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Modelling Production of Field Crops and its Requirements*

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ABSTRACT

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Simulation models are being developed that enable quantitative estimates of the growth and production of the main agricultural crops under a wide range of weather and soil conditions. For this purpose, several hierarchically ordered production situations are distinguished in such a way that the results of simulations on one hierarchical situation are used as input for the calculations of another. For the highest hierarchical production situation, water and plant nutrients are optimally available; in the next situation water may be limiting at times, whereas in further situations limited supplies of the main plant nutrients are also taken into account. The reclamation activities and the yield-increasing inputs that are needed to achieve the simulated yield levels for the various situations are estimated.

The weather data and the physical soil data that are needed for the calculations in the first two hierarchical production situations are specified. It is shown that environmental heterogeneity contributes considerably to the complexity of the problem and that especially the averaging of weather data over time and soil data over space leads to distortion or even destruction of data. To avoid this, the data from the original observation sites should remain accessible at all times. The easy accessibility of computers and data base management systems implies that there is no excuse anymore to average first and then calculate, instead of the other way round.

AN HIERARCHICAL ANALYSIS OF THE AGRICULTURAL PRODUCTION PROCESS

Crop ecology is an interdisciplinary science; so it relies heavily for its development on its supporting disciplines. These disciplines have of course an importance of their own with respect to crop science and this may easily lead

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to a situation where too many crop husbandry problems are treated in the first place as disciplinary problems and that the possibilities for improvements on this narrow basis are overestimated. A systems approach to the analysis of agricultural production tries to avoid reliance on bases that are too narrow and on findings from a single discipline. A tendency to overestimate the value of knowledge from one's own discipline comes so naturally, however, that even the emerging discipline of systems analysis does not escape this danger of overestimating its own possibilities.

This may explain that part of the research effort is directed to analysis of the entire agricultural production process with the aim of evaluating regional agricultural production possibilities. This is done by making quantitative estimates of growth and production of the main agricultural crops in a region under a wide range of conditions and of the means of production that are necessary to achieve these productions. It entails the cooperative effort of three institutes in Wageningen: the Department of Theoretical Production Ecology of the Agricultural University, the Centre for Agrobiological Research (CABO) and the Centre for World Food Studies (SOW).

For this purpose an approach is being developed (Van Keulen and Wolf, 1986), which is schematically presented in Fig. 1. In this figure, the factors that determine the possibilities of agricultural production are presented in the rectangles of the second row. Climate and soils are a part of the heritage of a region, but the level of reclamation (ranging from simple clearance to irrigated fields) may differ because of socio-economic and historical reasons. The three factors in combination determine the level of land quality and the choice of crops. The crop properties may be changed by breeding and selection, but the scope for improvements are reasonably well established for quite some time to come. There are now simulation programs available that enable the assessment of the production possibilities of the main crops for various reclamation levels with reasonable confidence, provided that weeds, pests and diseases do not interfere and sufficient nitrogen and mineral nutrients are available but that water may be at times a limiting factor.

The fourth row in Fig. 1 shows that the means of production necessary to realize these calculated production possibilities can be distinguished in means for executing the field work, in material means of production and in demands on management. The demands on management can also be translated into educational and extension needs, but these are not considered here.

The necessary field work depends mainly on the crop that is to be grown and can be described in physical requirements for soil cultivation, weeding, harvesting and so on. The time needed for these operations hardly varies with the yield level because they are always necessary. The time available to execute this work on the land, however, depends again to a large extent on the type of crop that is grown and on the level of land quality. The field work requires human labour and machines, but there is considerable scope for substitution

