Dit proefschrift met stellingen van Hermannes van Keulen, landbouwkundig ingenieur, geboren te Hellendoorn op 30 juli 1945, is goedgekeurd door de promotor, dr. ir. C.T. de Wit, buitengewoon hoogleraar in de theoretische teeltkunde.

Wageningen, 14 februari 1975

De rector Magnificus
van de Landbouwhogeschool,
J.P.H. van der Want

Simulation of water use and herbage growth in arid regions

H. van Keulen

Proefschrift
ter verkrijging van de graad van
doctor in de landbouwwetenschappen,
op gezag van de rector magnificus,
prof. dr. ir. J.P.H. van der Want, hoogleraar in de virologie,
in het openbaar te verdedigen
op vrijdag 16 mei 1975 des namiddags te vier uur
in de aula van de Landbouwhogeschool te Wageningen

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Stellingen

I

Voor het bepalen van relaties tussen weersgegevens en gewasopbrengsten is het gebruik van simulatiemodellen te prefereren boven dat van correlatieve methoden.

Dit proefschrift.

II

Op diepe bodems in veel semi-aride gebieden is niet water, maar stikstof de belangrijkste produktiebepalende factor.

Dit proefschrift.

III

De veredeling van gramineae heeft niet geleid tot de verhoging van de efficiëntie in het gebruik van zonneënergie en/of water.

Dit proefschrift.

IV

Onder aride omstandigheden levert iedere kilogram nitraatstikstof, toegediend aan voldoende diepe bodems, tenslotte ca. 6,25 kilogram ruw-eiwit.

Dit project.

V

Blijvende schade aan voornamelijk uit één-jarige soorten bestaande natuurlijke vegetatie in aride gebieden als gevolg van beweiding, treedt slechts op door overbeweiding in het natte seizoen.

Dit project.

VI

De bijdrage van het diffusieproces in de stikstofvoorziening van gewassen is veelal groot.

VII

Door het scheppen van in tijd en/of plaats gescheiden voorzieningen voor bepaalde groepen van de bevolking wordt het voortbestaan van

Voorwoord

Een proefschrift kan nauwelijks geschreven worden zonder de hulp van zeer velen, die de auteur tijdens zijn onderzoek en het op schrift stellen van de resultaten terzijde staan. Dit proefschrift maakt daarop geen uitzondering en ik wil iedereen die aan de voltooiing ervan meegewerkt heeft hartelijk bedanken.
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Tenslotte wil ik de overige leden van mijn gezin bedanken die, bewust of onbewust, het hunne ertoe hebben bijgedragen dat dit proefschrift op dit moment kan verschijnen.

Curriculum vitae

Hermannes van Keulen werd geboren op 30 juli 1945 te Hellendoorn. Zijn middelbare schoolopleiding aan het Christelijk Lyceum te Almelo werd afgesloten in 1962 met het behalen van het diploma HBS-B. Vervolgens studeerde hij aan de Landbouwhogeschool te Wageningen, waar hem in 1970 het ingenieurs-diploma in de richting Bodemkunde en Bemestingsleer werd uitgereikt. Na eerst als promotie-assistent op de afdeling Theoretische Teeltkunde werkzaam te zijn geweest, trad hij, als gastmedewerker van dezelfde afdeling, in 1971 in dienst van de Directie Internationale Technische Hulp van het Ministerie van Buitenlandse Zaken, ten dienste van het Nederlands-Israëlische samenwerkingsproject 'Actuele en potentiële produktie van grasachtige gewassen in aride gebieden'. In het kader van genoemd project werd ook dit proefschrift bewerkt, waarbij het onderzoek afwisselend in Nederland en Israël werd uitgevoerd.

Samenvatting

In de aride en semi-aride gebieden, gekenmerkt door lage en sterk fluctuerende neerslaghoeveelheden, die samen ±30% van het landoppervlak van de aarde vormen, wordt een belangrijk deel van het land gebruikt voor extensieve veeteelt. Het niveau van de secundaire produktie – melk, vlees of wol – wordt in hoge mate bepaald door de beschikbaarheid van plantaardige produkten voor veevoer. Een verhoging van de primaire produktie lijkt mogelijk tot twee niveau's:

zonder irrigatie
verhoging van de beschikbare hoeveelheid water en van de efficiëntie waarmee het beschikbare water wordt gebruikt. Bijvoorbeeld door nieuwe soorten te introduceren, die het water efficiënter benutten of door verbetering van de minerale voedingstoestand van de bodem – vooral stikstof – via introduktie van leguminosen of door het toedienen van kunstmest.

met irrigatie
onder omstandigheden waar de voorziening met zowel water als voedingsstoffen optimaal is, wordt de produktie gelimiteerd door klimatologische omstandigheden en vooral door de beschikbare hoeveelheid zonne-energie. In de meeste aride gebieden is dan de potentiële produktie zeer hoog, omdat het groeiseizoen lang is, de stralingsintensiteit hoog en de temperatuur gunstig.

Het doel van het projekt 'Actuele en potentiële produktie van grasachtige gewassen onder aride omstandigheden', waarvan deze studie een onderdeel is, is de bestaande kennis op het gebied van bodemkunde, plantenfysiologie en bemestingsleer samen te vatten in dynamische computermodellen, die de groei van een gewas beschrijven. Dergelijke modellen zijn in ontwikkeling voor drie verschillende produktieniveau's:
- optimale voorziening met water en voedingsstoffen;
- optimale voorziening met voedingsstoffen maar water limiterend;

- omstandigheden waarbij zowel water als minerale voeding limiterend kunnen zijn.

Verder zijn voor zover nodig relevante processen bestudeerd en experimenten uitgevoerd voor het verzamelen van gegevens om de modellen te testen.

De experimenten onder aride omstandigheden werden uitgevoerd in Migda, in de noordelijke Negev woestijn in Israël (34°25′ OL, 31°22′ NB). De gemiddelde regenval in dit gebied is 250 mm $jaar^{-1}$ en is geconcentreerd in de wintermaanden (oktober-maart). De jaarlijkse hoeveelheid neerslag is zeer variabel met in de laatste vijftien jaar extremen van 42 mm in '62/'63 en 414 mm in '64/'65. Stralingsintensiteiten variëren van 1150 J m^{-2} dag^{-1} in december tot 2750 J m^{-2} dag^{-1} in juni, terwijl de gemiddelde dagtemperatuur fluctueert tussen 12.6 °C in januari en 26.8 °C in augustus.

De bodem bestaat uit een 10–20 m dikke laag van löss, waarin zich een sierozem heeft ontwikkeld. De fysische eigenschappen van deze bodem zijn zeer gunstig voor plantengroei: goede bewortelbaarheid en een vochthoudend vermogen van ca. 450 mm in de bewortelbare zone. De vegetatie bestaat uit een mengsel van eenjarige planten met als voornaamste soorten: de grassen *Phalaris minor*, *Hordeum murimum* en *Stipa capensis*, de kruisbloemigen *Erucaria boveana* en *Reboudia pinnata*, de composieten *Anthemis melaleuca* en *Centaurea iberica* en de leguminosen *Trigonella arabica* en *Medicago polymorpha*. De botanische samenstelling wisselt zeer sterk zowel van jaar tot jaar als van plaats tot plaats, maar dat blijkt geen grote invloed te hebben op de drogestofproduktie.

Er werden proeven uitgevoerd, waarbij het verloop van de bovengrondse drogestofproduktie en van de hoeveelheid vocht in de bodem gedurende het groeiseizoen werden bepaald. De droge-stofopbrengsten werden gemeten via een techniek van visuele schattingen. Een groot aantal schattingen (200–400 per behandeling) van drogestof gewichten werd uitgevoerd, waarbij ieder vijfde monster tevens werd geoogst en droog gewogen. Met deze monsters werd een ijklijn bepaald, die gebruikt werd om de overige schattingen op droog gewicht om te rekenen. De hoeveelheid water in de bodem werd gemeten met een neutronen-sonde. In iedere behandeling werden 30-60 aluminium neutronen-buizen geplaatst, waarin gedurende het groeiseizoen iedere twee weken en na iedere voldoend grote regenval het vochtgehalte

werd bepaald in 30 cm intervallen. De meting werd gecompleteerd door gravimetrische bepaling van het vochtgehalte in de bovenste 30 cm in welk gebied de neutronen-sonde onnauwkeurig meet door ontsnapping van neutronen naar de atmosfeer.
De meteorologische waarnemingen werden verricht op een station van de Israëlische Meteorologische Dienst in Gilat, ca. acht kilometer van de proefvelden, behalve de regenval die ter plaatse werd gemeten.

Uit de resultaten van de proeven, die zowel werden uitgevoerd op percelen die alleen met P en K bemest waren, als op percelen die NPK-bemesting hadden, blijkt dat onder deze omstandigheden de produktie in vele gevallen niet wordt beperkt door de hoeveelheid beschikbaar water, maar door de beschikbaarheid van stikstof. Toediening van kunstmeststikstof kan de opbrengst verveelvoudigen. Onder optimale voedingsomstandigheden worden in de natuurlijke vegetatie groeisnelheden gemeten van ± 170 kg ha^{-1} dag^{-1}, evenals in een proef met tarwe. Deze groeisnelheden zijn gelijk aan het theoretische optimum dat onder deze omstandigheden berekend wordt.
De efficiëntie van waterverbruik blijkt ook gelijk te zijn voor de tarwe en voor de natuurlijke vegetatie onder vergelijkbare omstandigheden. In de niet met stikstof bemeste percelen is de hoeveelheid water die per kg geproduceerde droge stof verbruikt wordt echter veel groter, als gevolg van een lagere fotosynthesecapaciteit of van een groter verlies door herhaald afbreken en herbouwen van eiwitten.
De proeven die uitgevoerd werden om de invloed van beweiding door schapen, op de primaire produktie vast te stellen tonen aan, dat onder normale omstandigheden de hoeveelheid droge stof die tijdens het natte seizoen wordt gegeten, verwaarloosbaar is vergeleken met de groeisnelheid. Alleen onder zeer hoge beweidingsintensiteiten kan een effect op de produktie verwacht worden.
In het tweede deel van dit proefschrift wordt een computermodel – ARID CROP – beschreven (geschreven in de simulatietaal CSMP/360) om de groei van een gewas te berekenen onder omstandigheden waar water de beperkende faktor is.
De verschillende processen die een rol spelen worden beschreven. Een hierarchische benaderingswijze wordt toegepast om de resultaten van gedetailleerde modellen, die te kleine tijdsconstanten hebben, in het gewasgroei-programma in te bouwen.
Een gedetailleerd model van de verdamping van onbegroeide grond

wordt beschreven en gemeten en gesimuleerde resultaten worden vergeleken onder zowel laboratorium- als veldomstandigheden.
Een vereenvoudigde methode om de transpiratiecoefficiënt te berekenen op dagelijkse basis wordt gegeven, gebaseerd op de resultaten van een elders beschreven gedetailleerd model. De berekende waarden zijn vergeleken met waarden die gemeten zijn in potproeven, uitgevoerd in het kader van het projekt. Aangetoond wordt dat in de meeste gevallen de overeenkomst redelijk is (binnen 20%).
Vergelijking van het met het model berekende verloop van de drogestofproduktie en het vochtgehalte in de bodem met de gemeten waarden toont aan dat een goede overeenstemming wordt bereikt. Speciale moeilijkheden blijken zich voor te doen aan het begin van het groeiseizoen, ten gevolge van een weinig gedetailleerde behandeling van de kieming.
Tenslotte worden enige voorbeelden voor toepassing van het model uitgewerkt; de potentiële produktie onder water-beperkende omstandigheden wordt berekend op basis van historische weersgegevens voor een 15-jarige periode. Duidelijk blijkt hierbij dat niet alleen de totale hoeveelheid neerslag per seizoen, maar ook de verdeling in de tijd bepalend is voor het produktieniveau dat bereikt wordt. Een ongunstige verdeling – veel kleine buien – veroorzaakt een veel groter verlies door directe verdamping van de onbegroeide bodem en derhalve een kleinere hoeveelheid beschikbaar water voor het gewas. Vergelijking van de berekende produktie met de gemeten – veelal door stikstof gelimiteerde – opbrengsten laat zien, dat door bemesting niet alleen de gemiddelde produktiviteit omhoog gaat, maar vooral ook, dat de fluctuaties in opbrengst bijna even groot worden als die in regenval. Dit brengt problemen met zich mee voor het beheer omdat het niet mogelijk is de grootte van de veestapel op korte termijn aan te passen aan sterke fluctuaties in hoeveelheid beschikbaar voeder. Een mogelijke oplossing zou zijn een systeem als gebruikt door sommige Bedouienen-stammen in de Negev, die een deel van het areaal inzaaien met tarwe. In goede regenval-jaren kan hiervan graan geoogst worden, terwijl het in droge jaren als aanvullende weide wordt gebruikt.
Tenslotte wordt getoond, dat de inhomogeniteit van de bodem, die zoveel experimentele moeilijkheden geeft, oorzaak is dat in sommige jaren nog enige produktie wordt bereikt.
Concluderend kan gezegd worden, dat voor het doen van uitspraken

over de produktiecapaciteit van gebieden, waar geen onderzoek heeft plaatsgevonden, het gebruik van dynamische computermodellen, zoals in dit proefschrift getoond, aanzienlijk meer mogelijkheden biedt dan de toepassing van regressiemodellen. Tevens kan aan de hand van dergelijke modellen betrekkelijk snel doelgericht onderzoek plaatsvinden, wanneer nieuwe gebieden geëxploreerd moeten worden.

Contents

1 Introduction

1.1 Arid climates

A large part of the earth's surface consists of arid and semi-arid regions. The main causes of the existence of these climates are (McDonald, 1959):

- The low frequency of adiabatic rise of large bodies of air, because of the extension of flat areas;
- The remoteness from an oceanic source of moisture in the prevailing wind direction, caused either by large distance or by a natural barrier like mountains.

These causes are modified by the general circulation pattern of the atmosphere and the distribution of land and sea over the earth's surface.

The definition of the terms arid and semi-arid depends on the purpose of the classification. Climatologists will have different criteria from agronomists. By any criterion low and erratic rainfall is the most outstanding characteristic of these regions. A classification based solely on the amount of rain is not adequate, because other factors like the distribution of the rainfall, prevailing climatic conditions during the rainy period, the evaporative demand and soil properties have a decisive influence on the effect of low rainfall on plant growth. For agricultural purposes a classification like that of Thornthwaite (1948) based on rainfall and evaporative demand of the atmosphere is meaningful. In this way, the amount of water, available for plant growth and the effectiveness of its use are expressed.

In Thornthwaite's classification, a humid climate is defined as one in which during the greater part of the year precipitation exceeds potential evapotranspiration, while for arid climates the reverse holds. These properties are expressed in a moisture index, calculated as a weighted difference between surplus precipitation in one season and deficiency of precipitation in another, divided by the potential evapotranspiration. A moisture index of 0. divides arid from humid climates. A moisture index value of -40 represents the boundary between semi-arid regions,

where arable farming is possible under special management practices and arid regions where without irrigation, the risk of failure is too high. This value coincides with an annual rainfall of 200–300 mm when winter rains are prevailing and of ±500 mm when precipitation is concentrated in the hot summer months.
The semi-arid regions, with which this publication is mainly concerned form a wide belt, surrounding the deserts of the world. Their total area is about 22×10^6 km^2, which is 15% of the land surface of the world (Koeppe & Long, 1958). They are divided into hot semi-arid regions on the equatorial fringes of the deserts that have high temperatures and rainfall in summer, and mediterranean-type climates on the western continental coasts with dry warm summers and cool moist winters.

The main regions with rainfall concentrated in hot summers are (Meigs, 1953):
1 The Sahelian zone, south of the Sahara, ranging from Senegal on the west coast to Somalia on the east coast.
2 The eastern side of the Kalahari desert in South Africa.
3 Central Asia, a vast area, where the dominant characteristic is the extreme cold during winter.
4 South-west Asia, from the Iranian plateau through India and Pakistan.
5 The southern part of the Pacific Valley and the Intermountain Region on the west coast of North America.
6 A long narrow strip along the western coast of South America, in Peru and Chili, between the ocean and the Andes.
7 The northern part of Australia between 15° and 20° S.L.

The most important regions with a mediterranean-type climate, which are between 30° and 35° latitude both north and south include:
1 A narrow strip north of the Sahara, in Algeria, Morocco and Tunisia.
2 The region around the eastern side of the Mediterranean, including most of Asian Turkey and Israel.
3 The northern part of the Pacific Valley and the Intermountain Region in North America.
4 The southern part of the Australian continent between 30° and 35° S.L.

Many of these areas are used for extensive grazing as part of a subsistence farming system. In more favourable regions, this is combined with annual grain crops, generally in rotation with a fallow period, the length of which depends on the amount of rainfall. In some of these regions irrigation is introduced as a means of increasing the production.

1.2 Agricultural research in the arid zone

Arid zone agriculture is the subject of much research because of the increasing interest in the agricultural problems of developing countries, many of which are located in the arid and semi-arid regions of the world. Many developed countries take an active part in these studies, by investing either money or know-how in establishing special projects or in the development of certain regions. The studies are often aimed at the solution of a specific problem or at the immediate increase in production under the given circumstances. In each new project costly and time-consuming experiments are often done, to establish the problems and to decide whether a solution can be achieved in the framework of that project. What seems to be lacking, however, is a systematic and theoretically sound examination of the processes that are critical for the level of herbage and crop production in the arid zones. In particular, little has been done to investigate the interrelationships between these processes in the context of arid zone climates. Even less attention is paid to the development of means for extrapolating from the store of accumulated scientific knowledge to specific local conditions.
The aim of the project 'Actual and potential herbage production under semi-arid conditions'[1] is to gain understanding of the relevant processes, to collect additional information where this is lacking, to develop means of integrating the existing knowledge into meaningful systems and to indicate ways of extrapolating this knowledge. The understanding and information are integrated by developing computer models and calculation techniques that can then be used in programmes for regional development in arid regions.

[1] This project is sponsored by the Netherlands and Israeli governments (Section 2.2).

The results can also be helpful in deciding on the allocation of research funds available for the development of arid regions. This is of particular importance in developing countries where resources of capital and manpower are limited. The models can become an important means to evaluate the economical advantages that can be gained from investments in irrigation and fertilizer programmes. They can even be used to clarify problems of irrigation strategy, soil moisture and plant growth relations and of plant nutrition. As such they are not only a guide for budget allocation for research, but are a tool in defining research methodology.

Finally the project aimed at the training of students from developing countries in the techniques used in the quantitative approach of problems connected with dry matter production and management of natural resources.

This publication gives first a general outline of the project and of the research work carried out within its framework. The experiments on the relation between growth and water use are dealt with in detail. Models on soil physical processes, like infiltration, evaporation and heat flux and their validation are presented. A model that calculates dry matter production under conditions where water may be the limiting factor is described and evaluated. Finally it deals with the application of such a model to arid zone agriculture, its predictive value and indicates the weak points where further research is needed.

2 Description of the project

2.1 Introduction

As pointed out in Chapter 1, large parts of the world consist of arid and semi-arid regions. The occurrence of disasters especially drought and starvation have aroused increasing interest in the agricultural problems and potentialities of these regions. Traditionally most of these lands are used for extensive grazing, under a nomadic or half-nomadic way of life. In certain areas such as the Middle East and North Africa, this is connected with regular cultivation of small grains like wheat or barley. These are grown in patches which are located in natural depressions where run-off water is collected, or on low-lying land to which water can be diverted through channels or dams. In years of low rainfall, these cultivated areas will yield dry matter which is grazed when the natural vegetation is too sparse to supply food for the animals. In years of higher rainfall, the annuals of the natural vegetation will produce enough to feed the flock and the sown patches will yield grain, which can be used for subsistence or as a cash crop. The stubble then provides additional grazing in summer when the natural vegetation has completely dried out.
The level of secondary production – wool or meat – is mainly determined by the level of primary production that can be reached.
Two main ways of increasing primary production seem possible:

Without irrigation
Improvement of the botanical composition of the natural vegetation by legumes, or introduction of new species with a more efficient water use, if such species can be found.
Application of fertilizers especially more nitrogen fertilizer.

With irrigation
With water and nutrients non-limiting, the level of primary production is limited only by climatological factors, specifically by the amount of available radiant energy. With proper fertilization and management

a high level of production can then be achieved in most arid regions: the growing season is long, the temperatures are favourable and the radiation is high.

However, agricultural practice demands specific quantitative directives. These are generally obtained through local experiments, which is normally very expensive and time consuming. Such an approach makes too little use of the basic research in soil and plant science. A good and relatively cheap approach is the use of computer models in which knowledge about fundamental processes is integrated to be used on a quantitative basis. Under the assumption that these processes are the same for different conditions, it is possible to extrapolate from previous knowledge of simulated systems to actual problems in new project areas.

It is the aim of the project to develop or improve such models for primary production at three levels of interest:

1 under optimum supply of moisture and nutrients;

2 under conditions of optimum nutrients, but where water may be limiting;

3 under conditions where either water or nutrients may be limiting.

Furthermore, basic information about processes and data to validate the models is collected where needed.

2.2 Scope and objectives of the project

The project 'Actual and potential herbage production under semi-arid conditions' was initiated through the joint effort of the Netherlands and Israeli Ministries for International Co-operation. The research is a co-operative effort by the Hebrew University of Jerusalem (Department of Botany in Jerusalem and the Faculty of Agriculture in Rehovoth), the Agricultural University in Wageningen (Department of Theoretical Production Ecology) and the Institute for Biological and Chemical Research on Field Crops and Herbage (IBS) in Wageningen. Close contact is also maintained with other departments and institutes in both countries (for example: in Wageningen, the Department of Soil Physics and in Israel the Volcani Institute for Agricultural Research).

Four main fields of research can be distinguished, each one of them being the special responsibility of one researcher:

I *Physical processes:* Herman van Keulen.

Transport processes of water, heat and ions in soils, especially under unsaturated conditions. Interaction between growth and water status of the soil.

II *Growth and nutrients:* Yigal Harpaz.

Growth of crops under nutrient limiting conditions. The interaction between water and nutrients.

III *Potential production:* Ehud Dayan.

Study of production under optimum conditions of water and nutrients.

IV *Ecology and Plant Physiology:* Henk Lof.

Investigation of growth and development of relevant species. Interaction between different species. Study of the physiological properties of different species.

In the description of the research subjects, a number in brackets (I, II, III, IV) will refer to which member of the team is specially responsible for the subject under consideration. It is stressed, however, that in such an interdisciplinary project it is often difficult to separate the exact contribution of the various co-workers.

The aims of the project are being achieved through investigations in the following areas:

Primary production under optimum conditions of water and nutrients

Experiments were set up to determine the growth rate of a sward of Rhodes grass *(Chloris gayana)* under Israeli conditions both for uninterrupted growth and under different cutting regimes (III). The results of these experiments were compared with the values, calculated with a model describing the vegetative growth of a crop under optimum conditions that was developed at the Department of Theoretical Production Ecology (to be described in another monograph of this series). The main problem areas in the model were stomatal behaviour and aspects of root growth. The study of stomatal behaviour, both experimental and theoretical, is a continuous interest of the Department of Theoretical Production Ecology. The study of growth and functioning of the root system under different conditions is being carried out in Israel (III). Special attention is paid to the processes of suberization (or inactivation) and decay of the roots.

At the same time experiments are conducted under controlled conof these experiments are being combined with laboratory experiments on plant properties to develop models describing the competitive behaviour of these species. Here again, study and simulation of the basic processes is the only way to increase our knowledge of the ecology and to apply this knowledge under different circumstances.

Primary production under conditions where either water or nutrients (nitrogen) may be the limiting factor

The nutrient with probably the strongest influence on plant production is nitrogen. Therefore study of the dynamics of the nitrogen cycle in the soil and in the plant under arid conditions is an important part of the research project.

A model describing the dynamics of nitrogen in the soil under humid conditions was developed and published as another monograph of this series (Beek & Frissel, 1973). It includes microbiological processes like mineralization and nitrification and nitrogen transport in the soil. This model has been used as a basis for the development of a model describing the nitrogen behaviour under arid conditions (I, II).

The possibilities of simplifications under these circumstances are being investigated, under the assumptions that perma-dry conditions exist, i.e. there is no deep drainage and thus no loss of nitrogen through leaching, and denitrification is negligible because the requisite anaerobic conditions seldom occur (II).

The important terms in the nitrogen balance are thus: N fixed by symbiotic organisms, N from the atmosphere, N recycled through the animal and nitrogen removal by plants. These are being studied, partly from literature and partly through experiments. The processes connected with the recycling of N through the grazing animal, are being studied through experiments with sheep and with artificially applied excretions (II).

Another part of this project is the study of the dynamics of plant nitrogen, and the interrelation between water and nitrogen shortage in the plants. To collect information on this subject, the main species of the natural vegetation in both the fertilized and non-fertilized treatments are sampled and analysed for NO_3-N and total N, during the growing season.

Experiments to determine the growth rate and the water use of the natural vegetation in a field with no additional nitrogen fertilization have been carried out. Total annual yields of this vegetation have been determined over the last ten years in Migda, while fertilization trials have been carried out for four years (Tadmor et al., 1966–1970).

Influence of grazing on primary production

In many arid and semi-arid regions the risk of failure is too high to justify continuous arable farming. In these cases, subsistence is achieved through animal production. In the establishment of the project, it was recognized that the study of the grazing situation and the development of models in that area may be the final goal. This includes however a great deal of experimentation on animal behaviour, food intake, grazing performance and so on, which is beyond the scope of the present project. Only some preliminary studies are being done with respect to the influence of the animal on primary production. The experiments with sheep are being done in close co-operation with R. Benjamin, of the Volcani Institute of Agricultural Research, who is in charge of the grazing experiments in Migda. The influence of grazing animals on the level and seasonal distribution of primary production was studied in an experiment similar to the one described for optimum nutrient supply, in which part of the area was fenced off to prevent grazing while on the rest a floating stocking rate was maintained, the pressure being adjusted to the current growth rate so as to stress the effects of grazing.

Also some methods to determine the intake of the grazing sheep are being investigated. It was found that the tritium dilution technique is an easy and accurate method to determine dry matter intake through the rate of water turnover (Benjamin et al., 1973).

Further investigations into the role of the animal may include the effect of selective grazing. This may be of importance if there are considerable differences in the water use efficiency between plant species. It may also have ecological implications when certain species are grazed early in the season to an extent that prevents them maturing seeds.

Another effect of grazing could be a shift in the period of peak growth through defoliation which changes the radiation climate in the standing vegetation. This can have influences on water use efficiency, which changes throughout the season, as well as on the division of water loss between transpiration and direct soil evaporation. It should also be noted that in the grazing situation the moment of onset of growth is important, as the sheep are pregnant early in the growing

season (November/December) and the food situation during this period is of primary importance for the condition of the lamb.
From the foregoing it is clear, that much more information has to be collected, before a realistic model of the grazing situation can be developed.

2.3 Experiments in Migda

2.3.1 The experimental area

The dry land experiments were carried out at the Tadmor Experimental Farm in Migda, (long. 34°25′ E., lat. 31°22′ N. 100 m altitude above sea level) near Beersheva in the Northern Negev desert of Israel. The experimental fields are part of a large farm of the Volcani Institute for Agricultural Research, used for the study of animal productivity on the main pasture types of the area.

Climate
The fields are situated in a winter rainfall area, with a Mediterranean type of climate. Rain falls between October and April, with ±60% of the annual rainfall concentrated in December and January. The growing seasons are therefore referred to as 1971/1972, indicating October 1971 to September 1972, and so on. The average rainfall is 250 mm $year^{-1}$, but extreme fluctuations exist between years: 42 mm in 1962/1963, 414 mm in 1964/1965. The rainfall distribution pattern within a season greatly influences the vegetational development.
Temperatures are high in summer, August being the hottest month with mean minimum, daily mean and mean maximum temperatures of 20.2 °C, 26.8 °C and 33.5 °C, respectively. In winter the temperatures are mild. In January, the coldest month, the mean minimum, daily mean and mean maximum temperature are 7.6 °C, 12.6 °C and 18.1 °C, respectively. There are 20–30 frost nights a year, with the surface temperature dropping to −1 to −4 °C.
The radiation is high, from an average daily total of 1150 J m^{-2} day^{-1} in December to an average daily total of 2730 J m^{-2} day^{-1} in June. The interseasonal variation in radiation is much less than in rainfall, as a difference in rainfall of 350 mm, means only ±10 extra rainy days during the growing season.

Soil

The region consists of slightly undulating plains, with a deep subsoil of eocene chalk, covered by a 10–20 m thick mantle of löss (a young wind deposited material of desert origin). The profile developed is a buff-coloured lössial sierozem, fairly uniform, with lime concretions in the lower horizons. The bulk density varies between 1.35 and 1.45 g cm^{-3}.

