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A HIERARCHICAL APPROACH TO AGRICULTURAL PRODUCTION MODELING

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Introduction

The main objective of land evaluation and one of the objectives of production research is to indicate and elaborate options for development in agriculture. The actual development course in a given region depends not only on technical feasibilities, but also on the socio-economic situation and on politically motivated and therefore changing policies. To keep all options open as long as possible, the method of analyzing the system should be designed in such a way, that the introduction of normative concepts is postponed to the latest possible stage. In this way, entanglement with social and economic problems can be avoided in the early stages of work, the problem being already sufficiently complex without this.

Of course, all the elements of the agricultural production system are interrelated but the actual relationships are in many cases only partly understood. In order to use this partial knowledge as efficiently as possible, a hierarchical approach is adopted. In this schematized approach, the number of factors that has to be taken into account for the estimation of crop production at the highest hierarchical level is substantially reduced by assuming that constraints, that can feasibly be removed, have indeed been eliminated. At lower hierarchical levels, the factors taken into account at a higher level remain fixed and the effect of limiting factors, originally supposed to be eliminated is taken into consideration.

The analysis is elucidated with the help of a schematic presentation of the procedure followed and a more detailed discussion of the most important aspects. Finally, an application will be discussed for the synthesis and analysis of farming systems.

A Schematic Presentation

The hierarchical procedure is schematically presented in Figure 1. The rectangles in the second row represents 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 (de Wit et al., 1979). 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 should not be the definition of a production function describing the relationship between the yield and all possible combinations of growth factors, since, 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 present know-how. 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. This is reflected by the direction of the arrows in the diagram: towards the yield level as well as away from the yield level.