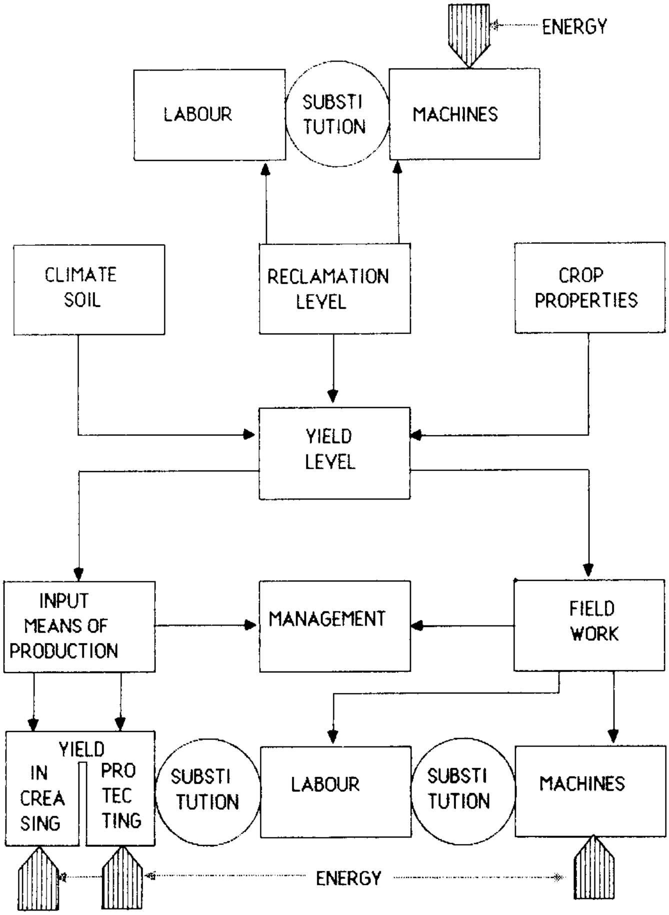

Fig. 1. A schematic presentation of the analysis of agricultural production systems.

of one for the other and therefore between the use of human labour versus that of fossil energy in machines.

The material means of production that are needed to achieve the calculated yield levels are subdivided in yield-increasing and yield-protecting materials, as shown in the last row of Fig. 1. The necessary yield-increasing materials, such as nutrients and water for irrigation, depend on the yield level which is aimed at and the quality of the land. A characteristic of these material means of production is that they cannot be replaced by labour. This is different for part of the field-protecting means of production. There are manual ways of controlling insects, e.g. picking colorado beetles, that can be replaced by the use of insecticides. Manual weeding, however, often requires between 500–1000 h/ha of tedious work in the field and therefore the possibilities of substitution between manual and mechanical weeding versus weeding by herbicides are by far the most important.

The activities that are necessary to reach a certain reclamation level are also quantified in physical terms, as for instance the amounts of soil that have to be moved during levelling and ditching or bunding of paddy fields. The first row of rectangles in Fig. 1 illustrates that these efforts are again translated into labour, machines and energy that are needed to execute the work, taking again into account the possibilities for substitution.

SIMULATING GROWTH AND PRODUCTION

In this paper emphasis will not be on problems of land clearance and reclamation but on problems that arise during the calculation of the various yield levels and on the influence of climate and soil on land quality. For this purpose, the knowledge and experience collected in various disciplines is integrated in dynamic simulation models in which the growth of crops is explained on the basis of the underlying physiological, physical and chemical processes in the crop and in its surroundings (De Wit, 1978).

By means of these simulation models, the most important processes, such as assimilation of carbon dioxide and nitrogen, distribution of these assimilates, respiration, transpiration and uptake of water from various soil layers are described. For each of these processes is shown how its rate at any moment depends on the constants, forcing variables and state variables of the system. Constants of the environment are, for instance, the carbon dioxide content of the air and the texture, the depth and the slope of the soil. Examples of forcing variables are the course of radiation, temperature and rainfall throughout the year. State variables characterize the changing situation of the crop and of the soil at any moment. State variables of the crop are among others the amounts of above- and below-ground materials, the amounts of leaves, their surfaces and their turgidity, the amount of nitrogen in the crop and the rooting depth. State variables that involve the soil are, for instance, the depth of the water table, the water and available nitrogen content of the various soil layers and the moisture content in the surface soil. The model updates all these state variables in recursive fashion by means of the calculated process rates at any moment. For instance, the amount of nitrogen that is taken up during a short interval at any point in time can be obtained by multiplying the calculated uptake rate at that moment with the length of this interval. The quantity that is calculated in this way is then added to the amount of nitrogen that is already in the crop to obtain the amount at the end of the time interval. The other state variables are updated in a similar way. This numerical integration is repeated again and again until the end of the growth period. Crucial in the whole operation is not so much the technique of integration as is the reliability of the description of the processes of change.