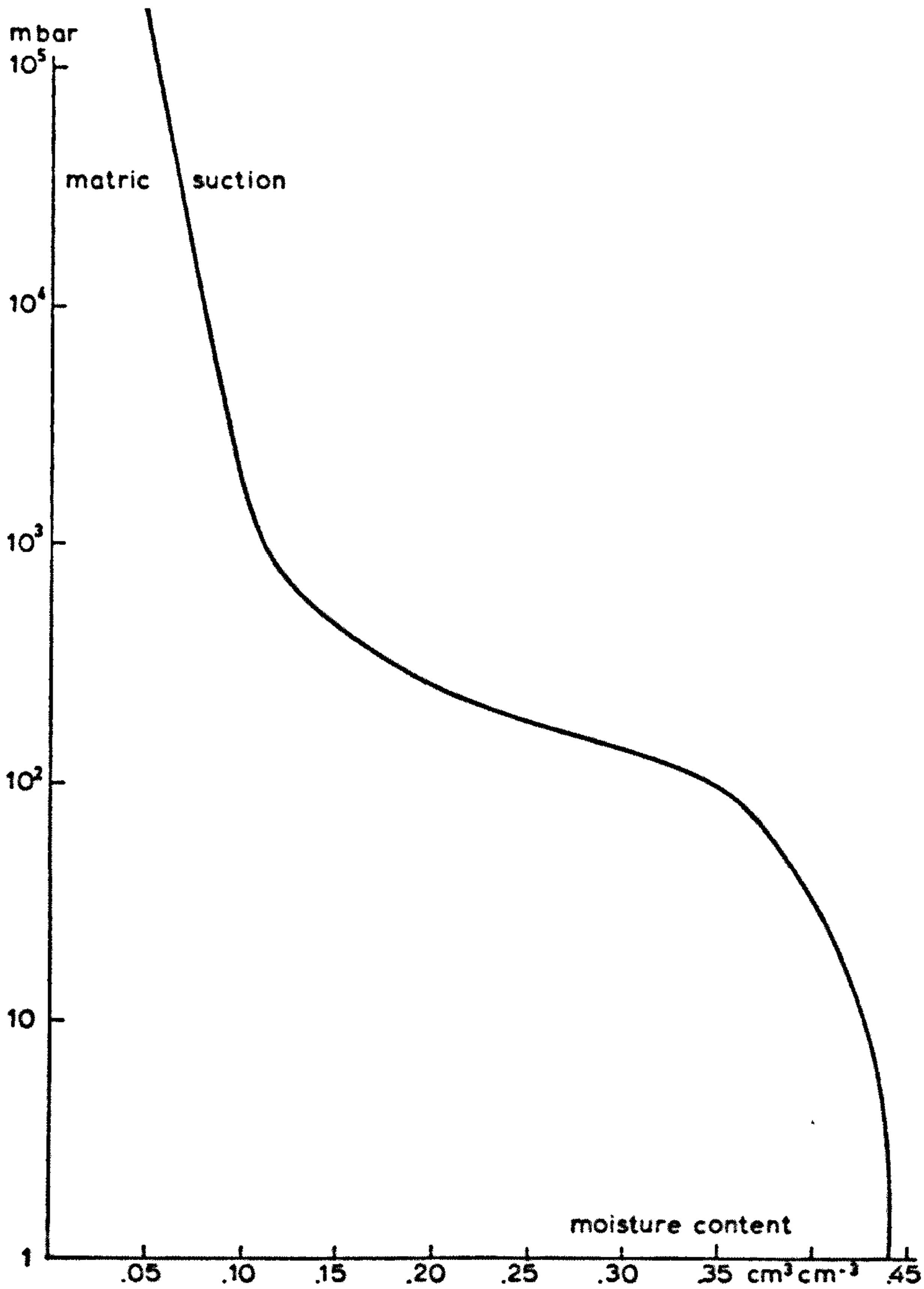

Fig. 1a | The relation between moisture content and matric suction for Migda löss.

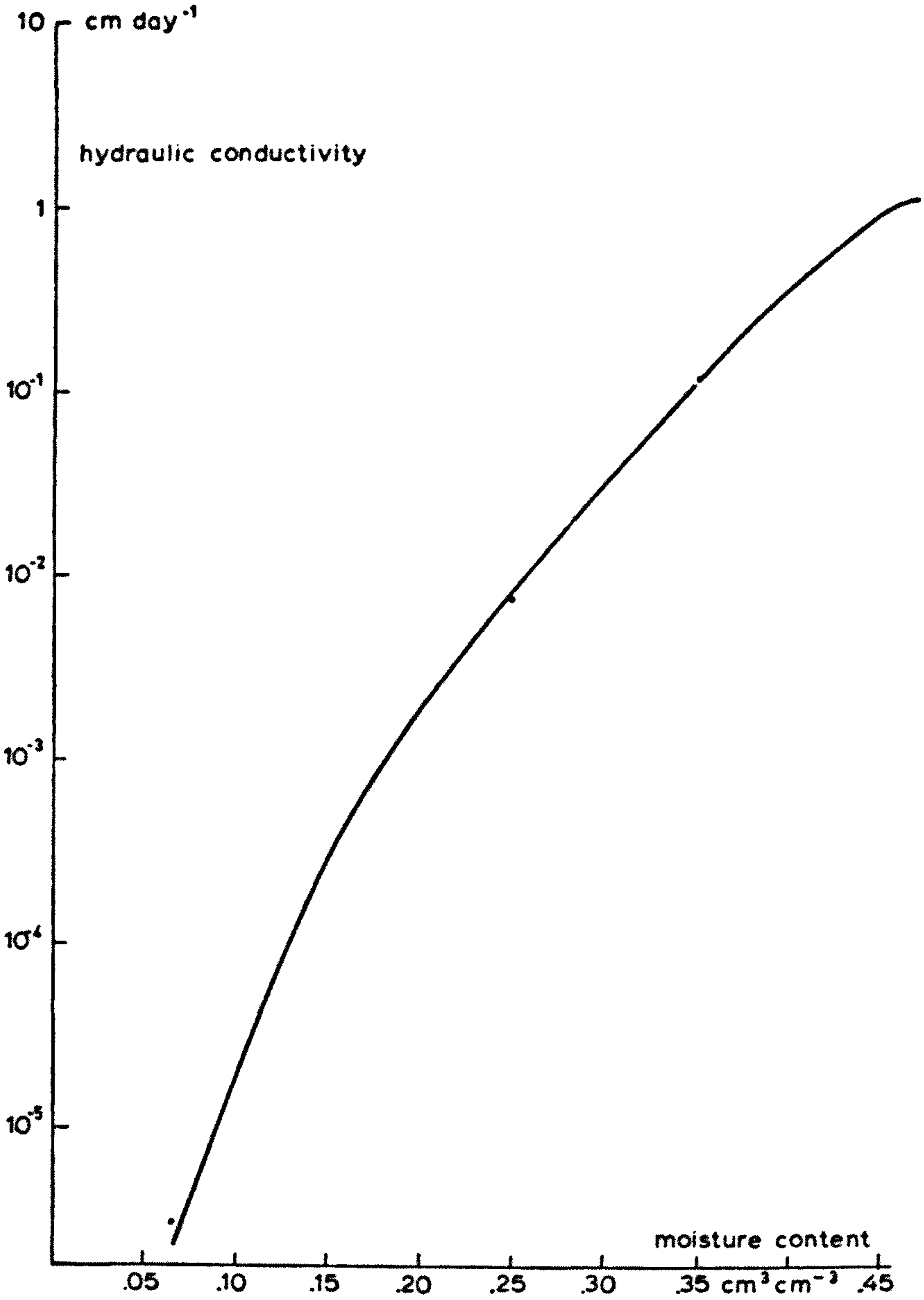

Fig. 1b | The relation between moisture content and hydraulic conductivity for Migda löss.

The matric suction versus water content curve and the conductivity-water content curve are shown in Fig. 1. The 'wilting point' (at 15 bar suction) is 0.075 cm^3 cm^{-3} and 'field capacity' (at 300 mbar suction) is 0.23 cm^3 cm^{-3}.

The soil is of desert dust origin and contains little organic matter ($\pm$1.5% in the upper layers, <0.5% in the lower ones) making it structureless and unstable. Under the influence of rain a crust is formed, causing run-off on even slight slopes. This is often local run-off/run-on not leading to loss of water but to differences in distribution, and to a patchy appearance of the vegetation.

Vegetation

The native vegetation at the experimental site is an abandoned crop land vegetation, consisting mainly of herbaceous annuals. The predominant species are: the grasses *Phalaris minor*, *Hordeum murinum* and *Stipa capensis*, the crucifers *Erucaria boveana* and *Reboudia pinnata*, the compositae *Anthemis melaleuca* and *Centaurea iberica* and the legumes *Trigonella arabica* and *Medicago polymorpha*.

The botanical composition varies considerably from year to year and may vary from spot to spot. The reason for this variation is not yet understood, but is a subject of study in another part of the project. From the point of view of dry matter production, the composition does not appear to be very important, though it may be so for grazing, as the palatability of the species differs. The period of plant development ranges from 1 to 5 months depending on amount and distribution of the rainfall. Germination starts after the first rains in November-December. This often happens in patches, because of the unequal distribution of water in the soil or uneven drying of the top soil layers due to microtopography. Successive waves of germination may occur after later showers, increasing the number of seedlings from an initial 500–700 m^{-2} to 3000–5000 m^{-2}. Seed availability and viability never seem to limit germination except in cases of heavy overgrazing when either the plants do not have a chance to mature seeds or the seeds with soil are eaten and digested. When germination occurs early in the season (second half of November till mid January), plant growth may be hampered in the beginning by low temperatures. The grand period of growth starts at the beginning of February and lasts till the water has been used or till the end of March/mid-April, even if water is still available. During this period peak growth rates of 160–180 kg dry matter ha^{-1} day^{-1} are attained when fertilized. There is a distinct difference in development pattern between species: some species like *Trigonella arabica* and *Erucaria boveana* form vegetative and generative organs synchronously, while the grasses first complete vegetative growth and then start flowering.

At the end of the growing season when the water is depleted, the vegetation dries up rapidly. It may turn from green to dry within two weeks. All the (remaining) seeds and the leaves are subsequently shed, causing a sudden drop in standing crop of 15–25%. The residue remains on the field as stem-cured hay which is eaten during the dry period by sheep or decomposed during summer or the following winter.

2.3.2 *Experimental layout*

Experiment 1

During the seasons '71/'72, '72/'73 and '73/'74 experiments were carried out to determine the growth curve of the natural vegetation. At the same time soil moisture was recorded.

An area of 4.8 ha was divided into four equal parts. In October 1971 the total area was amply fertilized with 150 kg K ha^{-1} and 100 kg P ha^{-1}, while two of the plots received an additional application of 400 kg N ha^{-1} as ammonia. The fertilizer was disked in to ensure proper mixing and to prevent loss of N through volatilization. In each of the four plots fifteen aluminium neutron access tubes were installed to a depth of two metres. They were placed in groups of five within 'permanent plots' of 100 m^2, randomly chosen from the area. In the season '72/'73, an additional four plots of five were installed, two in each treatment, because some of the permanent plots were not representative for the whole area anymore. This was apparently caused by the way the dried material was removed. Outside the plots the dry material was removed by grazing. In order to protect the aluminium access tubes in the permanent plots they were fenced off and the dry grass was raked off. The reason for the poor germination afterwards is not completely clear, but possible causes could be: no trampling of the seeds into the soil by sheep, no protection of the seeds from heat damage through incorporation in sheep droppings, or removal of the seeds by field mice. It was striking that there were relatively many more mouse holes inside the permanent plots than outside, probably because of the presence of the organic material on top.

Experiment 2

To investigate the disking effect, a parallel experiment was established in which a field received only P and K fertilization, while half the area was disked, and half was not disked. Twenty access tubes were installed in each treatment to a depth of two metres. Unfortunately the after-effects of previous fertilizer experiments in this field were too strong to enable one to draw conclusions on the effect of disking. In the second year this area was fertilized with 40 kg N ha^{-1} as calcium nitrate and was used to study methods of determining the amount of standing crop.

Experiment 3

To facilitate comparison of the results obtained within the present project with data from other locations, an experiment with a wheat crop was carried out in the season '72/'73. Wheat was sown at the end of November in a field of ±0.5 ha that had been under fallow the previous season. The area was divided into 48 plots of 100 m^2 in each of which a neutron access tube was installed to a depth of two metres. The field was fertilized according to local agricultural practice i.e. a basic dressing of 200 kg superphosphate ha^{-1} and an additional top dressing of 300 kg nitrochalk ha^{-1} after establishment. From the end of January onwards six plots, randomly chosen from the area, were harvested at two-weekly intervals. In the centre of the plot 25 m^2 were cut by hand, the total harvested amount was weighed fresh, a sample was taken and dried at 80 °C for two days. From the beginning of April onwards an area of 1 m^2 in each plot was carefully cleaned to determine the amount of leaves etc. shed.

Experiment 4

In the '72/'73 season the effect of grazing on primary production and water use was studied in an adjacent field. In the field of 4.8 ha, thirty neutron tubes were placed. The area was grazed at a fixed stocking rate of four sheep ha^{-1}, being the normal grazing density that can be maintained with year-round grazing. Four 100 m^2 plots were protected from grazing by fences. In each of these plots 5 neutron tubes were installed. Grazing started after establishment of the crop, which was rather late (15 February) because of poor germination. This was probably caused by the hard algal crust formed on top of the soil. Grazing hardly influenced primary production because the stocking rate was too low to appreciably affect the amount of standing crop in the period of peak growth. It may, of course, be quite different when the rate of removal is approximately equal to the growth rate. The experiment was therefore repeated in the season '73/'74 with a floating stocking rate.

2.3.3 Experimental techniques

Climatological observations

A standard climatological station is located at the Gilat Experimental Station, about eight kilometers from the experimental area. Here the meteorological data are recorded: air temperature, dew point, wind run and cloudiness. The daily total global radiation is measured with a Gunn Bellani distillometer. Comparison of this method with a Kipp radiometer showed agreement within 10%, with proper calibration (Stanhill, 1965). Rainfall is recorded with rain gauges on the experimental site. Both self-recording and small orifice tube gauges are dispersed throughout the area.

Soil moisture

Soil moisture is measured by the neutron moderation technique (IAEA, 1970). The measurements are carried out in 30 cm increments at two-weekly intervals and after sufficiently heavy rainfall during the growing season. In summer every 6–8 weeks the soil moisture is recorded, although hardly any changes occur during that time.

At the beginning of the growing season the neutron probe is calibrated. Over the whole moisture range that occurs approximately 200 samples are taken in the field and their moisture content is determined gravimetrically. In the resulting holes neutron access tubes are placed, either temporarily or permanent, and readings are taken with the neutron probe immediately after sampling at the same depths. From these data a linear regression equation is calculated, relating the soil moisture content to the reading of the probe. A typical calibration curve is given in Fig. 2, measured at the beginning of the season 1972/1973. The regression coefficient for these calibration curves is always above 0.93.

Because of scattering of the neutrons to the atmosphere the results of measurements in the upper layer are not reliable. Therefore the moisture content of the top 30 cm of the soil is determined gravimetrically at the same time as the neutron probe measurements.

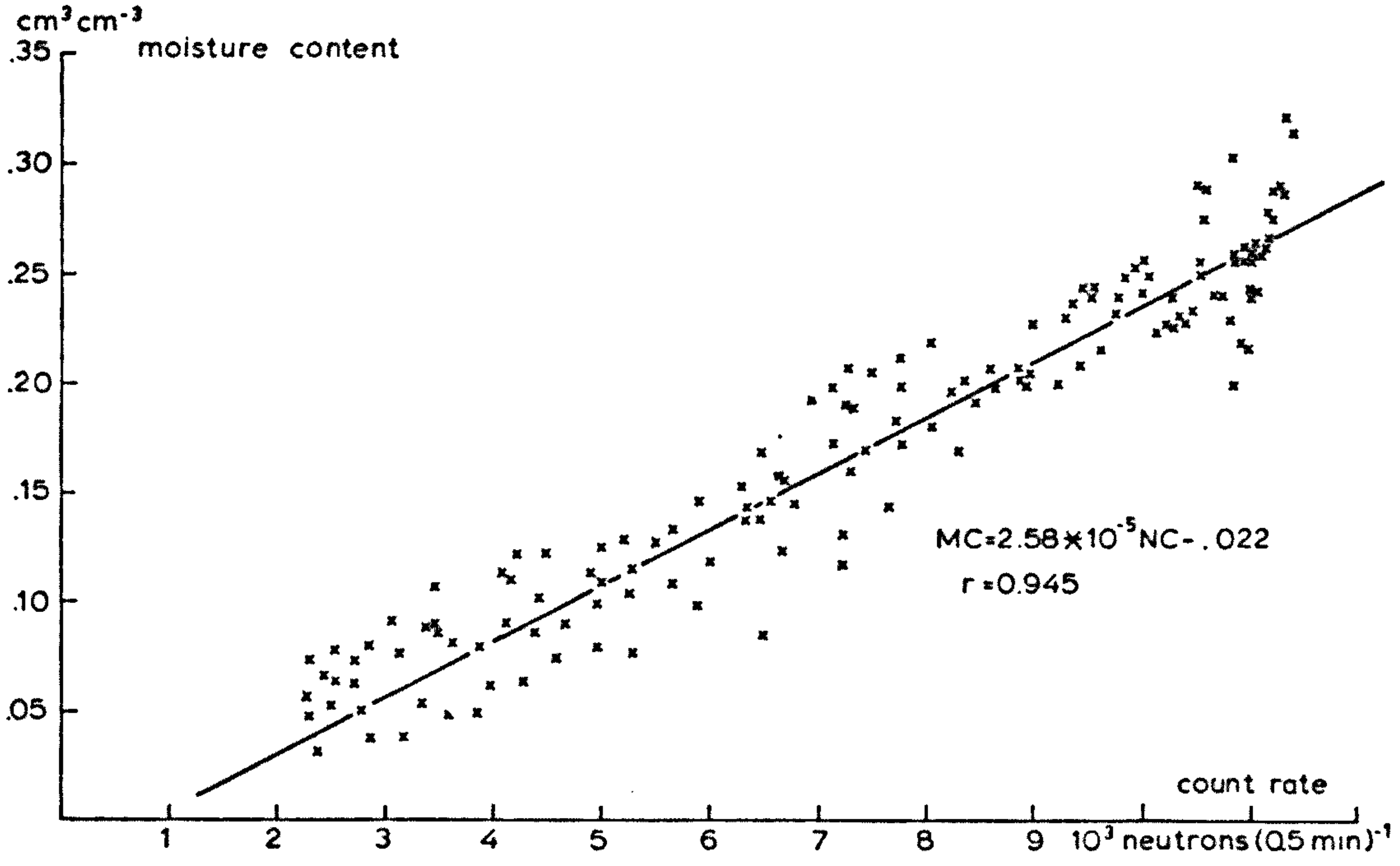

Fig. 2 | Typical calibration curve for neutron moisture meter.

Plant biomass and production

The annual vegetation at Migda shows much local variation in amount of standing crop and in composition. This makes estimation of the mean yield of a field with a reasonable accuracy (10–15%) a very time-consuming and difficult matter. The amount of aerial biomass, specially in the early season may range from 0 to 150 g m^{-2} in adjacent areas of 0.5 m^2. This means that several hundreds of samples have to be harvested to obtain the yield with reasonable accuracy. Such intensive harvesting is quite impractical when frequent sampling, once every fortnight, is necessary. Besides, with peak growth rates of 170 kg ha^{-1} day^{-1}, the sampling of a field must be finished within a few days to prevent biased estimates.

A double sampling technique of visual estimates calibrated by harvesting of a sub-sample has been adopted for the vegetation. Details of the method and the statistical treatment are discussed by Tadmor et al. (1974).

The principle of the method is that a large number (200–400 per treatment) of visual estimates of standing crop are collected. A wire frame of 25 × 25 cm in low vegetation and 50 × 50 cm in tall dense vegetation is put on the field. The weight (either fresh weight or dry weight) of the vegetation inside the frame is estimated. The samples are taken at random along transects in the field. One out of each five samples is harvested and the actual weight is determined. From these samples a calibration curve is constructed by means of linear regression. The calibration curve is used to give an estimate of the average yield of the field.

In the season '71/'72 estimation was done by fresh weight. The correlation coefficient between estimated fresh weight and actual dry weight varied between 0.98 in February (all green vegetation), to 0.60 in April (when the vegetation was partly dried up). In the season '72/'73 dry weight was estimated directly and the correlation coefficient then varied between 0.89 and 0.98.
The total standard error from the field mean estimated with this double sampling technique was between 5% and 13% of the mean (Tadmor et al., 1974).
The relatively short time required to get the results and the accuracy obtained show that this method is suitable to determine amount of biomass and rate of production in non-homogeneous vegetation, if skilled estimators are at hand or can be trained.
Special problems rise when there is a large variation in phenological stage in the vegetation (April '72) or when the standing crop is very tall and dense. In these cases the regression may be so bad, that only clipping can increase the accuracy. Additional clippings are therefore carried out at the end of the growing season.

2.3.4 Results

Rainfall

Differences in weather between growing seasons at the experimental site can be characterized by different rainfall conditions. Fig. 3 shows the cumulative amount of precipitation for the seasons '71/'72, '72/'73 and '73/'74. Compared with a long term average of 250 mm, all three seasons were wet, with 350, 245 and 370 mm of rain, respectively. The rainfall distribution, also a characteristic of importance for plant growth, was favourable in the first two seasons, the vegetation being never short of water throughout the growing period. In '73/'74 there was a drought period between the middle of December and mid January, with the vegetation showing signs of wilting during daytime

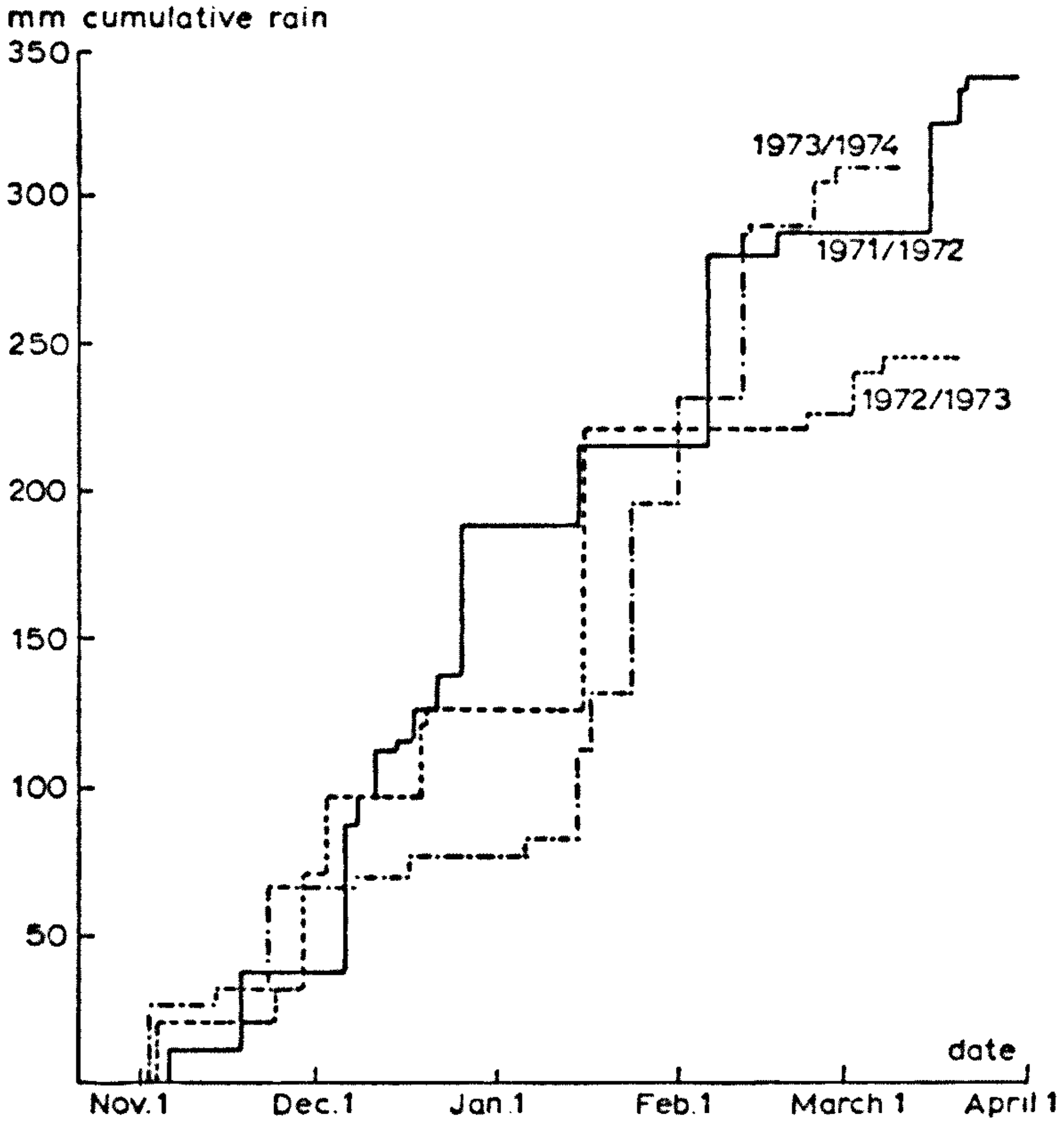

Fig. 3 | Cumulative rain in Migda during the seasons '71/'72, '72/'73 and '73/'74.

and a part of the rain fell so late in the season, that it was not used by the vegetation but remained in the soil. The first rains fell in all seasons in the first week of November, and by the end of that month enough water was available to ensure germination.

Soil moisture

The course of total soil moisture during the growing period is given in Figs. 4–8 for different treatments and various seasons. Observed data are connected by solid lines although the actual march of soil moisture deviates from these lines due to moisture withdrawal and recharge by transpiration and rainfall, respectively. There were only small differences between the various treatments. At the onset of the rains, the profile contained ± 150 mm of water, corresponding with an average volumetric water content of 0.085 $cm^3\ cm^{-3}$, which is at 'wilting point'. The initial situation was not measured in 1971/1972

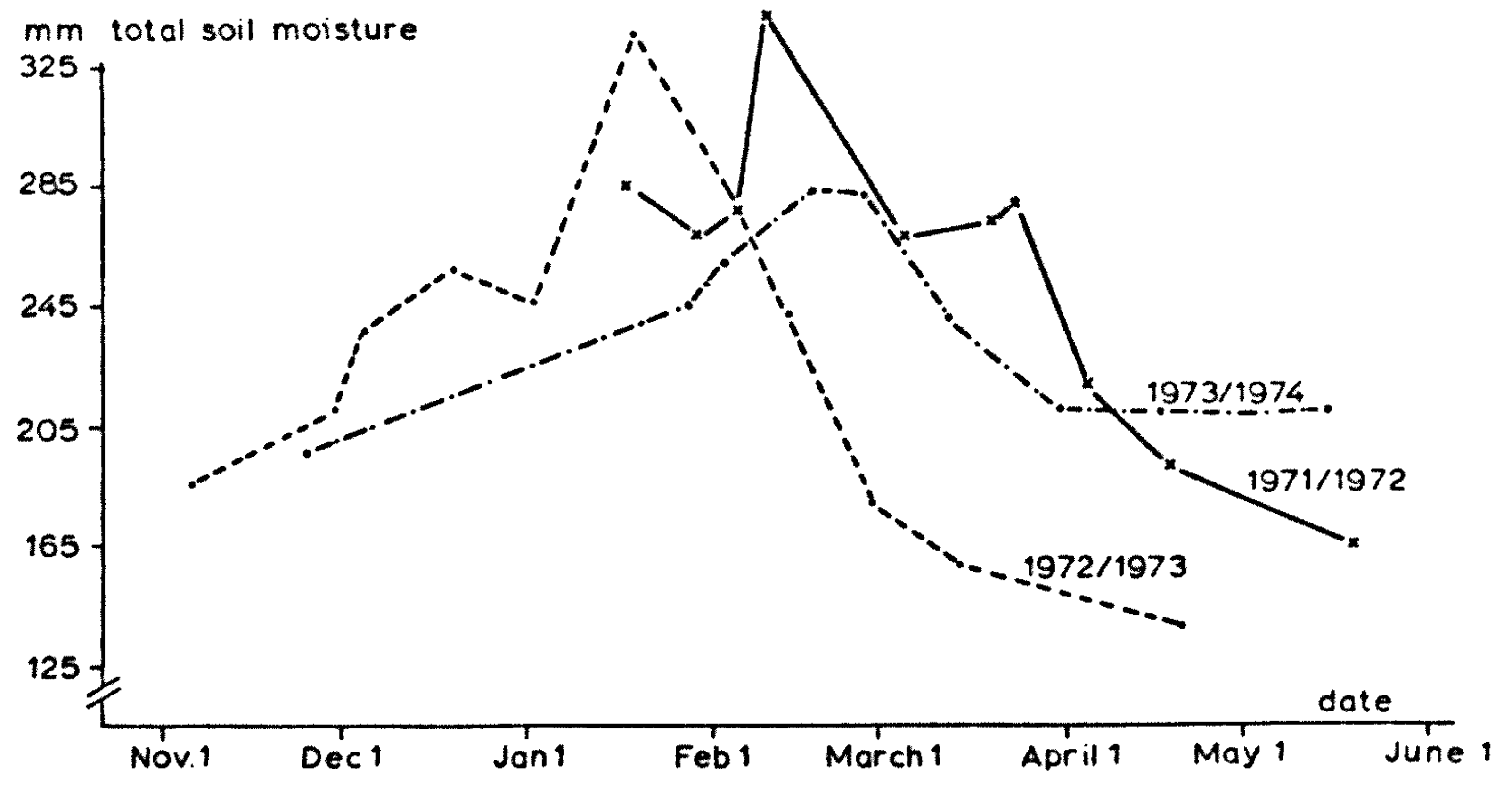

Fig. 4 | Measured course of soil moisture for the NPK treatment during three growing seasons.

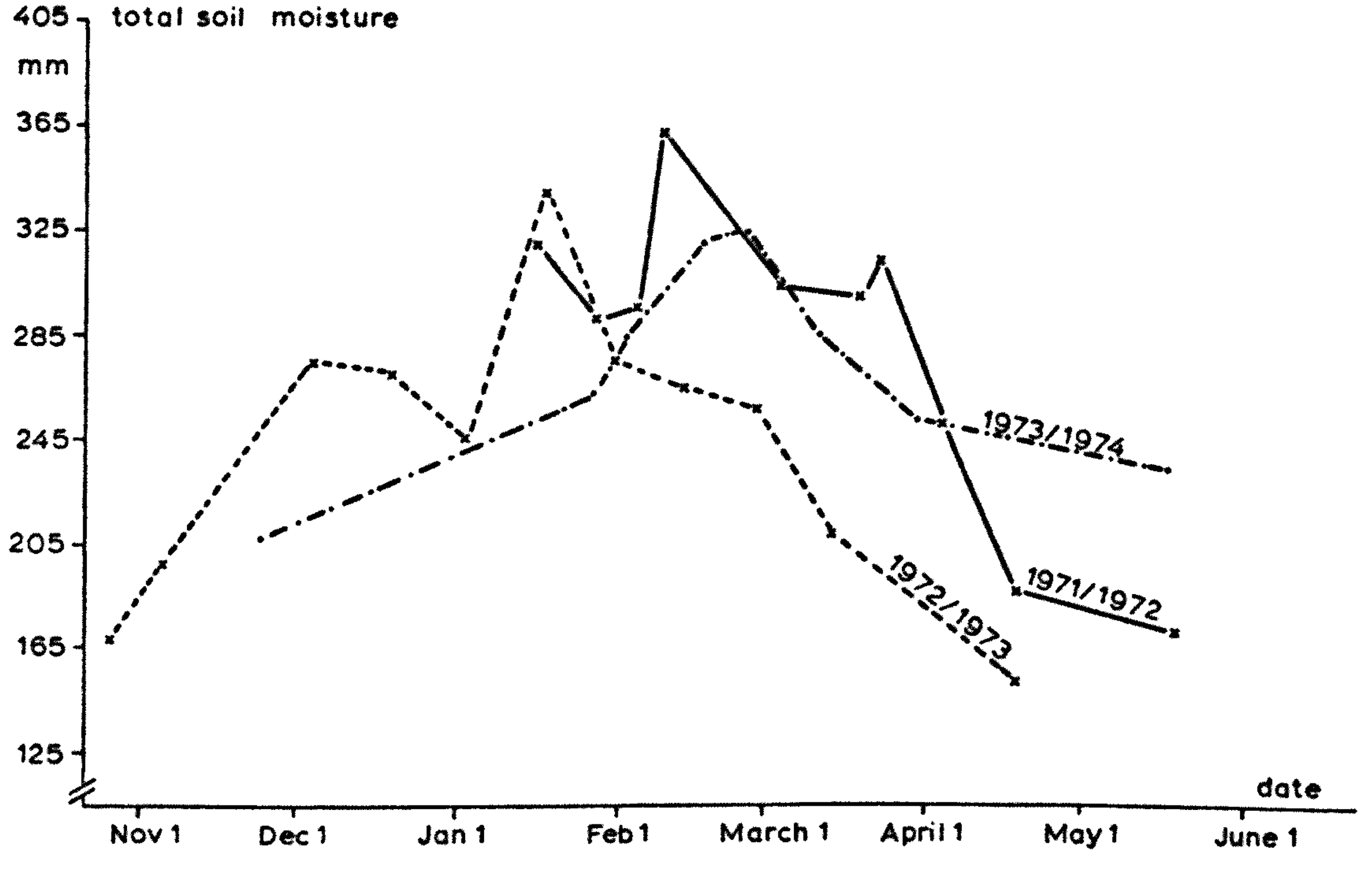

Fig. 5 | Measured course of soil moisture for the PK treatment during three growing seasons.

