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B. The Use of Simulation Models for Productivity Studies in Arid Regions

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I. Introduction

A large area of the world's surface consists of arid and semi-arid regions. Although the exact magnitude of the area covered by these climates depends on their definition, it is around 30% of the total land surface. The occurrence of disasters, especially drought and starvation, have caused increasing interest in the agricultural problems and potentialities of these regions. Many developed countries take an active part in agricultural research in the arid zone, through the investment of either money or knowledge for the establishment of special projects or the development of specific regions. This research is often aimed at the solution of a special problem, or at least at spectacular results through an immediate increase in production. Despite the efforts of international organizations and agencies, little progress seems to have been made towards a coordinated research program, in which a systematic and theoretically sound examination of the processes critical for the level of herbage production in arid zones is carried out. In particular, the interaction between the various processes and their relative importance in the arid zone have not been studied thoroughly. In the framework of a joint Dutch-Israeli research project on "Actual and Potential Herbage Production under Semi-Arid Conditions" special attention was paid to the development of tools to integrate the existing knowledge into meaningful systems and to indicate ways of using these for extrapolation to areas or circumstances that have not been studied in detail (see Evenari et al., this volume Part 6:E). This is done by developing computer models based on physical, physiological, and chemical processes, that can be applied in regional development programs in the arid zone. Such models can also be used in deciding on the allocation of limited funds available for development of arid regions or in the evaluation of economical advantages that can be gained from irrigation or fertilizer programs.

In this paper a simulation model 'ARID CROP' is treated. This model calculates the course of dry-matter production of a crop canopy and the distribution of moisture in the soil below that crop, from basic or derived physical and physiological properties of plant and soil. Meteorological data from standard weather stations are given as input. The basic assumption is that the crop is optimally supplied with nutrients and that moisture is the main factor liming growth.

A presentation of the complete model and a detailed treatment of the processes is given by van Keulen (1975).

II. The Structure of the Model

ARID CROP is a state-variable model. Such models are based on the assumption that the state of each system at any moment may be quantitatively characterized and that changes in state may be described by mathematical equations. This leads to models in which state-, rate- and driving variables are distinguished. State variables are quantities such as the amount of biomass, the leaf area index, the depth of the root system, the amount of water in various soil layers, and so on. Driving variables characterize the interactions at the boundary of the system and are continuously measured, like rainfall, temperature, and radiation. Each state variable is associated with rate variables that characterize their rate of change at a certain moment. Their value depends on the state and driving variables according to rules that are preferably formulated on the basis of the knowledge of the physical, chemical, and biological processes that take place.

After calculating all rates, these are realized over a short time interval according to the scheme: state variable on time $t+\Delta t$ is equal to state variable on time t plus the rate of time t times the time interval Δt. Obviously the time interval must be so short that even the relatively fast rates of change are materially constant during the time interval Δt. In its most elementary form this is a process of numerical integration over time and the simulation model may be replaced by an analytical solution in cases where the equations are simple enough.

However, most models are too complicated and contain too many discontinuities and even random processes to apply straightforward numerical integration methods, and therefore various simulation techniques for digital computers have been developed to handle the models. The model ARID CROP is written in CSMP, a simulation language that is widely used at present in plant physiology, ecology, and soil science.

The number of state variables that may be distinguished in plant growth models is depressingly large. For instance, not only the weight and surface of the leaves, but also their nitrogen and mineral content, their enzymes and other biochemical characteristics may be considered state variables. Models are, therefore, always simplified presentations of the real system and the simplification manifests itself by the limited number of state variables that are treated. It is assumed that considerable reduction of this number may be obtained by limiting the purpose of the model, it being tacitly assumed that processes may then be ordered with respect to their importance and that only those within focus of the purposes need to be handled in detail. For this reason ARID CROP is restricted to situations with optimal mineral and nitrogen supply.

It is further assumed that for each purpose there is an optimum in the number of state variables that should be considered. At first the applicability of the model increases with increasing number of state variables, but then it decreases again because the addition of new state variables diverts the attention from those that were introduced at first and considered the most important. The heuristic process of obtaining a set of state variables ordered in accordance with their importance takes much time in each modeling effort, and the more so, because a reduction in the number of state variables necessitates a hierarchical approach to model building. In such an approach, models of important sub-systems are developed on basis of sound physical, chemical, and biological principles, which are then used for the construction of smaller and more descriptive models for further use.