To remain in command of the subject and not to lose grasp of the problems, some hierarchically ordered production situations are distinguished in such a way that the results of simulations for one hierarchical situation are used as input for calculations of another (Penning de Vries and Van Laar, 1982). For the production situation that is the highest in hierarchy, water and plant nutrients are optimally available and pests, diseases and weeds are absent. The growth of the crop is then determined by its physiological properties and the weather. Well verified simulation models are available that calculate the potential production for a range of crops at a given place with the use of some additional practical data from the sowing and development calendars for those crops. Depending on crop species and weather conditions, these calculated potential production rates are between 150 and 350 kg ha^{-1} day^{-1}. This may lead to high seasonal yields, e.g. yields of 20.000 kg seed/ha are calculated for maize under favourable conditions. Such high yields are indeed achieved in regions with a favourable climate on well fertilized soils that are optimally supplied with water. In general, however, yields are considerably lower. These potential production calculations provide then a yardstick for the yields that are obtained in farm practice and in experimental situations.

In addition to the potential yield, the dry matter production and the transpiration in the course of the season are also simulated. These results are subsequently used in the next lower hierarchical production situation, where water may be a limiting factor but where the crop is still free of pests, diseases and weeds and is optimally supplied with nutrients. Because water may be short or in excess, the water content of the soil and the amount and distribution of rainfall have to be taken into account in this situation. For simulating this production situation, considerable information is needed on the properties of the soil that govern the water balance and on its physico-geographical situation.

At the following hierarchical production situation, a possible nitrogen limitation is also taken into acount by adding submodels that simulate the nitrogen balance and the organic matter content of the soil. A dynamic treatment of leaching and aeration processes is then also required. The models that have been developed thus far help to understand the complex processes in this production situation. To produce results that can be used in practice, however, information from classical fertilizer experiments is still indispensable. This is also the case in the next hierarchical situation where the possibility of short supplies of mineral nutrients are considered and soil chemistry plays a role in model development. At this level, special attention is given to the phosphorus problem. As mentioned earlier, for any production situation yields may be adversely affected by pests, diseases and weeds, but this is not the place to elaborate on these constraints.

DATA REQUIREMENTS

The basic data needed in the simulation programs can be distinguished into those related to the plants, the weather and the soil. The type and number of data necessary for the simulation of crop growth under field conditions depend to a large extent on the amount of detail that is pursued. In a system analysis that aims at understanding the basic interrelations considerable detail is needed. For instance, the carbon dioxide assimilation rate of the whole crop is then obtained by integrating the assimilation of the single leaves in dependence of the amount of light these absorb.

This requires a quantitative analysis of the properties of the individual leaves, a detailed description of the daily course of the global radiation components and a quantitative description of the architecture of the crop canopy. Likewise, the environment of the roots and the achitecture and development of the root system have to be described in considerable detail to determine the uptake of nutrients and water. Such comprehensive models require far too many data to explore the actual agricultural production possibilities of a whole region. They are, however, indispensable for the development of summarizing models that may serve this purpose, yet require less data. Clearly, a compromise has to be found between the degree of detail that is retained in the models and the minimum number of different data that are needed for their use.

At the second production level where water may be limiting at times, the minimum data requirements remain considerable. The weather data that are needed include the radiation, the minimum and maximum air temperature, the rainfall and the additional data that are needed to calculate the potential evaporation according to Penman (Van Keulen and Wolf, 1986). The minimum soil physical data requirements are the slope angle of the land, the groundwater depth, the potential surface storage, the sorptivity of the surface soil, the soil texture, the pore space, the field capacity, wilting point and the saturated hydraulic conductivity of the distinguished layers of the profile. In addition, data are needed that depend on the management, as for instance, the surface roughness, and the drain depth and spacing.

Many of these data are needed for the description of the water balance. The major problems here are not so much associated with the transport processes in the soil as with the processes at the soil surface. How much of the rain infiltrates at the place where it falls, where does the water go that runs off and under what conditions and then how fast are mulch layers formed? To develop useful simulation models for these processes, far too much detailed knowledge is required on the infiltration capacity, the physical structure and the topography of the surface soil and on the number, the length and the intensity of the individual rain showers. Therefore, rather simple rules of thumb are used to describe infiltration and run-off/run-on phenomena. This environmental heterogeneity may lead to considerable uncertainties and therefore much sophistication in the description of other processes does not pay.