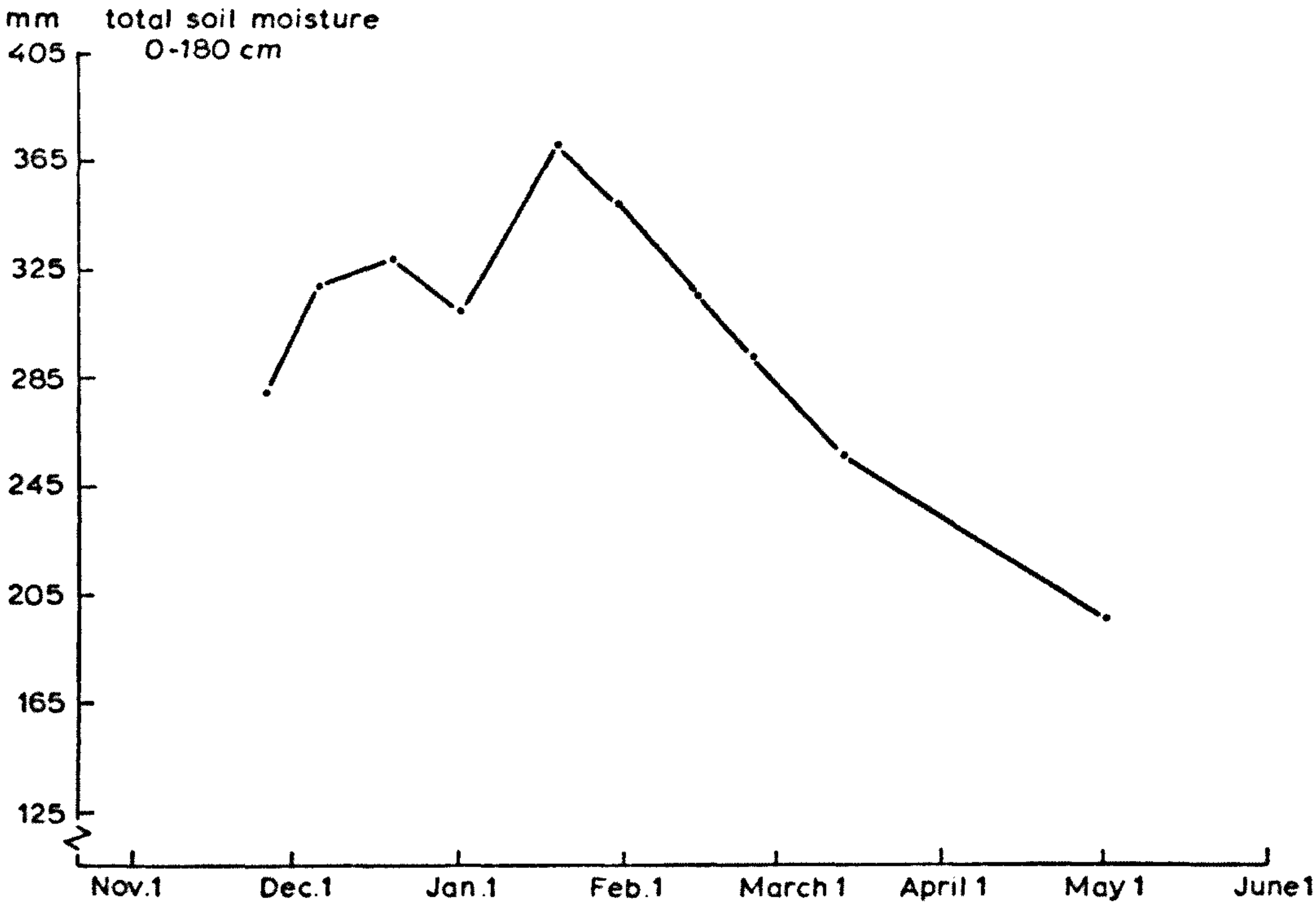

Fig. 6 | Measured course of soil moisture for the wheat field in '72/'73.

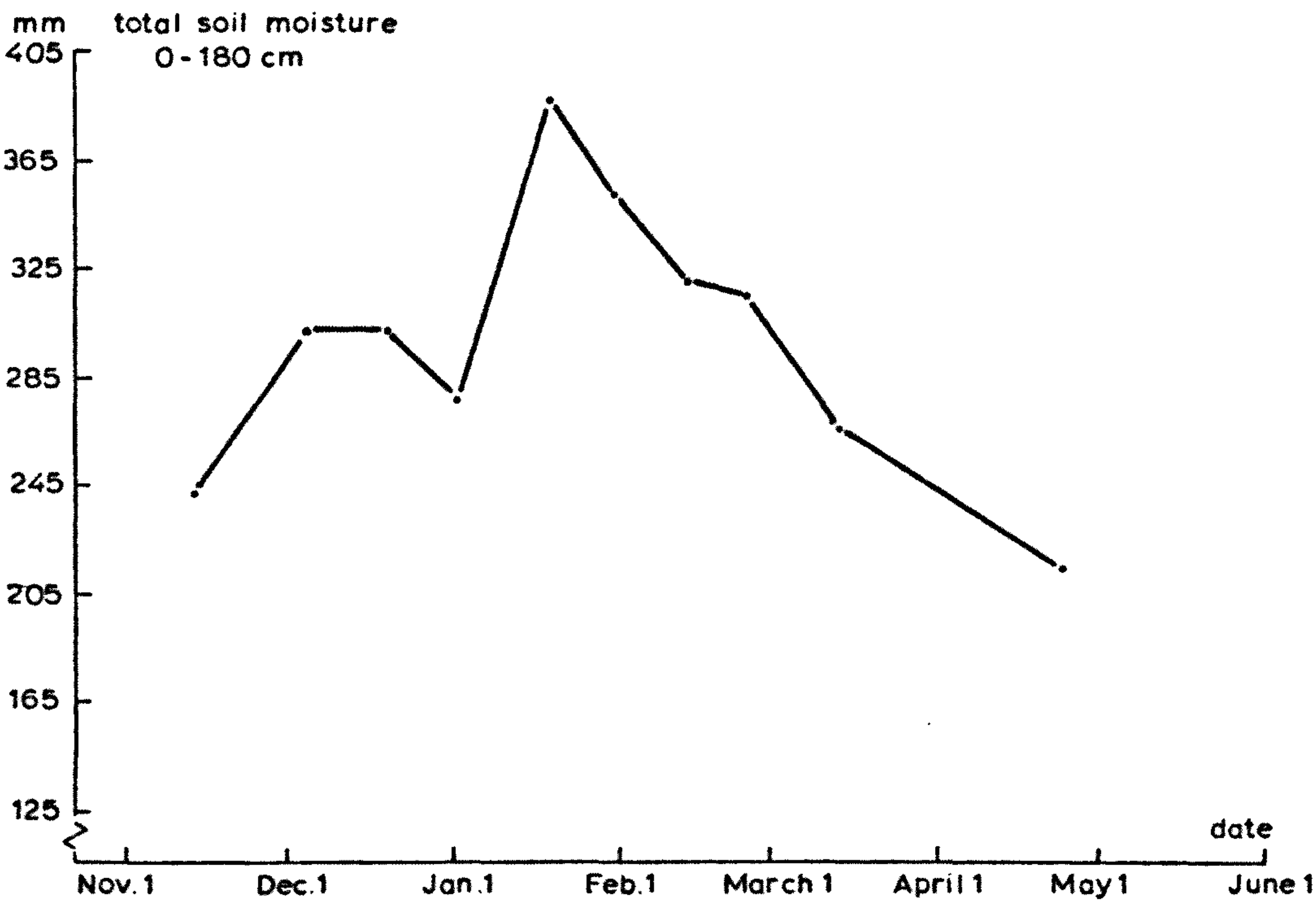

Fig. 7a | Measured course of soil moisture for the grazed and non-grazed treatment in '72/'73.

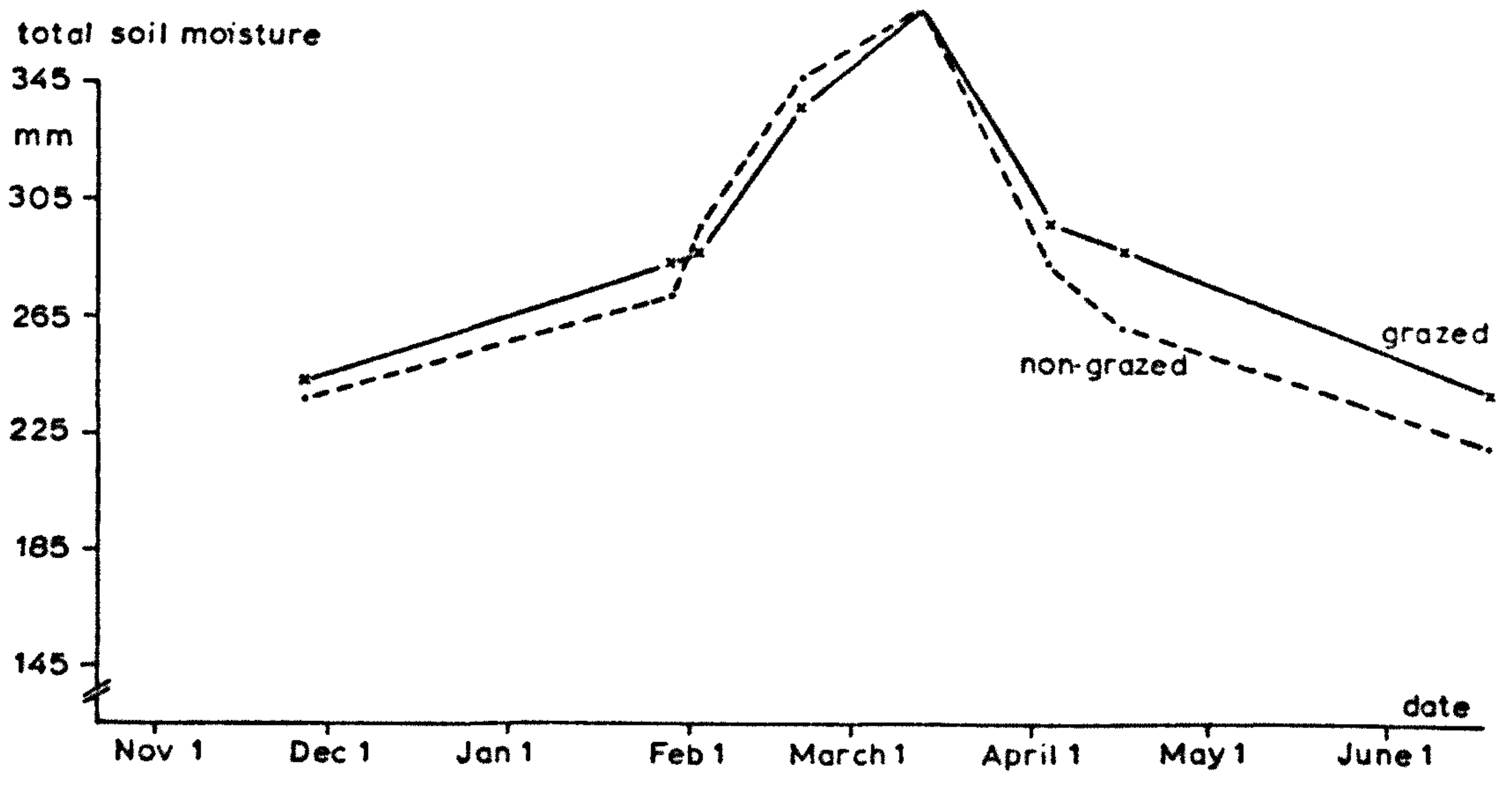

Fig. 7b | Measured course of soil moisture for the grazed and non-grazed treatments in '73/'74.

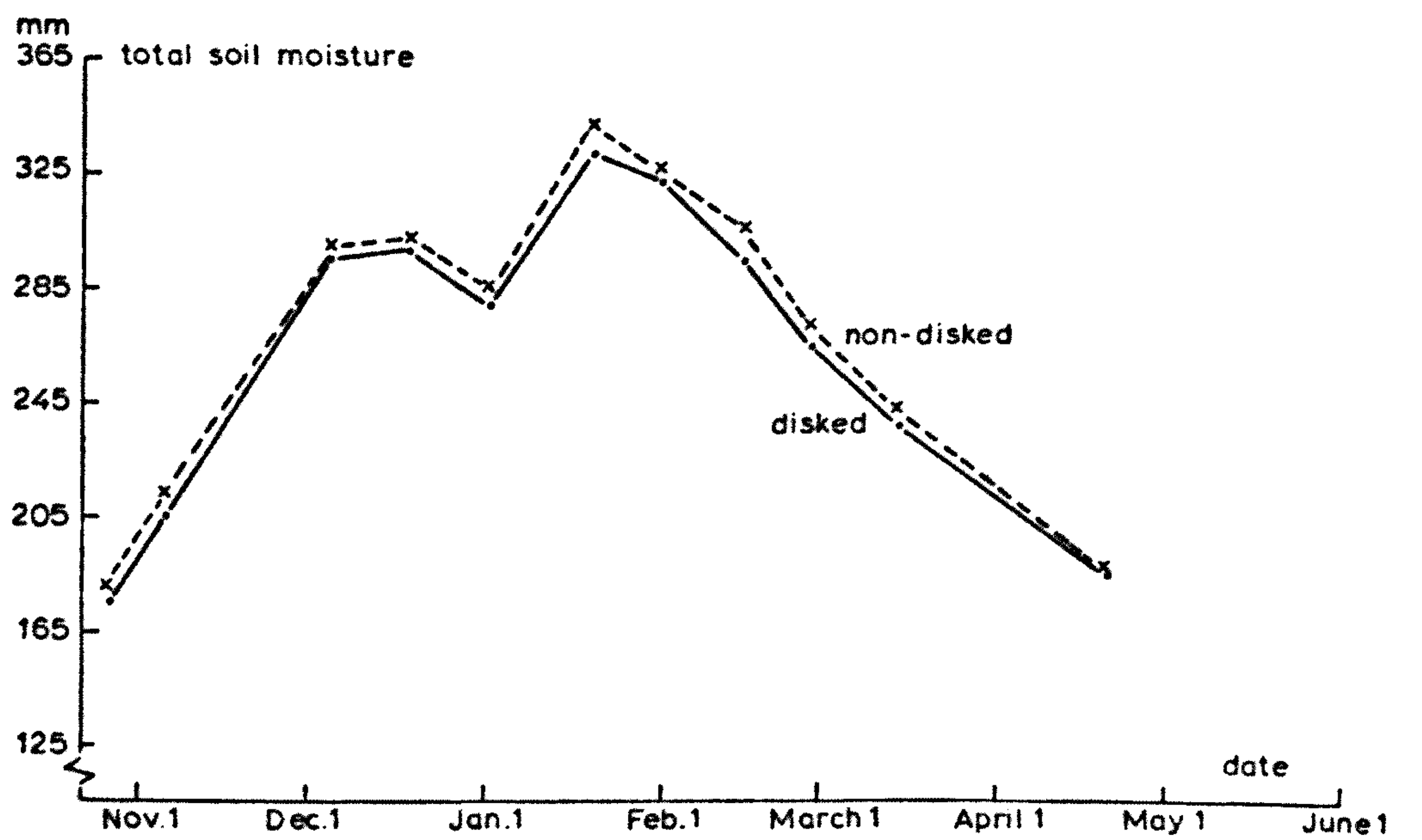

Fig. 8 | Measured course of soil moisture for the disked and non-disked treatments in '71/'72.

because the access tubes were only installed in January 1972 and in the wheat and grazing experiments only in November 1972 after the first rains.

The high initial moisture content under the wheat (Fig. 6) was due to fallowing in the preceding growing season, which saved about 85 mm of soil moisture. This was only 30% of the total amount of water used for transpiration by the natural vegetation in the season '71/'72. The efficiency of the fallow period in terms of saving water was thus very low, due to losses by evaporation and transpiration by weeds. Generally, the increase in dry matter production in a season after fallow is less than what would have grown in that fallow period. Application of this technique is only profitable in very low rainfall areas, where an increase of 30 to 40% in available water makes up the difference between success and failure of a crop. This may be the case when special parts of the plants, for instance seeds, and not dry matter is the desired product. An additional advantage of a fallow period is a higher level of nitrogen during periods of crop growth as mineralization proceeds during the fallow period. Hence the often observed increased growth rates after fallowing may have been caused by increased nitrogen availability, rather than by the extra amount of water.

The initially high water content in the grazing experiment (Fig. 7) also originated from the previous season. The vegetation which started late in that year matured and died while still available water was present in the profile. Because of the relatively small amount of vegetation, the rate of transpiration was low during the main growing period.

Comparison of the moisture content at the end of '71/'72 and the beginning of '72/'73 in Figs. 4 and 5 shows that practically no water was lost during the hot summer. This is because very little evaporation can occur from the completely dry topsoil. The rate of water withdrawal during the grand period of growth was practically the same in all cases, indicating that transpiration was hardly affected by the level of soil fertility and that the cultivated wheat behaved identically to the natural vegetation. The differences between the NPK field and the PK field in the second half of the growing period of '72/'73 were caused by the difference in biomass.

Dry matter production

The course of dry matter production for the various treatments is given in Figs. 9 to 15. For the 1971/1972 season, the standing crop was first determined after the establishment of the experiments at the end of January, but not much information was lost because growth started very late. The points connected by the solid lines give the amount of standing vegetation, while the broken lines were obtained by carefully collecting all the material from the soil surface after harvesting. This shows, that during drying of the vegetation a large portion of the leaves and the seeds are shed.

The crosses give dry matter yields that were obtained by visual estimates, while the open circles were determined by harvesting 10–15 strips of 10 m^2 each. This harvesting was in general necessary when the vegetation was too high or too dense for visual estimation (Section 2.3.3). In situations where both techniques were applied, on the same plots, Fig. 9, March 27, 1972 and March 7, 1973, Fig. 10, April 12, 1972 and April 11, 1973, the results are the same. The

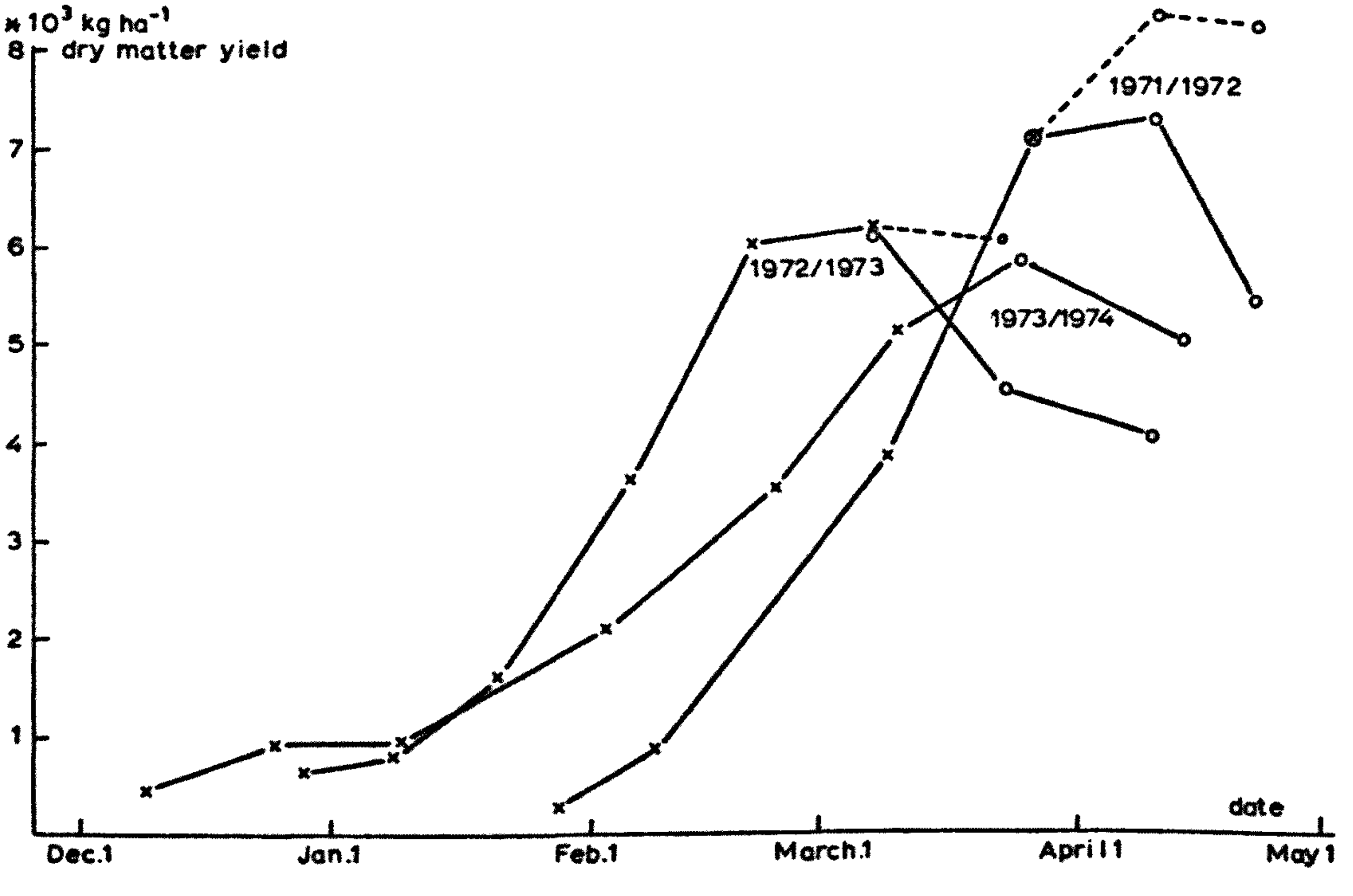

Fig. 9 | Cumulative dry matter production of the NPK treatment for three growing seasons.

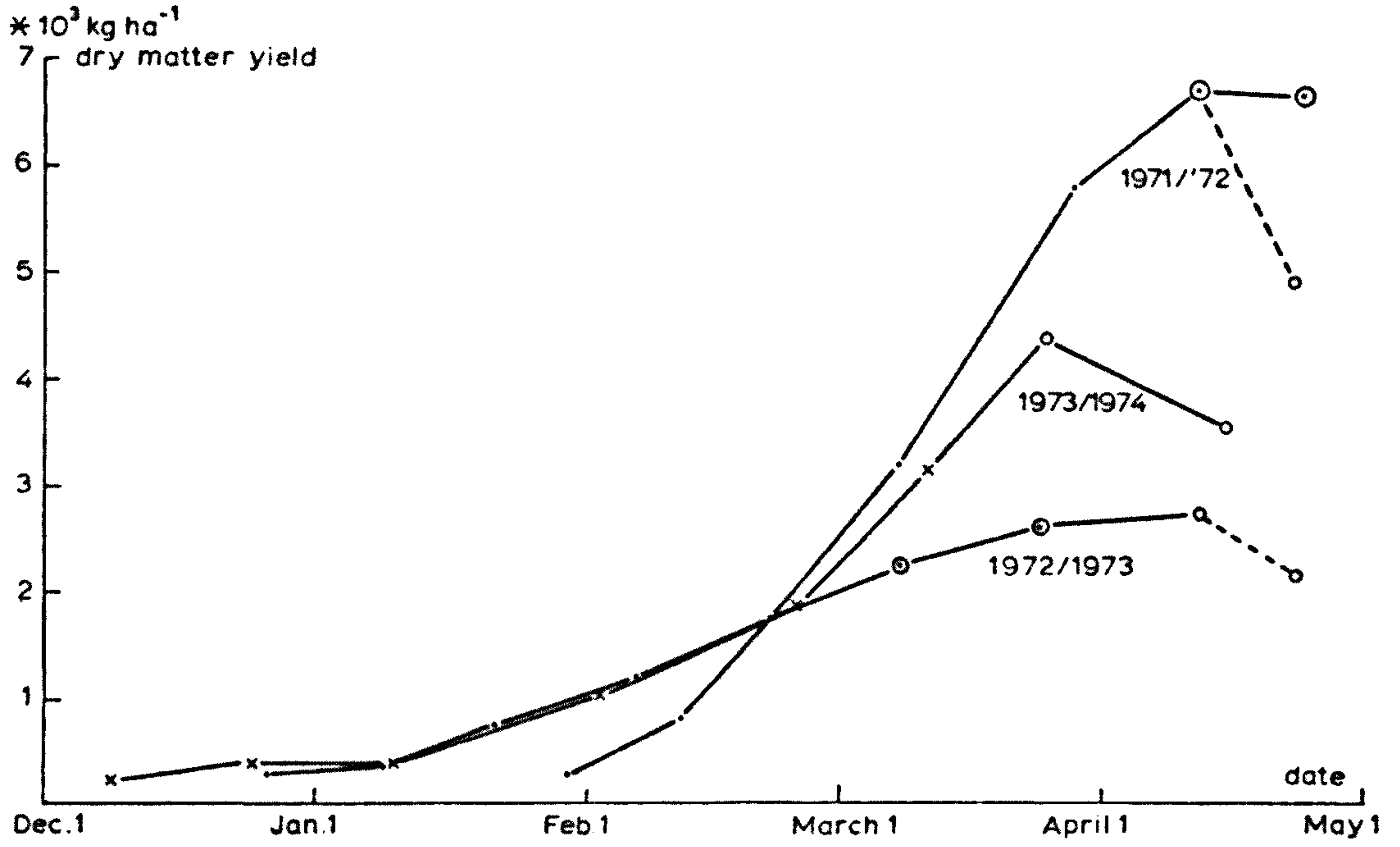

Fig. 10 | Cumulative dry matter production of the PK treatment for three growing seasons.

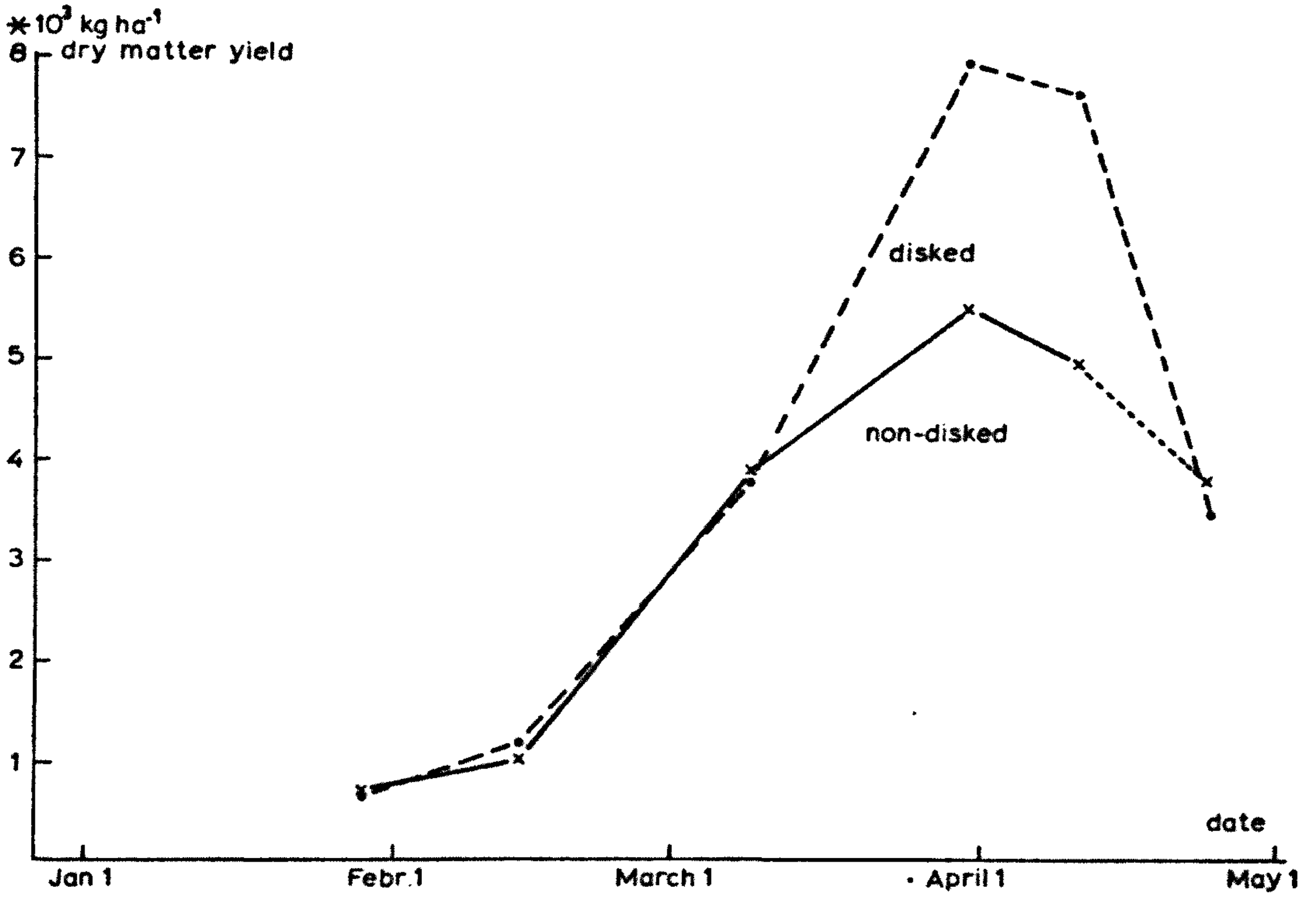

Fig. 11 | Cumulative dry matter production of the disked and non-disked treatments in '71/'72.

