the moisture store in the soil is not replenished in time and crops may suffer from temporary water shortage. The effect of such periods on production and yield can be estimated if the degree and duration of water stress can be quantified. For that purpose it is necessary to keep track of the processes of supply and loss of water from the soil: a soil moisture balance must be drawn up. The quantitative relationships involved in the soil moisture balance are detailed by Driessen (1984). Here, only the broad outlines are given.

The soil is a porous medium, in which solid particles are interspersed with voids of different size. In these voids, called pores, moisture can be stored, or they contain air. The pore size distribution varies for different soils as a function of the size of the particles of the solid phase. The latter are defined as soil texture classes. Moisture enters the soil by rain or by irrigation or from water termporarily stored on the soil surface from previous rain or irrigation. In the soil, the smaller pores are filled with water first and with increasing supply, gradually the bigger ones fill up also. In the porous system, adhesive, cohesive and capillary forces act upon the water, so that force must be applied to remove water from the soil. The force that must be applied is inversely related to the size of the pores in which the water is stored. The availability of moisture is therefore different in different soil types. At high moisture contents, the gravity forces are sufficient to create moisture transport, hence water can leave the rooted soil volume by percolation.

If the soil surface is wet, water diffuses from the wet soil surface towards the atmosphere, called soil surface evaporation. Such a process creates a gradient in moisture content in the soil, leading to upward transport of water, so that evaporation can be maintained for a considerable period of time. This process is enhanced if at a relatively shallow depth in the soil a free water surface —a groundwater table— is present. Then there is capillary rise, which transports water from the groundwater to the zone where roots are present and provides the plant with water. The process of transpiration by the plants which also removes water from the root zone has already been discussed.

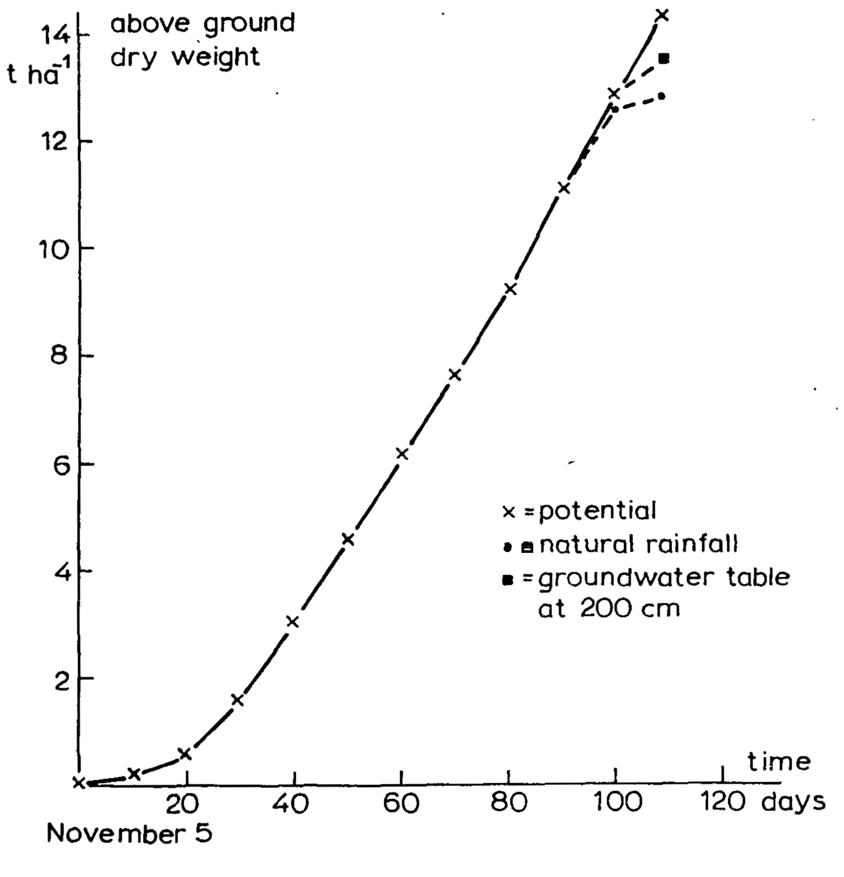
Since all the relationships involved in the soil moisture balance can be described in quantitative terms, a model of this system can be added to the model of potential production, thus enabling the calculation of the amount of water available to the crop at any time. If this amount is insufficient to meet the transpirational demand, assimilation declines about proportionally to transpiration (Van Keulen, 1984b; De Wit, 1958). When this relation is quantified it enables calculation of crop production and yield in situations where temporary water shortage may occur (Van Keulen, 1984c).

The wheat crop treated in the previous section is taken as a first example. As explained, important differences exist between soil types with respect to hydraulic properties. First, it is assumed that the soil is a sandy loam with hydraulic characteristiscs as given by Driessen (1984). Wheat was assumed to have been sown at the end of October and emergence was completed on November 5th. It is furthermore assumed that at emergence the profile is at field capacity and that the plot is located on a terrace, where the level of the groundwater table is at 10 meters, so that no appreciable influence of the groundwater can be expected on the moisture supply to the crop.

The results of the calculations (Figure 5) show, that for the conditions under which this wheat crop grows, there is only a limited effect of the moisture supply on total dry matter accumulation: total dry matter at maturity reaches 12,600 kg ha^{-1} under natural rainfall compared to 14,200 kg ha^{-1} in the potential production situation. This is due to the fact that during November and December sufficient rain (109 and 34 mm, respectively) is falling to replenish the water transpired by the crop. Thus until 80 days after emergence (January 23) the wheat crop transpires and grows at its potential rate. After that date, soil moisture content in the root zone drops to values below field capacity, and both transpiration and growth are reduced. This occurs at the end of the growth cycle, however, where all the assimilates are monopolized by the growing grain. The reduction in dry matter accumulation is thus at the full expense of the grain yield, which under natural rainfall reaches 5,400 kg ha^{-1} compared to 7,100 kg ha^{-1} (both at 14 % moisture content) in the potential production situation. The harvest index decreases therefore from a value of 0.47 in the potential production situation to 0.41 under natural rainfall conditions.

A completely different situation arises, when for some reason the crop can only be sown towards the end of November and emerges on December 5. Under otherwise identical conditions, poten-

Figure 5. Time course of total above ground dry weight for wheat, emerging November 5, under optimum growing conditions and under natural rainfall in Dhaka, Bangladesh.



tial dry matter accumulation amounts to 14,800 kg ha^{-1} in a growth period of 107 days from emergence till maturity. The calculated grain yield (14 % moisture content) amounts to 7,050 kg ha^{-1}, hence a harvest index of 0.45. When, however, the actual waterbalance is taken into account (Figure 6a), total dry matter is only 6,700 kg ha^{-1} and grain yield not more than 428 kg ha^{-1} , due to the fact that after day 60 there is hardly any rain (6 and 5 mm in January and February, respectively). Soil moisture in the root zone drops rapidly to values approaching the permanent wilting point and the crop is just able to stay alive, its assimilation being slightly above the maintenance requirements but production virtually absent.