In general, heterogeneity indeed contributes considerably to the complexity of the analyses and the remainder of this paper will be mainly devoted to this problem. A distinction has to be made between temporal and spatial hetero-

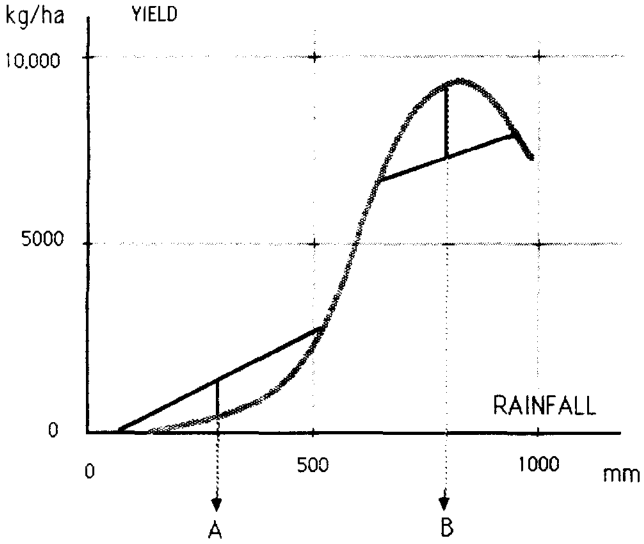

Fig. 2. The influence of averaging rainfall on its calculated yield response. The yield is underestimated by averaging in the lower rainfall region (*A*) and overestimated in the higher rainfall region (*B*).

geneity. The problems that arise from the former are of special importance in case of the treatment of weather data and the latter in case of treatment of soil data.

TEMPORAL WEATHER VARIABILITY

The weather data that are needed may be derived with some difficulty from climate maps and associated tables. The use of these average data may lead, however, to a considerable overestimation or underestimation of the possibilities in climates where the weather varies considerably from year to year.

This is, in its most simple form, illustrated in the schematic graph of Fig. 2 with rainfall along the horizontal axis and the seed yield of some grain crop along the vertical axis under otherwise identical conditions. Below a certain amount of annual rainfall there is no seed yield at all and above that level, there is a practically linear relation until some maximum is reached above which the yield decreases with increasing rainfall, because of the occurrence of periods with severe waterlogging. At an average rainfall "A", the production would be practically zero. In some years, however, rainfall is lower and production is indeed zero, but in other years rainfall is higher so that there is a harvestable crop. The average production is therefore higher than the production calculated with the average rainfall. At an average rainfall of "B" the situation is reversed: the average production is now lower than the production