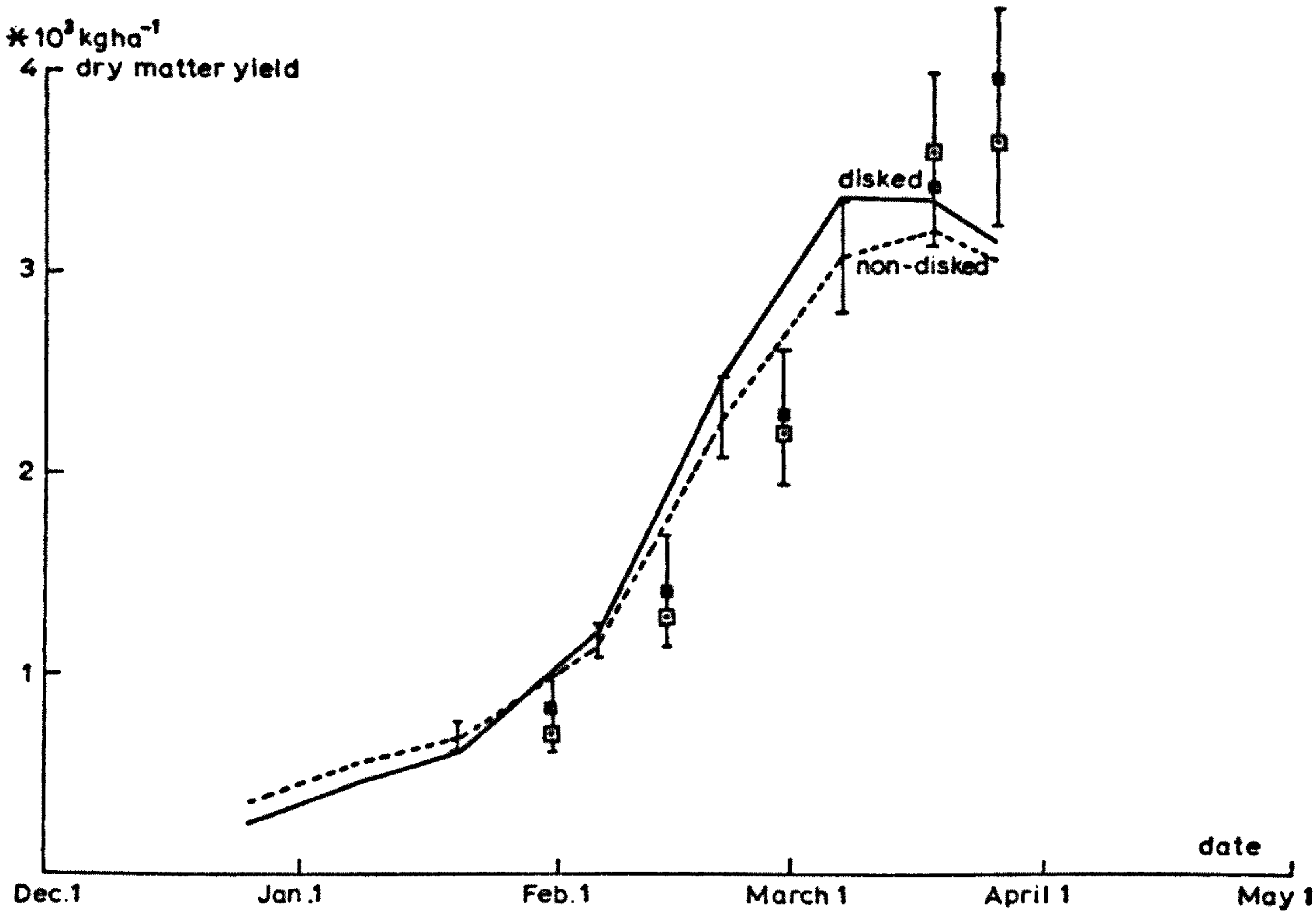

Fig. 12 | Cumulative dry matter production of the originally disked and non-disked treatments in '72/'73.

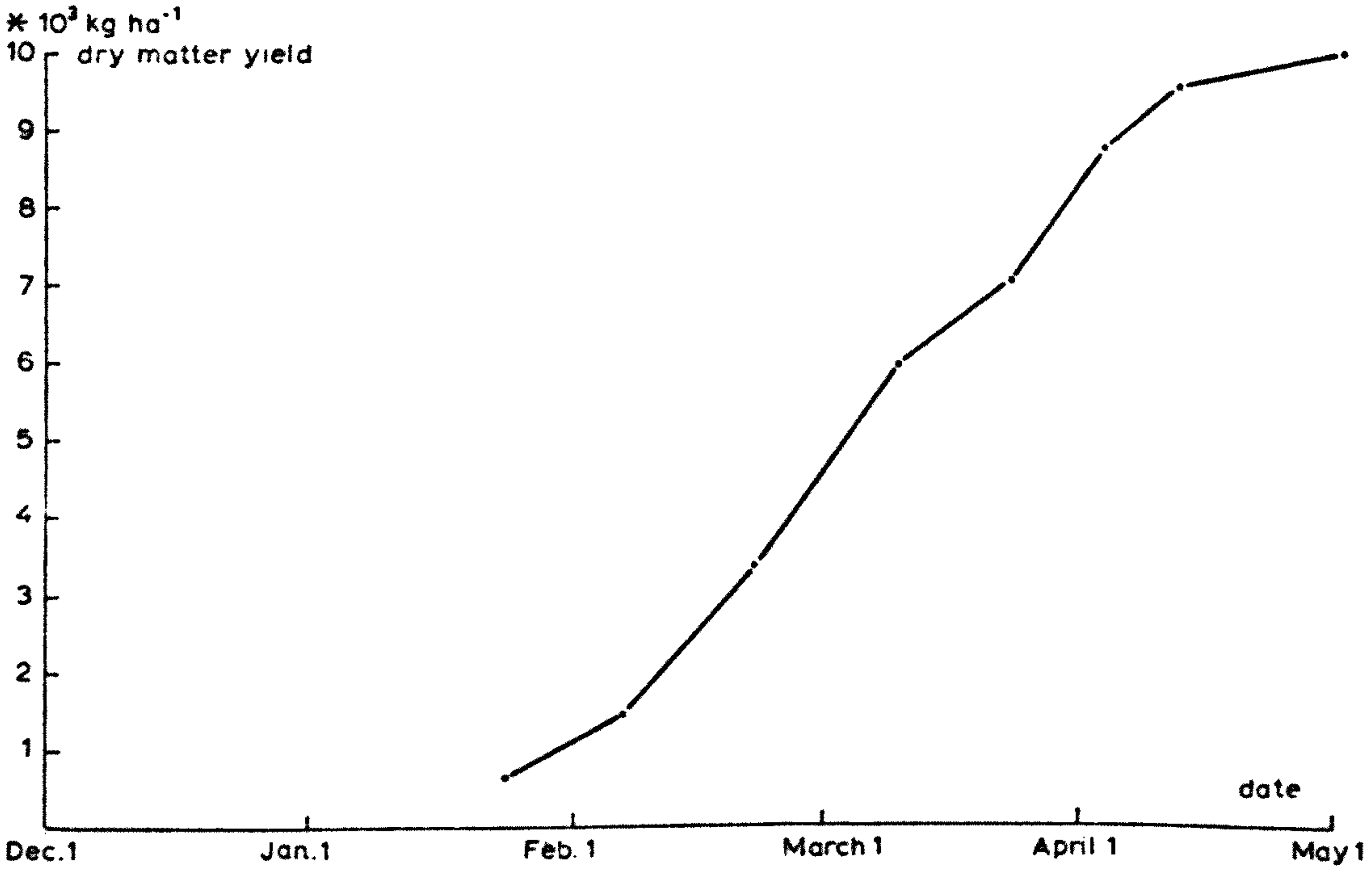

Fig. 13 | Cumulative dry matter production of the wheat experiment in '72/'73.

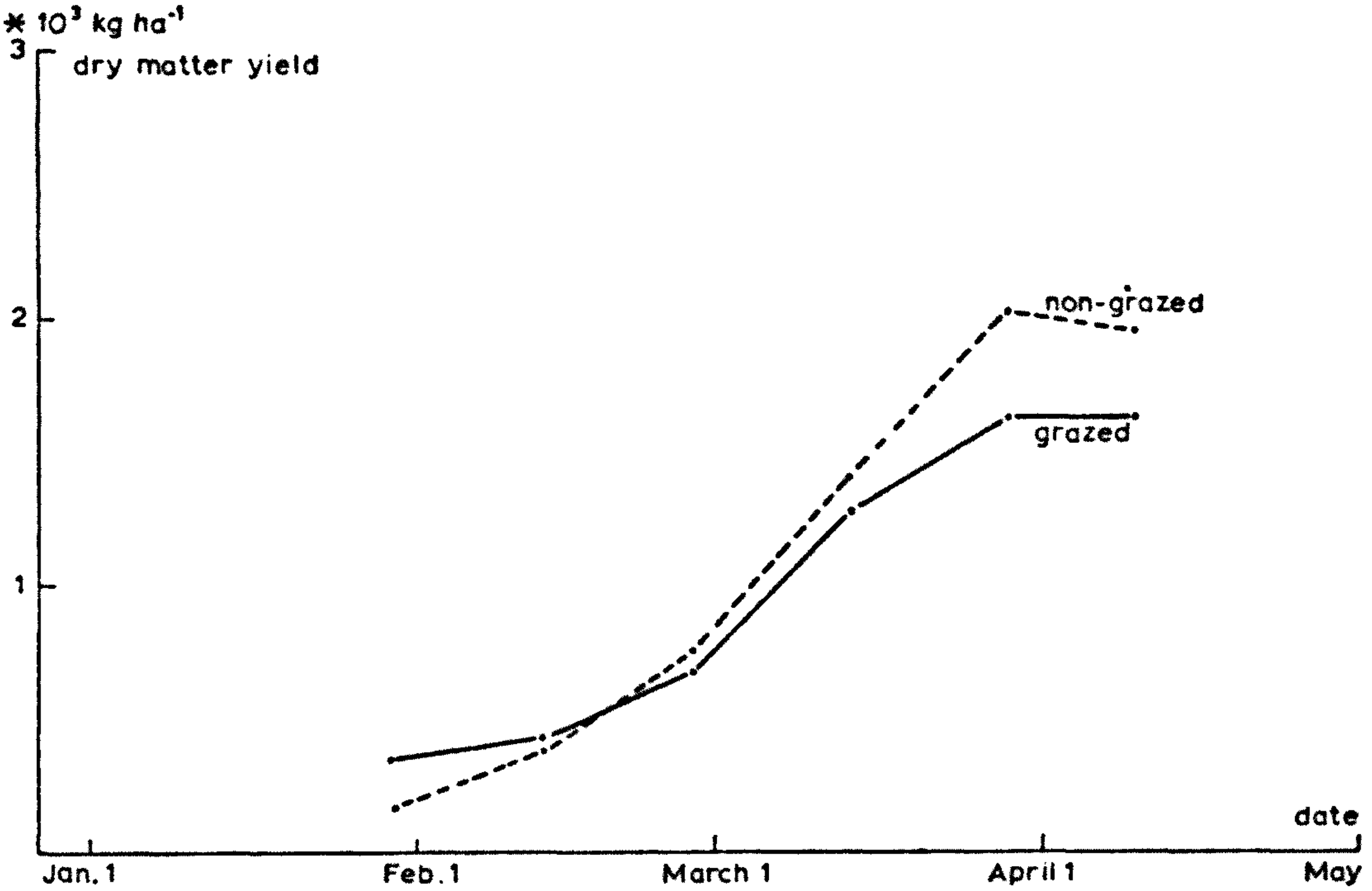

Fig. 14 | Cumulative dry matter production of the grazed and non-grazed treatments in '72/'73.

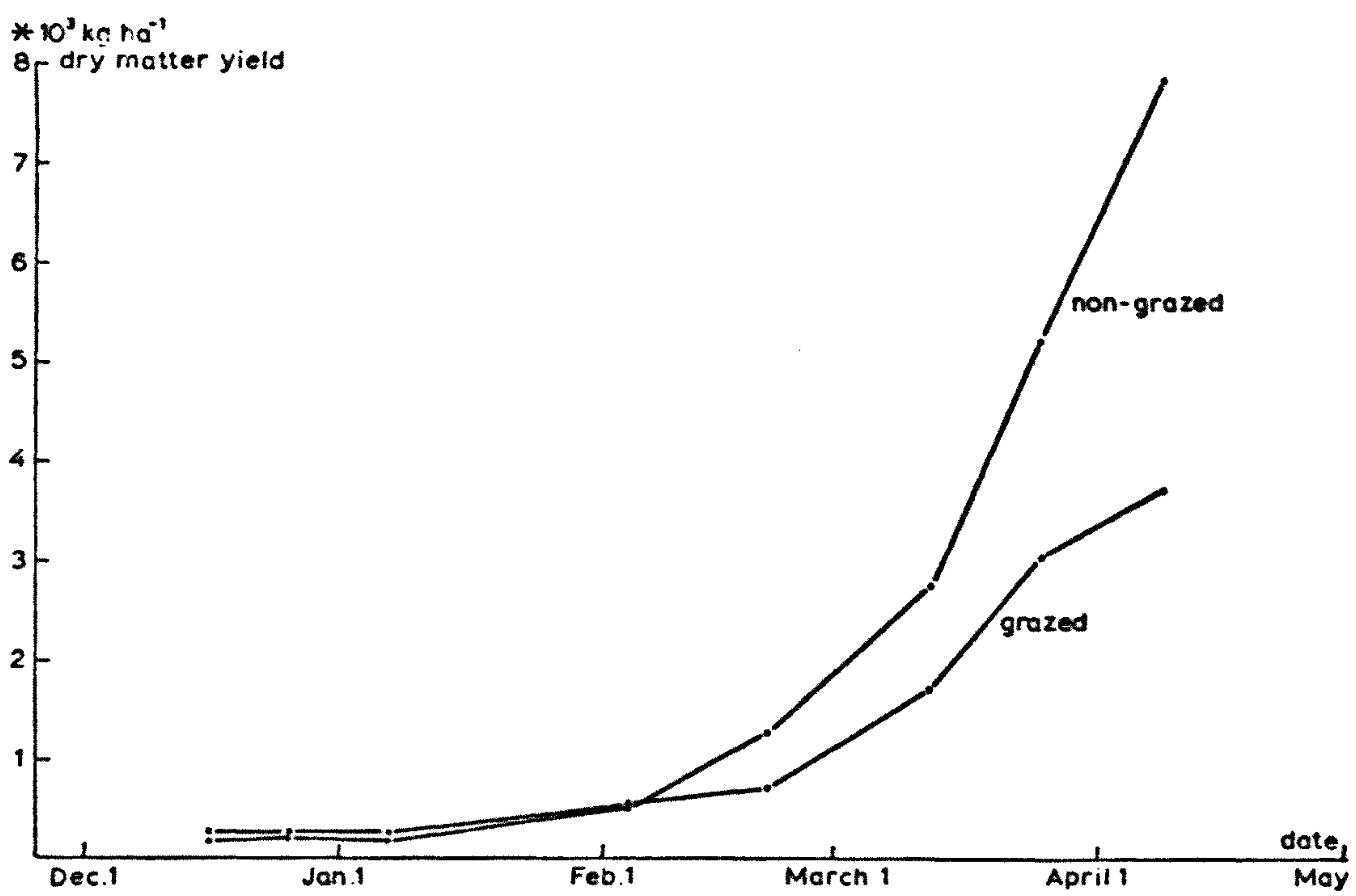

Fig. 15 | Cumulative dry matter production of the grazed and non-grazed treatments in '73/'74.

standard deviation from the harvests is, however, about 20% of the field mean, while for the visual estimates at the end of the growing season it is about 15%. Earlier in the season, the standard error of the average yield of the field determined with the technique of visual estimates is between 5 and 10% of the field mean (Tadmor et al., 1974). All growth curves show the same typical sigmoid pattern of exponential growth in the beginning which levels off at the end due to limiting factors like lack of water (1972/1973) or completion of the development cycle.

Nitrogen uptake

In Figs. 16 and 17 the total amount of nitrogen taken up by the vegetation in the various treatments is given as a function of time. These amounts are calculated by sampling the plant species comprising the vegetation and analysing them for total N. Sampling was not detailed enough to permit a full analysis of the uptake pattern with time but some interesting phenomena were observed. In the season '71/'72 (Fig. 16) the analysis was carried out twice in the beginning of the growing season and again practically at the end which prevents comparison with the '72/'73 season when the sampling was more frequent. Fig. 16 shows that the ranking in nitrogen uptake is the same as in dry matter production. The actual amounts reflect the different levels of availability: NPK not limited; disked: effect of disking and after-effects of fertilizer; PK: disking effect only; non-disked: historical

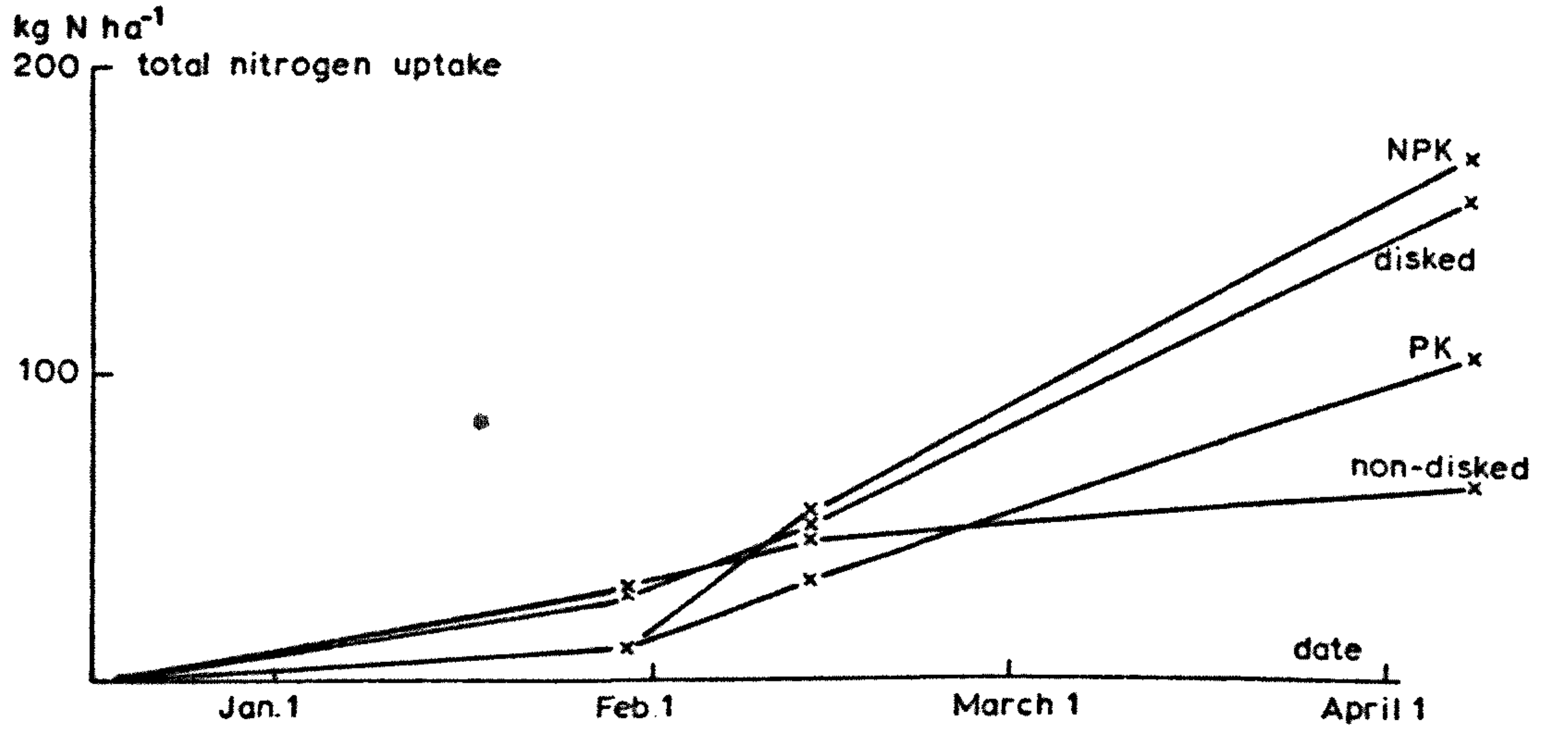

Fig. 16 | Cumulative nitrogen uptake for various treatments in '71/'72.

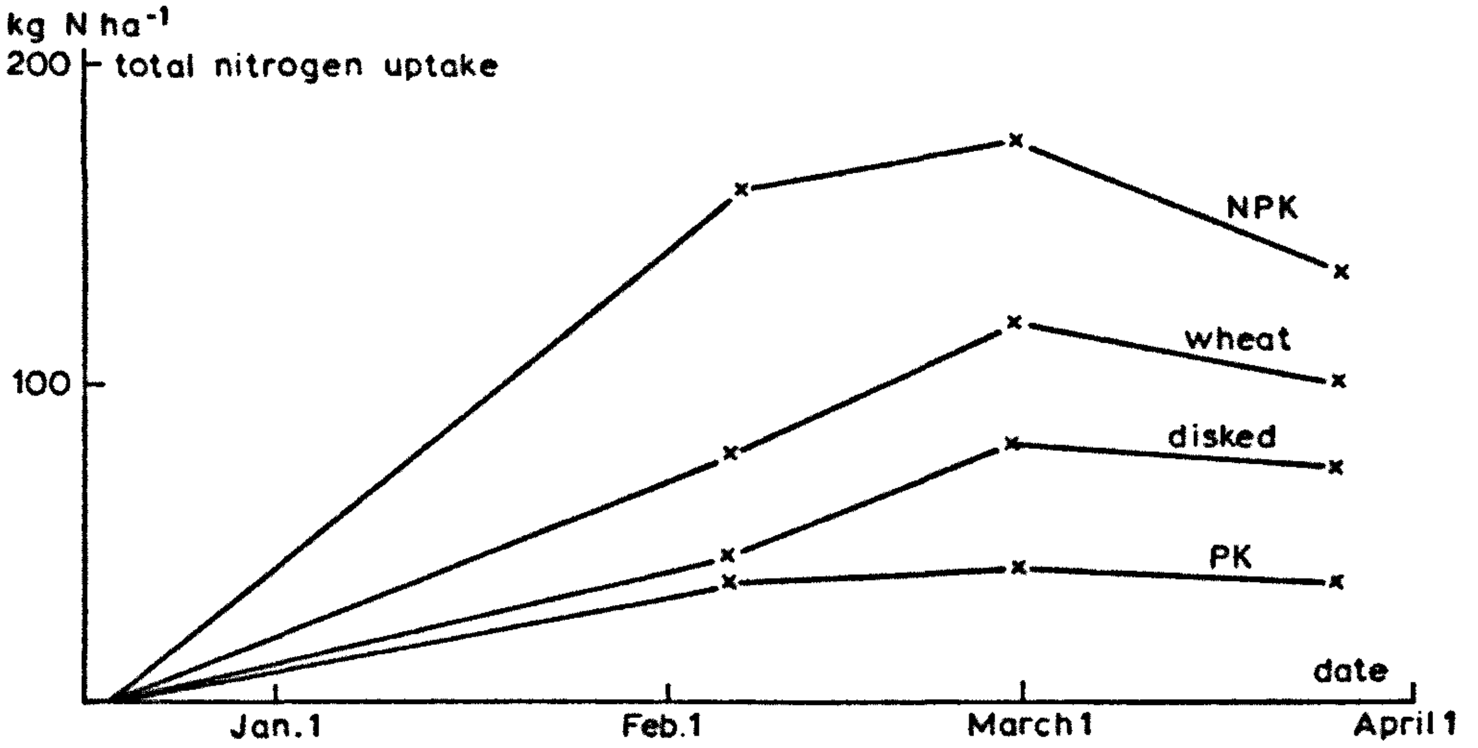

Fig. 17 | Cumulative nitrogen uptake for various treatments in '72/'73.

nitrogen only. It is difficult to give a quantitative analysis of the various effects because also the grazing history (sheep droppings) has an effect. In Fig. 17 the most striking phenomenon is that in all treatments a very high portion of the total nitrogen uptake occurred at the beginning of the growing season. Dry matter production increased much more than nitrogen uptake even when there was ample supply (NPK). This shows that after a certain moment nitrogen is diluted in the vegetation. Why no more nitrogen is taken up is not clear (Seligman et al., in prep.).
Comparison of the PK treatment with the disked treatment (which was identical to the non-disked, therefore only one curve is given) shows that fertilization decreases the amount of nitrogen available from other sources, as the difference between the two is less than the 40 kg added by fertilization. This may be ascribed to a lower percentage of legumes under fertilization, while also the fixation by free living micro-organisms is hampered in the presence of free NO_3.
The decrease in total N at the end of the growing season is due to shedding of the relatively protein-rich seeds, while the remaining vegetative material has a low nitrogen content.

Botanical composition
As mentioned in Section 2.2, there is a great variability in the botanical composition of the natural vegetation, both from year to year and from place to place. In Tables 1, 2 and 3 the average botanical

composition of the natural vegetation is given for the NPK treatment and for the PK treatment for the three seasons and for the disked and non-disked treatment in '71/'72. The botanical composition was estimated as a percentage of the total dry matter during the visual estimates. The results may therefore not be very accurate, but they give a fair indication of the existing differences. Only three groups were distinguished: grasses, legumes and herbs. A more detailed

Table 1 Botanical composition of the natural vegetation in the NPK treatment.

Date	% grasses	% herbs	% legumes
1971/1972			
72-01-30	16	42	42
72-02-13	7.5	50.5	42
72-03-07	4	72	24
72-03-29	3	82	15
72-04-11	5	84	11
72-04-23	6	82	12
1972/1973			
72-12-27	15	85	—
73-01-08	21	77	2
73-01-21	21	75	4
73-02-06	27	68	5
73-02-21	34	61	5
73-03-07	40	59	1
73-03-27	45	54	1
1973/1974			
73-12-09	43	49	8
73-12-25	44	50	6
74-01-09	45	50	5
74-02-03	44	45.5	10.5
74-02-24	58	31	11
74-03-10	55	31	14

Table 2 Botanical composition of the natural vegetation in the PK treatment.

Date	% grasses	% herbs	% legumes
1971/1972			
72-01-30	13.5	57.5	29
72-02-13	10.5	52.5	37
72-03-07	3	67	30
72-03-29	4	67.5	28.5
72-04-11	6.5	70.5	23
72-04-23	6.5	71.5	22
1972/1973			
72-12-27	15	80	5
73-01-08	21	75	4
73-01-22	31	59	10
73-02-06	44	41	15
73-02-21	30	46.5	23.5
73-03-08	27	47	26
73-03-18	31.5	49	19.5
1973/1974			
73-12-09	30	49	21
73-12-25	29	50	21
74-01-09	22	50	28
74-02-03	15	40	45
74-02-24	7	14	79
74-03-10	8	15	77

classification is meaningless in this study, both because the method of sampling is not accurate enough and because interpretation of possible differences would be pure guesswork with the present knowledge. Even changes in the relative ratio of the three groups could not always be explained.

The very low percentage of grasses in the season '71/'72 in the NPK

and PK treatments was probably due to poor germination as a result of disking. A phenomenon that does not appear from the tables and which shows the disturbance of the system by disking, was that in the early stage in '71/'72, the herbs in the NPK treatment consisted predominantly of *Fumaria densiflora* D.C., a species normally not abundant in the natural vegetation in Migda.
In the disked treatment (Table 3) the grasses were far less affected by disking. Probably the amount of seeds in this treatment was (much) higher as the area had been fertilized and had not been grazed in the preceding years.
In the season '73/'74 there is again a marked shift in the botanical

Table 3 Botanical composition of the natural vegetation in the disked and non-disked field in 1971/1972.

	Disked		
Date	% grasses	% herbs	% legumes
72-01-30	52	42.5	5.5
72-02-14	31	54	15
72-03-09	35	54	11
72-03-31	66	29	5
72-04-11	83	14	3
72-04-24	47	38	15
	Non-disked		
Date	% grasses	% herbs	% legumes
72-01-30	53	46	1
72-02-14	31	63	6
72-03-09	45	54	1
72-03-31	48	51	1
72-04-11	38	59	3
72-04-24	54	39	7

composition compared with the preceding season. In the NPK treatment the relatively high proportion of legumes appearing in the grand period of growth is striking. This could be an indication that at that time nitrogen was not readily available (see Section 6.2). The relative proportion of grasses and herbs gives no additional information on this point, as both groups contain certain species which react strongly to N deficiency and others which are less affected.
The PK treatment shows the phenomenon of a 'legume-year', as at the period of peak production 77% is legumes. They experience favourable conditions when the nitrogen that was available, becomes depleted by the early development of herbs and grasses. The reason for the abundance in a certain season is not completely clear.
Prediction of the botanical composition, that will appear in a certain season is impossible at present. This is not only influenced by the conditions in the soil at time of germination, but also by the amounts and condition of the seeds, which is determined by their history. Determination of amount and properties of the seeds would involve complete disturbance of the system, leading to different germination conditions and hence to another botanical composition.

2.3.5 Discussion

Early growth
Early development of the vegetation is governed by the germination conditions, as these determine the amount of biomass present after establishment. Not too much is known at present about the germination characteristics of the species comprising the natural vegetation, so that not all the differences in early development could be explained. In the NPK and PK treatments (Figs. 9 and 10) growth started much earlier in the season '72/'73 than in '71/'72. It is most likely that the late start in '71/'72 was caused by unfavourable germination conditions, due to disking, which buried the seeds to such a depth that they did not emerge or produced very weak seedlings (Tadmor & Cohen, 1968). Especially the very small seeds of the grasses would be affected and Table 1 shows that the percentage of grasses in the vegetation was very low in the season '71/'72. The effect may have been enhanced by the application of fertilizers, which caused high osmotic pressures in the soil water around the germinating seeds (Tadmor et al., 1969a).