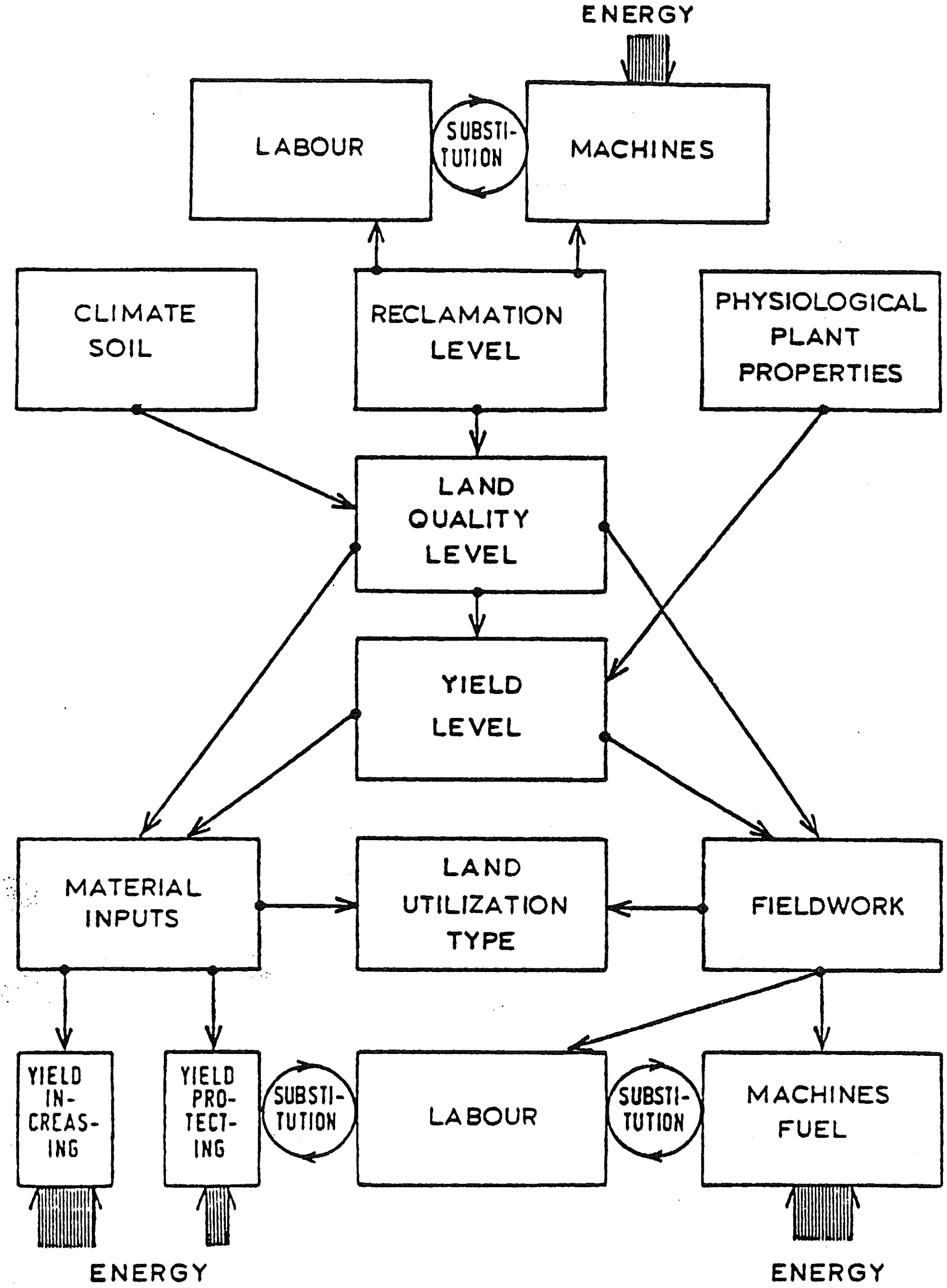

Figure 1. A schematic presentation of the analyses.

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, frequency of 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 required yield level as they are needed anyway. The time requirements are, however, strongly influenced by soil type and weather conditions. In performing the field work, considerable substitution is possible between manual labor 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, particularly rainfall. Characteristic for these production materials is, that they cannot be substituted by labor. This is in contrast to the yield protecting materials, biocides, for which alternatives, e.g. labor-intensive weeding versus the use of herbicides and manual insect eradication versus spray-killing are possible.

The rectangle "land utilization type" indicates a preliminary synthesis of the various interacting factors which play a role in the design of crop rotations on a given acreage. Farming systems are built up from elements of different land quality levels under various types of land use. The existence of specific farming systems is not only determined by the technical feasibilities but also by the socio-economic environment. We shall return to the subject later.

Land Quality Level

The land quality level represents the integrated effect of various land qualities. It is, on the one hand, determined by intrinsic soil properties and the prevailing weather conditions and, on the other hand, by the degree of soil amelioration. In the schematized set up, four levels of soil amelioration are being distinguished.

The lowest level refers to land in an almost virgin condition and allows only cultivation with extended fallow periods. Hardly any land improvements have been carried out. Water supply is totally dependent on rainfall and flooding is avoided only if possible by simple modifications of the topography. The next level provides opportunities for more permanent use with or without fallow periods. The moisture regime is again fully dictated by weather conditions. The distinction between these two levels depends to a large extent on natural differences. The next level pertains to land where improvements have been carried out, such as leveling, simple terracing and the construction of open ditches to control excess water. The final level refers to land in a favorable condition for crop growth, well leveled, with complete water control and the necessary infrastructure. Sufficient water is available to allow unrestricted irrigation.

Apart from defining the present status of the land in a given region, it is also important to quantify the reclamation activities necessary to bring the land to another land quality level. This applies especially to the amount of vegetation and stones to be removed, number of m^4 (volume x distance), soil to be moved and the infrastructure that must be built. This aspect of the analysis is represented in the first row of the diagram in Figure 1. Reclamation can be carried out with manual labor. However, that is often only a theoretical possibility, since most of the acreage that could easily be reclaimed has already been developed, whereas the population density and hence labor availability in the remaining areas is often low. Even in China, one has come to the conclusion that it is almost inevitable to resort to the use of mechanical means. The activities to be performed are therefore analyzed for various technological levels in terms of the available equipment.

Production Level

The highest hierarchical production level can not always be achieved in practice. By definition, it is the level at which water, minerals, and nitrogen are not limiting to growth. Crop yield is then only determined by the type of crop, the prevailing level of irradiance, and the temperature regime. Simulation models to calculate the potential growth rates of healthy closed green crop surfaces are available and have been validated under a wide range of conditions (de Wit et al., 1978). These models also provide potential transpiration rates, so that the total water requirement may be obtained for any given combination of crop species and climatic conditions. Combining the above with the rainfall regime and physical soil properties also yields the irrigation requirement for optimum growth conditions. For most regions, sufficient experimental data are available to judge the feasibility of growing the major crops and to define the so-called cropping calendars: time of sowing, emergence, flowering, ripening, etc. Theoretical consideration and field data may then be combined to develop simple calculation models for the relevant crops, yielding the time course of dry matter production and transpiration, and economic yield as outputs. The model for bunded rice by van Keulen (1976) is a good example. The results of these models are directly applicable under irrigated conditions, but are also used as the basis for yield calculations in sub-optimum situations.