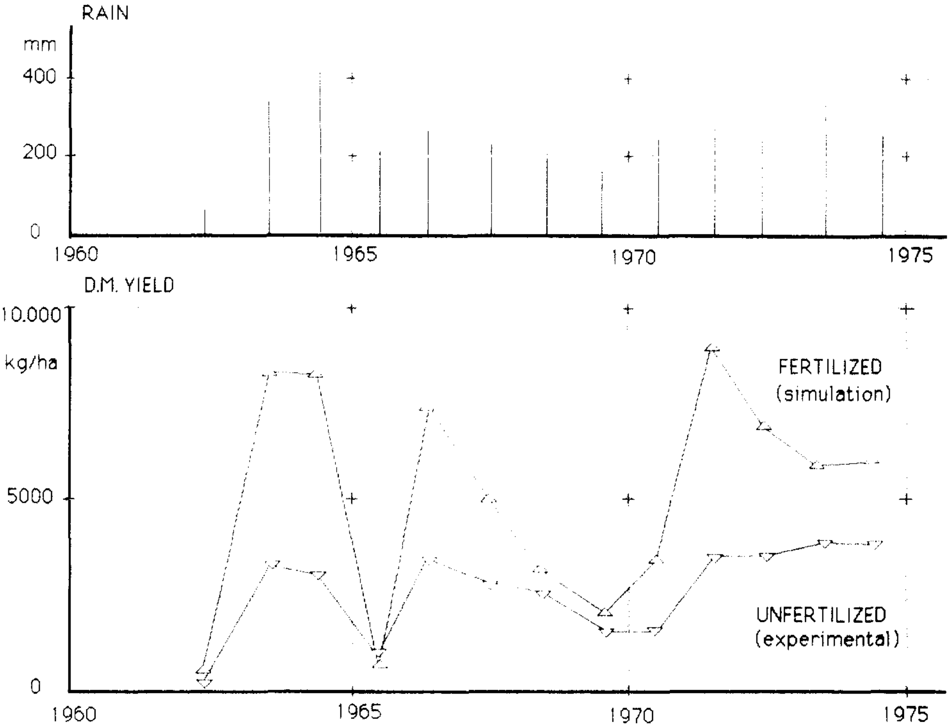

Fig. 3. The rainfall and the yield of fertilized and unfertilized natural grassland in the Negev during 13 years. The yields on the unfertilized rangeland were observed and on the fertilized rangeland were simulated (van Keulen, 1975).

calculated with the average rainfall. Clearly, the non-linearity of the relation between production and rainfall is the cause of this phenomenon.

An important reason that crop production models are so complicated that they can be solved only by means of numerical integration is the existence of many non-linear relations between the variables that govern crop growth and production. Examples are the relation between radiation and carbon dioxide assimilation, between turgidity and stomatal conductivity, between root density and uptake of water and nutrients and between water content, water potential and capillary conductivity, to mention just a few.

A field example of the consequences of this phenomenon is given in Fig. 3, where the dry matter yields of unfertilized and fertilized natural rangelands are given for 13 years in the northern Negev.

The yields of unfertilized rangelands are experimental results and those of the fertilized ones are obtained by means of a well-verified simulation program for the growth and production of natural rangelands in semi-arid regions that are well supplied with mineral nutrients and nitrogen (Van Keulen, 1975). The yields of unfertilized rangelands appear more or less stabilized at a relatively low level due to lack of nutrients. The yields of fertilized rangelands, however, vary considerably from year to year, mainly as a result of the large differences in annual rainfall and its seasonal distribution.

In dry years, the production in the fertilized situation is not higher than in the unfertilized situation at about 500 kg/ha, but in good years it may increase to 9000 kg/ha. On the average, the production of the fertilized natural rangeland at some 5000 kg/ha is about twice the production in the unfertilized situation. These production levels were simulated under the assumption of an equal distribution of the average monthly rainfall over the average number of monthly showers. The production is zero, however, if calculated with the average monthly rainfall evenly distributed over all days of the months, because then the resulting small daily showers do not penetrate into the soil to any depth and the water is lost by direct evaporation from the soil surface. By distributing the average amount of monthly rainfall over a few well spaced showers, the simulated production increases, however, from 5000 kg/ha to more than 7000 kg/ha. In that case only 45 mm of the water is lost by direct soil surface evaporation against 80 mm in the situation where the average amount of rainfall is distributed over the average number of showers for each month.

The use of average climatic data to calculate production where the weather varies considerably from year to year may lead therefore to biased results to either side. This bias can be avoided by calculating first the production for a number of years on the basis of actual weather data and subsequently averaging the results. Of course, this requires many more calculations than the other way round of averaging first and calculating later. Because the calculations are strictly repetitive and not complicated in themselves, they require only a limited amount of time on some simple computer. Therefore no excuse exists for not handling the information in the proper way, except for the fact that even at the present day the access to the original data base is often lost in the process of reduction of data to climatic tables and maps. A second best solution in that situation is to regenerate the variability of the original phenomena by means of random procedures. For understandable reasons, these procedures have been developed especially for rainfall. The input is then the average rainfall and the averaged number of showers in for instance each ten-day period and the output, the number and size of showers throughout an arbitrary year.

SPATIAL SOIL VARIABILITY

Traditional soil maps are, at present, the most widely available source of information on soils. The problem of temporal variation does not play a role here because only those parameters are surveyed that are practically constant functions of time. Variable parameters, such as the water content of the soil and the amounts of available nitrogen in the soil are treated in other ways. For instance, in simulation models the groundwater table may be introduced as a forcing function when it is sufficiently controlled, but in other situations it has to be endogenously simulated, like the water content of the rooted soil profile. The available nutrients in the soil have to be simulated also endogenously if they vary rapidly, but it suffices often to assume constancy throughout one growing season.