The retarding effect was practically absent in the comparison between the disked and non-disked treatments (Fig. 11) where early growth was the same for both. It is not clear, why the combined effect of disking and fertilization was so much stronger than disking alone. Probably there was some influence here of seed availability. The area used for the disked and non-disked treatments had been used for some years for fertilizer experiments without grazing, while the NPK and PK fields had been under grazing till the season '70/'71.
In '73/'74 early growth was even somewhat better than in '72/'73. However in the dry spell between mid December and half of January growth stopped practically, so that the grand period of growth started later.
In the PK treatment growth in the beginning of the season was exactly the same as in the previous season. This is, however, most likely caused by somewhat better germination conditions because here the influence of the dry period is also visible.
In the grazing experiment (Fig. 14) growth started very late, not until the beginning of February. Germination may have been retarded here for two reasons: the field had been grazed under a high stocking rate in previous years, which prevented the vegetation from maturing seeds and in many places an algal crust was formed on top of the soil presenting a high resistance for seedling emergence. It is impossible to distinguish between these possibilities.
Early development in both the grazed and non-grazed parts in '73/'74 was again much later than in the other treatments (Fig. 15). It seems most likely that environmental conditions (most probably soil physical properties) hamper germination as most plants matured and formed seed under the low stocking rate of the previous season. However this is not an absolute proof because these seeds may still be dormant and take a longer time to germinate or are not able to germinate at all.

The role of nitrogen

Although the role of nitrogen in the arid zone will be treated extensively as another part of this project (Section 2.2), its influence in the experiments was so large that some aspects will be discussed here. The level of dry matter production in the NPK treatment as compared with that from any other treatment shows that production was in general limited by insufficient available nitrogen rather than by moisture, which would be limiting only under much lower rainfall conditions. The differences between the NPK and PK treatment in the seasons '71/'72 and '72/'73 illustrate the prominent role of nitrogen. In '71/'72 there was a difference of only 20% between the two treatments, while in '72/'73 it was more than 100%. The small difference in '71/'72 must have been due to an increased nitrogen supply in the PK plots caused by disking which incorporated into the soil fresh organic material and dry sheep droppings that had accumulated on the surface during previous years. The nitrogen which was then mineralized ensured favourable nutritional conditions until the middle of March. In '72/'73 when there was practically no additional nitrogen the total dry matter yield in the PK treatment was 2750 kg ha^{-1} containing approximately 40 kg N ha^{-1}. This is rather a high value for the total amount of nitrogen from fixation by free living microorganisms, from fixation by the symbiotic organisms of the legumes and from the atmosphere supplied by rain. There may still have been some residual effect of disking. After-effects of previous nitrogen fertilization showed up in the disked and non-disked treatments. This field had been used for fertilization experiments in previous years, not all the nitrogen being taken up. The growth rates in the beginning of '71/'72 were equal to those in the NPK treatment, indicating that no lack of nitrogen existed in either treatment. Later on nitrogen shortage affected the growth rate in the non-disked treatment. Unfortunately no quantitative data on the amount of nitrogen removed in previous years were available, so that no separation could be made between effects of disking and of residual nitrogen. In the wheat experiment 100 kg N ha^{-1} was applied as nitrate. By the end of February this amount was completely recovered in the vegetation, indicating practically no losses. Thus fertilization increases the production in most cases, while the risk of loss of nitrogen is very low. Anaerobic conditions favourable for denitrification seldom occur and in these perma-dry conditions there are virtually no drainage losses. Nitrates are thus as safely stored in or on top of the soil as in any other place. Ammonium nitrogen, however, may be lost by volatilization when applied before the rains or when a prolonged dry period occurs. Recovery of nitrogen applied as nitrate should be always complete either in the same season or when the moisture conditions are unfavourable for growth, in a subsequent season. Hence each kilogram of NO_3-N applied to medium to heavy deep soils should eventually yield 6.25 kg of protein under arid conditions.

Grand period of growth

The length of the grand period of growth varied between ±40 and ±75 days. The length of this period was mainly determined by the amount of water available for growth. However, growth may also cease, when the development cycle of the plants is completed, even if there is still water available in the soil. This was so in the NPK treatment at the beginning of April 1972 and end of March 1974 and in the wheat in April 1973.

The observed maximum growth rates were ±170 kg ha^{-1} day^{-1} in the NPK treatment of the natural vegetation (Fig. 9) and ±160 kg ha^{-1} day for the wheat (Fig. 13). These rates are equal to the maximum growth rates, under optimum conditions, calculated according to de Wit et al. (1970) for the existing climatic conditions. The close agreement between the natural vegetation and the wheat shows that years of plant breeding have hardly influenced the efficiency of converting solar energy into biomass.

In '73/'74 the observed maximum growth rate in the NPK treatment did not exceed 115 kg ha^{-1} day^{-1} despite the fact that water was abundantly available between end of January and half of March. It seems thus that the fertilization was not adequate and that the vegetation was suffering from nitrogen deficiency (Section 6.2).

In the PK treatment of the natural vegetation, the maximum growth rate was ±40 kg ha^{-1} day^{-1} in the season '72/'73, while it was ±130 kg ha^{-1} day^{-1} in the season '71/'72. This difference was completely caused by differences in nitrogen availability.

In the season '73/'74 a growth rate of 90 kg ha^{-1} day^{-1} was observed. This must be attributed to the high percentage of legumes, which did not suffer from the nitrogen deficiency. This again shows that production in such regions could also be considerably increased if a stable grass-legume mixture could be grown (Tadmor et al., 1974). This may in many regions be the only possibility in view of the strongly increasing fertilizer prices.

Maximum growth rates in the originally disked and non-disked treatments, which received 40 kg N ha^{-1} before the season '72/'73 amounted to 85 kg ha^{-1} day^{-1} in that season, showing that despite fertilization, nitrogen was still the limiting factor for growth. In the season '71/'72 the observed peak growth rates in the disked and non-disked treatment were 180 kg ha^{-1} day^{-1} and 130 kg ha^{-1} day^{-1}, respectively, indicating that nitrogen supply was very close to optimum conditions. The similar growth rates measured in treatments with a completely different botanical composition (Tables 1 and 3) show that there is very little difference in production capacity between the various species. The grand period of growth started very late in the grazing experiment in '72/'73 (Fig. 14). Measured peak growth rates did not exceed 40 kg ha^{-1} day^{-1} although the field had been fertilized with 40 kg N ha^{-1}. This field, however, never reached complete cover as a result of the poor germination.

In the season '73/'74 however peak growth rates of 170 kg ha^{-1} day^{-1} maintained over a long period were attained in the non-grazed treatment (Fig. 15) showing that with adequate N-supply again maximum growth rates are reached. In this field some of the nitrogen given in the previous season had not been used because of the poor growth and this extra amount was sufficient to prevent N deficiency. It is not quite clear why the growing period was extended in this experiment but probably this was influenced by the later germination, so that the crop reached maturity at a later stage. It is obvious from these data that under any normal grazing pressure the influence of the sheep can be neglected, as with these growth rates 75–100 sheep per ha could be maintained.

Total production and water use efficiency

The total amount of dry matter produced is either determined by the available water or by the nitrogen availability. In the favourable rainfall year '71/'72 a very high production of 8300 kg dry matter ha^{-1} was obtained in the NPK treatment. In the season '72/'73 the yield was 6175 kg ha^{-1}, the difference between the two seasons reflecting approximately the different rainfall conditions. In the nitrogen deficient situation, total yield amounted to only 2750 kg ha^{-1}, which is in agreement with values observed by Tadmor et al. (1974) under comparable rainfall conditions. Values of the proportionality factor M between dry matter production and the ratio transpiration: free water evaporation are presented in Table 4 for the various experiments. They were calculated, assuming that in both seasons ±15% of the water was lost by direct soil surface evaporation. Average daily free water evaporation was estimated at 3.5 mm day^{-1} for the season '71/'72 and 3.0 mm for '72/'73 in which year most of the production took place in the cooler season. In the '73/'74 season also the amount of water left in the soil at the end of the growing season

Table 4 M values calculated for the experiments in Migda (see text for explanation).

season	crop	treatment	M (kg ha^{-1} day^{-1})
'71/'72	natural vegetation	NPK	98
'72/'73	natural vegetation	NPK	89
'73/'74	natural vegetation	NPK	70
'71/'72	natural vegetation	PK	80
'72/'73	natural vegetation	PK	39.5
'73/'74	natural vegetation	PK	48
'71/'72	natural vegetation	disked	94
'71/'72	natural vegetation	non-disked	65
'72/'73	natural vegetation	disked	49
'72/'73	natural vegetation	non-disked	46
'72/'73	wheat	NPK	110

was taken into account.

The different M-values in the first two seasons for the NPK treatment, 98 kg ha^{-1} day^{-1} and 89 kg ha^{-1} day^{-1}, may be explained by the difference in growing period, the value of M changing throughout the season (Section 5.1); the value of 70 for the '73/'74 season again reflects the negative influence of nitrogen shortage. For wheat a value of 110 kg ha^{-1} day^{-1} was calculated, compared with 115 by de Wit (1958) for wheat grown in the Great Plains of the USA. There is only ±20% difference between this value and the one calculated for the natural vegetation, showing that there was also not much difference in efficiency of water use between the native and the cultivated species. However, the very low values under conditions where nitrogen was limiting are striking. Shortage of nitrogen has a stronger effect on dry matter production than on transpiration, probably through direct influence on photosynthesis (Dantuma, 1973) or through a lower efficiency of conversion into dry matter as a result of repetitive breaking down and rebuilding of nitrogenous compounds. The water use efficiency of plants grown under deficient conditions is consequently much lower (de Wit, 1958; Viets, 1962). In many arid regions there is a high proportion of unproductive moisture loss, even though the water is lost by transpiration and not by evaporation. The relation between precipitation and dry matter production as presented by Tadmor et al. (1974) is probably a truer reflection of the relation between dry matter production and nitrogen availability. This is related to precipitation via the direct contribution of atmospheric N and due to the effect of moisture on nitrogen fixation and mineralization (Harpaz, in prep.).

Grazing pressure

Most of the experimental data obtained refer to situations without grazing. To test whether these results may be applied under grazing, experiments on the effect of grazing on primary production were carried out in '72/'73, and '73/'74. The normal stocking rate to enable year-round grazing under the Migda conditions is 4 sheep ha^{-1}. The average growth rate during the grand period of growth was $\pm 37.5\ ha^{-1}\ day^{-1}$, while the sheep will eat at the most 8 kg day^{-1} (Benjamin et al., 1973). It is therefore expected that under the normal grazing conditions, the presence of animals in the field will have very little effect on primary production during the grand period of growth. In this experiment 4 sheep ha^{-1} were grazing from the beginning of February onwards. Figs. 7 and 14 show that the sheep had no appreciable effect.

Additional effects of grazing on primary production like a shift in the period of peak growth due to defoliation or a change in the ratio transpiration: evaporation must be studied, however, in situations where the grazing pressure is such, that removal by the animals keeps up with the growth rate.

Even the high stocking rate in the '73/'74 season did not fully succeed in maintaining standing crop at a very low level. From the data it cannot be concluded with certainty whether grazing had any effect on the efficiency of water use, which is practically the only variable that is interesting in these experiments.

3 Simulation

3.1 Simulation technique

Simulation may be defined as: 'the building of a model and the study of its dynamic behaviour'. A model is a simplified representation of a system, a limited part of reality, with well defined boundaries. A model can be built if the structure of the system under consideration is sufficiently known, so that the various processes playing a role in the system can be described mathematically. Simplification of the real system is axiomatic in modelling, otherwise the system itself could be used in the study; moreover, our understanding of reality is often limited.

Classical mathematical analysis often used in technical sciences has the disadvantage that the dynamics of a system cannot be studied without a detailed and time-consuming mathematical treatment, and in many cases its use even leads to the application of false assumptions, to enable a solution at all. When using simulation models, much of the effort of the scientist can shift from the problem of finding a solution for his model, to the study of the behaviour of the model and thus of the system that interests him. In the models described below, the state variable approach is used. This assumes that at any moment the state of the system can be defined quantitatively and that changes in the state can be described mathematically.

The values of the state variables (mathematically represented by integrals), like the amount of water, heat content and so on, are known at any moment. The rate of change of each state variable is determined by the state of the system and the environment, so that rates are never mutually dependent. When all rates are calculated they are realized over a short time-interval to arrive at the new values of the state variables. In recent years sophisticated simulation languages for digital computers have been developed. These languages contain features to overcome the disadvantages of digital calculation machines, which contrary to natural systems, operate discontinuously and sequentially. The mutual independence of the rates makes the use of

a sorting routine possible, which sorts the statements, to calculate the rates, in an algorithmic order. Integration is performed in a semi-parallel fashion after all the rates have been calculated.
Errors arising from the use of finite time-intervals can be kept within reasonable limits by the use of appropriate integration techniques, which are available.
Besides the above mentioned features, the simulation languages have additional advantages. They are in general problem oriented, so that the program can be written in conceptional rather than in computational order which improves readability. This is specially important for the communication between the increasing number of scientists involved in modelling. Input and output facilities are many and easy to handle. Much of the internal organization of the computer is kept away from the programmer, thus facilitating the use by scientists with only a basic knowledge of programming.
The programs presented here are written in CSMP (Continuous System Modelling Program), a language developed by IBM for its 360 and 370 series of machines. A User's Manual of the language is available as IBM Technical Publication H20–0367–2. The language is used widely by research workers of the Agricultural University and Institutes in Wageningen. Reports of this work are published in the monograph series 'Simulation Monographs, a series on computer simulation in agriculture and its supporting sciences'. Specially the volumes on 'Transport processes in soils' by de Wit and van Keulen (1972) and on 'Ecological processes' by de Wit and Goudriaan (1974) are recommended for further study of the language.

3.2 Simulation of evaporation

To illustrate the use of CSMP, a model of the evaporation and the heat balance of a layer of water of finite thickness is developed.
The heat content of the water (in Joule m^{-3}) is the only state variable of the system:

```
HC = INTGRL(HCI,RCHC)                                   (3.1)
```

The initial heat content of the system (HCI) can be calculated from the initial temperature of the water layer and its thickness. Assuming a layer of 0.05 m (TWL), and an initial temperature of 20°C, it follows that

```
INCON     HCI = 4.2 E6          in J m-3
PARAM     TWL = 0.05            in m
```

The rate of change of the heat content (RCHC) in $J\,m^{-3}\,sec^{-1}$, is the difference between the absorbed short wave radiation (ASWR), the net long-wave radiation (LWR), the sensible heat loss (SHL) and the evaporative heat loss (EHL), divided by the thickness of the layer.

```
RCHC = (ASWR-EHL-SHL-LWR)/TWL
```

The absorbed short-wave radiation is equal to the measured short-wave radiation intensity (SWR in $J\,m^{-2}\,sec^{-1}$) at screen height minus the reflection.

```
ASWR = SWR × (1.-REFLC)
```

The measured short wave radiation is given as a tabulated function of time in hours:

```
                SWR = AFGEN(SRWTB,HTIME)
FUNCTION SRWTB = (0.,0.),(5.,3.),
                (12.,700.),(18.,250.),(24.,0.)
```

The first number of each pair being the independent variable time in hours, the second number the dependent variable short wave radiation intensity in $J\,m^{-2}\,sec^{-1}$. The time in hours is calculated from the time in seconds which is tracked by CSMP with

```
HTIME = AMOD(TIME/3600.,24.)
```

The AMOD function provides resetting to 0. when the value 24 is reached by the first argument. The AFGEN function provides linear interpolation between the given pairs of data. The reflection coefficient of water for short wave radiation is now given with

```
PARAM     REFLC = 0.05
```

In a not too detailed treatment, the long wave radiation may be estimated from a formula given by Brunt (1932) as

```
LWR = 5.72 E-8×(TS+273)××4×
  ×(0.56-0.092×SQRT(EA))          in J m-2 sec-1
```

in which E-8 stands for 10^{-8}, the double multiplication sign indicates involution and the function SQRT takes the square root of the argument. The formula is applied here without critical comment for shorter periods of time than intended. The sensible heat loss is proportional to the difference in temperature between the surface and the air at screen height (TS-TA), and the evaporative heat loss is proportional to the difference in vapour pressure between these two sites (ES-EA).

```
SHL = HEC × (TS-TA)                                    (3.2)

EHL = VEC × (ES-EA)                                    (3.3)
```

Both exchange processes are governed by the same physical processes (diffusion and convection) depending on the turbulence of the air, therefore the exchange coefficients are proportional according to:

```
VEC = HEC/PC                                           (3.4)
```

the vapour exchange coefficient, VEC, being in J m^{-2} $mbar^{-1}$ sec^{-1}. The proportionality factor, the psychrometric constant in mbar $°C^{-1}$ is:

```
PARAM    PC = 0.67
```

The heat exchange coefficient (HEC) in J m^{-2} $°C^{-1}$ sec^{-1} is, in general, expressed as a function of the wind speed at screen height and experimental formulae relating both are available:

```
HEC = 4.9 × (1. + 0.54 × WS)
```

The measured wind speed at screen height in m sec^{-1} is given as a tabulated function of time by

```
               WS = AFGEN(WSTB,HTIME)
FUNCTION WSTB = (0.,0.5),(5.,0.5),(12.,3.),
                  (18.,3.),(24.,0.5)
```

The temperature of the air is also introduced as a forcing function, i.e. a driving variable which influences the system but is itself not influenced by the behaviour of the system, by

```
               TA = AFGEN(TATB,HTIME)
 FUNCTION TATB = (0.,12.),(5.,10.),
                  (12.,20.),(18.,20.),(24.,10.)
```

The temperature of the surface is directly obtained from the heat content, the only state variable, with

```
TS = HC/(TWL×4.2E6)
```

assuming that the heat capacity of water equals 4.2×10^6 Joules m^{-3} °C^{-1}. The vapour pressure at the wet surface, ES in mbar is derived from the surface temperature and the saturated vapour pressure curve, which is entered as a tabulated function

```
         ES = AFGEN (SVPTB,TS)
FUNCTION SVPTB = (0.,6.1),(10.,12.3),
                 (15.,17.1),(20.,23.4),
                 (25.,31.7),(30.,42.5)
```

The actual vapour pressure at screen height is calculated from the same tabulated function and the measured dew point temperature (DPT)

```
         DPT = AFGEN (DPTTB,HTIME)
         EA  = AFGEN (SVPTB,DPT)
FUNCTION DPTTB = (0.,7.5),(5.,5.),
                 (12.,12.),(18.,12.),
                 (24.,5.)
```

The structure of the system has been defined now completely and the program is continued with specification of the desired integration method.
With

```
METHOD RKS
```

an integration routine is called upon, which selects its own time-interval of integration in accordance with the magnitude of the relative rate of change of the integral.
With

```
TIMER    PRDEL = 3600., FINTIM = 86400.
```

the length of the simulated period is set at 1 day, output being asked for each hour.
The whole program is finished with the lines

```
END
STOP
```

```
TITLE SIMULATION OF EVAPORATION

      HC = INTGRL(HCI,RCHC)

PARAM TWL = 0.05,TI = 9.3
INCON HCI = 1.953E6

      RCHC = (ASWR-LWR-SHL-EHL)/TWL

      ASWR = SWR*(1.-REFLC)
      SWR = AFGEN(SWRTB,HTIME)

      HTIME = AMOD(TIME/3600.,96.)

FUNCTION SWRTB = 0.,4.,1.,4.,2.,4.,3.,1.,4.,45.,5.,119.,6.,127.,   ...MONT
        7.,175.,8.,322.,9.,248.,10.,205.,11.,185.,12.,157.,13.,77.,...MONT
        14.,218.,15.,380.,16.,286.,17.,162.,18.,77.,19.,31.,20.,6.,...MONT
        21.,2.,22.,4.,23.,4.,24.,1.,26.,0.,27.,5.,28.,35.,29.,135.,...MONT
        30.,244.,32.,629.,33.,370.,34.,206.,35.,466.,36.,509.,     ...MONT
       37.,430.,38.,249.,39.,377.,40.,321.,41.,51.,42.,79.,        ...MONT
       43.,27.,44.,3.,45.,0.,46.,2.,47.,4.,48.,4.,49.,3.,50.,3.,   ...MONT
        51.,4.,52.,18.,53.,63.,54.,127.,55.,373.,56.,266.,57.,433.,...MONT
        58.,653.,59.,278.,60.,373.,61.,512.,62.,587.,63.,429.,     ...MONT
        64.,1110.,65.,836.,66.,84.,67.,25.,68.,2.,69.,0.,70.,0.,   ...MONT
        71.,4.,72.,4.,73.,4.,74.,4.,75.,4.,76.,14.,77.,37.,        ...MONT
        78.,201.,79.,84.,80.,248.,81.,204.,82.,497.,83.,812.,      ...MONT
        84.,439.,85.,645.,86.,658.,87.,800.,88.,1332.,89.,886.,    ...MONT
        90.,160.,91.,52.,92.,3.,93.,0.,98.,0.,99.,4.,100.,22.

PARAM REFLC = 0.05

      LWR = 5.66E-8*(TS+273.)**4*(0.56-0.092*SQRT(EA))

      SHL = HEC*(TS-TA)
      EHL = VEC*(ES-EA)

      VEC = HEC/PC
PARAM PC = 0.67

      HEC = 4.9*(1.+0.54*WS)

      WS = AFGEN(WSTB,HTIME)

FUNCTION WSTB = 0.,2.5,1.,3.4,2.,2.2,3.,1.1,4.,1.0,5.,2.8,6.,2.5,   ... MONT
       7.,2.5,8.,2.3,9.,3.6,10.,3.8,11.,3.6,12.,3.6,13.,3.5,        ...MONT
       14.,4.4,15.,2.9,16.,4.8,17.,4.6,18.,4.2,19.,3.8,20.,3.2,     ...MONT
        21.,4.4,22.,3.7,23.,3.2,24.,2.8,25.,2.8,26.,3.0,27.,2.5,    ...MONT
       29.,3.6,30.,3.8,31.,4.5,32.,8.0,33.,4.9,34.,4.5,35.,5.4,     ...MONT
        36.,5.3,37.,5.7,38.,5.7,39.,5.5,40.,6.0,41.,4.8,42.,4.2,    ...MONT
        43.,3.5,44.,3.7,45.,3.1,46.,3.5,47.,3.6,48.,3.9,49.,3.4,    ...MONT
        50.,3.8,51.,3.4,52.,3.8,53.,4.0,54.,4.4,55.,4.5,56.,5.6,    ...MONT
        57.,5.9,58.,6.4,59.,5.9,60.,6.1,61.,6.3,62.,6.3,63.,6.0,    ...MONT
        64.,8.4,65.,8.1,66.,4.5,67.,4.8,68.,4.0,69.,4.0,70.,2.1,    ...MONT
        71.,3.1,72.,2.3,73.,3.1,74.,3.6,75.,4.4,76.,4.6,77.,4.3,    ...MONT
        78.,4.4,79.,4.1,80.,5.1,81.,5.0,82.,5.1,83.,5.4,84.,5.2,    ...MONT
        85.,6.8,86.,4.8,87.,4.7,88.,5.3,89.,5.1,90.,3.9,91.,2.5,    ...MONT
        92.,2.2,93.,2.0,94.,1.9,95.,1.3,96.,1.0,97.,0.8,98.,0.6,    ...MONT
        99.,0.6,100.,1.0

      TS = HC/(TWL*HCPW)
PARAM HCPW = 4.2E6

      ES = AFGEN(SVPTB,TS)

FUNCTION SVPTB = -10.,2.9,-7.5,3.75,-5.,4.2,-2.5,5.1,0.,6.1,2.5,7.4, ...
        5.,8.7,7.5,10.4,10.,12.3,12.5,14.6,15.,17.1,17.5,20.1,       ...
        20.,23.4,22.5,25.8,25.,31.7,27.5,36.7,30.,42.5,32.5,49.1,    ...
        35.,56.3,37.5,64.6,40.,73.9,42.5,84.4,45.,96.0,47.5,109.1,   ...
        50.,123.5

      TA = AFGEN(TATB,HTIME)

FUNCTION TATB = 0.,9.3,1.,8.7,2.,7.3,3.,6.6,4.,7.6,5.,9.7,6.,9.9,   ...MONT
        7.,10.6,8.,12.3,9.,12.2,10.,11.7,11.,12.1,12.,12.4,13.,12.2,...MONT
```

```
          14.,13.1,15.,14.6,16.,14.9,17.,14.7,18.,13.9,19.,12.8,       ...MONT
          20.,11.8,21.,11.6,22.,11.1,23.,10.5,24.,10.0,25.,9.6,         ...MONT
          26.,9.0,27.,8.7,28.,9.3,29.,10.4,30.,11.7,31.,13.3,           ...MONT
          33.,13.3,34.,12.6,35.,13.6,36.,14.0,37.,13.5,38.,12.6,        ...MONT
          39.,13.2,40.,13.4,41.,11.1,42.,9.5,43.,9.9,44.,9.6,45.,9.3,...MONT
          46.,9.3,47.,9.3,48.,9.2,49.,8.8,50.,9.0,51.,8.6,52.,8.9,      ...MONT
          53.,8.9,54.,10.3,55.,11.6,56.,12.0,57.,12.4,58.,13.5,         ...MONT
          59.,13.0,60.,13.1,61.,13.9,62.,14.8,63.,14.4,64.,14.8,        ...MONT
          65.,14.6,66.,12.7,67.,11.4,68.,10.0,69.,8.3,70.,8.6,          ...MONT
          71.,8.4,72.,8.8,73.,9.0,74.,9.1,75.,9.1,76.,9.3,77.,9.4,      ...MONT
          78.,10.1,79.,9.2,80.,10.7,81.,11.5,82.,12.6,83.,14.0,         ...MONT
          84.,13.5,85.,14.5,86.,14.7,87.,15.0,88.,14.3,89.,13.8,        ...MONT
          90.,13.1,91.,11.4,92.,9.7,93.,9.0,94.,8.5,95.,7.5,96.,6.7, ...MONT
          97.,6.1,98.,6.0,99.,5.6,100.,6.0

      DPT = AFGEN(DPTT,HTIME)

FUNCTION DPTT = 0.,5.3,1.,5.5,2.,5.0,3.,4.4,4.,4.6,5.,6.1,6.,5.9,     ...MONT
         7.,6.5,8.,8.3,9.,7.3,10.,7.9,11.,8.6,12.,8.6,13.,9.0,         ...MONT
          14.,10.3,15.,10.5,16.,10.3,17.,8.9,18.,7.5,19.,7.2,20.,7.0,...MONT
          21.,6.6,22.,7.0,23.,6.8,24.,6.5,25.,6.6,26.,6.4,28.,6.4,      ...MONT
          29.,6.5,30.,6.7,31.,5.7,33.,5.7,34.,5.0,35.,5.0,36.,5.2,      ...MONT
          37.,6.0,38.,6.0,39.,6.6,40.,6.0,41.,6.5,42.,7.0,43.,6.5,      ...MONT
          44.,6.6,45.,6.2,46.,6.1,47.,6.1,48.,6.0,50.,6.0,51.,5.7,      ...MONT
          52.,6.0,53.,5.8,54.,6.0,55.,6.3,56.,5.8,57.,5.8,58.,5.2,      ...MONT
          59.,5.0,61.,5.0,62.,5.3,63.,5.0,64.,3.5,65.,4.6,66.,5.6,      ...MONT
          67.,6.0,68.,6.1,69.,6.8,70.,6.8,71.,7.0,72.,7.3,73.,7.0,      ...MONT
          75.,7.0,76.,6.0,77.,6.0,78.,6.5,79.,7.1,80.,6.9,81.,6.3,      ...MONT
          82.,6.2,83.,6.1,84.,6.2,85.,7.3,86.,6.0,87.,5.0,88.,5.7,      ...MONT
          89.,5.0,90.,4.0,91.,4.6,92.,5.6,93.,5.9,94.,6.0,95.,6.0,      ...MONT
          96.,5.5,97.,5.1,98.,4.8,99.,4.6,100.,4.8

      EA = AFGEN(SVPTB,DPT)


      EVAP = EHL/VAPH
*   EVAPORATION RATE IN MM/SEC
PARAM VAPH = 2.39E6
*   VAPH = LATENT HEAT OF VAPORISATION IN J/MM
      TEVAP = INTGRL(0.,EVAP)
      DEVAP = TEVAP-ZHOLD(IMPULS(DELT,86400.)*KEEP,TEVAP)


PRINT TS,TA,ES,EA,EHL,SHL,EVAP,TEVAP,DEVAP

METHOD RKS
TIMER FINTIM = 1036800.,PRDEL = 3600.
END
PARAM TWL = 0.10,TI = 9.3
INCON HCI = 3.906E6
END
INCON HCI = 3.906E7
PARAM TWL = 1.,TI = 9.3
END
STOP
```

When additional runs are required with different values of the parameters, new lines may be entered between the END and STOP card

```
PARAM     TWL = 0.10
END
```

The program and the results of one run are given in Fig. 18. The simpler rectilinear method of integration or the point-slope method of Euler is used when the line

```
METHOD RECT
```

is introduced. In that case, the time interval of integration must be specified with

```
TIMER     DELT = 180.
```

By trial and error or by a more formal method (de Wit & Goudriaan, 1974) it can be found that a value DELT=180 is small enough.

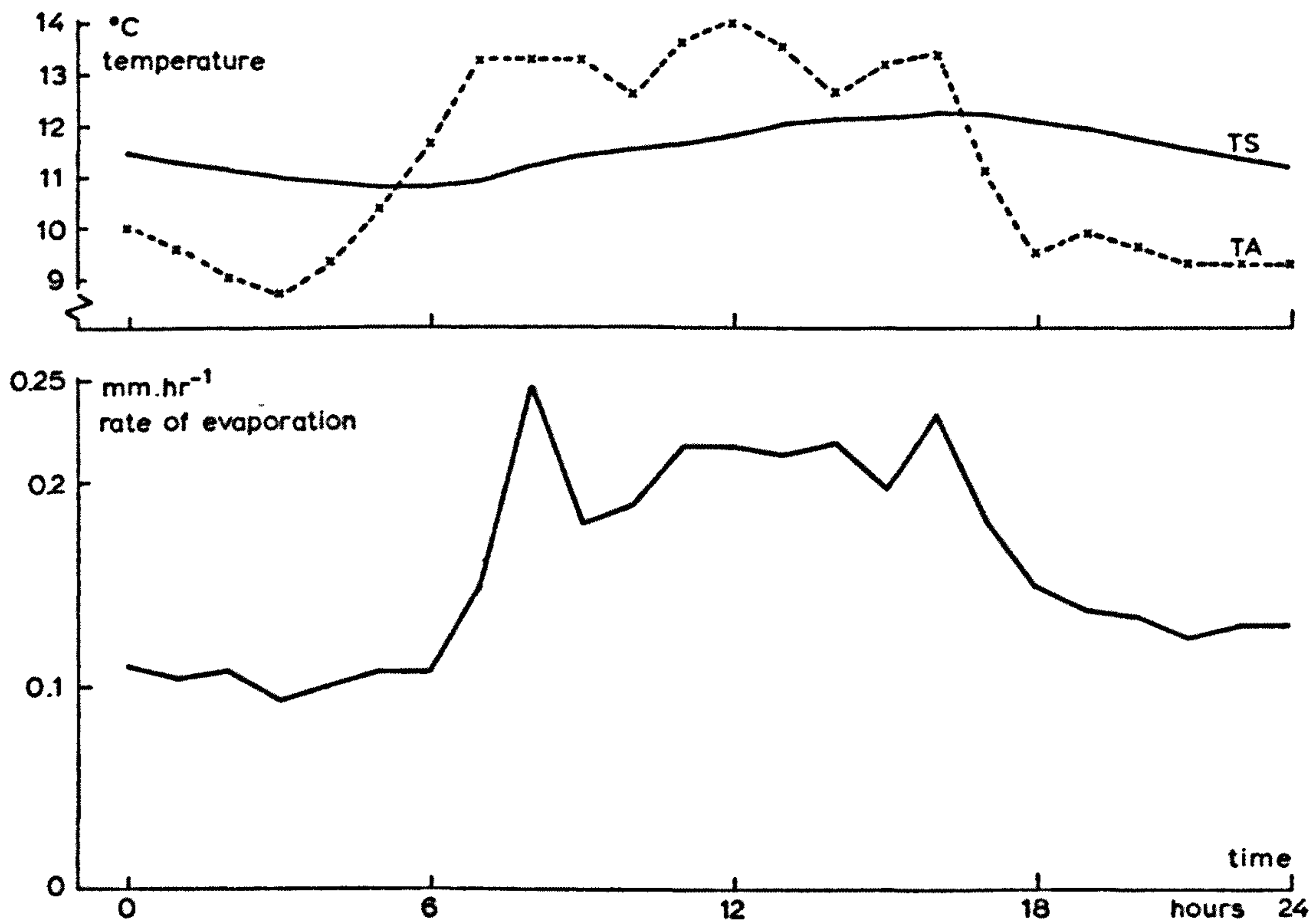

Fig. 18 | Daily course of evaporation rate and surface temperature (TS) calculated with the simulation model.