There are also aspects of the system that are not sufficiently understood to apply this approach. Sub-models are then based on an experimental analysis of the system in situations where the model will be applied, so that generality may be lost. Such a procedure is justified when it is shown that the behavior of the model is relatively insensitive with respect to these aspects. In the case of ARID CROP, this concerns especially the processes that govern the morphogenesis of the leaf- and root apparatus.

III. Description of the Model ARID CROP

1. Driving and State Variables

The main driving variables of ARID CROP are the macro-meteorological data on a daily basis: daylength (latitude and date), total global radiation (relative duration of sunshine), rain, maximum and minimum temperature, dewpoint in morning and afternoon, and average windspeed.

The soil is characterized by its physical properties of which the water content at field capacity, at wilting point, and in air-dry condition are the most important.

The physiological characteristics that govern the growth of the plant are net CO_2-assimilation and transpiration of the leaves, distribution of dry matter, leaf area growth, and the rate of advance of the rooting front.

The main state variables that are distinguished are the water content of the soil up to 200 cm, the temperature of the soil, the live biomass of the plant above and below ground, the leaf area, and the rooting depth. The plant water status is eliminated as a state variable to avoid time steps smaller than a day.

2. Soil Physical Processes

For the description of the physical processes in the soil (see this volume Part 2), the total soil depth is divided into an arbitrary number of compartments, not necessarily of the same size, each one of which is considered to be homogeneous (de Wit and van Keulen, 1972).

Moisture transport between compartments under the influence of developing potential gradients is not simulated, but descriptive formulations for redistribution of the water are used, based on the result of detailed models for infiltration and evaporation. It has been shown that the use of these simplifications has little influence of the availability of water for plant roots, which is the main interest here, rather than detailed soil moisture dynamics.

The total amount of water infiltrating into the soil, which consists of the precipitation corrected for the influence of run-off or run-on, is distributed over the various layers, in such a way that they are subsequently filled up till "field capacity" from the top one down, until all the water is dissipated. Possible surplus is lost by drainage below the potential rooting zone.

Potential evaporation from the soil surface is obtained from the evaporative demand of the atmosphere, calculated with the Penman equation (1956) and the division of energy between canopy and bare soil. The actual rate of evaporation is calculated taking into account the reduction due to drying of the upper soil compartment. The reduction factor, as a function of soil moisture content in the top compartment, is obtained from a detailed model of soil evaporation. The total moisture loss by evaporation is withdrawn from the various compartments, taking into account the physical properties of the soil and the actual moisture distribution.

Soil temperature is calculated as the running average of the air temperature. A detailed treatment of soil heat flow seems unnecessary, as the influence of the temperature on root growth and water uptake is not known accurately. Moreover, during the greater part of the season these processes take place in the deeper soil layers, where the fluctuations are less pronounced. Uptake of water by the root system depends on both the distribution of roots and the distribution of moisture in the soil. The root system is considered to be homogeneous in horizontal direction. Allowance is made for a partial compensatory effect when part of the roots are in dry soil layers, by assuming a greater uptake by those roots which are in wet soil. Actual moisture withdrawal is determined by the potential crop transpiration and the moisture status in the soil, taking into account the effect of soil temperature on water viscosity and root permeability.

3. Growth of the Crop

The germination process of species from natural vegetation is very complicated, because both the properties of the available seed stock and the micro-environment in the upper soil layers show great fluctuations. The importance of these factors for germination of winter annuals has been shown by Janssen (1974). As in this model, however, the main interest is in total dry matter production rather than in the botanical composition of the vegetation, such a detailed treatment is not included. Germination proceeds when the moisture content in the upper 10 cm of the soil is above wilting point and establishment is assumed after a temperature sum of 150 days °C above zero is obtained (Tadmor et al., 1968). When the soil is dried by evaporation before the required temperature sum is reached, the seedlings die and a new wave of germination starts only after rewetting. At the establishment the biomass is set equal to the initial biomass, for which a constant value of 100 kg ha^{-1} is assumed, irrespective of the germination conditions. Total seasonal dry matter production is not very sensitive to this value, but the growth pattern may change, which is an important factor when the vegetation is used for grazing. Initialization therefore remains a major difficulty in this model.