In case of soils, the problem is the treatment of the spatial variability. This phenomenon is neither observed in the field nor mapped in the office with the detail necessary for application in production models. This is very understandable for several reasons. Soil surveys and soil maps are not only made for agricultural purposes. To enable their interpretation, they should reflect the physical geography of the region and the relevant soil formation processes. But, as a result the map units are often not homogeneous enough for agricultural application. Also much detail may be lacking with respect to differences that are the result of differences in agricultural use. Moreover, it should be realized that the soil surveyor in the field cannot carry much more than his auger, ruler, note book and pencil and hardly has time to visit a particular location more than once. He is therefore not very well equipped to collect the quantitative data that are needed for production modelling and much crucial information, for instance on water availability and fertility, is the result of intuitive guesses. However useful these may be for further intuitive judgements, they hardly form a basis for further calculations.

An effect of spatial heterogeneity, albeit on a limited field scale, is illustrated in Fig. 4, presenting the results obtained from a detailed model of spring wheat production (Van Keulen and Seligman, 1986). The model was run for a 21-year period, using weather data from a station in the northern Negev of Israel and for the same site as used for Fig. 3. Two situations were considered: one where the soil was assumed to be homogeneous, and one where local heterogeneity was introduced by assuming that 30% of the rainfall runs off from patches that cover half the area and is subsequently collected on patches that cover another half of the area. It appears that in favourable rainfall years soil heterogeneity leads to lower overall grain yields, because the yield depression on the "run-off" sites is not compensated by the yield increase on the "run-on" sites. In unfavourable rainfall years, however, overall yield increases due to spatial heterogeneity because the collection sites still support a reasonable crop, whereas with homogeneous soil so much water is lost by evaporation from the soil surface that nothing is left for transpiration and crop growth. The spatial soil heterogeneity on a micro-scale results thus in decreasing variability in crop yield. This is a common phenomenon in marginal situations.

A considerable amount of physical detail is needed for these and similar simulations. Unfortunately, however, the limited amount of quantitative information on, for instance, depth of roots and hardpans and on the range of the depth of the water table that becomes available from the work in the field, is often destroyed in the process of mapping, because it is practically always