Figure 6b shows that between day 60 and maturity, the transpiration deficit, that is the difference between the water requirement of the crop (in analogy to potential production defined as potential transpiration) and actual transpiration, gradually increases to ± 100 mm at maturity. Under these conditions it would have been necessary to apply that additional amount by irrigation. It may be expected that when irrigation is applied, there is also some additional water loss through soil evaporation (the surface of the soil will be wet for some time) and through percolation, the magnitude of which will mainly depend on irrigation amount and frequency. Furthermore the application efficiency must be taken into account (Driessen, 1984), so

Figure 6. Time course of total above ground dry weight for wheat, emerging December 5, under optimum growing conditions and under natural rainfall in Dhaka, Bangladesh (a); cumulative transpiration for a wheat crop growing under optimum moisture supply and under natural rainfall (b).

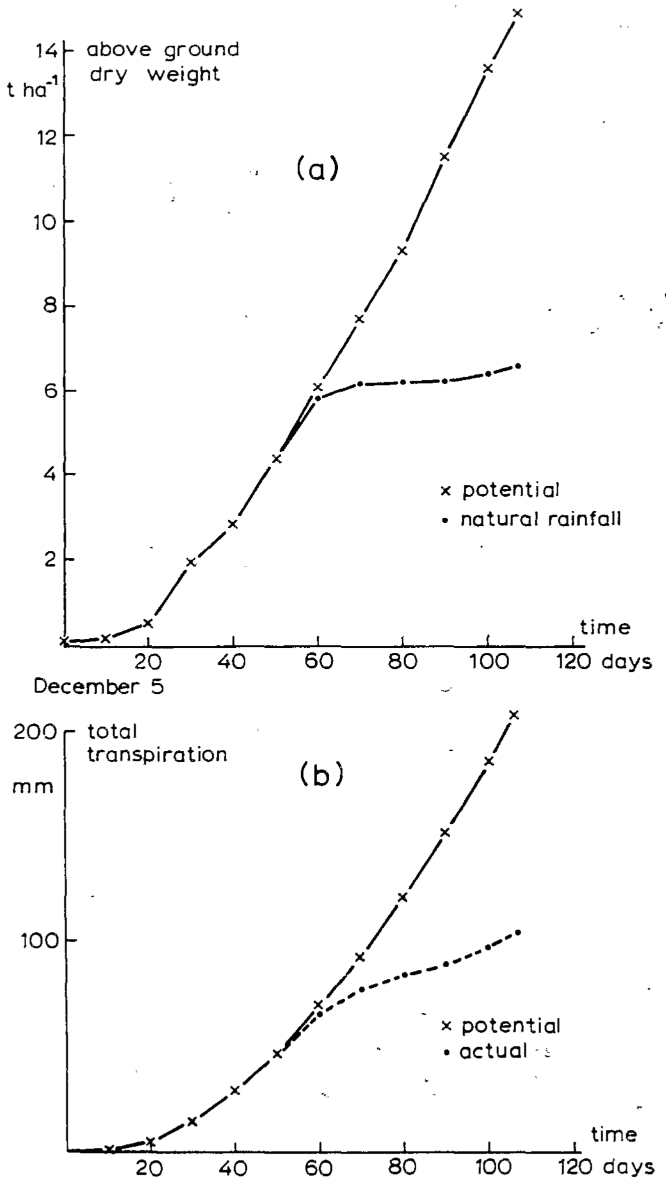
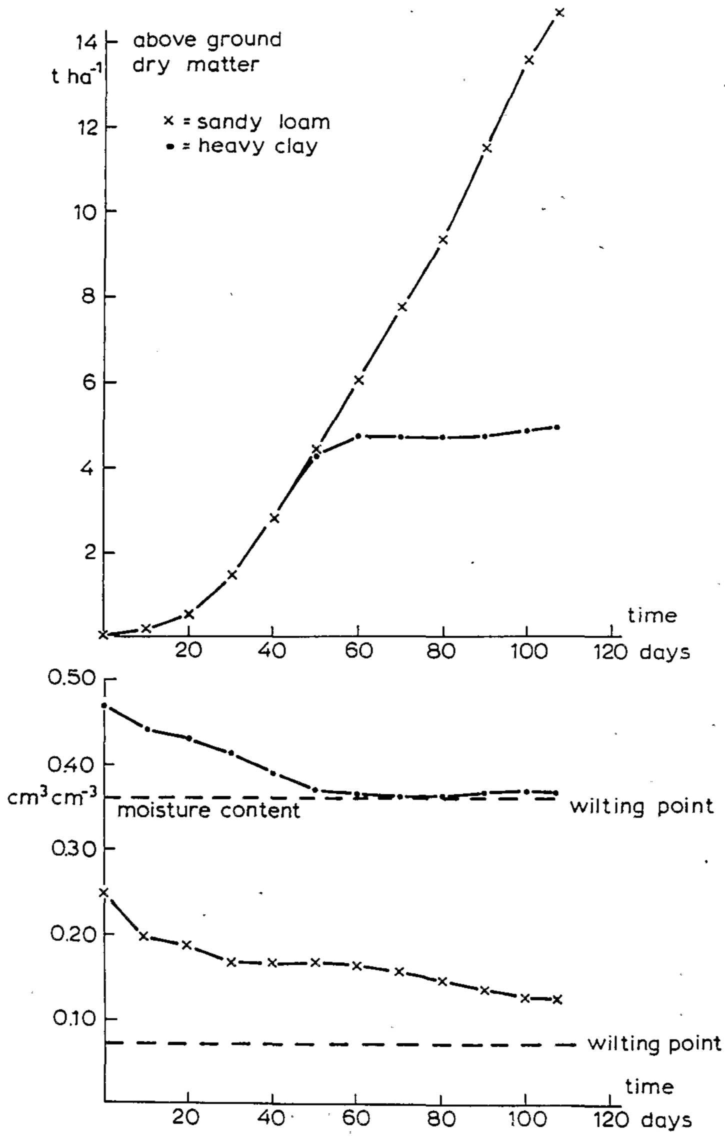


Figure 7. Time course of total above ground dry weight for wheat, emerging December 5, growing on a sandy loam soil and on a heavy clay soil in Dhaka, Bangladesh (a); time course of volumetric soil moisture content in the root zone in a sandy loam soil and a heavy clay soil (b).