The rate of growth of the vegetation is determined by the transpiration rate and the water use efficiency. The latter is obtained as the ratio between potential growth and potential transpiration (see Bierhuizen, this volume Part 6:C), assuming that its value is independent of soil moisture conditions or canopy properties. The independence of soil moisture status may not be true for some of the species, which may adopt a more efficient use of the available water, when under stress (Lof, 1975; see Hall et al., this volume Part 3:D). However, the absolute amounts of water transpired during such periods are so small, that the effect of a different efficiency on dry matter production is negligible.

The potential rate of transpiration is calculated from the evaporative demand of the atmosphere, determined by radiation intensity and the combined effect of wind speed and humidity, and the leaf area of the canopy.

The equations to calculate the potential transpiration from daily meteorological data are derived from comparison with the detailed model mentioned before, whose results showed good agreement with measured data (van Keulen and Louwerse, 1975).

The potential rate of growth, being defined as the increase in dry weight, is obtained from the rate of gross photosynthesis, taking into account losses for maintenance respiration, depending on amount of dry matter present and temperature, and efficiency of conversion of primary photosynthates into structural material (growth respiration) (Penning de Vries, 1974). Gross photosynthesis as a function of radiation intensity and leaf area index is read from tabulated functions, which are obtained as outputs of the higher resolution model (hierarchical approach). The actual rate of growth is obtained by multiplying the water use efficiency with the actual rate of transpiration.

It is assumed that plant material is continuously dying, under favorable conditions at a relative rate of 0.005 day^{-1}, going up to 0.1 day^{-1}, when either severe water stress develops or when the crop reaches maturity. When, as a result of dying material, the amount of living biomass drops below a limiting value, the canopy is assumed to be completely dead and growth will continue only after a new wave of germination.

The development pattern of the canopy, characterized by the rate and order of appearance of vegetative and generative organs, is governed by genetic and environmental factors. For a given crop at a certain location i.e. at a given daylength, temperature is the most important external factor (van Dobben, 1962). The relation between air temperature and development rate applied in the model is constructed from field experience, assuming that it is linear in the normal range of temperatures (van Schaik and Probst, 1958). The development stage of the crop influences the growth rate through an effect on the potential transpiration rate, is being reduced from 1 to 0 between development stage 0.75 and 1 (ripeness). Although the numerical values are chosen somewhat arbitrary, the qualitative effect, causing cessation of growth at a certain time, even when water is still available in the soil, is in agreement with observed phenomena.

The morphological characteristics of the canopy, governing the relation between weight and leaf area, are difficult to simulate, as the underlying processes are not yet fully understood. However, the leaf area is a factor in the calculation of water use efficiency as well as in the ratio between evaporation and transpiration. Therefore, leaf area growth is simulated from the growth rate, assuming a leaf area ratio dependent on air temperature. Data are used derived from classical growth analysis experiments with wheat. Although this may seem an over-simplification in a situation where the canopy consists of a mixture of species quite different in morphological properties, it is justified by the fact that deviations do not have a decisive influence on the final result.

The rooting system of the canopy is defined by both its vertical extension and its dry weight. It is assumed that a "root front" moves down at a constant rate when conditions are favorable. Allowance is made for the influence of temperature on the rate of vertical extension, and growth stops when the roots reach a dry soil layer, because of the high mechanical resistance. The root system is considered to be homogeneous in the horizontal direction, so that moisture uptake is governed by the average moisture content in each compartment and not by gradients developing around individual roots. The latter is based on evidence that new roots can develop within a very short time (1–2 days). Root weight is obtained from the growth rate by imposing a ratio of division of the material between above ground and underground plant parts, depending on the development stage of the canopy. When development proceeds, progressively less of the newly-formed material is transferred to the roots, leading to an increasing shoot to root ratio towards maturity. Under normal growing conditions a ratio of 3 to 4 is reached at the end of the growing season. Because of lack of data there is no feedback of root weight to vertical extension or root activity.