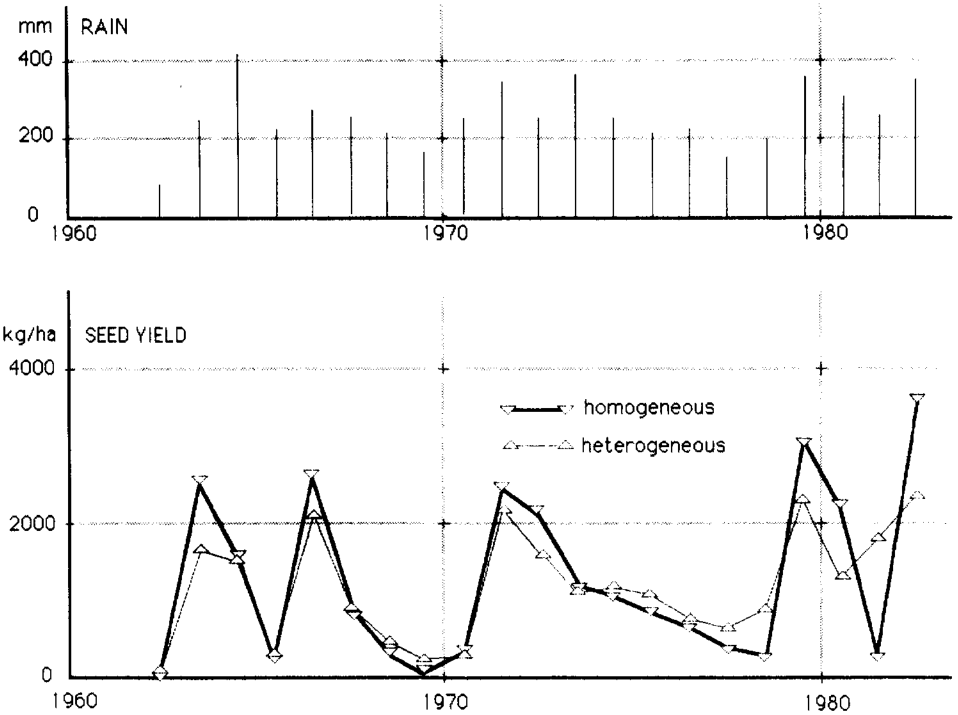

Fig. 4. Simulated wheat yields on a field in which the rain infiltrates homogeneously and on an heterogeneous field where on patches that cover half of the circa 30% of the rainfall runs off and infiltrates on patches that cover the other half. As in Fig. 3, it concerns here the northern Negev.

necessary to use coarse classifications. An example is the depth at which an impermeable layer is present in the profile. A feasible legend could very well be: shallower than 40 cm, between 40 and 120 cm, between 120 and 200 cm and below 200 cm, if the auger was that long. In simulating root growth, availability of water and drainage, however, it may make a big difference whether the impermeable layer starts at 40 or 120 cm or at 120 or 200 cm. It is therefore more than unfortunate that such information that may have been available in the note book of the surveyor was juggled always in the process of data handling and mapping.

To meet the need of quantitative information, the classical field observations are increasingly supplemented by laboratory measurements. The physical measurements may include determination of particle size distribution, bulk density and water content and capillary conductivity at some water potentials. Soil chemical measurements may include determination of organic matter content, acidity, base saturation and contents and availability of some major nutrients. Concurrently, techniques have been developed that allow interpolation of these quantitative data either collected directly in the field or measured in the laboratory and that make automatic generation of maps possible (Nielsen and Bouma, 1985). These methods generate parameter values for locations that were not studied, on the basis of observed values at neighbouring locations that were studied. In this way, it is possible to calculate average values for the points of a regular grid. This procedure may be applied to each parameter that is of importance for a particular application.

The averages of the parameter values for each grid point may be considered to characterize the soil at that location. Such averages, however, may form in combination an artefact because of the existence of many non-linearities as discussed earlier for the weather (Fig. 2). A few examples may serve to illustrate this point. In general, the relation between plant growth and measured nutrient availability is of the saturation type, so that averaging the latter may overestimate the first. The same holds for the effect of pH on root growth, for instance. If wilting points and field capacities are averaged individually, the results may very well be a soil with a relatively high wilting point compared to the field capacity and therefore a relatively low water holding capacity.

In the further process of data reduction such averages are classified and subsequently combined in mapping units for each grid point. The number of legend units that is generated in this way easily runs out of hand, unless only a small number of parameters is considered and coarse classifications are used. The use of sophisticated techniques does not prevent the presentation of information in maps from burying much of the available information.

Whatever the treatment of the basic data, the result is always destruction or distortion of data or both. Therefore, much is to be said for the use of the untampered data from each original observation site or pedon. Or, in other words: not averaging first and calculating later, but calculating first and averaging later. Not too long ago, this was practically impossible, but the widespread availability of main-frame and personal computers and their capabilities has changed that situation. In the first place, there have been developed geographical and relational data-base-management systems for these purposes so that an important argument for data reduction has lost its weight. Secondly, these machines can handle simulations and other calculations, as discussed in this paper, in such a convenient, rapid and cheap fashion, that there is no reason not to apply these techniques to the original data and to supplement in that way the data set for each location with derived, secondary data.

This leaves aside the question in which way the primary and secondary data on weather, soils and production possibilities have to be used in further work, as for instance in planning or in technical-economic models. Also in these situations, averaging too early may lead to a destruction of information which cannot be restored by statistical techniques.

There is at least one solace for makers of maps. At each stage of the work, maps of any scale, form and colour remain one of the most suitable means enabling possible users to judge the availability of primary and secondary information on soils and their potentials. The function of these maps is then, however, mainly instructive and educative. They are far too primitive to use as a data bank because only a part of the original wealth of data can be retrieved and then in a distorted fashion. That does not justify the expense of collecting the data often at great personal sacrifice of the surveyor.

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