that it may well be necessary to release 1500 m^3 of water per ha at the system's head works to achieve potential production under the conditions described. Some of the consequences of the differences in hydraulic properties between soil types are illustrated in Figure 7. Figure 7a shows the growth curve of the wheat crop, emerging on December 5, when grown on a sandy loam soil and on a heavy clay, both initially at field capacity and with a groundwater table at a depth of 200 cm below the soil surface. The difference is very distinct: on the sandy loam soil the crop grows almost till the end of its growth cycle at the potential rate (Figure 6), and only in the last days before maturity does water shortage interfere. The result is that the grain yield in this case amounts to 6,675 kg ha^{-1}, a reduction of only 375 kg ha^{-1} compared to the potential growth situation. On the heavy clay soil, growth virtually ceases after day 50, the crop barely manages to stay alive and grain yield is therefore negligible. The pores in the clay soil are much smaller than in the sandy loam, as evidenced by the big difference in moisture content at field capacity (Figure 7b). In the clay soil, a high proportion of the water is stored in such small pores that even at wilting point, the volumetric moisture content is still

0.36 cm^3 cm^{-3}. In these small pores the hydraulic conductivity, the inverse of the flow resistance, is much smaller than in the larger pores. The velocity of flow from the ground water table towards the rooting zone is directly proportional to this hydraulic conductivity. In the heavy clay soil the total amount of moisture contributed to the growing crop by capillary rise from the groundwater is only 16 mm over the total growing period. The rate of 0.15 mm d^{-1} is far too low to meet the transpirational demand of the growing vegetation, which around day 50 after emergence is about 2.5 mm d^{-1}. In the sandy loam soil, the hydraulic conductivity is higher, and between day 40 and day 60, capillary rise reaches values of ± 1.5 mm d^{-1}, so that the decline in soil moisture content is much slower (Figure 7b). Totalled over the growing period, the contribution from the groundwater table amounts to almost 100 mm. The difference of 85 mm explains most of the difference in production on the two soil types under otherwise identical conditions. The difference in hydraulic properties not only plays a role with respect to the contribution from the groundwater table, but the amount of water, available to the crop between field capacity and wilting point also plays a role, as may be deduced from a comparison of Figures 6a and 7a. In the heavy clay soil with a water table at 200 cm below the soil surface, the wheat crop yields less than in the sandy loam without any contribution from the groundwater. The difference can be explained on the basis of available water: for the clay soil, 0.47 cm^3 cm^{-3} at field capacity and 0.36 cm^3 cm^{-3} at wilting point, implies, over a rooting depth of one meter about 110 mm of available water; for the sandy loam soil the data are 0.25 and 0.07 cm^3 cm^{-3}, respectively, which translates into 180 mm of available water. A sandy loam soil is therefore more favourable in terms of moisture availability than a heavy clay soil.

c. Production situation 3: Influence of nutrient supply

The organic components produced by the plants not only contain carbon, hydrogen and oxygen derived from carbon dioxide and water, but also other elements such as nitrogen and phosphorus, as constituents of proteins, potassium, necessary for physiological functioning and many other elements, which in small quantities have specific functions in biological and biochemical functioning of green plants. As an example, the green pigment chlorophyll which plays a key role in the assimilation process cannot be formed in the absence of iron.

In the first half of the last century it was found that the crop extracts these nutrients from the soil, and that yields could be considerably improved by the addition of the macro-elements nitrogen, phosphorus and potassium. It appeared that even in situations where the amount of nutrients that was withdrawn with the produce was fully replenished, the concentration of these elements in the soil proved in general far too low to sustain production levels as dictated by climate and soil water availability. To achieve that, a considerable larger supply of these macro-nutrients appeared to be needed. And since the supply of animal manure was very much limited by the limited availability of natural grasslands or heather soils, the quantities needed could be only obtained by the use of chemical fertilizers. This is even the more so at present since the demand for food has increased manifold.

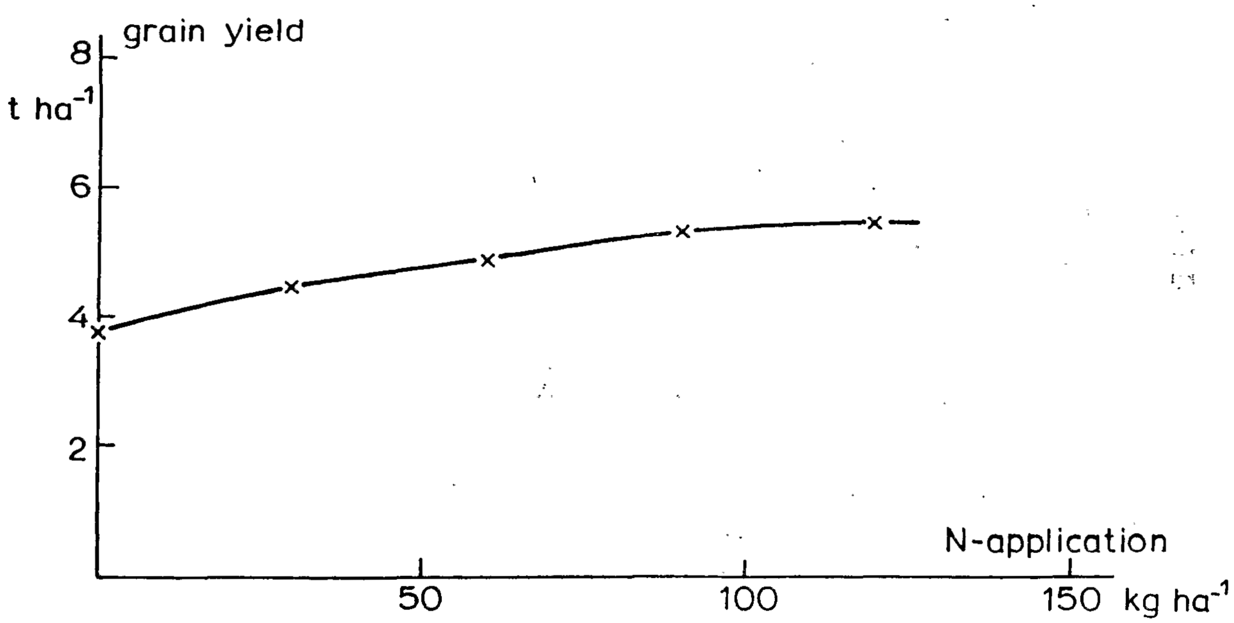
In order to establish the amount of chemical fertilizer needed to achieve a certain production target, fertilizer trials have been carried out. The normal way in which the results of such trials are reported is illustrated in Figure 8, using observations from an experiment with bunded rice at the BRRI experimental farm in Joydebpur in the 1982 boro season: Grain yield is given as a function of the amount of a certain nutrient element applied. If a comparison is made of such response curves for the same crop, determined at different locations, or at the same location but for different growing periods, they are disappointingly variable, so that they seem to be of little use for extrapolation or prediction. To understand this variation it should be realized that between the application of the chemical fertilizer and the response in economic yield, two processes have to take place. Firstly, the nutrient element that is applied to the soil surface (or in case of bunded rice to the water surface) must be taken up by the vegetation. Secondly, after uptake it must be utilized by the vegetation to produce the required economic plant parts.