The above described simulation program describes the basis for the Penman (1948) equation to calculate free water evaporation. In his approximation, the heat storage of the water is neglected, assuming instantaneous equilibrium. This means:

```
NRAD = EHL + SHL                                        (3.5)
```

Combination of this formula with Eqns (3.2), (3.3) and (3.4) yields the expression

```
NRAD = HEC × (TS-TA) +
  + HEC/PC × (ES-EA)                                    (3.6)
```

an equation with two unknowns: TS and ES. Linearization of the relation between temperature and saturated vapour pressure gives:

```
ES-EA = SLOPE × (TS-DPT)                                (3.7)
```

in which DPT is the dew point temperature of the air and SLOPE is the average slope of the saturated vapour pressure curve. Substituting Eqn (3.7) into Eqn (3.6) yields:

```
NRAD = HEC × (TS-TA) +
  + HEC/PC × SLOPE × (TS-DPT)                           (3.8)
```

in which the surface temperature is the only unknown and can be made explicit

```
TS = TA+PC/(PC+SLOPE) ×
  × NRAD/HEC-SLOPE/(PC+SLOPE) ×
  × (TA-DPT)                                            (3.9)
```

Subtraction of the combination of Eqns (3.5) and (3.9) from NRAD yields the expression

```
EHL = SLOPE/(PC+SLOPE) ×
  × (NRAD+HEC × (TA-DPT))                               (3.10)
```

which is the well-known Penman equation.

During the last 25 years much research has been done on the evaluation of this formula. The discussions and investigations centered around the proper measurement of net radiation, the development of acceptable relations between cloudiness, temperature, humidity and net radiation, evaluation of the dependency of the heat exchange coefficient on the wind speed. The relations and parameters used in this book are based upon the authorative research of van Bavel (1966), Tanner & Pelton (1960) and Slatyer & McIlroy (1960).

Whenever possible Penman's approximate solution is used. However, in more detailed basic studies, the simulation solution is needed, because it allows the treatment of transient phenomena. For instance, if the water and heat balance of a leaf are considered the water content of that leaf varies according to:

```
WCNT = INTGRL(WCNTI,WUPTR-TRANS)
```

in which WUPTR is the rate of water uptake by the root system and TRANS is the rate of transpiration of the leaf neglecting storage in other organs. The water content of the leaf in turn does not only affect the heat capacity, but may also feed back to the rate of transpiration through the effect on stomatal opening, according to:

```
FUNCTION SRWTB = (0.5,20000),
  (0.6,10000.),(0.7,5000.),(0.8,500.),
  (0.85,250.),(0.9,200.),(0.95,120.),
  (1.,120.),
```

in which the first number of each pair gives the relative water content of the leaf as a fraction, and the second number the stomatal resistance in sec m^{-1}. This resistance is introduced in the equation for the calculation of the evaporative heat loss with

```
EHL = (SLOPE × ASWR + (ES-EA) ×
  × RHOCP/RA)/((RA+SRW)/RA × PSCH +
  + SLOPE)
```

A detailed simulation program, describing this phenomenon, which takes also into account the uptake of water from the soil, the supply by the root system and the feedback of stomatal opening to the photosynthesis of the leaves is given by Lambert & Penning de Vries (1973).

3.3 Description of the program principles

3.3.1 Introduction

The simulation model ARID CROP calculates the course of dry matter

production of a crop and the distribution of water in the soil below that crop from basic or derived physical and physiological properties of plant and soil and from meteorological observations from standard weather stations. The basic assumption is, that the crop is well supplied with nutrients and that growth is mainly determined by the availability of water.
The crop under consideration is a natural vegetation consisting of a mixture of annual grasses, herbs and legumes in a region with winter rains (Section 2.3.1). In the model, it is considered as a homogeneous crop with specified properties. This may be an oversimplification because of differences, for instance in morphology of the various species. However, little variation was found between the dry matter yield of plots with differing botanical composition. If significant differences between species are found, then the same model can be used with different parameters for each of them.

3.3.2 Soil physical processes

To simulate the physical processes in the soil, mainly transport processes, the total soil depth is divided into compartments (de Wit & van Keulen, 1972). The total depth considered in the model is 180 cm in compartments of 2, 3, 5, 2 × 10,5 × 30 cm respectively. Neither the number of layers, nor their thickness are fixed, both being very easy changeable. Each compartment is considered to be homogeneous.

Infiltration

Infiltration into the soil occurs when there is rain. The rate of infiltration into a given compartment is calculated from the rain intensity and the cumulative rate of change in water content of the overlying compartments. When it does not rain the infiltration rate for all compartments is zero, indicating that redistribution between compartments caused by potential gradients originating from unequal wetting or drying is neglected (Section 4.1). The rate of change of the water content in each compartment is set equal to the difference between the amount of moisture at field capacity and the actual amount of water present, divided by the time interval used. In this way, the compartments are filled up to field capacity from the top one down until the total amount of rain is dissipated or till the remainder has drained below 180 cm. Run-off is not taken into account in the

Migda situation as no real loss of water through surface flow occurs. Local situations of run-off and run-on occur over distances of the order of metres, through differences in microtopography or caused by local variations in infiltration rate through animal activity (mainly ants and rodents).

Evaporation

In deep soils in the semi-arid regions where deep drainage is negligible, the overall efficiency of the precipitation in terms of dry matter production is highly dependent on the ratio of evaporation to transpiration. The distribution of the rain is the main determining factor as many light showers result in long periods when the soil surface is wet. These cause more loss from evaporation than do a few heavy showers.

The potential rate of evaporation is calculated from the evaporative demand and the energy intercepted by the vegetation. The actual evaporation rate is then determined by the moisture content of the top soil compartment. The evaporation rate drops below the potential value because the vapour pressure at the evaporating site drops below the saturated value at high water potentials, which develop as the top soil dries out. The relation between the water content in the topsoil and the depression in evaporation rate is worked out in Section 4.2. The water loss through evaporation is distributed over the various compartments of the soil, by means of an extinction coefficient depending on soil physical properties. In this way, the recharge of the upper compartment, by flow from lower compartments along the resulting potential gradient is 'mimicked'.

Soil heat flow

The processes of water uptake by the root and root growth are temperature dependent (Section 4.3). The exact relation between these processes and the temperature is not known for the species of the natural vegetation, so it does not seem necessary to include a detailed treatment of the soil heat flux. As shown by de Wit & van Keulen (1972), the temperature regime in the soil can be simulated accurately from the energy terms at the soil surface. In this model the temperature of the soil compartments is calculated from a running average of the air temperature, thus neglecting diurnal variations, but accounting for seasonal changes. This is also justified because the processes of root growth and water uptake are for the greater part of the season most important in the deeper layers, where the diurnal fluctuation has the least influence. When a more detailed treatment of the germination is required, the heat regime of the soil should also be treated with greater accuracy.

Water uptake by the roots
The rate of transpiration of the canopy depends on the distribution and functioning of the root system and the distribution of water in the soil. Very little experimental data on the interrelation of these two factors are present. It is clear, however, that when part of the root system is in an environment with water at a high potential, the rate of water withdrawal from that place decreases while the rate of water uptake by the other part, exposed to low potentials increases (Lawlor, 1973). The magnitude of this compensatory effect depends on the actual values of the potentials in the soil around the roots. In the model this is achieved by first calculating an 'effective root length' in each compartment, depending on the soil moisture content of that compartment and the actual rooted depth.
The actual rate of water uptake from a soil compartment is then calculated from the effective root length, the water content in that compartment, and the temperature effect. The last factor includes both the influence of temperature on the conductivity of the root system and its effect on the viscosity of the water (Kuiper, 1964).

3.3.3 Growth of the crop

Germination
The process of germination of seeds of winter annuals is complicated. A detailed simulation model is given by Janssen (1974), which describes the process of germination and the various factors influencing the rate of germination in detail. Such a detailed treatment is not included in this model, as the total dry matter production, rather than the botanical composition is the main interest. Germination is treated here as a process governed by the presence of moisture and the temperature sum only. Seeds are assumed to germinate between the soil surface and 10 cm depth in the soil. Only very few seeds germinating below that depth will contribute to the biomass of the standing crop. Germination starts with the imbibition of the seeds by

the uptake of water from the surrounding soil. According to Hadas (1970) the rate of water uptake by the seeds is not much affected by the moisture content of the soil as long as that is above 'wilting point'. It is postulated thus, that germination takes place whenever one of the soil compartments above 10 cm has a moisture content above 'wilting point'. The rate of germination is affected by temperature and from Tadmor et al. (1968) it is deduced that for range plants an average temperature sum of 150 days × °C, above 0 °C is needed to reach establishment. The temperature sum is calculated only when soil moisture conditions are favourable for germination. If the soil dries out again before the required temperature sum is reached, the germinating seedlings are killed and a new wave starts after rewetting only. When the temperature sum needed for establishment is reached, the germinating biomass is used as the initial value of the standing crop. Successive waves of germination, which may occur in the field, are not taken into account in the model as seeds that germinate later are at a competitive disadvantage and often even die (Brennan et al., 1970).

Development of the crop

The development pattern of a growing plant is characterized by a given rate of leaf appearance and a parallel or subsequent appearance of vegetative and generative organs. The rate of development of plants is partly governed by genetic factors and partly by environmental conditions. In a certain region, that is at a given daylength, the most important rate determining factor is the temperature (van Dobben, 1962) whereas the actual growth rate has only a minor influence, although phenomena of emergency ripening may occur when nutrients are limiting. The relation between temperature and rate of development is curvilinear and varies for different species (Fig. 19a).

An experiment with soya beans, grown under both constant and alternating temperatures was done by Van Schaik & Probst (1958). Rearrangement of their data gives Fig. 20. The crosses give the measured development rates of plants, grown alternately for 14 hours at the higher and for 10 hours at the lower of the two temperatures connected by the broken line. The linear effect of different temperatures indicates that only one process is involved. This is contrary to the temperature effect on germination where the rate at

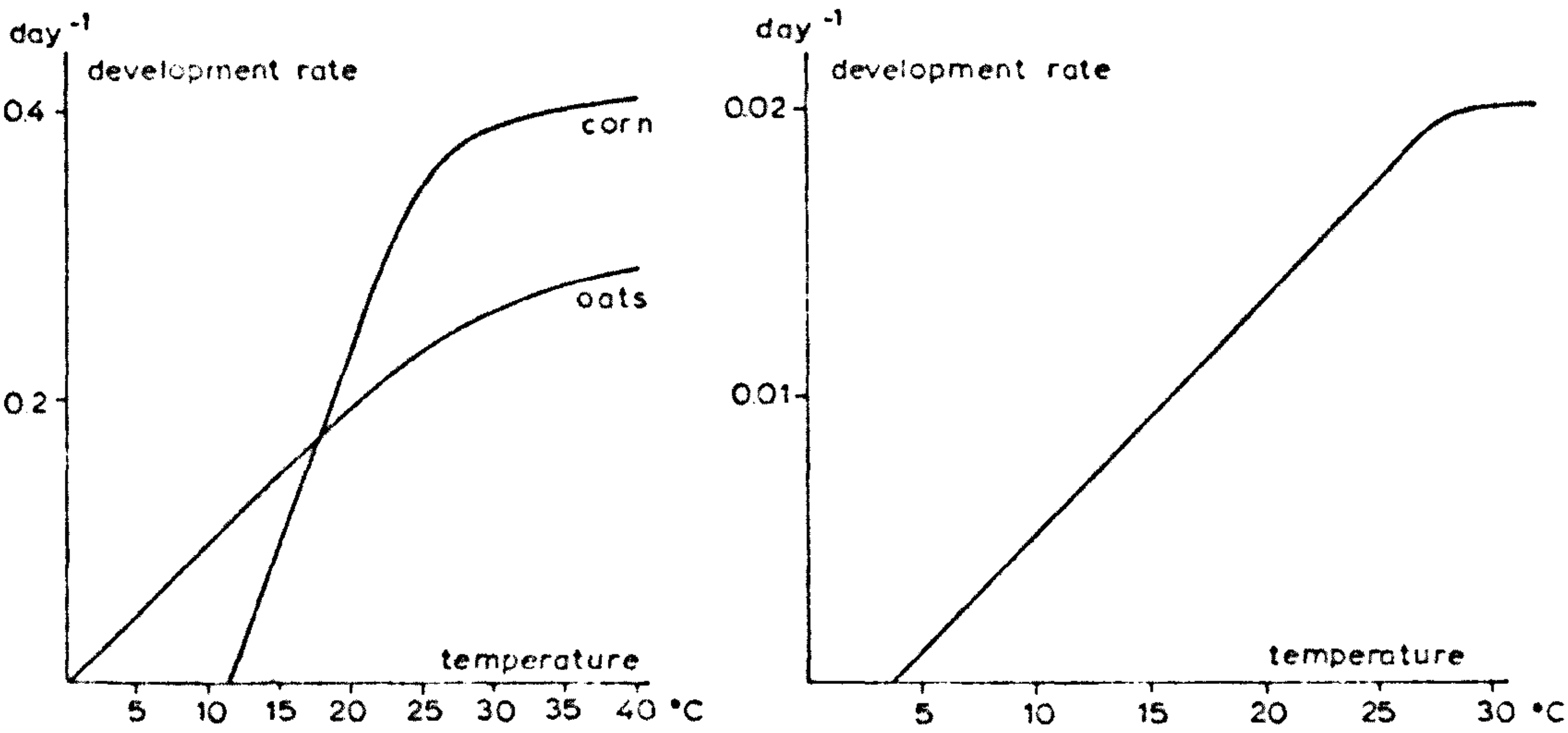

Fig. 19 | Development rate of corn and oats (left) and of natural vegetation (right) as a function of temperature.

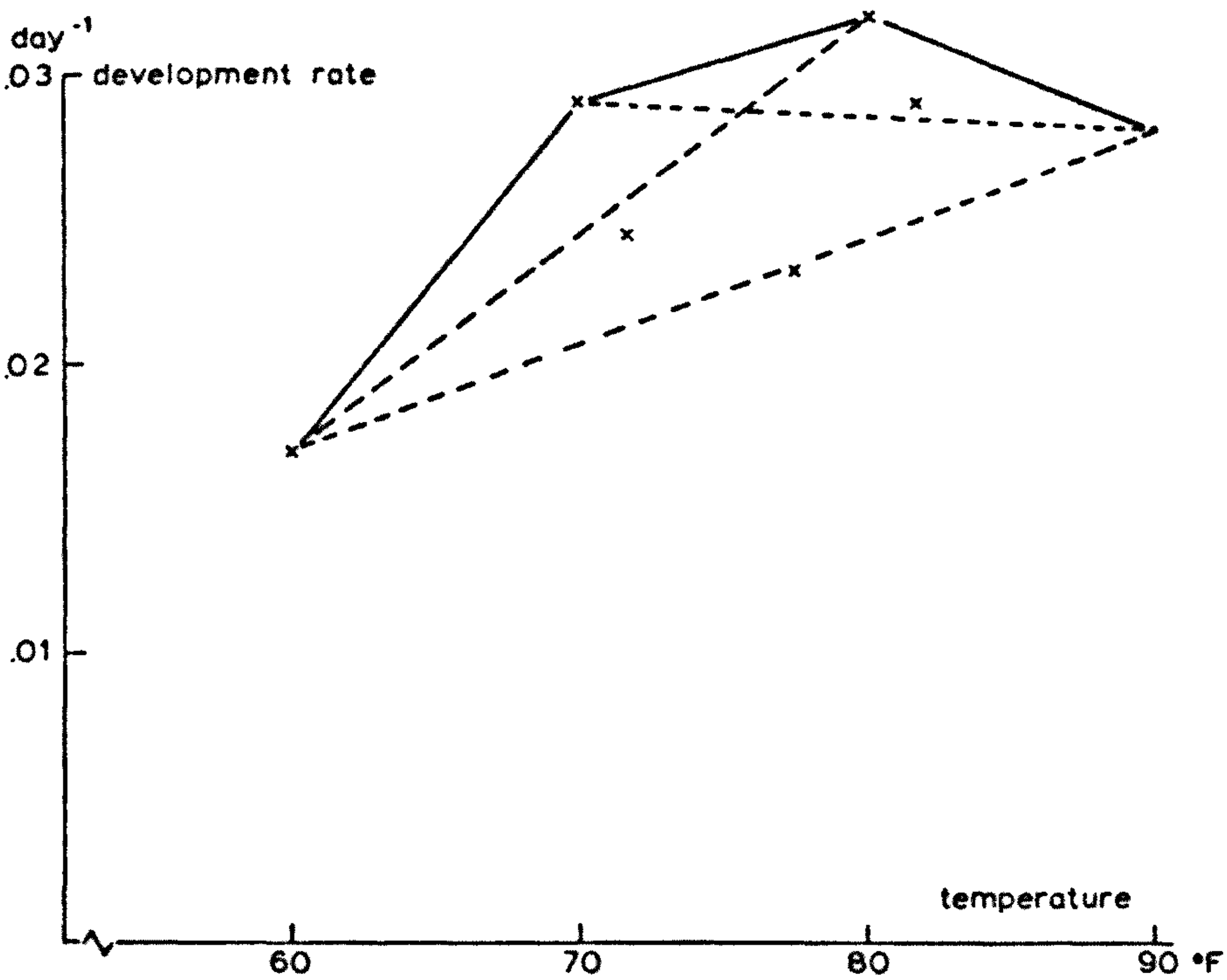

Fig. 20 | Development rate of soya beans grown at constant (dots) and alternating (crosses) temperatures (after Van Schaik & Probst, 1958).

alternating temperatures can deviate considerably from the average rates at the two extremes (Janssen, 1974). Here two processes with different temperature relations play a role. From observations it is known that a delay in germination of ±1 month causes a delay in ripening of about 2 weeks at the end of the growing season. This indicates that the rate of development at an average temperature of 23 °C is twice that at a temperature of 12 °C. From these data the curve relating the development rate and the temperature is constructed as given in Fig. 19b. Data on the temperature influence on the development rate of the species comprising the natural vegetation of the Migda area are not available. Hence, the following assumptions can be made to construct the curve: the relation between temperature of the air and development rate is linearized; under conditions of non-limiting water the growing period lasts about 120 days (from the middle of December to mid-April). At the prevailing average temperatures, this gives a temperature sum of ±1600 days °C. So at 16 °C the development rate will be 0.01 day^{-1}. The development stage of the crop influences the rate of growth. When the crop reaches the generative stage a large part of the photosynthates are used for seed formation so that less is available to form new leaves. It is also known that leaves age and cease to photosynthesize so that if new leaves do not appear crop growth stops. This process may be shortened by transfer of material from existing leaves to the seeds. In the model this effect is simulated through a reduction factor for transpiration dependent on the development stage. When development stage 0.75 is reached, the rate of transpiration starts to decline gradually until it stops at development stage 1 (maturity). This can lead to situations that in a season with a high rainfall the crop dries and ripens when there is still water in the soil.

Growth of the standing crop

The standing crop starts growing after establishment with the value of the germinated biomass. In the model a value of 100 kg ha^{-1} is used, assuming 2×10^7 seedlings ha^{-1}, with an average dry weight of 5 mg (Tadmor et al., 1968). The calculated amount of dry matter produced in a growing season is not very sensitive to this initial value, but the period of peak production may be shifted. This is due to the influence of initial biomass on the ratio between direct soil evaporation and transpiration and to the seasonal shift in water use efficiency. The

calculation of the growth rate is based on the determination of the rate of transpiration of the canopy and on the water use efficiency (Section 5.4).
The relationship between these variables is given by the expression:

$$P = W \times WUE,$$

in which

P = rate of increase in dry weight in kg ha^{-1} day^{-1}
W = rate of transpiration in mm day^{-1}
WUE = water use efficiency in kg ha^{-1} mm^{-1}

The water use efficiency is determined as the ratio of potential growth rate of the canopy to potential rate of transpiration. The potential growth rate depends on the photosynthetic capacity of the species, the leaf area index and the average radiation intensity, which determine the potential gross photosynthesis rate and on the amount of dry matter present, which determines the rate of maintenance respiration. A constant efficiency factor for the conversion from primary photosynthetic products into structural material is introduced, it being, however, possible to make that dependent on the chemical composition of the material formed, when that is known. The potential transpiration rate is obtained from the evaporative demand of the atmosphere and the leaf area index of the vegetation. A detailed description of this calculation is given in Section 5.4.
It is assumed that the water use efficiency is independent of the moisture conditions in the soil and of the condition of the vegetation. The independence of soil moisture status may not be valid, for some of the species, as they tend to close their stomata during that part of the day with highest evaporative demand when the soil is dry, thus producing only in relatively favourable conditions (Lof, in prep.). However, the actual amount of water transpired during these periods is so low that it does not make much difference in terms of dry matter production.
The actual rate of transpiration of the canopy is calculated from the potential rate, the conditions of the crop and the soil water status. The water uptake from the soil depends on the distribution of water and of roots in the profile, as described in Section 4.3. The condition of the crop is defined by its development stage.
During growth of the crop, there is continuous dying of leaves,

because of physiological processes. Under favourable growth conditions this is a negligible part of the standing crop. When, however, the soil dries out or when the crop has ripened (development stage = 1), the rate of dying increases drastically. The death rate of the standing crop is thus a function of the water content of the soil and the development stage. In the model, these processes are assumed to be independent and the actual death rate is taken as the greater of the two. The death rate due to lack of water is based on the concept of Viehmeyer (1955) which indicates that the availability of water decreases only slightly as the water content falls from 'field capacity' but a sharp decrease follows at approximately 'wilting point'. Therefore under favourable conditions the relative death rate of the crop is only 0.005 day^{-1}. When soil moisture is below wilting point, the relative death rate is 0.1 day^{-1}. This value is based on observations that half of the vegetation dries in about 7 days, if soil moisture is limiting. The vegetation is assumed to be completely dead when the living biomass, reduced by death drops below a given limiting value. If this occurs soon after germination, growth will cease until a new wave of germination provides a new crop of seedlings. New germination does not take place after the beginning of March, even if favourable conditions occur.

Irrespective of the soil moisture conditions, the relative death rate also assumes the maximum value of 0.1 day^{-1}, when the crop has ripened.

Leaf area growth

The leaf area of the vegetation is needed to calculate the water use efficiency and the division of the incoming radiation between canopy and bare soil. The simulation of morphological characteristics of plants is complex and difficult because many of the underlying processes are not yet understood. There exists a relation between the dry weight of a plant and its leaf area. From many growth analysis data it appears that this relation depends among other factors, certainly on the temperature at which the plant material is grown, and on the moisture status of the plant material (Friends, 1966). Although the morphological characteristics have a clear influence on the calculation of the water use efficiency, it is not possible to simulate the leaf area growth in much detail. The determination of the division of incoming energy between canopy and soil surface has its main influence in the beginning of the growing season when the field is practically bare and then mainly through a change in the direct soil surface evaporation. The approximation used is that the leaf area grows proportionally to the increase in dry weight. The proportionality factor (the leaf area ratio, in cm^2 of leaf per g dry weight) is dependent on the air temperature. Such data were not available for plants from the natural vegetation, therefore values for wheat have been used. It is recognized that this is an oversimplification for a mixture of plants so different in morphology, but it seems justified because deviations from these values do not have a decisive influence on the final result.

Root growth

In this model rooth growth may refer both to vertical extension and to the increase in dry weight of the total root system. It assumes that a root 'front' is formed in which no horizontal gradients exist. This is based on observations by Klepper et al. (1973) that when favourable conditions for root growth exist a plant is able to form new secondary roots very fast (1–2 days). In terms of this model it means that when water becomes available to part of the existing root system, the plant rapidly provides the roots to take it up unless nutrient deficiency is limiting root growth.

Root growth responds to variations in mechanical impedance (Pearson et al., 1970, Camp & Lund, 1968), which is strongly related to the water content of the soil. Thus root growth rates are in general dependent on the water content of the soil (Klute & Peters, 1969). The relations reported show a slow decline with decreasing water content and a rather sharp break near the wilting point. Observations in Migda also showed that the roots stopped growing when they reached the dry layer.

Under favourable moisture conditions the rate of vertical extension of the roots is practically constant (Tadmor et al., 1969b). For species of the natural vegetation grown under irrigated conditions this value ranged between 1.2 and 1.5 cm day^{-1}.

Root growth rates are also affected by temperature (Hilton & Mason, 1971). The relation for species from the natural vegetation has not been investigated so that exact data are lacking. From the general shape, however, it seems that only extreme values drastically change the rate. Hence root growth rate is calculated as: the constant daily growth rate times a temperature effect, provided that the root 'front' is at a

water content above wilting point.
The initial root length, that is the length at establishment is 10 cm. Tadmor & Cohen (1968) found that the primary root, growing from the seed reaches this length and then practically stops growing, until new assimilates are available from photosynthesis.
The dry weight of the root system is derived from the growth rate of the canopy by division of the newly formed structural material between aerial and underground plant parts. This ratio changes with the development stage of the vegetation, in such a way, that in the beginning the shoot:root ratio is approximately one, while at the end of the growing season only 2.5% of the total dry matter increase is transferred to the roots. These data were deduced from pot trials (Section 5.3) where plants were harvested after various growing periods. The weight of the root system has no feedback to any of the other processes and is thus only an acceptor of photosynthetic products. A more detailed treatment of the processes of root growth, suberization and decay will be given in another part of this project (Section 2.2).

3.4 Time constants of processes

From the previous section it is clear that process simulation of a dynamic soil-plant-atmosphere system requires a model of great complexity. In such a model, where many biological processes play a role, the relaxation times (the time needed to recover from small disturbances), of different phenomena vary widely. For example, the transpiration rate may be adapted within minutes to a change in light intensity, the soil water reaches a new equilibrium in days after a rainfall, and it may take the whole crop weeks to recover from a drought. The time scale on which such changes occur, is characterized by the time constant of that process. The time constant can be estimated, when the rate of change of a state variable is approximated by a differential equation of the form:

$$\frac{dA}{dt} = \pm A/\tau$$

in which τ with dimension time is the time constant. When simulating the dynamic behaviour of a system, one must proceed in time with intervals that are much smaller than the time constant of that system.

Otherwise, the postulate that the rate of change of the system does not change during that interval is invalid. The time constant of the fastest process therefore determines the time interval to be employed in the simulation. When the time constants are a factor 10^5 apart, as in the model described above, it is necessary to advance in time with steps of 1/100000 or less of the total period of interest. Even with the present day fast computers, study of such models is soon limited by the available computer time. The use of implicit integration methods in which the rates of change are calculated by matrix methods can in general increase the time interval. However, the actual number of arithmetic operations at each step is greater, and the programming itself more difficult. Moreover programs written for the use of implicit integration methods are difficult to decipher, and thus hamper communication about the program. Another approach to solve this problem is therefore proposed in the following section.

3.5 The hierarchical approach

In order to avoid handling of several levels of resolution in parallel in one model, an hierarchical approach can be used. This approach is based on the idea that in principle only two levels should be distinguished in a model. In the most detailed models the processes on the explanatory level are described on the basis of physical or physiological principles. Running the model yields results on the explainable level. In models at a lower level of resolution, these results are incorporated on the explanatory level. Whether this incorporation is done through multiple entry tables or through analytical expressions is a matter of convenience.
The hierarchical approach in model building not only saves much computer time but also avoids the use of empirical relations, which are not rigid enough for extrapolation. Moreover multilevel models soon become unwieldy and greatly increase the risk of introducing unknown and undetected errors.
Examples of the approach are given in this publication for the soil physical processes. In the infiltration program the results of a simulation model based on an exact physical description are compared with a simplification in which flow between soil compartments is considered only during rain. In the evaporation program the result of the detailed physical model is entered into the main program through

a function, relating soil moisture content and actual evaporation (Section 4.2). In the plant section the detailed physical and physiological description of photosynthesis and transpiration is replaced by the integrated result, presented as the water use efficiency.

To achieve the full benefit of simulation models in terms of explanation, prediction and extrapolation, the hierarchical approach seems the most promising (Goodall, 1974).

4 Soil submodels

4.1 Infiltration

Introduction

The amount of water available for plant growth depends on the amount of rainfall, but is also determined by the infiltration characteristics of the soil and the distribution of the rain. The main cause for water loss in the infiltration process is run-off. Run-off occurs on sloping terrain when the intensity of the rain is higher than the maximum infiltration rate of the soil. It may occur at high rainfall intensities, but also at lower intensities when infiltration is hampered. The latter is the situation in large parts of the Negev desert, where the soil consists of very unstable material. Under the influence of the rain drops, the material is dispersed and a soil/water puddle forms. This puddle prevents the escape of air entrapped in the soil, which builds up pressure, thus strongly reducing the infiltration rate. Run-off there always starts after a certain amount of rainfall, practically independent of the intensity (Tadmor & Shanan, 1969). In the present model run-off is not taken into account, because the necessary slopes are absent in the experimental area. However because of differences in microtopography or in hydraulic properties of the topsoil, local situations of run-off and run-on do occur. The effect of this phenomenon will be shown in Section 6.3.