The model is executed with time steps of one day, this being small enough as compared to the time constant of crop growth, which is equal to the reciprocal of its relative growth rate (de Wit and Goudriaan, 1974). Moreover it is very unlikely that more detailed meteorological data are available.

Integration is performed according to the simple rectilinear method.

IV. Validation of the Model

Experiments to collect validation data for the model were carried out at the "Tadmor Experimental Farm" near Beersheva in the Northern Negev Desert of Israel. It is an area with a mediterranean type climate, having warm dry summers and cool moist winters. The long-term average rainfall is about 250 mm year^{-1}, the fluctuations between seasons being considerable: 42 mm in 1962/63 and 414 mm in 1964/65.

The soil consists of a homogeneous thick layer of 'Löss' (young eolean material) with practically no profile development. The physical properties are favorable for plant growth, with a water-holding capacity of $\pm 0.15\,cm^3\,cm^{-3}$ between field capacity and wilting point, and no mechanical barriers for root growth.

The vegetation is an abandoned crop land vegetation, predominantly made up of herbaceous annual species. The predominant species are the grasses *Phalaris minor*, *Hordeum murinum* and *Stipa capensis*, the *Cruciferae Erucaria boveana* and *Reboudia pinnata*, the *Compositae Arthemis melaleuca* and *Centaurea iberica*, and the *Fabaceae Trigonella arabica* and *Medicago polymorpha*. The botanical composition may change considerably both from year to year and from place to place, as a result both of germination conditions and composition of the available seed stock. That seems, however, to have very little effect on the production potential, as no great differences in water use efficiency between species could be established.

The experiments were carried out in the seasons 1971/72, 1972/73 and 1973/74, which were wet years with 315, 245 and 350 mm of rain respectively, and with a favorable distribution. Standing crop was measured via a double-sampling technique based on visual estimates (Tadmor et al., 1974, 1975). The measurements were performed about every fortnight during the growing season. Soil moisture was determined also every two weeks and after each sufficiently large fall of rain with the neutron moderation technique in 30 cm increments to a depth of 180 cm. This was combined with gravimetric sampling of the top 30 cm, where the neutron method is not reliable because of scatter to the atmosphere. In Figs. 1–6 the measured and simulated values of above ground dry matter production and total soil moisture are given for the three growing seasons. When comparing the results of dry matter production, the difference between the season 1971/72—where measured and simulated data never show differences exceeding $\pm 5\%$—and the next two seasons is striking. The reason for this discrepancy points to an inherent difficulty in model building. During development of the model, the 1971/72 data have always been used to test the behavior of the model. In the situation where both modeling and experimentation are carried out by the same scientist—or team—it is almost impossible to avoid continuous interaction between the two, leading to the—subconscious—introduction of subjective functions in the model, which may be difficult to pinpoint. It is, therefore, of great importance that in the evaluation phase of the model completely independent data are used to test the validity of the opinion expressed in the model (van Keulen, 1974). Another difference between 1971/72 and the other seasons is the initial biomass that must be assumed to simulate the measured growth pattern. In 1971/72, 25 kg of dry matter ha^{-1} was introduced, which, when applied in 1972/73, lead to a much lower growth rate than measured (Fig. 3). It is most likely that the disking, which was carried out before the season 1971/72 to ensure proper mixing of the fertilizer that was applied, had a strong negative effect on germination, probably through burying of the seeds to such a depth that the seedlings did not reach the surface (the disking also caused a rather abnormal botanical composition of the vegetation). The different initial biomass values have, however, only a small effect on the final yield, indicating that eventually the available amount of water determines the total production, the differences being caused by somewhat higher evaporative losses when full cover is postponed, and by differences in water use efficiency in different periods. Initialization remains, however, a major problem (see Evenari et al., this volume Part 6:E), especially when the model is to be applied in connection