Uptake of the element by the vegetation may be obstructed because there are many other processes in the soil that compete with the plant roots for the limited amount of nurients available. Processes such as fixation by the solid phase of the soil, transport to soil layers beyond the depth of root penetration, immobilization by soil microbes or transformation into gaseous compounds that escape from the soil. Under unfavourable conditions only a small proportion of the applied element is recovered in the vegetation.

If the element has been taken up by the vegetation, a response in terms of economic yield may still not occur because only the production of crop residues increases or because some other growth factor is in short supply and prevents realization of the yield potential set by the availability of the element applied as fertilizer. To judge the results of a particular fertilizer experiment it is necessary to be able to differentiate between the contribution of these two processes in the observed response. For that purpose, the material harvested in fertilizer experiments must also be analyzed to determine its chemical composition. If both yield and composition have been obtained, they may be graphically presented as illustrated in Figure 9, using the same experiment as in Figure 8, and explained in detail by Van Keulen (1984d, 1982, 1977).

Figure 9 contains three relations: in quadrant (a) the relation is given between yield and the total uptake of the applied element by the vegetation. In this case the uptake in both grain and straw. This relation is of the well-known saturation type, i. e. in the lower region of element availability there is a proportional relation between uptake and yield. This proportionality indicates that each unit of the element taken up results in an equal amount of yield produced. Examination of a large number of experimental results where these uptake-yield curves could be constructed has shown that their slope is a crop-characteristic, that is largely independent of the variety, or the growing conditions. The constancy of this slope reflects the fact that in the economic plant parts as well as in the crop residues a crop-characteristic minimum element concentration exists at maturity. Taking rice as an example, the element can be diluted in the grain to a minimum concentration by the addition of carbohydrates. When that minimum concentration is reached, further accumulation of dry matter is inhibited. In the straw, remobilization of nutrient elements takes place after anthesis and transport to the growing storage organs, but further remobilization is prevented when the minimum concentration is reached. When a certain element is the limiting factor for growth and production, the element concentration in the harvested material will be at its minimum value and the yield will be at the characteristic yield-uptake relation. Because the minimum concentration is not identical in the grain (0.01 kg N per kg dry matter) and in the straw (0.004 kg N per kg dry matter), variations in grain to straw ratio (or in harvest index) will influence the slope of the yield-uptake curve to some extent. When availability of the nutrient element increases and therewith uptake, the relation in quadrant (a) deviates from the straight line, because the concentration in the harvested material is above the minimum. Finally, the yield reaches a plateau level, at the point where the element under consideration no longer is the yield-constraining factor. Then another growth factor is in short supply, which can be either another nutrient element, or water (production

Figure 8. Relation between nitrogen fertilizer application and grain yield for bunded rice in Joydepbur, Bangladesh, boro season 1982.

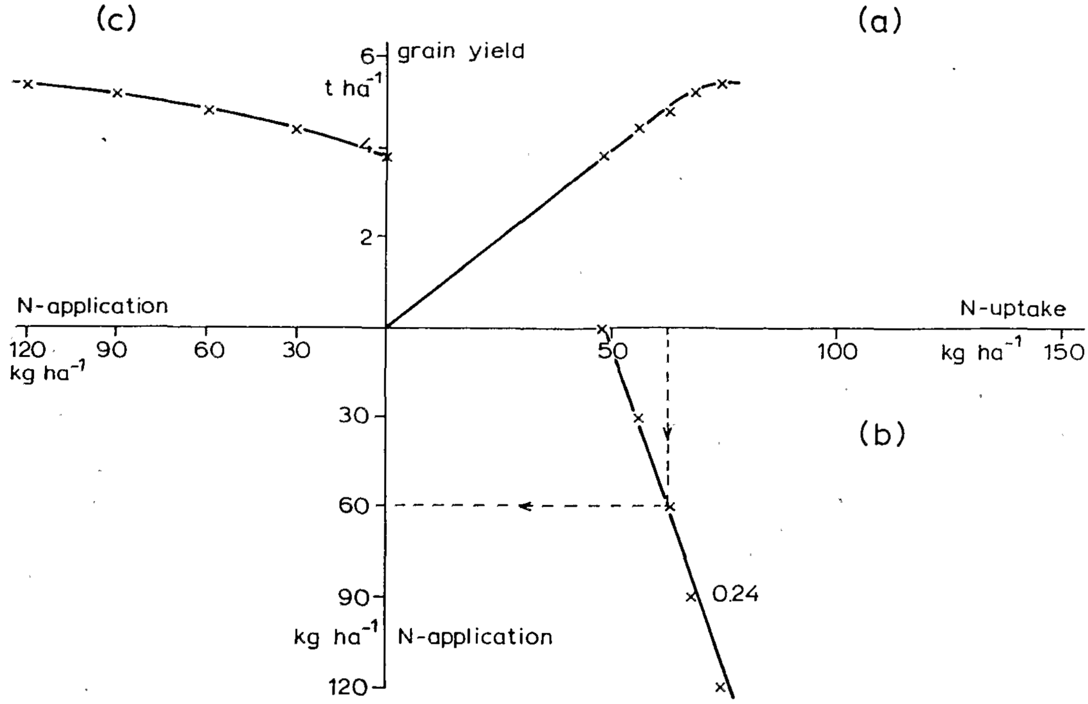


situation 2) or radiation and length of the crop growth cycle (production situation 1). In the example given in Figure 9 the plateau level is barely reached so that it may be expected that further uptake of nitrogen could have resulted in higher grain yields.

Quadrant (b) of Figure 9 shares the uptake axis with quadrant (a) and contains the application rate, increasing in downward direction. It presents the relation between the amount of a nutrient element applied as chemical fertilizer and its uptake by the (above ground portion of the) crop. This relation appears to be linear in Figure 9 over the full range of application rates, which is characteristic for the majority of fertilizer experiments involving nitrogenous fertilizers. This linear relation between application rate and uptake by the crop implies that the proportion of the fertilizer taken up, which is called the recovery fraction, is independent of the rate of application.