For the calculation of the second hierarchical production level, it is also assumed that nitrogen and minerals are optimal, but the influence of moisture availability to the crop is taken into account. The degree of water control is such, that temporary water-logging can be avoided by appropriate drainage. Water supply to the canopy is dependent mainly on rainfall and, to a limited extent, on supplementary irrigation. The physical properties of the soil and the climatic conditions are of major importance. On the basis of these data, the water balance is calculated to enable determination of periods with insufficient water supply to the canopy, resulting in reduced transpiration and consequently sub-optimum growth rates. Such calculations may be performed on a daily basis (van Keulen, 1975, Makkink and van Heemst, 1975) for periods of some weeks, up to a month (Arbab, 1972, Buringh et al., 1979). The purpose of the simulations and the degree of detail of the available data dictate the resolution of the calculations. The model is set up such, that the moisture status of the top soil is tracked separately to enable the calculation of the number of workable hours in the field: an important parameter in the farming systems synthesis.

At the third hierarchical production level, not only periods of water shortage have to be taken into account, but also periods with excess water. At this level, the possibilities of run-on and water-harvesting are also of importance. The water balance in these areas is often so complex, however, that the present models can hardly cope with the situation. Maps and photographic material, interpreted with the help of experts acquainted with the local situation, may then provide additional information, since the situation is often close to the existing one.

Yield Increasing Inputs

A fourth hierarchical production level is obtained, when in each of the above situations the availability of nitrogen and minerals is also considered. Apart from the physical properties, other characteristics of the soil, such as organic matter content, cation exchange capacity, clay content, and mineralogical composition, have to be taken into account.

Hence, as the next step, the nitrogen supply is considered, assuming that the situation with respect to minerals is still non-limiting. This special status of nitrogen is due to the amounts required, its costs and its mobility in the soil-plant-atmosphere system.

The effect of nitrogen on production is analyzed by separating the relation between yield and application into two components: yield versus uptake and uptake versus application (de Wit, 1953), as in Figure 2. The relation between yield and uptake (quadrant B) is of the well-known saturation type but the relation between application and uptake is rectilinear