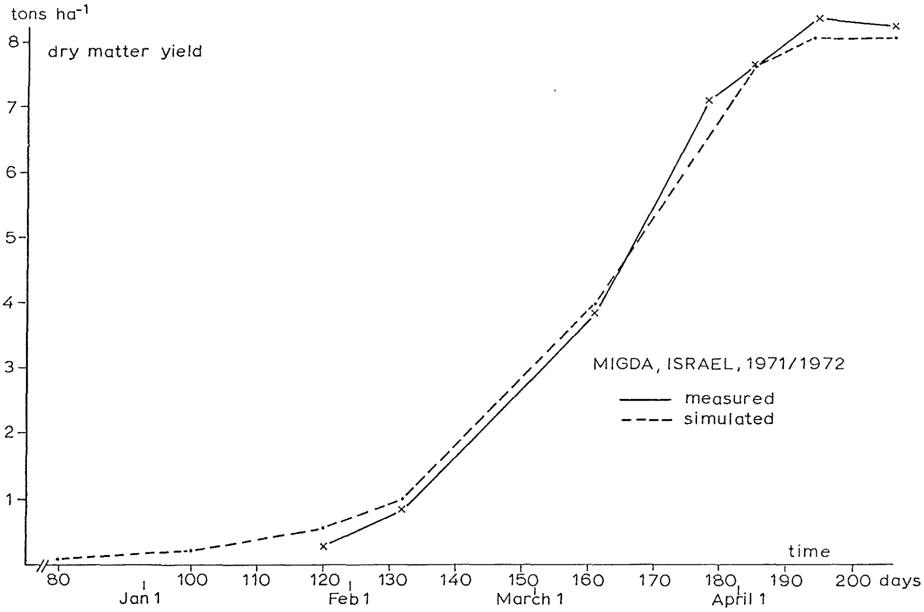

Fig. 1. Comparison between measured and simulated dry matter production of natural vegetation in Migda 1971/72. (After van Keulen, 1975)

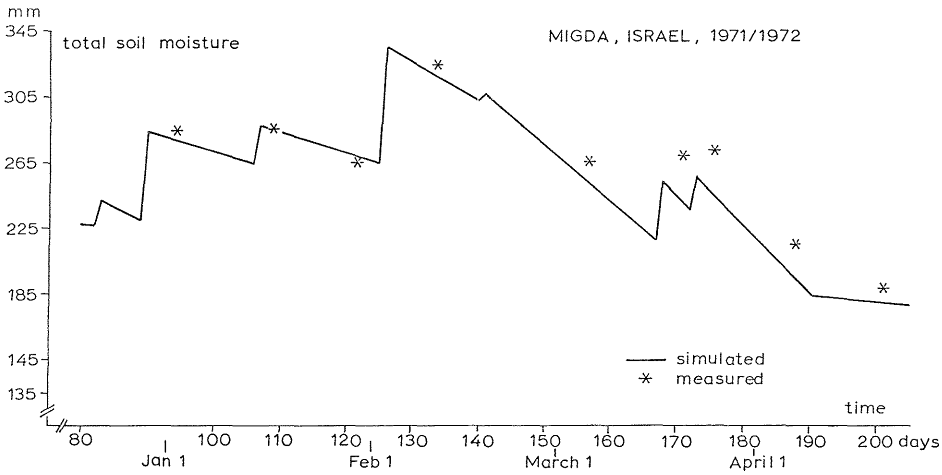

Fig. 2. Comparison between measured and simulated course of total soil moisture under natural vegetation in Migda 1971/72. (After van Keulen, 1975)

with grazing models. For sheep, which are pregnant during that period, the amount of food available in the beginning of the growing season is of primary importance. In such situations the best solution seems to be to measure standing crop at some early stage and apply that as initial value in the model.

The differences in measured and simulated growth rate in 1972/73 (day 130–day 145) cannot satisfactorily be explained. There may be some speculation