The recovery fraction in this case is thus 0.24 kg N per kg N applied, or in other words, more than four kilograms of N in the chemical fertilizer have to be applied to realize uptake of one kg N by the vegetation. (The actual proportion will be somewhat higher because the roots, which were not included in this analysis also contain some nitrogen, but that is in general less than 10 % of that in the above ground plant parts). Such low recoveries are not uncommon in the agricultural practice of bunded rice (Van Keulen, 1977). The main reason is that the fertilizer, either as ammonium or as urea, is applied to the shallow water layer on top of the field, which is relatively oxygen-rich. In that environment, hydrolysis of urea to ammonium and subsequent nitrification to nitrate nitrogen takes place readily. The nitrate ions are very mobile in the system and enter the root zone either transported by flowing water, or if the infiltration rate is low, by diffusion under the influence of a concentration gradient. In the root zone the oxygen concentration is very low, because the resistance for transport of oxygen from the atmosphere to the root zone is magnified by the layer of water on top of the soil. In this low oxygen environment, some micro-organisms use the oxygen contained in the nitrate ion as a source of energy, thereby transforming its nitrogen into gaseous compounds which easily escape

Figure 9. Relation between total nitrogen uptake and grain yield (a), that between nitrogen fertilizer application and nitrogen uptake (b) and the relation between nitrogen fertilizer application and grain yield for bunded rice in Joydepbur, Bangladesh, boro season 1982.



to the atmosphere (denitrification). Especially when the nitrogen is applied early in the crop's life cycle, when the plants are small and can utilize only small quantities of the element, its average residence time in the soil system is very long and the chances for losses high. Therefore, the recovery improves in general when the fertilizer is applied in several dressings ("split application"), and at growth stages when the plants can utilize the element at a higher rate. An even better proposition is the so-called placement of the fertilizer directly in the low-oxygen environment. The absence of oxygen there, prevents the transformation of ammonium ion into the nitrate form and consequently the denitrification. Doubling of the recovery fraction to values as high as 0.6 to 0.7 has been achieved using this practice.

The straight line in Figure 9b is thus on one hand characterized by its slope, the recovery fraction, on the other hand by its intercept with the uptake axis, the base fertility of the soil. This latter characteristic is as variable as the recovery fraction. It is partly a soil characteristic, determined by the mineralogical composition of the soil, but above all its organic matter content and quality. Decomposition of the organic matter by micro-organims leads to liberation in mineral form of the nitrogen contained in this organic matter, the so-called mineralization. Concurrently, however, mineral nitrogen is immobilized by the micro-organisms to build proteins for their body tissue. Whether the balance between the two processes yields a net gain or a nêt loss of mineral nitrogen depends on the composition of the organic material being decomposed and particularly on the proportion of carbon and nitrogen in that material, the C/N ratio. In general a C/N ratio below 15 will result in net mineralization of nitrogen upon decomposition, whereas above 15 the reverse will be the case. It may thus be expected that soils having a high organic matter content of reasonable quality will have a higher base fertility than soils low in organic matter. In addition to this, also environmental conditions play a role, because temperature and moisture conditions in the soil affect the activity and size of the microbial population in the soil and hence the intensity of decomposition, and the amount of nitrogen immobilized in the body tissue.

Apart from the soil organic matter there are other nitrogen sources that contribute to the availability of nitrogen in the absence of chemical fertilizer application: organic manures may be applied, for which in principle the same processes apply as for the native organic material; atmospheric N may be contributed by precipitation, which especially in industrialized areas may amount to considerable quantities; in bunded rice the blue-green algae in the floodwater are capable of fixing atmospheric nitrogen, part of which can contribute to the nitrogen supply of the concurrently growing rice crop.

Once the mineral N is in the soil system, there is no longer a distinction between ions originating from natural sources or those coming from a fertilizer bag. Hence, all the processes that render fertilizer N unavailable to the plant, also act on N from natural sources. Therefore, one will find in general that higher recovery fractions coincide with higher values of the base fertility (Van Keulen, 1982).

The analysis of nutrient requirements has concentrated so far on nitrogen, because of the large quantities needed each year, its relatively high costs and the fact that the soil-plant-atmosphere system is an open system for nitrogen.

The other macro-nutrients can in principle be treated in the same fashion, crop —and organ— specific minimum concentrations for phosphorus and potassium at maturity can be established and yield-uptake curves for these elements can be constructed in a similar way as for nitrogen (Van Keulen, 1984d; Van Keulen & Van Heemst, 1982). In the case of phosphorus, the relation between fertilizer application rate and nutrient uptake by the vegetation is, however, much more complex than the linear relationship valid for nitrogen and potassium. For phosphorus a concave relationship between application rate and uptake is most common, i. e. the recovery fraction decreases with increasing application rates. The concavity is caused by the fact that the reactions involving phosphorus are equilibrium reactions, where many low solubility compounds play a role. This results in general in effective precipitation of phosphorus compounds in the soil system, leading to a situation where the concentration of soluble phosphorus components in the soil solution remains more or less constant. Thus, when more P is added to the solution in the form of chemical fertilizers, a larger proportion is immobilized by the soil system, hence the proportion available to the plant and as a consequence the recovery fraction decreases. The interaction between the solid phase of the soil and phosphorus is not of the same intensity for all soils, but depends on the mineralogical and chemical properties, such as the proportion of aluminium and iron ions in the solution and the type of clay minerals present.