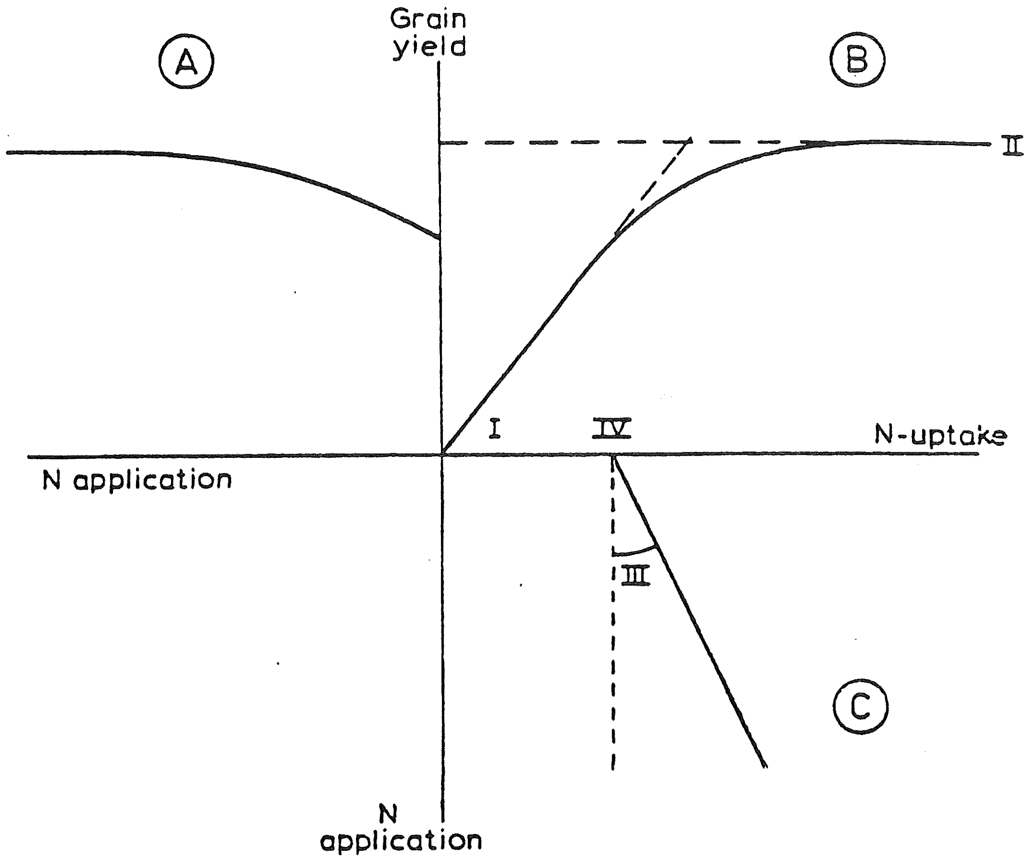

Figure 2: The relation between yield and nitrogen-application (A), desegregated in the relation between yield and nitrogen uptake (B) and nitrogen uptake and nitrogen application (C).

in the relevant range (van Keulen, 1977). Based on the presentation in Figure 2, the problem of nitrogen nutrition can be separated into four partial problems, schematically indicated by roman numerals in the graph.

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 seed per kg N absorbed by the crop. The maximum yield level (II), no mineral and nitrogen shortage, has been considered in the preceding section. The hierarchical build-up of the analysis requires the assumption that the water balance is independent of the nitrogen supply. This assumption is debatable, but quantitative treatment of the interaction between nitrogen supply and moisture balance is difficult and requires in most cases too much detailed knowledge of the actual growing conditions.

The moisture regime in the soil affects the processes of denitrification and leaching and, hence, the recovery of the applied nitrogen fertilizer. That is the fraction of the annual dressing taken up by the plant in its above ground parts, preferably calculated for an equilibrium situation where each year aproximately the same amount is applied. The recovery fraction of nitrogenous fertilizers may vary from a low of 0.1, when applied injudiciously or on poorly reclaimed soils to as much as 0.8 under favorable conditions and proper management.

The amount of nitrogen available from natural resources (IV) is often so low, that it may be obtained from available yield data, using slope I (van Keulen, 1977). For the time being, this is simpler and often more reliable than the use of existing models of nitrogen transformations. The grain yield of many cereal crops without any fertilizer application is around 1000 kg ha^{-1}, corresponding to a typical uptake of 14 kg N ha^{-1}. Depending on actual growing conditions, these amounts may vary by a factor or two. These differences in nitrogen availability from natural sources are negligible at the higher technological levels where chemical fertilizers are available, but they may mean the difference between food and famine in situations where these products are lacking.

For the elements Ca and Mg and to a lesser extent for P and K, the magnitude of the basic dressing is of major importance. The problem to be solved with respect to these elements can also be split up into a number of partial problems. Is a basic dressing required at the time of soil reclamation to achieve a sufficient fertility level, and what are the amounts involved? What is the magnitude of losses by fixation and leaching, how much is removed by the crop and what amounts have to be applied periodically to compensate for these losses?

Answering these questions for Ca and Mg hardly ever presents great problems but that does not imply that the fertilizer application itself is always simple: many acid soils are located at considerable distances from limestone formations. For potassium, the major criterion is the recognition of soils with high potassium fixing capacity.

Phosphate application without nitrogen fertilizer application often results in appreciable yield increases, but this leads inevitably to the withdrawal of considerable amounts of nitrogen and hence to depletion of the soil nitrogen store (Report PPS-project, 1980). Phosphate dressings should therefore be adjusted to the level of nitrogen application. In practice this is achieved with the aid of soil analyses, crop analyses and fertilizer experiments, but in prospective land evaluation studies the purpose is frequently quantification of the P requirement for land utilization types that do not yet exist. This requires a rather detailed analysis of the elements of the P cycle, as carried out by Cole et al. (1977) for organic phosphates and by Beek (1979) for inorganic phosphates. In the framework of the present study, attempts are being made to integrate these analyses in a model, but for the time being it is necessary to rely to a large extent on local experience.