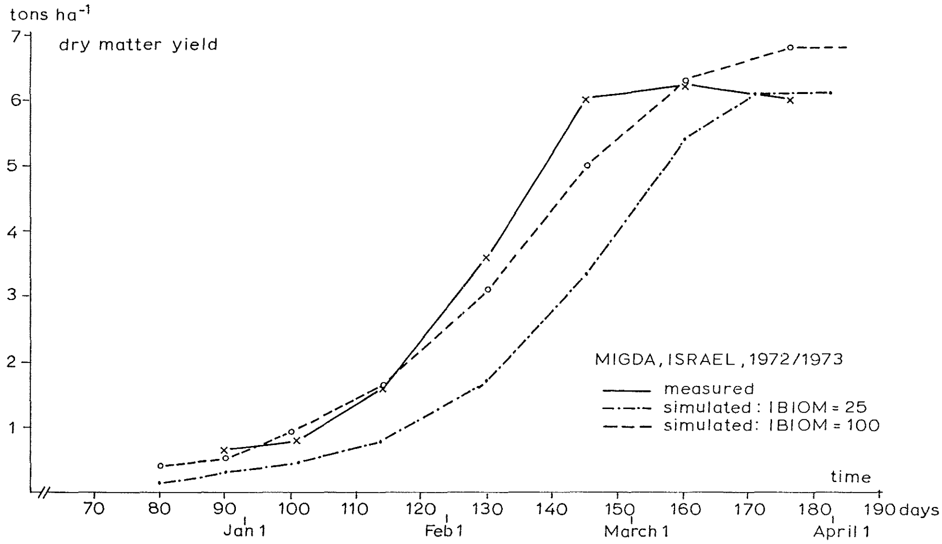

Fig. 3. Comparison between measured and simulated dry matter production of natural vegetation in Migda 1972/73. (After van Keulen, 1975)

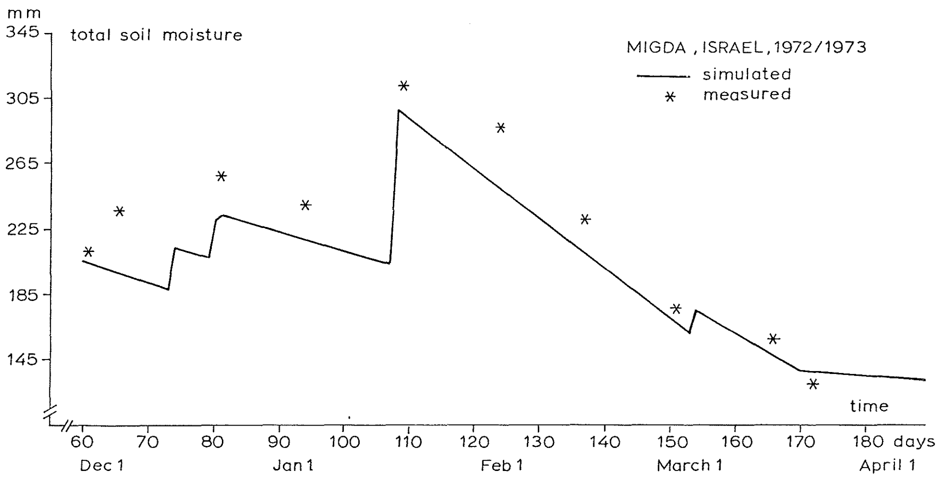

Fig. 4. Comparison between measured and simulated course of total soil moisture under natural vegetation in Migda 1972/73. (After van Keulen, 1975)

about a different division of dry matter between shoot and root, due to the very favorable conditions in the soil, but without more information about the process of root growth no conclusion can be drawn. In 1973/74 the deviations between simulation and experiment must be attributed to nitrogen status in the field. In the first two seasons 440 kg N ha^{-1} was applied, of which 400 kg