d. Establishment of fertilizer requirements

With respect to plant nutrition the two most important questions to be answered are: which nutrient is the limiting factor in a particular growth situation and how much fertilizer must be applied to remove that constraint. Experimental data are required to answer the first question as well as some estimate of the yield that may be expected in the absence of nutrient stress (see Sections above). If in a particular experiment the yield estimated for production situation 1 (with irrigation) or for production situation 2 (without irrigation) is achieved, nutrient shortage is not likely to have played a major role. If the harvested yield falls substantially short of the expected level, the yield constraining factor could well have been one of the macro-nutrients. To determine which element is involved, chemical analysis of the harvested plant material is necessary. If the nitrogen concentration in the plant at maturity, subdivided into economic plant parts and crop residues, is at or close to its minimum concentration, it is likely that nitrogen has been the limiting factor for production and yield. The combination of dry matter production and chemical composition also provides the amount of nitrogen taken up by the crop in the unfertilized situation, which is the starting point for determination of the fertilizer requirement. As detailed in the preceding paragraph this amount is not independent of environmental conditions, thus there is always some degree of uncertainty, but if the management practices do not change significantly, such an experiment provides a reasonable basis for estimation of fertilizer requirements. If completely different management practices are adopted, experiments will have to be repeated, because our understanding of the basic processes influencing the nitrogen cycle in the soil is too fragmentary at present to predict the consequences of such changes in a quantitative fashion. However, assuming that the nitrogen supply in the unfertilized situation is known, the uptake-yield curve can be constructed on the basis of calculated production and established minimum concentrations in the tissue. In the case of the wheat crop (see above) total dry matter production for the crop emerging on December 5 was 14,800 kg ha^{-1}, of which 6,180 kg ha^{-1} is grain (dry!), and consequently 8,620 kg ha^{-1} consists of straw. On the basis of the minimum concentrations for nitrogen in grain and straw a value of 65 kg grain dry weight per kg N absorbed or 73 kg grain at a moisture content of 14 % is obtained. This slope is introduced in quadrant a of Figure 10. In the schematized set up, applied here, the yield-uptake relation is considered linear up to the point where it reaches the potential yield of 7,050 kg of grain, the curvature due to increasing concentrations in the harvested material being disregarded. From the graph it can be read, that at least 95 kg N ha^{-1} must be taken up by the crop to achieve the potential yield (point A, Figure 10).

The next question is how much nitrogen the unfertilized soil will provide in this situation. The most accurate determination would be to analyze grain and straw of a wheat crop growing in an unfertilized field under as much as possible identical conditions. A first impression can be obtained from a yield determination, using slope a in Figure 10: suppose that the grain yield without fertilizer application was 1,200 kg ha^{-1}, implying a nitrogen uptake of 16 kg ha^{-1} (point B in Figure 10). The crop must therefore take up an additional 79 kg N ha^{-1} from the fertilizer. When the fertilizer is applied as urea, and for reasons of labour availability or otherwise, as a single basic dressing, a recovery fraction of 0.35 is a reasonable estimate. The required application of fertilizer nitrogen is obtained from Figure 10 by extending the vertical ending in A till the recovery line I and from the intersection a line is drawn to the application axis (point C; Figure 10). The graph shows that, to achieve potential yield under these conditions, an application of 225 kg pure N ha^{-1} is necessary. This estimate is purely based on agrotechnical considerations while economic arguments are not taken into account. If the nitrogen fertilizer is applied in optimally timed gifts, the recovery fraction can be increased to values between 0.5 and 0.6. Assuming a value of 0.55 as reasonable, a line II can be drawn in Figure 10 and the procedure can be repeated. Under these different conditions, the fertilizer N requirement is substantially lower, amounting to 144 kg N ha^{-1} to achieve a yield of 7,050 kg ha^{-1}.

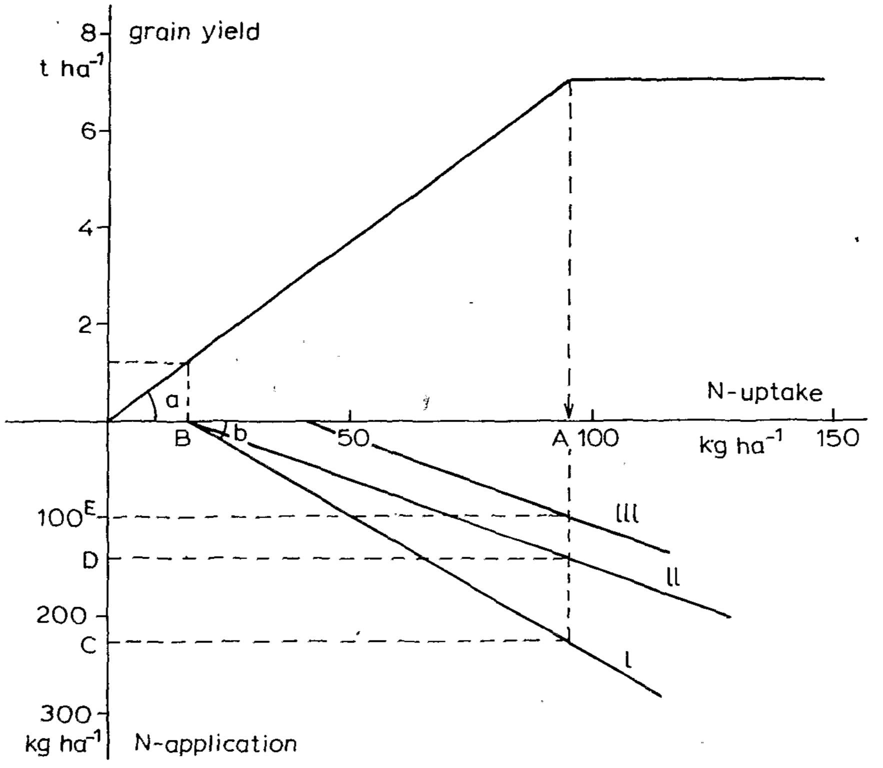
Comparison of the two application rates of 225 and 144 kg ha^{-1}, respectively, shows that timeliness and proper management can lead to considerable improvements in the efficiency of the agricultural production system. It should be realized, however, that these improvements include a costs aspect, such as a higher input of labour and skill, especially with respect to judgment of the optimum timing for fertilizer application. These skills must not only exist at the individual farmer level, but should first and foremost be embodied in a well-organized extension service.

The other characteristic of the application rate-uptake curve, the uptake at zero fertilizer application may also be changed. As already mentioned, the use of organic manures as well as green manures provides such a possibility. Suppose that in the situation described above, a leguminous crop could be plowed in before the wheat was sown and that the decomposition of that material would result in the mineralization of an additional 25 kg of N ha^{-1} in the course of the growing season. The consequence for fertilizer requirement is illustrated in Figure 10, point E at a value of 98 kg N ha^{-1} . This result indicates that each additional kg N that is contributed by natural sources under these conditions gives a saving of 2 kg of fertilizer N. Any measures aimed at improving the base fertility are therefore almost always worthwile.

Although in many situations of interest, nitrogen is likely to be the first limiting factor, the influence of other nutrients cannot be neglected. Especially, when as a result of the use of increasing amounts of nitrogen fertilizers, yields increase, the amount of other elements removed with the products will concurrently increase and shortage. of phosphorus and in the somewhat longer run of potassium will become apparent. Of course, on certain soil types shortage of phosphorus or potassium may be the limiting factor before nitrogen shortage plays a role, especially on soils that have strongly phosphorus or potassium fixing properties. Such a situation is relatively easily recognized, when the concepts outlined in this section are applied. If the yield level obtained with ample nitrogen fertilizer application is much lower than that expected for production situation 2 (if moisture supply is suboptimal), or for production situation 1 (if rainfall is adequate or if irrigation facilities are available), shortage of other nutrients could be a likely cause. In the production situation considered here, it is assumed that micro-element deficiency, soil acidity (pH) or toxicity does not play a major role.