The infiltration model

In previous papers (van Keulen & van Beek, 1971; Stroosnijder et al., 1972) it has been shown, that the process of infiltration can be simulated accurately, provided that the hydraulic properties of the soil are known in sufficient detail. The disadvantage of these models is, however, their small time-constant which means that to advance in time, intervals of the order of minutes must be taken. In the crop growth model this is not feasible, firstly because too much computer time would be needed and secondly because the data on rainfall are not available in such detail. Moreover, in this model the interest is not so much in the dynamics of soil water, but mainly in the effect of the distribution on its availability for plant roots and on soil surface evaporation. Under arid conditions a situation exists without a watertable, and there is free drainage of water. After a shower an equilibrium situation will develop in which a rather sharp wetting front exists, while the water content above the wetting front is practically constant (Bolt et al., 1965).

Simplified model

In the simplified model, instantaneous equilibrium is assumed, i.e. after a rainy day the moisture content is constant ('field capacity') from the top layer downwards until all the rain is dissipated or till the remainder has drained below the rooting zone. The latter occurs seldom under these perma-dry conditions. In this section a comparison is made between the results obtained with the simplified model and results from the infiltration model. The infiltration model as

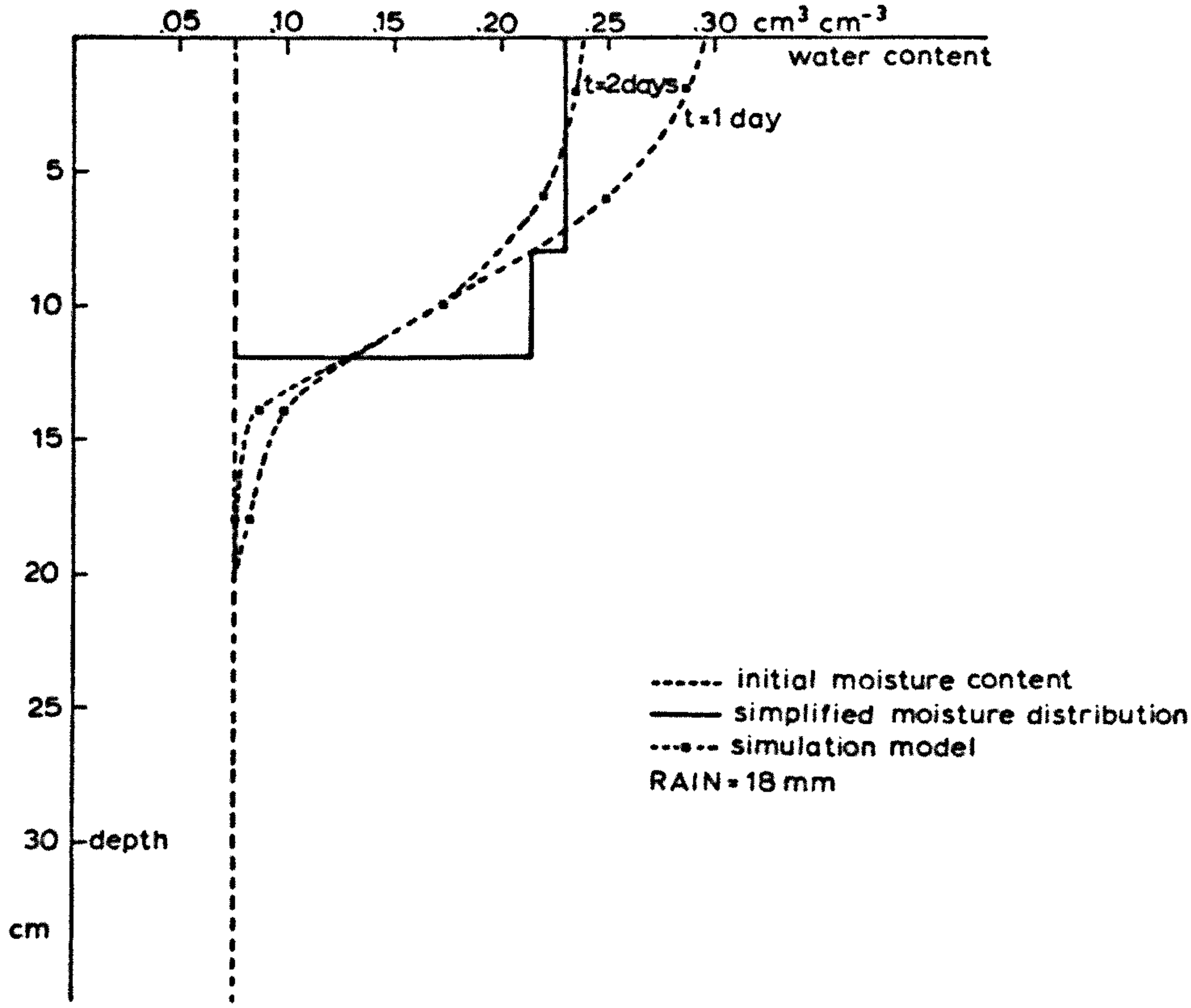

Fig. 21 | Comparison of moisture content profiles, calculated with the simulation model and the simplified method, after moderate rain on dry soil.

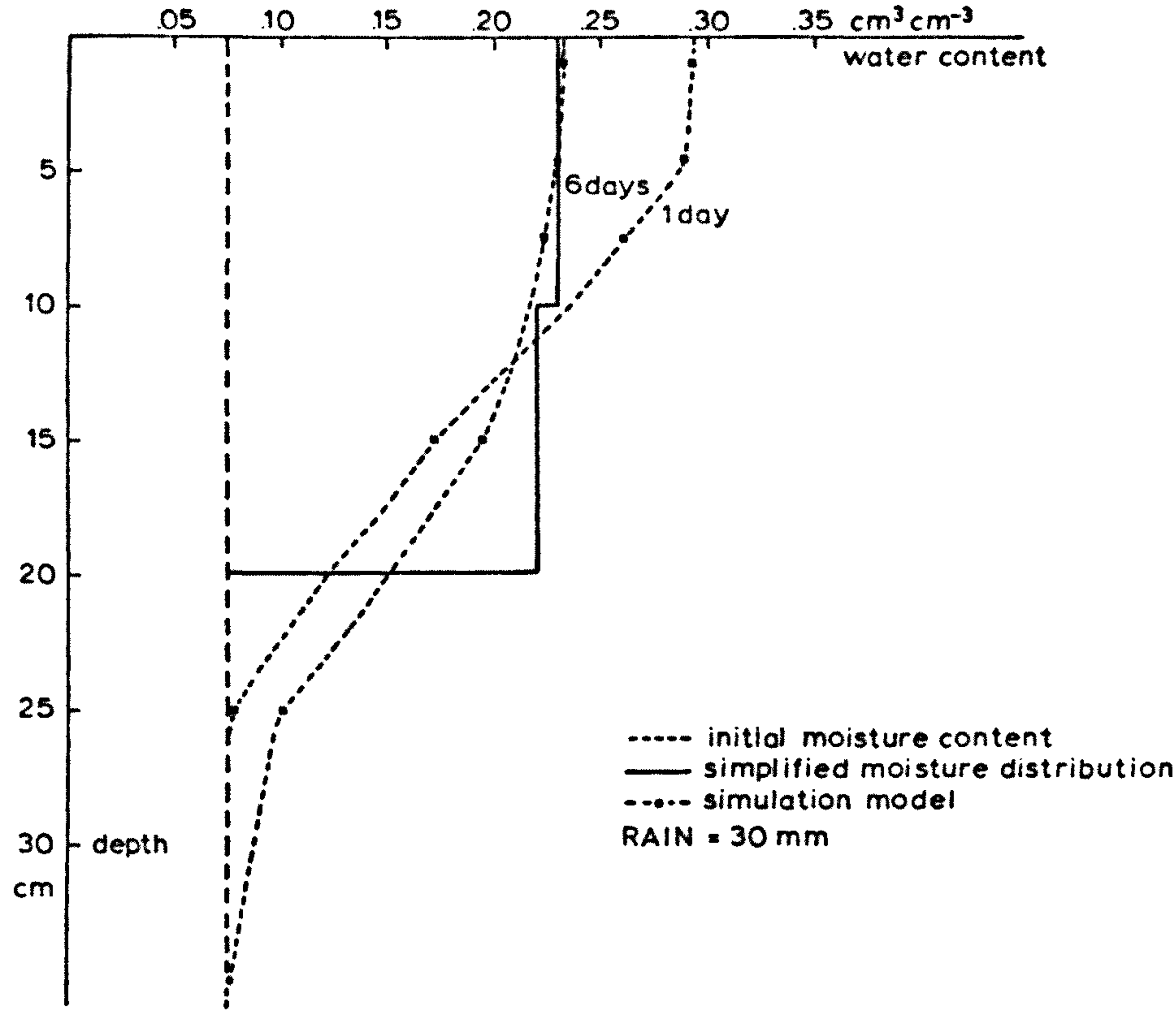

Fig. 22 | Comparison of moisture content profiles calculated with the simulation model and the simplified method, after heavy rain on dry soil.

described by van Keulen & van Beek (1971) has been used, except that the soil is homogeneous, i.e. the hydraulic properties are assumed to be constant throughout the profile.

In Fig. 21 a situation, typical for the beginning of the growing season, is considered: the whole profile is initially at wilting point and a first small shower occurs. The simulated profile two days after the end of the rain is practically the same as the simplified distribution. In fact, the difference is even smaller because part of the 'tailing' at the wetting front, calculated with the simulation model is due to the use of compartments of finite thickness. About 90% of the infiltrated water is stored at the same depth of the profile. The lower water content at the top in the simplified model has no influence on evaporation, because in that range of surface moisture contents it is equal to the potential evaporation.

In Fig. 22 initially the same situation exists, but the rainfall is higher. Here it takes about six days until the surface water content reaches

the value assumed in the simplification. But the influence on evaporation again is negligible. Because the lower compartments are 10 cm here, the effect of 'tailing' is even stronger, but about 95% of the water is stored in the same part of the profile.
In Fig. 23 a situation is simulated, which may occur at the beginning of the grand period of growth (end of January). The rooting depth is ± 1 m, but relatively little water has been withdrawn from the profile,

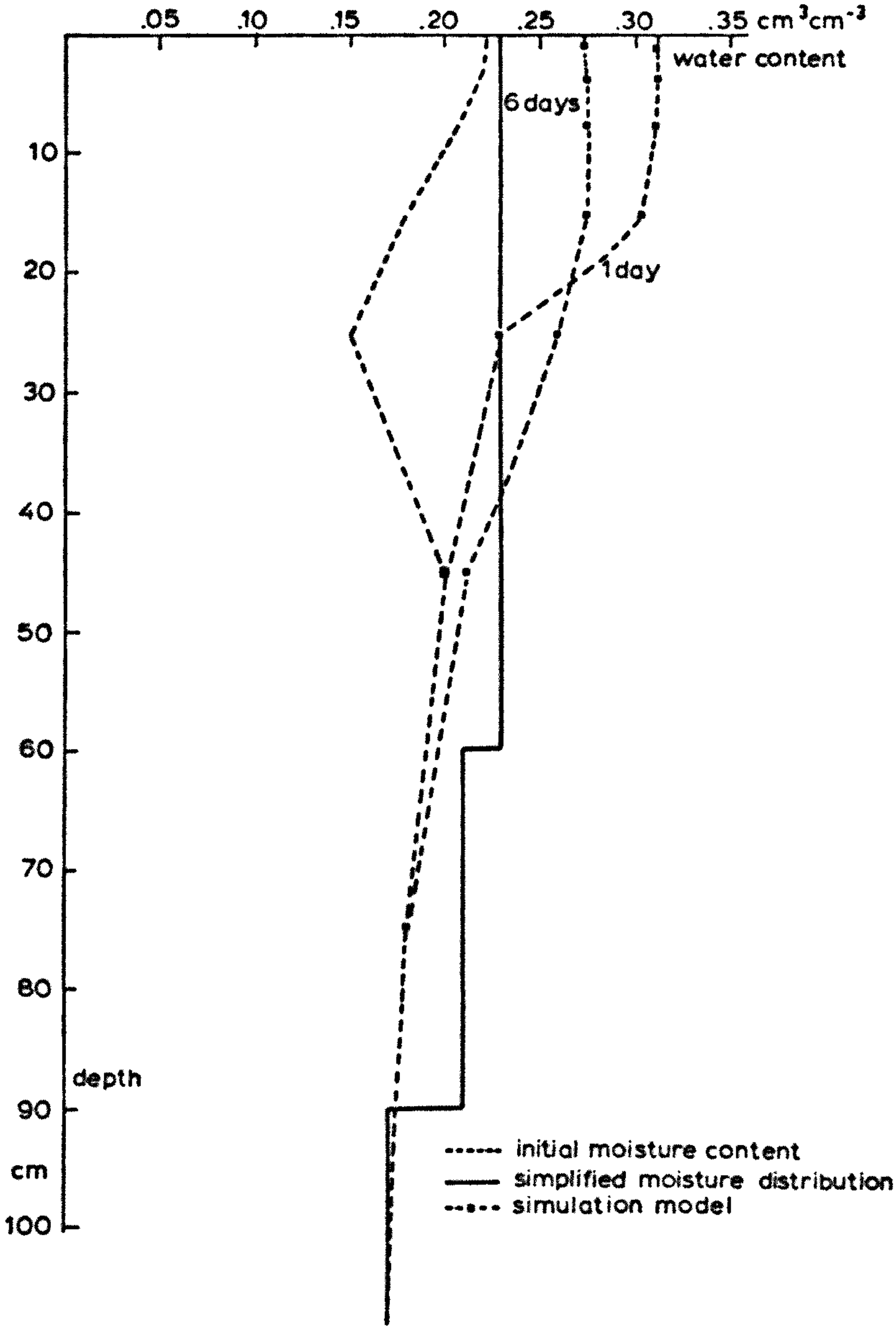

Fig. 23 | Comparison of moisture content profiles calculated with the simulation model and the simplified model, after moderate rain on wet soil.

due to the low evaporative demand and the low temperatures restricting plant growth in the winter period. Under these conditions, the simplified model predicts instantaneous influence of rainfall to a depth of 90 cm, while in fact it takes about six days before the water reaches that depth. It tends to underestimate the moisture content of the upper compartments for the first period after a shower.

The observed differences in moisture distribution between the two methods have little effect on the water uptake by the roots. When a somewhat more diffuse wetting front exists, the roots may grow a little bit deeper than calculated with the model and still make the water equally available. Besides, the relation between moisture distribution and root distribution is not known very accurately, so that differences as found here do not influence water uptake by the roots. Very little water drains within a short time below the rooted depth in either case.

From the results presented here, it is concluded that the approach used in the crop growth model will not introduce big deviations and may therefore be applied for this purpose. It is emphasized, however, that when the objective of the simulation is different, for instance the dynamics of soil water movement, or if the system contains elements, which are sensitive to small changes in water content or oxygen level, it is necessary to simulate with small time-intervals.

4.2 Evaporation

When the water has entered the soil the most important cause of unproductive loss of water is direct evaporation from the soil surface. Under arid and semi-arid conditions and where deep drainage can generally be ignored, evaporation is practically the only way of losing water, without getting plant growth in return. The ratio of direct soil surface evaporation to transpiration is therefore of decisive importance for the overall efficiency of water use, i.e. the amount of dry matter produced per unit water from precipitation or irrigation. A large part of the scatter, found in statistical analysis relating yield and rainfall in different years or in various regions is due to the varying portion of direct evaporation in the total water loss.

The importance of evaporation in dry land and irrigated farming has been recognized for a long time and numerous experiments have been carried out through the years to study that process. Too often, how-

ever, these experiments were completely phenomenological and not based on physical knowledge of the process of evaporation as influenced by soil and environmental factors.
With increasing knowledge of the theory of soil-moisture flow under non-saturated conditions and application of simulation techniques on high speed computers, in studying transport processes in soils at present soil surface evaporation can be examined as a transient process. In this section a simulation model is presented calculating the rate of evaporation from a bare soil surface, under varying external evaporative conditions. The surface temperature is calculated from the energy budget at the soil surface and the simultaneous flow of moisture and heat in the soil is simulated. Moisture flow may take place either in the liquid or in the vapour phase, under the influence of potential gradients and vapour pressure gradients, respectively. Any time dependent flow rate or potential may be used at the lower boundary.

4.2.1 Description of the simulation model

The model presented calculates the rate of evaporation from a soil surface from basic physical properties of the soil and from environmental conditions. It is based on the principles for simulation of transport processes in soils as outlined by de Wit & van Keulen (1972). To avoid the use of FORTRAN DO-loops and NOSORT sections, a pre-processing programming feature, developed at the Department of Theoretical Production Ecology is applied. Some examples of its use are given by de Wit & Goudriaan (1974). The 'preprocessor' generates single output names and multiple statements from lines containing numerical arrays embedded in apostrophes, i.e.

A'1,3' = B × C'2,4'   generates
A1 = B × C2
A2 = B × C3
A3 = B × C4

The generated text is subject to normal CSMP rules. This feature facilitates writing and reading of the programs.
A complete listing of the model is given in Table 5, where the apostrophes have been replaced by ≠ – sings as the result of the use of a different computer for printing.

```
TITLE EVAPORATION COMPARTMENTALIZED, UNIFORM SOIL PROFILE
TITLE CONSTANT EVAPORATIVITY
*  ALL CALCULATIONS PERFORMED IN UNITS M-SEC-KG-J-DEG C
INITIAL
PARAM TCM#1,25# = 10*.02,5*.03,5*.05,5*.06
*  THICKNESS OF COMPARTMENTS IN M
      RTC#1,25# = 1./TCM#1,25#
*  RTC = RECIPROCAL THICKNESS OF COMPARTMENTS IN M**(-1)
      RDF1 = 1./(0.5*TCM1)
      RDF#2,25# = 1./(0.5*(TCM#1,24#+TCM#2,25#))
*  RDF = RECIPROCAL DISTANCE BETWEEN CENTRES OF ADJACENT COMPARTMENTS
      RDF26 = 1./(0.5*TCM25)
PARAM WI1 = .305
*  INITIAL MOISTURE CONTENT OF THE FIRST COMPARTMENT
*  CALCULATION OF THE INITIAL SUCTION OF THE COMPARTMENTS
      SI1 = AFGEN(STB,WI1)
      SI#2,25#=SI#1,24#-100./RDF#2,25#
      WI#2,25#=AFGEN(RSTB,SI#2,25#)

FUNCTION RSTB = -600.,1.35,0.,0.35,60.,.3325,126.,.325,151.,.30,      ...
      158.,.275,170.,.25,182.,.225,190.,.20,215.,.175,230.,.15,       ...
      265.,.125,      ...
      365.,.10,1475.,.075,2.E4,.05,4.65E5,.025,1.E6,.01,1.E9,.001
*  RSTB = RECIPROCAL SUCTION TABLE, WATER CONTENT IN M**3/M**3
*  AS A FUNCTION OF THE POTENTIAL IN CM

      HCI#1,25#=TI#1,25#*(VSOL*HCS+WI#1,25#*HCW+(1.-VSOL-WI#1,25#)*HCA)
*  INITIAL VOLUMETRIC HEAT CONTENT OF COMPARTMENTS
PARAM TI#1,25# = 25*21
*  INITIAL TEMPERATURE OF COMPARTMENTS IN DEGR C



      TLLR = 0.

DYNAMIC


**************  SECTION 1  *************




****** MOISTURE REGIME OF SOIL LAYERS ****

      W#1,25#=INTGRL(WI#1,25#,(FLR#1,25#-FLR#2,26#+WVF#1,25#-WVF#2,   ...
        26#)*RTC#1,25#)
*  VOLUMETRIC WATER CONTENT IN M**3/M**3
      FLR#2,25#=(TER#1,24#+TER#2,25#)/(W#1,24#+W#2,25#)  ...
                              *((S#1,24#-S#2,25#)*RDF#2,25#+1.)
*  FLOW RATE OF WATER IN LIQUID PHASE IN M**3/M**2,SEC
      TER#1,25#=W#1,25#*1.157E-7*AFGEN(KTB,W#1,25#)
*  INTERMEDIATE VARIABLE TO CALCULATE WEIGHTED AVERAGE OF CONDUCTIVITIES
FUNCTION KTB =.001,1.E-8,.01,1.E-7,.05,2.5E-6,.075,5.0E-5,.10,5.0E-3,...
      .125,.07,.15,.15,.175,.26,.20,.650,.225,1.00,.25,1.5,.275,2.2, ...
      .30,3.2,.325,5.,.35,10.
*  HYDRAULIC CONDUCTIVITY IN CM/DAY AS A FUNCTION OF WATER CONTENT IN
*  M**3/M**3
      S#1,25#=-1.E-2*AFGEN(STB,W#1,25#)
*  EQUIVALENT POTENTIAL IN M WATER PRESSURE

FUNCTION STB = .001,1.E9,                                              ...
            .01,1.E7,.025,2.50E6,.05,2.E5,.075,1.475E3,.10,365.,       ...
      .125,265.,.15,230.,.175,215.,.20,190.,.225,182.,.25,170.,        ...
      .275,158.,.30,151.,.325,126.,.3325,60.,.35,0.,1.35,-600.
*  EQUIVALENT WATER POTENTIAL IN CM WATER PRESSURE AS A FUNCTION OF
*  WATER CONTENT IN M**3/M**3

      WVF#2,25# = DWV#2,25#*(VPC#1,24#-VPC#2,25#)*RDF#2,25#
*  WATER VAPOR FLUX IN M**3/M**2,SEC
      DWV#2,25#=(TCM#1,24#*AFGEN(WVDT,W#1,24#)+TCM#2,25#*AFGEN(WVDT, ...
         W#2,25#))/(TCM#1,24#+TCM#2,25#)
*  AVERAGE DIFFUSIVITY FOR WATER VAPOR IN M**2/SEC
*  WVD = DIFFUSIVITY FOR WATER VAPOR
```

```
FUNCTION WVDT = .01,2.89E-11,.05,2.55E-11,.10,2.46E-11,.20,9.84E-12, ...
      .35,8.68E-14,0.4,1.E-14
*  WVDT = RELATION BETWEEN DIFFUSIVITY FOR WATER VAPOR IN M**2/SEC
*  AND WATER CONTENT IN M**3/M**3
*         VPC#1,25#=1.E-6*273/(273+T#1,25#)*0.804*VPM#1,25#*DF#1,25#
*  VPC = VAPOR CONCENTRATION IN COMPARTMENT IN M**3/M**3
*  0.804 = G H2O/L/MBAR PRESSURE AT 0 DEGR C
*      VPM#1,25#=6.11*EXP(17.4*T#1,25#/(T#1,25#+239.))
*  VPM = VAPOR PRESSURE IN MBAR PER LAYER
*       DF#1,25#=EXP(S#1,25#*G/(R*(T#1,25#+273.)))
*  DF = DEPRESSION FACTOR FOR VAPOR PRESSURE DUE TO HIGH SUCTION
*  THESE STATEMENTS ARE COMBINED FOR REASONS OF PROGRAM SIZE INTO
      VPC#1,25#=1.3411E-3/(273+T#1,25#)*EXP(17.4*T#1,25#/(T#1,25#+239....
         )+S#1,25#*G/(R*(T#1,25#+273)))

**************** SECTION 2    ***********

**  TEMPERATURE REGIME OF SOIL COMPARTMENTS

      HC#1,25#=INTGRL(HCI#1,25#,(HFL#1,25#-HFL#2,26#)*RTC#1,25#)
*  HEAT CONTENT OF THE COMPARTMENTS IS ON VOLUME BASIS, J/M**3
      HFL#2,25#=0.5*(CH#1,24#+CH#2,25#)*(T#1,24#-T#2,25#)*RDF#2,25#  ...
            +FLR#2,25#*T#2,25#*HCW
*  NET HEAT FLOW IS IN J/M**3/SEC
*  MFL = HEAT TRANSPORT WITH MASS FLOW OF THE WATER
      CH#1,25# = PARM*AFGEN(HCTB,W#1,25#)
PARAMETER PARM = 420.
*  PARM = PARAMETER TO CONVERT FROM CAL/CM TO J/M

AFGEN HCTB = 0.,.625E-3,.05,.75E-3,.10,2.5E-3,.15,3.E-3,      ...
      .20,3.625E-3,.30,4.25E-3,.40,4.625E-3,.50,5.E-3
*  HCDT = RELATION BETWEEN HEAT CONDUCTIVITY IN CAL/CM/DEGREE C/SEC
*  AND WATER CONTENT IN M**3/M**3

      T#1,25#=HC#1,25#/(VSOL*HCS+W#1,25#*HCW+(1-VSOL-W#1,25#)*HCA)
PARAMETER VSOL = 0.65,HCS = 2.1E6,HCW=4.2E6,HCA=.00126E6
*  HCP = HEAT CAPACITY OF SOLID PHASE,WATER AND AIR RESP INJ/M**3/DEG C
*  VSOL = VOLUME OF SOLID PHASE(=1.-PORE VOLUME) IN M**3/M**3


************ SECTION 3   *******
*           ENVIRONMENTAL CONDITIONS
PARAMETER TA=21.,SVP=24.85,DPT=15.5,VPA=17.45,RAD=0.,WS=0.6
*  SVP,AVP IN MBAR,WS IN M/SEC
*  RAD = INTENSITY OF RADIATION AT THE SURFACE IN J/M**2/SEC

**************** SECTION 4    *************

****** ENERGY BALANCE AT THE SURFACE ****


      ARAD = RAD*(1.-REFLC)
*  ARAD = ABSORBED RADIATION, REFLC= REFLECTION COEFFICIENT
      REFLC = AFGEN(REFLCT,W1)
FUNCTION REFLCT = 0.01,0.25,0.1,0.2,0.2,0.15,0.5,0.1

      SHL = (TSURF-TA)/RA*RHOCP
*  SHL = SENSIBLE HEAT LOSS IN J/M**2/SEC
PARAM RHOCP = 1200.
*  RHOCP = HEAT CAPACITY OF THE AIR IN J/M**3/DEG C
      RA = SQRT(AHC*KNVIS/WS)/DIF
*  RA = RESISTANCE OF LAMINAR LAYER ABOVE THE SOIL IN SEC/M

PARAMETER DIF=.21E-4,KNVIS=.15E-4,AHC=0.003
*  DIF = DIFFUSIVITY OF THE AIR FOR HEAT IN M**2/SEC
*  KNVIS = KINEMATIC VISCOSITY OF THE AIR IN M**2/SEC
*  AHC = AVERAGE SIZE OF THE CLODS AT THE SURFACE IN M

      EHL = (VPSS-VPA)*RHOCP/(RA*PSCH)
*  EHL = EVAPORATIVE HEAT LOSS IN J/M**2/SEC
PARAM PSCH = 0.67
*  PSCH = PSYCHROMETER CONSTANT IN MBAR/DEG C
      VPSS = (SVP+SLOPE*(TSURF-TA))*DF
```

```
*   VPSS = VAPOR PRESSURE AT THE SOIL SURFACE                              EVAP4270
       SLOPE=106.3*EXP(17.4*T1/(T1+239.))*(1-T1/(T1+239.))/(T1+239.)       EVAP4280
*   SLOPE OF THE SATURATED VAPOR PRESSURE CURVE AT PROPER TEMP             EVAP4290
                                                                           EVAP4300
       DF = EXP(S1*G/(R*(T1+273)))                                         EVAP4310
                                                                           EVAP4320
PARAMETER G = 9.81,R=461.5                                                 EVAP4330
*   G = ACCELERATION OF GRAVITY IN M/SEC**2,R = GAS CONSTANT IN            EVAP4340
*   J/M**3,DEGR C                                                          EVAP4350
       LWR = LWRTA+DLWR*(TSURF-TA)                                         EVAP4360
*   NET OUTGOING LONG WAVE RADIATION IN J/M**2/SEC                         EVAP4370
       LWRTA=5.72E-8*(TA+273.)**4*(.56-.092*SQRT(VPA))                     EVAP4380
       DLWR = 5.72E-8*4.*(TA+273)**3                                       EVAP4390
                                                                           EVAP4400
       HFL1 = (TSURF-T1)*RHOCS/RESS                                        EVAP4410
*   HFL1 = HFS = HEAT FLOW INTO THE SOIL IN J/M**2,SEC                     EVAP4420
                                                                           EVAP4430
       RHOCS = HCP1                                                        EVAP4440
*   RHOCS = HEAT CAPACITY OF THE SOIL IN J/M**3/DEG C                      EVAP4450
                                                                           EVAP4460
       RESS = HCP1*(.5*TCM1)/CH1                                           EVAP4470
       HCP1=VSOL*HCS+W1*HCW+(1.-VSOL-W1)*HCA                               EVAP4480
*   RESS RESISTANCE OF THE SOIL IN SEC/M                                   EVAP4490
                                                                           EVAP4500
       TSURF=(ARAD-LWRTA+TA*(RHOCP/RA+DF*RHOCP*SLOPE/RAPS+DLWR)+T1*     ...EVAP4510
             RHOCS/RESS-RHOCP/RAPS*(SVP*DF-VPA))/(RHOCP/RA+DF*RHOCP/    ...EVAP4520
             RAPS*SLOPE+DLWR+RHOCS/RESS)                                   EVAP4530
                                                                           EVAP4540
*   TSURF IS TEMPERATURE AT THE SURFACE IN DEG C                           EVAP4550
                                                                           EVAP4560
                                                                           EVAP4570
       RAPS=RA*PSCH                                                        EVAP4580
                                                                           EVAP4590
                                                                           EVAP4600
                                                                           EVAP4610
**************    SECTION 5    ***********                                 EVAP5000
*      LOWER BOUNDARY CONDITIONS                                           EVAP5010
****** BOUNDARY CONDITIONS FOR MOISTURE REGIME ***                         EVAP5020
                                                                           EVAP5030
       FLR26 = INSW(WTB,0.,KA26*(S25-S26)*RDF26)                           EVAP5040
       S26 = 0.                                                            EVAP5050
       WVF26 = 0.                                                          EVAP5060
PARAMETER WTB = -1.                                                        EVAP5070
*   WTB = PARAM INDICATING WATERTABLE, IF POS THERE IS WATERTABLE          EVAP5080
*   IF NEGATIVE CLOSED SYSTEM                                              EVAP5090
       KA26 = (1.157E-7*AFGEN(KTB,W25)+KSAT*WSAT)/(W25+WSAT)               EVAP5100
PARAMETER WSAT = 0.35                                                      EVAP5110
       KSAT = AFGEN(KTB,WSAT)*1.157E-7                                     EVAP5120
                                                                           EVAP5130
                                                                           EVAP5140
******  BOUNDARY CONDITIONS FOR HEAT REGIME ******                         EVAP5150
                                                                           EVAP5160
PARAMETER T26 = 21.                                                        EVAP5170
       HFL26 = CH25*(T25-T26)*RDF26+FLR26*T26*HCW                          EVAP5180
                                                                           EVAP5190
************** BOUNDARY CONDITIONS FOR UPPER BOUNDARY ******                EVAP5200
       FLR1 = 0.                                                           EVAP5210
       WVF1 = -EVFL                                                        EVAP5220
************* SECTION 6  *******************                               EVAP6000
*   CALCULATION OF OUTPUT VARIABLES                                        EVAP6010
       CUMEV = INTGRL(0.,EVFL)                                             EVAP6020
*   CUMEV = CUMULATIVE EVAPORATION IN M                                    EVAP6030
                                                                           EVAP6040
       EVFL = EHL/VAPH                                                     EVAP6050
*   EVFL = EVAPORATIVE WATER FLOW IN M**3/M**2/SEC                         EVAP6060
PARAMETER VAPH = 2.39E9                                                    EVAP6070
*   VAPH = HEAT OF VAPORISATION OF WATER IN J/M**3                         EVAP6080
       EQSR=(SVP-VPA+(TSURF-TA)*SLOPE)*RHOCP/(PSCH*EHL)-RA                 EVAP6090
                                                                           EVAP6100
*   EQSR = ,EQUIVALENT STOMATAL, RESISTANCE OF THE SOIL IN SEC/M           EVAP6110
                                                                           EVAP6120
```

```
**************** SECTION 7 ***************************
*  OUTPUT AND RUN CONTROL
PRINT W#1,25#,T#1,15#,HFL1,TLLR,EVFL,TSURF,EQSR,RESS,EHL,SHL,CUMEV
METHOD MILNE
ABSERR HC1 = 1.E-3
RELERR HC1 = 1.E-3
TIMER FINTIM = 0.
FINISH W1=-0.01,W1=0.75,TLLR=1.E5

NOSORT
      TLLR = TLLR+KEEP
      IF(KEEP.LT.0.5) GOTO 1
      DEB1 = DEBUG(2,0.)
      DEB2 = DEBUG(1,86400.)
      DEB3 = DEBUG(1,172800.)
      DEB4 = DEBUG(1,259200.)
      DEB5 = DEBUG(1,345600.)
      DEB6 = DEBUG(1,432000.)
      DEB7 = DEBUG(1,691200.)
      DEB8 = DEBUG(1,1036800)
    1 CONTINUE

END
STOP
```

The model calculates the simultaneous flow of water and heat in a soil column of unit area (m^2) divided into a number of compartments of different thickness. Each compartment is considered to be homogeneous. The smallest compartments are at the soil-air interface, where the steepest gradients may occur and gradually the thickness increases.