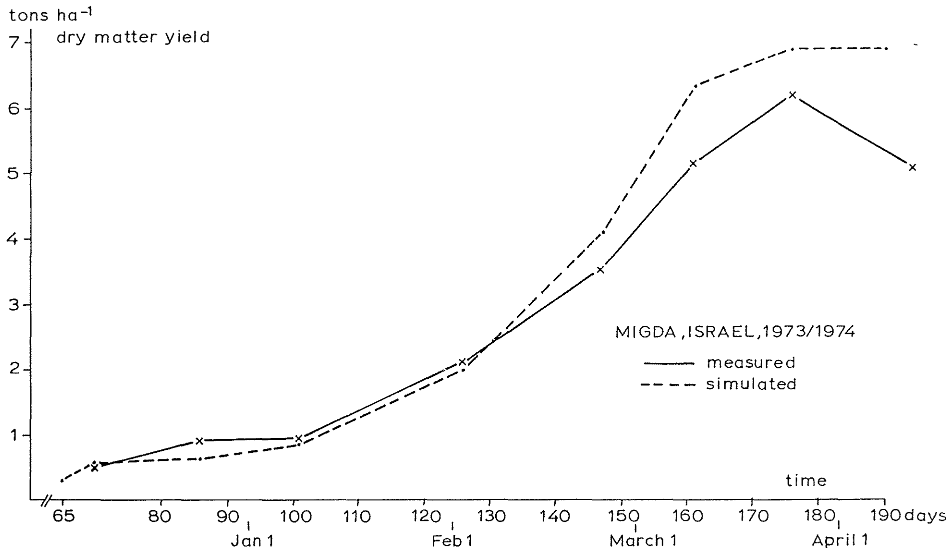

Fig. 5. Comparison between measured and simulated dry matter production of natural vegetation in Migda 1973/74. (After van Keulen, 1975)

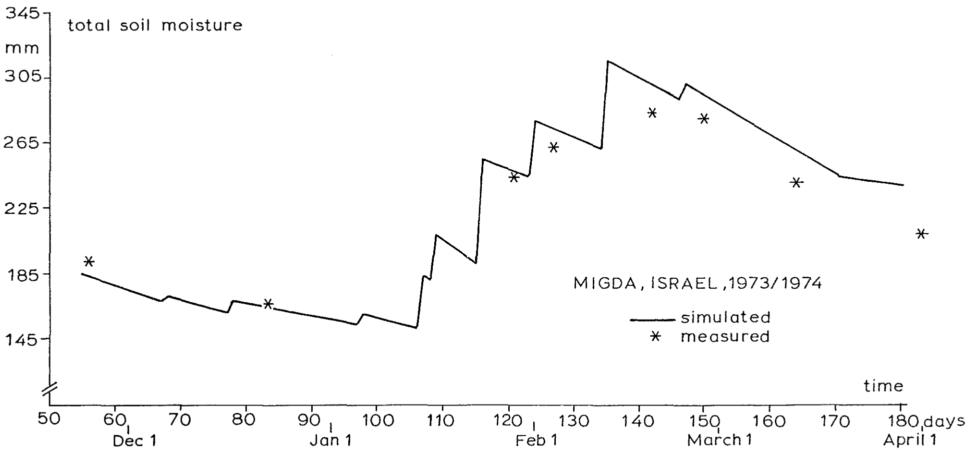

Fig. 6. Comparison between measured and simulated course of total soil moisture under natural vegetation in Migda 1973/74. (After van Keulen, 1975)

was in the form of ammonia, which is subject to volatilization. In these two seasons 350 kg N ha^{-1} was removed by the canopy, so that the store of N in the soil could have been depleted by the end of 1972/73. The amount of 100 kg N ha^{-1} applied at the beginning of 1973/74 would not be sufficient to maintain potential growth throughout the season. This is supported by the N-analysis of the vegetation, which showed lower N-percentages at the end of 1973/74 than in the previous seasons.

The soil moisture data show in all three seasons good agreement between simulation and experiment, taking into account the great variability in the field, restricting the accuracy of measurement to about 10% of the field mean.

From the overall comparison between the simulated and measured data, it may be concluded that the model simulates rather accurately the dry matter production of the vegetation and the water balance in the soil below it, under conditions of optimal nutrient supply and moisture limitation. It is, however, also clear from the description of the model that, despite the reasonable results, there are still some areas where our knowledge is only fragmentary and where improvements are possible. However, such a model should not reach a static state, as the growing insight in the relevant processes and the research which could be initiated by its results must lead to continuous improvement of the model.

V. Application of the Model

In order to get an insight in the production capacity of the northern Negev, the model ARID CROP was executed with thirteen years of historical weather data, collected at the Gilat Experimental Station, ± 8 km from the experimental site.

During this period the experimental area was used for grazing experiments on the main vegetation types of the region. As part of this research program standing crop on ungrazed plots was determined at about the moment of peak production (Tadmor et al., 1974). The results of the simulation runs are summarized in Table 1, together with some data on weather and actual production.