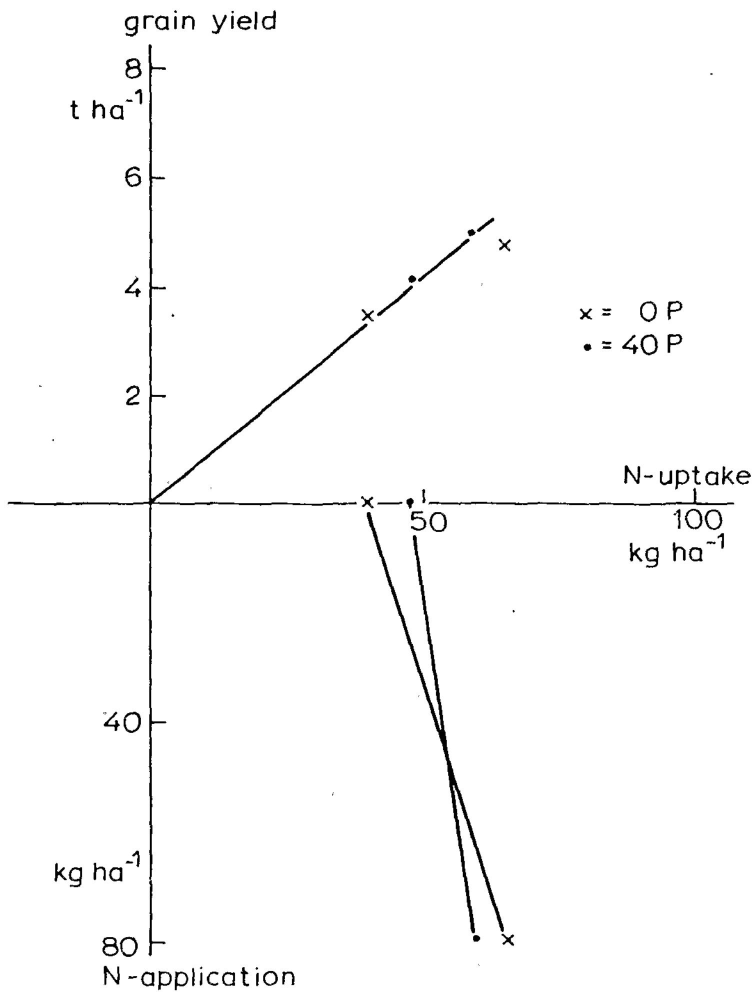
A first indication of shortage of other macro-elements can be obtained from chemical analysis of the harvested material. If the nitrogen concentration at maturity is substantially above the minimum level established for the crop-organ, it

Figure 10. Illustration of the graphical procedure to determine nitrogen fertilizer requirements for optimum yield of wheat (see text for explanation).



certainly is not nitrogen that was yield-constraining. Analysis for the other macro-elements may reveal a minimum concentration of either P or K, hinting at shortage of that element. However, if the nitrogen concentration is at the minimum level, it cannot unequivocally be concluded that application of nitrogen will result in higher yield. There appears to be a strong correlation between the nitrogen status of plants and their phosphorus status (Van Keulen, 1984d; Penning De Vries & Van Keulen, 1982). The functions of the two elements in the plants are interrelated: nitrogen and phosphorus are both constituents of proteins, particularly in the nucleic acids, N is part of the enzymes and P is found in molecules that transfer energy for enzymatic reactions. The consequence of this interdependence is, that the ratio between the concentration of phosphorus in the plant and of nitrogen, the P/N ratio, varies only within relatively small margins. The boundary values observed in various field and greenhouse studies are 0.05 and 0.15, respectively. Hence, when one of the elements is limiting and its concentration in the tissue is at the minimum value, the concentration of the other element, even though available in relative abundance, can never be at its maximum value. Or, in other words, a relative shortage of one element affects the uptake of the other element. This effect is illustrated in Figure 11 by results reported by BRRI, referring to the 9th crop in a long term fertility trial at Joydebpur, in which N and P were applied in different quantities. At zero fertilizer application the grain yield is 3.4 t ha^{-1} (14 % moisture content) at an uptake of 40 kg N ha^{-1}. These values provide a

Figure 11. The relation between grain yield and nitrogen uptake (a) and that between nitrogen fetilizer application and nitrogen uptake, with and without application of phosphorus fertilizer in Joydepbur, Bangladesh, aman season 1982.



slope of the yield-uptake curve of 85 kg of grain per kg N taken up. The "theoretical" slope calculated on the basis of measured grain / straw ratio and minimum N concentrations would have been 83, which is close enough. Application of phosphorus fertilizer at a rate of 40 kg $P_2 O_5$ ha^{-1} increased yield to 4.1 t ha^{-1}. However, that data point is still at the N determined yield-uptake curve (Figure 11). Hence, the phosphorus response is in fact a "disguised" nitrogen response: greater availability of phosphorus permitted the crop to take up more nitrogen and increased yield in that way. This is also witnessed by the P / N ratio in the straw, which is 0.05 without fertilizer application, hence at its minimum value, indicating a relative shortage of phosphorus. With application of 40 kg $P_2 O_5$ ha^{-1} the P / N ratio in the straw is 0.052, or only slightly higher. Application of nitrogen only, increases yield to 4.8 t ha^{-1}, which is not surprising since growth was nitrogen limited. The recovery of the nitrogen fertilizer is relatively low at 0.31 kg kg^{-1}, considering the fact that the fertilizer was applied in three gifts, but that may have been caused by the heavy rainfall, reported to have taken place shortly after the 2nd topdressing, which would have washed down most of that application. Application of both phosphorus and nitrogen fertilizer gives the highest yield of almost 5.0 t ha^{-1}, without however increasing the uptake of nitrogen compared to the previous treatment. This is a somewhat unexpected result, that cannot be explained off-hand.

The considerations with respect to the P / N ratio in plant tissue do provide a handle for a first estimation of phosphorus fertilizer requirements. In situations where both nitrogen and phosphorus are amply available, the P / N ratio in plant tissue assumes an optimum value of about 0.1. The P requirement can thus be derived by multiplying the calculated crop requirement for nitrogen, by 0.1. The amount of phosphorus available in the non-fertilized situation is not easily estimated as illustrated in the Joydebpur example, because N-limiting conditions, i. e. were the N concentration in the harvested material is at its minimum value, does not automatically mean that phosphorus is not limiting. However, a range can be derived from yield in the non-fertilized situation, because the P / N ratio ranges between 0.05 and 0.15. This still leaves a variation of a factor three, but considering the generally low recovery fractions for phosphorus fertilizers and the fact that overfertilization with phosphorus is harmless, this does not seem problematic.