Labor Requirements

During the calculation of potential yield levels, the number of workable hours is also estimated, which enables the scheduling of the crop calenders in time. It is, in general, 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 mechanization. Four such levels are distinguished: manual labor, animal traction, light two-wheeled mechanization and complete mechanization.

The task-times for recurring activities are reasonably well-established for mechanized operations (van Heemst et. al., in prep.). However, hardly any attention has been paid in agricultural research to manual labor and animal traction. At that level, data on time requirements are only approximative since they were inferred from sociological and anthropological studies.

Labor requirements at the various technological levels vary considerably. In hours per ha: 750 for spading or similar activities, 35 for ploughing with horses, 15 for ploughing with a two-wheeled tractor and 5 for ploughing with a normal tractor. One weeding with a hoe takes about 100 hours per ha but with herbicides and tractor-driven spray equipment only a few hours per ha. Pest and disease control virtually always involves biocides. The major problem here is not the estimation of the time requirements, but the estimation of the yield loss without control and hence the necessity of the operation.

In summary, it may be concluded that indicative task times are available at the four mechanization levels, but that the scatter in the basic data is such that without local knowledge, no meaningful differentiation can be made between various soil types, different levels of training and so on.

Synthesis of Farming Systems

The foregoing analysis results in tables containing the yield levels per region, per land quality level, per mechanization level and per crop, and the associated material inputs, the labor requirements in the course of the crop growth cycle, the number of workable hours and so on. This mass of data can be handled more meaningfully when summarized on the basis of farming systems. The farming systems which will develop in practice not only depend on the physical environment and the technical know-how, but also on the historically determined situation, the socio-economic environment, and the prevailing political aims. To analyze this complex situation, interdisciplinary research has been initiated, which is much more sophisticated than discussed here (Center for World Food Studies, Amsterdam/Wageningen). However, a more simplified approach, aiming at a more limited objective, may be helpful from a bio-technical point of view.

For this purpose, the analysis is limited to a family farm (a farmer, his wife, and two working children) and to four possible crop rotations with emphasis on cereals, root or tuber crops, fibre crops and seed legumes, respectively. For any given region, the specific crops that comprise the rotation are choosen on the basis of the farmers knowledge and research results obtained in the same or in comparable regions, the choice remaining partly arbitrary.

Questions that can now reasonably be answered from a biotechnical point of view are of the following type: What should be the size of the farm for maximum utilization of the available labor? During which periods in the season is labor availability a limiting factor, and can this constraint be removed by increasing the mechanization level? How much labor is idle, and during which periods, and is it possible to improve this situation by improving the land quality level or by growing more or other secondary crops? To what extent would the optimum farm size change upon variation of the ratio between the main crop and secondary crops in the rotation? Which yield increasing and yield protecting inputs are required, and in what quantities, and what should be the level of skill of the farmer? The answers should be judged, of course, in the light of the assumptions that explicitly or implicitly underlie the analysis.

In principle, 64 farming systems result from a combination of four land quality levels, four mechanization levels and four crop rotations. In practice, that number is never reached since in every region a considerable number of the combinations is not feasible for obvious reasons. Such a systematic approach enables a comparison between regions and countries. A comparison of the man/land ratio and the present levels of land quality and mechanization indicates also where feasible opportunities exist or where problems could develop. Which systems are economically feasible, or for other reasons acceptable or unacceptable, is outside the scope of this analysis.

Concluding Remarks

The present paper contains so many speculative elements that it is presented under the responsibility of only two authors. However, it would never have been completed without using the internal reports of other members of the Wageningen staff of the "Center for World Food Studies" (SOW): J.A.A. Berkhout, P. Buringh, P.M. Driessen, J.D.J. van Heemst, and J.J. Merkelijn.

Many aspects of the complex problem are actively elaborated, but the synthesis of farming systems is only in a preliminary stage. Here, the Wageningen members of the Center will have to supply the basic material for the Amsterdam members who are in charge of developing the social economic model components. At that level we are still struggling with an old problem: economists ask questions that technicians cannot answer, whereas the latter have answers to questions that are not asked by economists. But we are making progress.

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