The first striking phenomenon is, that in 8 out of 13 years, the calculated production is higher than the measured production. This is caused by the fact that the calculation assumes optimum supply with nutrients, while under field conditions without fertilization nitrogen is very often the limiting factor. This

Table 1. Summary of results of simulation model ARID CROP (for explanation see text)

Season	Rainfall mm	Aboveground Simulated production kg ha^{-1}	Aboveground Measured production kg ha^{-1}	TRCT g H_2O (g DM)$^{-1}$	TRCR g H_2O (g DM)$^{-1}$
1961/62	120	280	—	422	4285
1962/63	72	185	—	343	3890
1963/64	357	6305	3400	310	566
1964/65	414	6171	3100	299	671
1965/66	220	1675	1600	354	1314
1966/67	284	5571	3600	312	510
1967/68	235	4420	2800	272	532
1968/69	212	2473	2500	254	857
1969/70	172	1193	1200	306	1442
1970/71	260	2529	1100	312	1028
1971/72	315	6242	3600	239	505
1972/73	245	5922	3500	291	414
1973/74	351	5833	3800	228	602

has been shown in experimental fields, where in the last three seasons calculated and measured yield are the same with fertilization. Moreover, recent work by Harpaz (1975) shows that when nitrogen is also introduced in a model as a possible limiting factor, the simulated yields are in fair agreement with the measured ones. This shows that, under the weather conditions prevailing in the Negev, in most cases not moisture but nitrogen is the main factor limiting production. This could also be the case in other semi-arid regions with comparable climatological conditions. In these areas, therefore, increased production may be obtained by introducing nitrogen into the system, either through fertilization or by the introduction of leguminous species in the sward.

The next point of interest is the calculation of the transpiration coefficient (TRC), which is given both with respect to total calculated transpiration (TRCT) and with respect to total rainfall (TRCR). The variation in TRCT is almost a factor 2, which reflects the different external conditions during the actual growth period. In periods with a low humidity of the air and a rather high radiation level, more water is lost at the same level of photosynthesis. Such periods prevail in the northern Negev, especially when the wind is blowing from the east, in extreme conditions leading to the so-called sharav (chamsin).

The variation in TRCR is even greater, as this is also influenced by the distribution of the rainfall. A larger number of showers causes a greater loss of water through direct evaporation from the soil surface, thus decreasing the overall efficiency of water use.

These results show that, even when nutrition is eliminated as a decisive factor, it is very difficult to predict productivity on the basis of statistical analysis. It seems, thus, more promising to use simulation models for the calculation of the production potential of new areas. It should, however, be kept in mind, that prediction in the actual situation is still completely dependent on the quality of the meteorological forecasts.

VI. Conclusions

It has been firmly established in theory and practice that the potential growth rate of natural grassland species is as high as that of cultivated species during periods that water and nutrients happen to be available, so that yield potential, as such, is now reason for the introduction of so-called improved species. This is the more so, because some of the natural annual species already start to form ripe seeds within a few months after germination, which may safeguard the crop of next year.

Eco-physiological studies of some winter annuals show that, when conditions happen to be optimal, little difference exists between species in terms of productivity and water use efficiency. However, under stress conditions a general distinction may be made between savers and spenders (Lof, 1975), but this distinction is of small practical importance as long as all available water is used during the growth period.

Under good nutritional conditions in the Negev, yields of 6000 kg ha^{-1} with a reasonable nitrogen content may be obtained with a rainfall of only

250 mm during the winter season. However, in 8 out of 13 years, it appeared that the yields were considerable lower than could be expected, because of nitrogen shortage. Simulated and measured yields in these years are also in fair agreement when nitrogen is introduced as a limiting factor into the model (Harpaz, 1975).

Especially in years with little rain, several germination flushes occur and a considerable fraction of the water may be lost by evaporation. It appears then that the yield may be considerably improved by soil heterogeneity that promotes the occurrence of local run-off/run-on.

Systems analyses, followed by model synthesis that covers the whole field or primary production, grazing, animal production, herd management, and marketing seem a promising way to develop new grazing methods and options for new ways of life in arid regions. The experience with only a small part of the system (primary production), is that only thorough attempts, in which scientific analyses and field experimentation are closely linked, may lead to trustworthy results and that quick results, however attractive on first sight, may be very costly in the long run.

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