Recovery fractions for phosphorus fertilizers vary even more than those for nitrogen fertilizers because of the sometimes intense interaction of phosphates with the solid phase of the soil.

On the basis of the reasoning followed so far an estimate of phosphorus fertilizer requirements can be made, using again the wheat crop discussed above. Total nitrogen uptake by the crop was 95 kg ha^{-1}, hence phosphorus requirement is 9.5 kg P ha^{-1}. In the unfertilized situation 16 kg N per ha^{-1} was taken up, hence the phosphorus content of that material must have been between 0.8 and 2.4 kg P ha^{-1} (P / N ratio between 0.05 and 0.15). A value of 1 kg P ha^{-1} seems a safe estimate. If it is assumed that the soil is an alluvial clay soil, a recovery fraction of 0.1 for phosphorus fertilizers may be assumed. The fertilizer requirement amounts to 85 kg P ha^{-1}, or equivalent to 195 kg P_2O_5 ha^{-1}. If the recovery fraction, in practice turns out to be at the upper limit of its class at a value of 0.15, actual uptake by the vegetation could amount to 13.75 kg P ha^{-1}, which could lead to a P / N ratio in the tissue of $13.75 / 95 = 0.14$, hence still within acceptable limits.

From this Section it is clear, that in many situations in the actual agricultural production process, growth and yield of crops are constrained by nutrient availability. Under continuous cropping, without extended fallow periods, the export of agricultural products from the land, the purpose of the activity, and other losses because of cultivation inevitably leads to a decline in fertility of the soil (Schouten, 1984; De Wit, 1974), and hence to decreasing yields, except perhaps on young volcanic soils or where floodwaters ensure adequate yearly supply of nutrients. In all other situations this decrease can only be halted by the use of chemical fertilizers, to maintain the availability of plant nutrients to the crop at a sufficiently high level. As has been said before, this involves more than mere replenishment of the amount withdrawn with the product, because inevitable losses from the system must be accounted for and moreover, a sufficiently high concentration must be maintained to satisfy the demand of the crop. Whether such a proposition is feasible from an economic point of view has not been considered here, and can hardly be treated in a generalized fashion. The answer to that question depends on local conditions, such as availability and prices of fertilizers, prices of agricultural products, capital availability etc. For a proper judgment, however, of the economic feasibility, a realistic estimate of crop response and fertilizer requirements is a necessity and the basis for such an assessment is the analysis outlined in this Section.

CONCLUSIONS

The material presented in this paper provides a clear picture of the capabilities of the agronomic model structures developed in the framework of the CWFS, their data requirements and the possibilities for their use.

The model structure does provide a tool to determine crop production data, both of economic plant parts and crop residues for various production situations, as affected by the physical environment. On the basis of these calculations, estimates are also made of the yield-increasing material inputs, such as irrigation water and fertilizer that are needed to achieve the calculated production levels.

It is therefore possible to judge on this basis the scope for expansion of agricultural production in a given environment. It should be emphasized here, that in many situations a conversion from a "natural" ecosystem to an agricultural system involves a change in the mode of exploitation, whic may have a strong impact, especially on the nutrient cycle in the system (Melillo, this vol.). It will therefore be difficult —if not impossible— to predict agricultural production directly from the production of the natural ecosystem, without going into details with respect to the dynamics of the main limiting factors.

BIBLIOGRAPHY

DRIESSEN, P. M. 1984. The soil water balance. In: (H. van Keulen and J. Wolf, Eds.) Modelling agricultural production: weather, soils and crops. Simulation Monographs, Pudoc, Wageningen (in press).

KEULEN, H. VAN, 1984a. A simple model of potential production. In: (H. van Keulen and J. Wolf, Eds.) Modelling agricultural production: weather, soils and crops. Simulation Monographs, Pudoc, Wageningen (in press).

KEULEN, H. VAN, 1984b. The relation between water use and crop production. In: (H. van Keulen and J. Wolf, Eds.) Modelling agricultural production: weather, soils and crops. Simulation Monographs, Pudoc, Wageningen (in press).

KEULEN, H. VAN, 1984c. A simple model of water limited production. In: (H. van Keulen and J. Wolf, Eds.) Modelling agricultural production: weather, soils and crops. Simulation Monographs, Pudoc Wageningen (in press).

KEULEN, H. VAN, 1984d. Crop response to nutrient supply. In: (H. van Keulen and J. Wolf, Eds.) Modelling agricultural production: weather, soils and crops. Simulation Monographs, Pudoc, Wageningen (in press).

KEULEN, H. VAN, 1982. Graphical analysis of annual crop response to fertilizer application. Agr. Syst. 9: 113-126.

KEULEN, H. VAN, 1977. Nitrogen requirements of rice, with special reference to Java. Contr. Centr. Res. Inst. Agr. Bogor, no. 30, 67 pp.

KEULEN, H. VAN and H. D. J. VAN HEEMST, 1982. Crop response to the supply of macronutrients. Agr. Res. Rep. 916, Pudoc, Wageningen, 46 pp.

MELILLO, J., 1984. Prediction of the productivity of agricultural systems from natural ecosystem productivity (this volume).

PENNING DE VRIES, F. W. T., 1974. Substrate utilization and respiration in relation to growth and maintenance in higher plants. Neth. J. agric. Sci. 22: 40-44.

PENNING DE VRIES, F. W. T. and H. VAN KEULEN, 1982. La production actuelle et l'action de l'azote et du phosphore In: (F. W. T. Penning de Vries and A. M. Djiteye, Eds.). La productivité des pâturages sahéliens. Une étude des sols, des végétations et de l'exploitation de cette ressource naturelle. Agr. Res. Rep. 918, Pudoc, Wageningen, pp. 196-226.

PIMENTEL, D., 1984. Energy flows in natural and agricultural ecosystems (this volume).

SCHOUTEN, H., 1984. Low input farming. In: (H. van Keulen and J. Wolf, Eds.) Modelling agricultural production: weather, soils and crops. Simulation Monographs, Pudoc, Wageningen (in press).

WIT, C. T. DE, 1958. Transpiration and crop yields. Agr. Res. Rep. 64. 6, Staatsdrukkerij, 's Gravenhage, 88 pp.

WIT, C. T. DE, 1974. Early theoretical concepts in soil fertility. Neth. J. agric. Sci. 22: 319-324.