Moisture regime

The volumetric water content W in m^3m^{-3} is defined in an integral; its rate of change is governed by the difference between incoming and outgoing flow rate.

The flow rate of water, assumed to occur between the centres of two adjacent compartments, in $m^3m^{-2}\,sec^{-1}$, consists of two terms:

– flow of water in the liquid phase (FLR) governed by potential differences (S) and by the average hydraulic conductivity of the soil (TER), both read from tabulated functions (van Keulen & van Beek, 1971), and

– flow of water vapour (WVF) governed by gradients in vapour concentration (VPC), and the diffusivity for water vapour (WVD). The vapour concentration in each compartment, VPC in m^3m^{-3} is calculated from its temperature assuming saturated vapour pressure, according to an analytical expression, while allowance is made for vapour pressure depressions due to dryness of the soil (DF). The water vapour diffusivity, WVD in m^2sec^{-1} is read from a table, (WVDT) as a function of the volumetric water content. This table was obtained from a formula suggested by Philip & de Vries (1957).

Temperature regime

The volumetric heat content in J m^{-3} is tracked in an integral HC, governed by the net flow rate of heat. The temperature, T in °C, is calculated from the heat content, dividing it by the volumetric heat capacity in J m^{-3} $°C^{-1}$, obtained from the water content, the fraction of solid phase (VSOL in m^3 m^{-3}) and the fraction of air. The specific heat capacities of each of the components, HCW, HCS and HCA, respectively, in J m^{-3} $°C^{-1}$, are introduced as parameters.
Two components are distinguished in the flow rate, in J m^{-2} sec^{-1} between compartments: 1) heat flow by diffusion (HFL), depending on the temperature gradient and the conductivity for heat (CH). The conductivity, in J m^{-1} sec^{-1} $°C^{-1}$ is obtained from a tabulated function, HCTB, with the volumetric water content as the independent variable. Here also, the arithmetic average of the values from the two compartments is used in the calculation. 2) Heat is also transported by mass flow of the water (MFL) and although this is normally only a small term, compared with the diffusion flow, it is included here for the sake of completeness.
Only the main transport coefficients have been taken into account and coupling coefficients like for instance liquid moisture transport under temperature gradients are omitted. These transport processes are only of importance under extreme conditions (Troelstra & Blom, 1972) and have hardly any practical implications. There are, however, no basic difficulties in introducing these components in the model.

Boundary conditions

To describe the flow over the boundaries different equations have to be introduced. The evaporative demand of the atmosphere is calculated from the environmental conditions. These variables, incoming global radiation, also called short-wave radiation intensity, RAD in J m^{-2} sec, air temperature, TA in °C, vapour pressure in the air, VPA in mbar, and wind speed WS in m sec^{-1}, are introduced as forcing functions. They are either given as tabulated functions of time, or they may be derived from daily values (de Wit et al., in prep.). The rate of evaporation is governed by the exchange processes between the soil surface and the atmosphere. According to the conservation of energy principle, the energy balance equation for the surface can be written as:

$$\text{ARAD} = \text{EHL} + \text{SHL} + \text{HFS} + \text{LWR} \qquad (4.1)$$

in which

ARAD = short-wave radiation absorbed by the soil surface
EHL = evaporative heat loss
SHL = sensible heat flux
HFS = heat flow into the soil
LWR = net outgoing long-wave radiation

The value of ARAD is determined by the radiation intensity above the surface and the reflectivity of that surface:

$$\text{ARAD} = \text{RAD} \times (1.\text{-REFLC}) \qquad \text{in J m}^{-2}\ \text{sec}^{-1}$$

The reflection coefficient of bare soil is dependent on its water content (Ritchie, 1971; Gates & Hanks, 1967). It may of course vary for soils with a different colour, but the values reported are fairly consistent. Therefore

REFLC = AFGEN(REFLCT,W1)

and

FUNCTION REFLCT = (0.01, 0.25), (0.1, 0.2), (0.2, 0.15),
(0.5, 0.10)

in which the first number of each pair is the independent variable W1, the volumetric water content of the surface layer in $m^3\ m^{-3}$, and the second number the reflection coefficient. The heat transfer from the soil surface to the atmosphere is calculated from the difference in temperature and the resistance to heat exchange.

$$\text{SHL} = (\text{TSURF} - \text{TA})/\text{RA} \times \text{RHOCP} \qquad \text{in J m}^{-2}\ \text{sec}^{-1} \qquad (4.2)$$

in which

PARAM RHOCP = 1200. $\quad$ $J\ m^{-3}\ {}^{\circ}C^{-1}$

is the volumetric heat capacity of the air.
The resistance to heat exchange depends on the thickness of the laminar boundary layer immediately above the soil surface, which is determined by the height of the roughness elements at the surface,

the wind speed and the kinematic viscosity of the air. Moreover the diffusion resistance is inversely proportional to the diffusivity for heat of air. Several semi-empirical equations relating these variables have been proposed (Linacre, 1972, Chamberlain, 1968). In the model the relation given by Linacre is used:

RA = SQRT(AHC × KNVIS/WS)/DIFF (4.3)

in which WS is the wind speed above the soil surface.
With

PARAM AHC = 0.01, KNVIS = .15E−4, DIFF = .21E−4

the average height of the soil clods in m, the kinematic viscosity of the air in $m^2\ sec^{-1}$ and the diffusivity of air for heat in $m^2\ sec^{-1}$ are given.
This formula, which has been derived from measurements of the laminar resistance above leaves, yields good results when applied to laboratory columns, with a fan blowing over a very smooth soil surface. It underestimates, however, the resistance in the field situation. A major difficulty in estimating the resistance in the field situation is the irregularity of the surface. Chamberlain showed that the resistance is sensitive to the roughness height. Because of the irregular form and distribution of surface aggregates in the field, this value is difficult to obtain, For that situation the formulas developed by Chamberlain (1968) are used:

RA = WS/(USTARS × USTARS) + BM1H/USTARS (4.4)
USTARS = WS × KARMAN/ALOG(MH/ZNOTS)

USTARS is the friction velocity above the surface in $m\ sec^{-1}$, ALOG takes the natural logarithm of the argument, which is here the ratio of the measuring height of the wind speed to the roughness length. For the latter Chamberlains' data suggest a value of about 0.1 of the mean height of the surface elements. These values are given with

PARAM MH = 2., ZNOTS = 0.001, KARMAN = 0.4

the last value being Von Karman's constant.
According to this formula the resistance RA above the soil surface is the sum of two components, the first term being the resistance to momentum extraction, while the second term accounts for additional resistance to the transfer of heat or mass.

This additional resistance must be included for two reasons:
- There is a boundary layer immediately above the surface elements which must be traversed by mass, but is not involved in destroying momentum.
- The molecular diffusion of other entities varies with the kinematic viscosity.

Theoretical and experimental considerations suggest for BM1H the expression:

$$\mathrm{BM1H} = \mathrm{ALPHA} \times (\mathrm{USTARS} \times 30. \times \mathrm{ZNOTS/KNVIS}) \times \times$$
$$\times \times 0.45 \times \mathrm{PR} \times \times 0.8$$

in which

ALPHA = a constant depending on the shape of the roughness elements (= 0.52)
PR = Prandtl number (=0.7)

Chamberlain showed reasonably good agreement between his experimental data and the data calculated with Eqn (4.4).

The evaporative heat flux is governed by the difference in vapour pressure between the atmosphere and the evaporating surface, and depends on the resistance to vapour transport. The exchange of water vapour and of heat is governed by the same physical processes and therefore the resistances are proportional. Thus

$$\mathrm{EHL} = (\mathrm{VPSS} - \mathrm{VPA}) \times \mathrm{RHOCP/(RA \times PSCH)} \text{ in J m}^{-2} \text{ sec}^{-1} \quad (4.5)$$

in which

PARAM PSCH = 0.67 mbar °C^{-1}

is the psychrometric constant.

The diffusivities for heat and water vapour differ ±10% but this is neglected here.

The vapour pressure at the soil surface, VPSS in mbar, depends on two factors: the temperature of the surface and the moisture content at the surface. In the first stage of the evaporation process, the moisture content is high enough to maintain saturated vapour pressure at the surface. When the soil dries out, the moisture content becomes so low, that an appreciable decrease in relative humidity occurs. Linearization of the relationship between saturated vapour pressure and temperature gives

$$\text{VPSS} = (\text{SVP} + \text{SLOPE} \times (\text{TSURF} - \text{TA})) \times \text{DF} \tag{4.6}$$

in which SLOPE, the average slope of the saturated vapour pressure curve is given by an analytical expression:

$$\text{SLOPE} = 106.3 \times \text{EXP}(17.4 \times \text{T1}/(\text{T1}+239)) \times (1 - \text{T1}/(\text{T1}+239))/(\text{T1}+239) \tag{4.7}$$

The dimensionless fractional relative humidity, DF, can be calculated from the gas law. According to Bolt et al. (1965), the potential of water vapour in the soil air, in equilibrium with liquid water in the medium can be written as

$$\Psi_{\text{vapour}} = \frac{\rho RT}{M} \ln P/P_0 \equiv \rho g S \tag{4.8}$$

in which

Ψ = potential of the water vapour in J m^{-3}
R = the gas constant in J °K^{-1} mol^{-1}
T = temperature in °K
M = molecular weight of water
ρ = density of liquid water in kg m^{-3}
g = acceleration of gravity in m sec^{-2}
S = hydraulic pressure head in m

Re-arrangement of the terms yields

$$P/P_0 = e^{(S \times g/(R_w \times T))} \tag{4.9}$$

in which P/P_0 is the fractional relative humidity and

$R_w = R/M$ in J kg^{-1} °K^{-1}

Substituting the temperature (T1) and the water potential (S1) of the first thin compartment in Eqn (4.9) gives

$$\text{DF} = \text{EXP}(\text{S1} \times \text{G}/(\text{R} \times (\text{T1}+273)) \tag{4.10}$$

The values of the acceleration of gravity and the gas constant for water vapour are given by

PARAM G = 9.81, R = 461.5

Because in most cases no data for net radiation are available, the outgoing long-wave radiation must be calculated. Relatively little attention has been paid to this subject and usually a modified form of the formula given by Brunt (1932) is used:

$$\text{LWR} = 5.72\text{E}-8 \times (\text{TSURF}+273) \times \times 4 \times (.56-.092 \times \text{SQRT(VPA)}) \times (1-0.9 \times \text{FOV}) \quad (4.11)$$

This semi-empirical formula is used here for much shorter periods of time than intended and the results are not very accurate. For reasons of simplification this equation is linearized and used as

$$\text{LWR} = \text{LWRTA} + \text{DLWR} \times (\text{TSURF}-\text{TA}) \quad \text{J m}^{-2}\,\text{sec}^{-1} \quad (4.12)$$
$$\text{LWRTA} = 5.72\text{E}-8 \times (\text{TA}+273) \times \times 4 \times (.56-.092 \times \text{SQRT(VPA)}) \times (1-0.9 \times \text{FOV})$$
$$\text{DLWR} = 5.72\text{E}-8 \times 4 \times (\text{TA}+273) \times \times 3$$

Although Eqns (4.11) and (4.12) do not give the same results, the deviations are within the accuracy limits of the approximation.
The flow of heat from the surface into the soil is derived from the temperature difference between the soil surface and the underlying soil compartment, and the thermal properties of the soil.

$$\text{HFS} = (\text{TSURF}-\text{T1}) \times \text{COND1}/(0.5 \times \text{TCM1}) \quad \text{J m}^{-2}\,\text{sec}^{-1} \quad (4.13)$$

The conductivity for heat flow in the soil in J $\text{m}^{-1}\,\text{sec}^{-1}\,°\text{C}^{-1}$ is dependent on the water content and read from a tabulated function, by

COND1 = AFGEN(HCTB,W1)

The thickness of the first compartment is given as a parameter by

PARAM TCM1 = 0.01 m

Equations (4.1), (4.2), (4.4), (4.12) and (4.13) are combined to arrive at an explicit expression for TSURF, containing environmental and soil factors which are all known. This expression is given in the lines 4510–4530 of Table 5 and is not repeated here. When the surface temperature is known, the above mentioned equations are solved, giving the heat and the water exchange at the soil-air interface.
At the lower boundary different conditions may be introduced. For moisture transport two options are included. Either a watertable is assumed at the boundary of the column (WTB = +1), or the system is isolated from its environment (WTB = −1.). Any other time-dependent potential or flow rate may however be introduced by

changing the expression for FLR26, the moisture flow rate at the bottom. The temperature at the lower boundary, T26, is assumed to be constant, but here the same reasoning applies.

4.2.2 Results

The model has been tested with laboratory columns, in co-operation with the Department of Soil Physics of the Agricultural University. A 90-cm long perspex column with inner diameter of 4.5 cm was carefully packed with löss at a bulk density of ± 1.4 g cm^{-3}. After initial wetting the column was allowed to drain for 4 days, at which moment an equilibrium situation nearly existed. It was placed in a constant environment room at a temperature of $21° \pm 1$ °C and a dewpoint temperature of 15.5 ± 1 °C. An electric fan was blowing at the top of the column, providing a windspeed of 0.6 m sec^{-1}. Soil moisture profiles were measured daily by γ-ray attenuation, according to the method described by de Swart & Groenevelt (1971). Hydraulic conductivity values of the löss were determined in separate small columns packed at the same density, by applying different constant rates of infiltration and measurement of the resulting moisture content with γ-ray attenuation. The soil moisture retention curve for desorption was determined in small samples first saturated and placed at different suction levels.

In Fig. 24 measured cumulative evaporation is compared with the simulated values. Measured values were calculated from the successive moisture profiles. There is very good agreement between both values. The curve shows the typical pattern: A first stage of drying in which the evaporation is completely determined by the external evaporative conditions and the moisture content at the soil surface is high enough to maintain saturated vapour pressure. After 4 days the rate of evaporation decreases as a result of drying of the surface and the development of a vapour pressure depression. Eventually a very low and practically constant evaporation rate is maintained.

The measured and simulated moisture profiles are compared in Fig. 25. Obviously there are deviations here, of the order of 10 to 15% of the actual moisture content values. There are probably a number of reasons for these differences. Firstly there is always some 'tailing' in the simulated results due to the use of compartments of finite size,

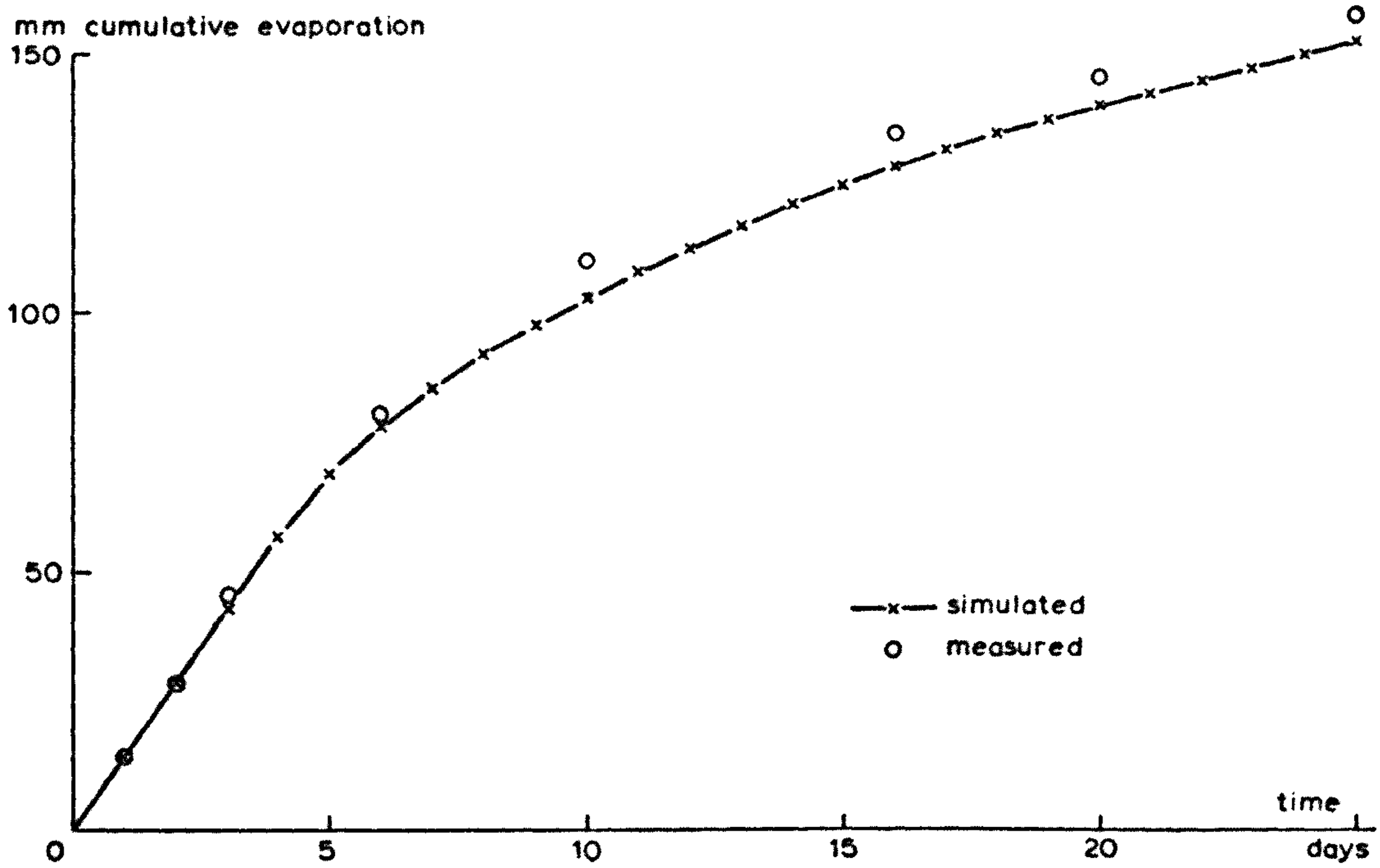

Fig. 24 | Comparison of measured and simulated cumulative evaporation from a löss column in the laboratory in Wageningen.

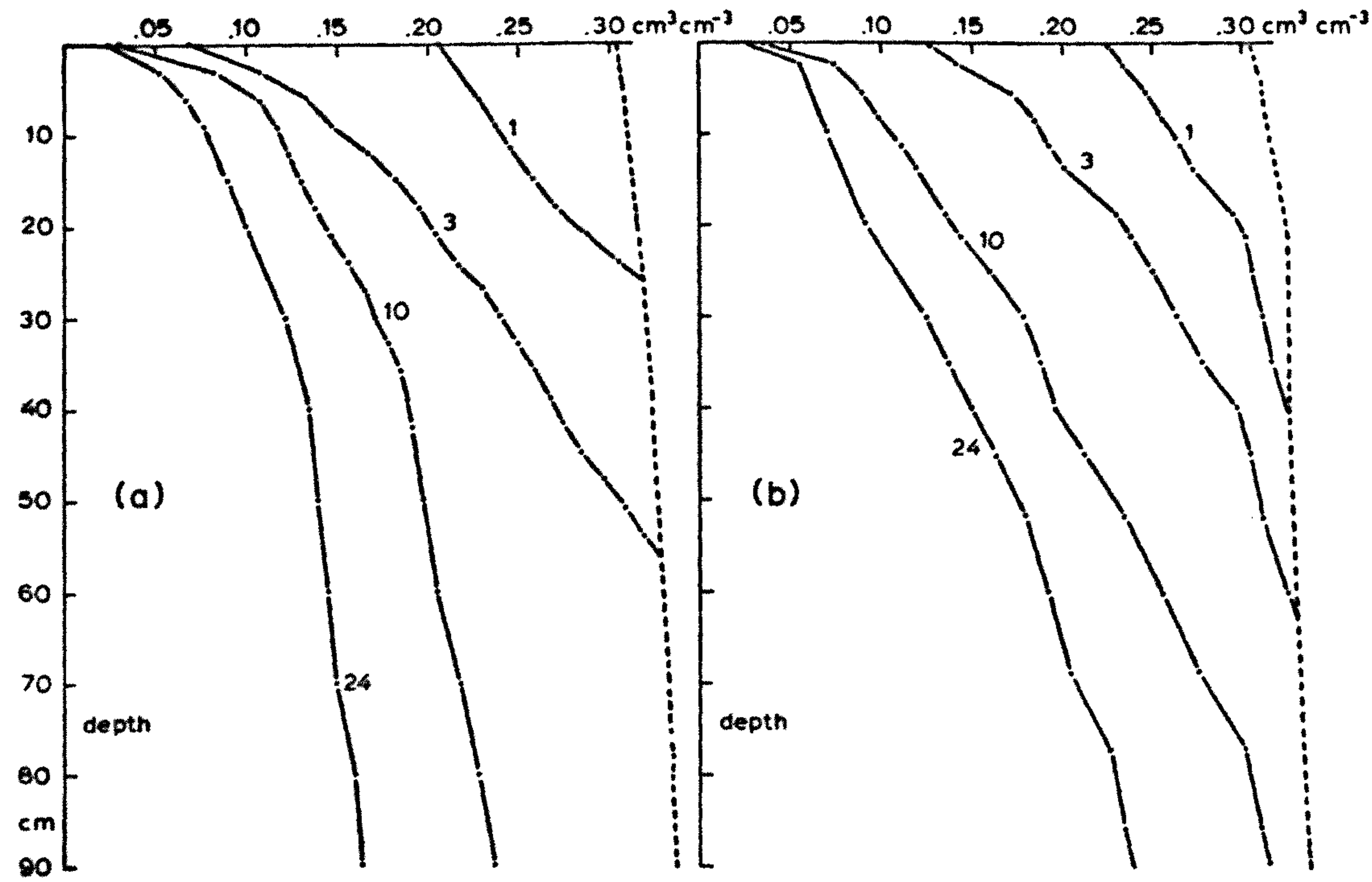

Fig. 25 | Comparison of measured (a) and simulated (b) moisture content profiles in a löss column in the laboratory in Wageningen.

leading to less pronounced gradients (van Keulen & van Beek, 1971). Secondly, the hydraulic properties of the soil column may not have been exactly the same as those determined from the separate columns. Moreover these properties may have changed both with time and depth in the column. At least during measurement distortions were visible in the column: at the surface small cracks developed under the influence of drying and at some places there was shrinkage from the walls probably as a result of temperature gradients across the perspex wall.

The influence of the conductivity values particularly is shown in Fig. 26, where the results of two runs with a different $K-\theta$ relationship (Fig. 27) are compared. Although the cumulative evaporation differs less than 10% after 10 days, the profiles show differences of the same magnitude as observed between the measured and simulated results.

A second test was carried out with experiments from Hillel (1968). In his study, lucite cylinders, 69 cm long, internal diameter 5.0 cm, were packed with löss, at a bulk density of $\pm 1.45\ g\ cm^{-3}$. The columns were placed in a constant environment with temperature of $22 \pm 1\ °C$ and a relative humidity of 30–40%. The columns were weighed daily to determine the evaporation rate; the distribution of water content was periodically measured either by sectioning replicate columns or by means of γ-ray attenuation. In Fig. 28 the cumulative evaporation and the moisture content profiles are compared. There is an overestimation of the cumulative evaporation of about 13% after 12 days. This is mainly because the calculated water content at the soil surface is somewhat higher than the measured value. This may again be due to inaccuracies in the conductivity-water content relationship, which was not determined in the same experiment but taken from other experiments with the same soil (Hillel, 1971). The overall agreement suggests however that the model predicts fairly accurately the rate of evaporation and the moisture distribution of a bare soil. Although many laboratory experiments are reported in the literature, essential quantitative data are always missing, so that unfortunately no more tests could be carried out.
In order to test whether the model also gives good results under field conditions, an experiment carried out at the Avdat Desert Experi-

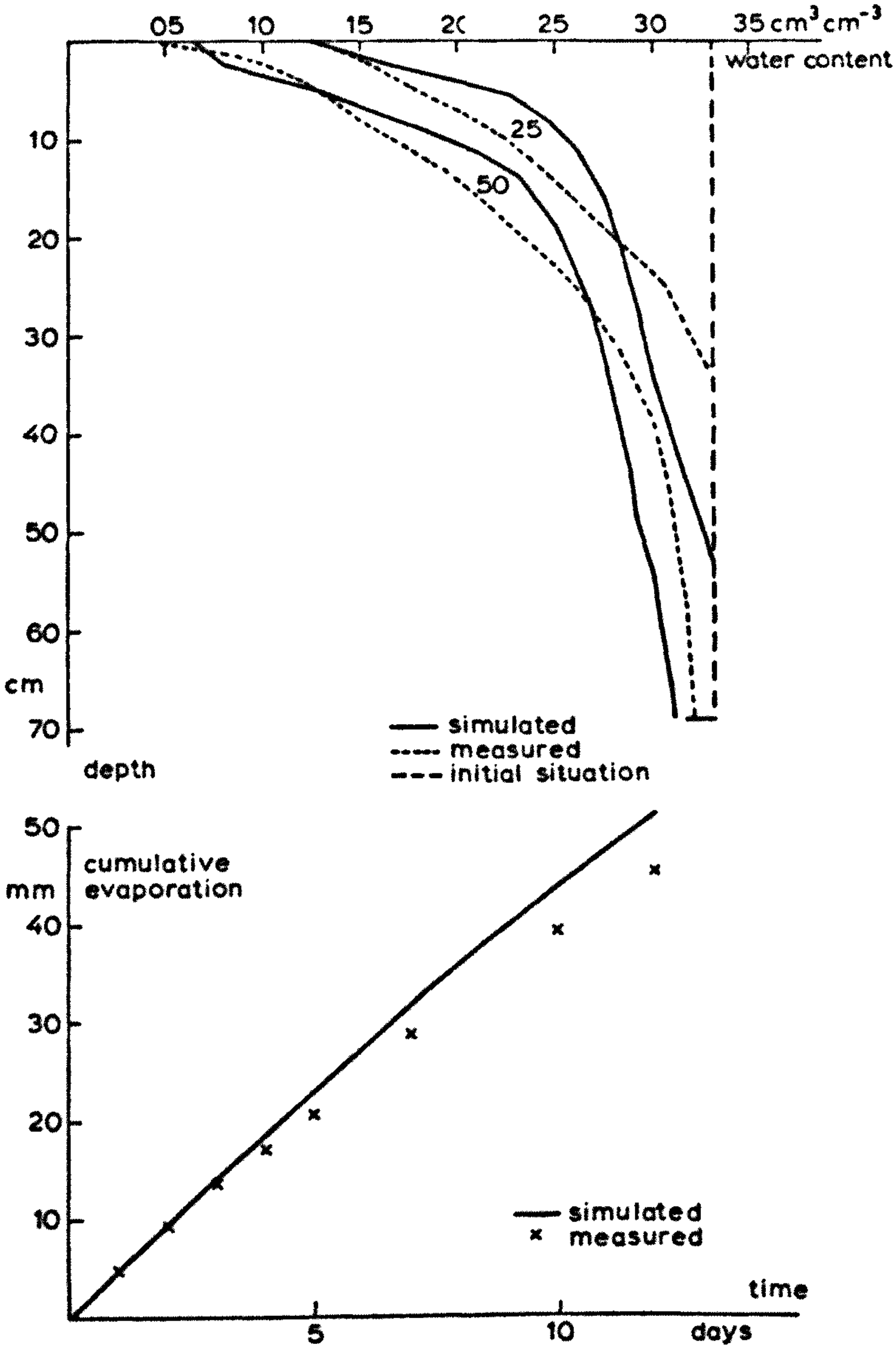

Fig. 26 | Comparison of measured and simulated moisture content profiles (top) and cumulative evaporation (bottom) from löss columns in the laboratory in Rehovot.

mental Station was simulated. Soil moisture was followed under a bare plot that had been irrigated 5 days earlier and received some rain the day before the experiment started. Only the top 30 cm of the profile were sampled in increments of 2 cm for the first 10 cm and increments of 5 cm for the next 20 cm.

Weather data from a standard weather station ±1 km from the experimental site were used: maximum and minimum temperature,

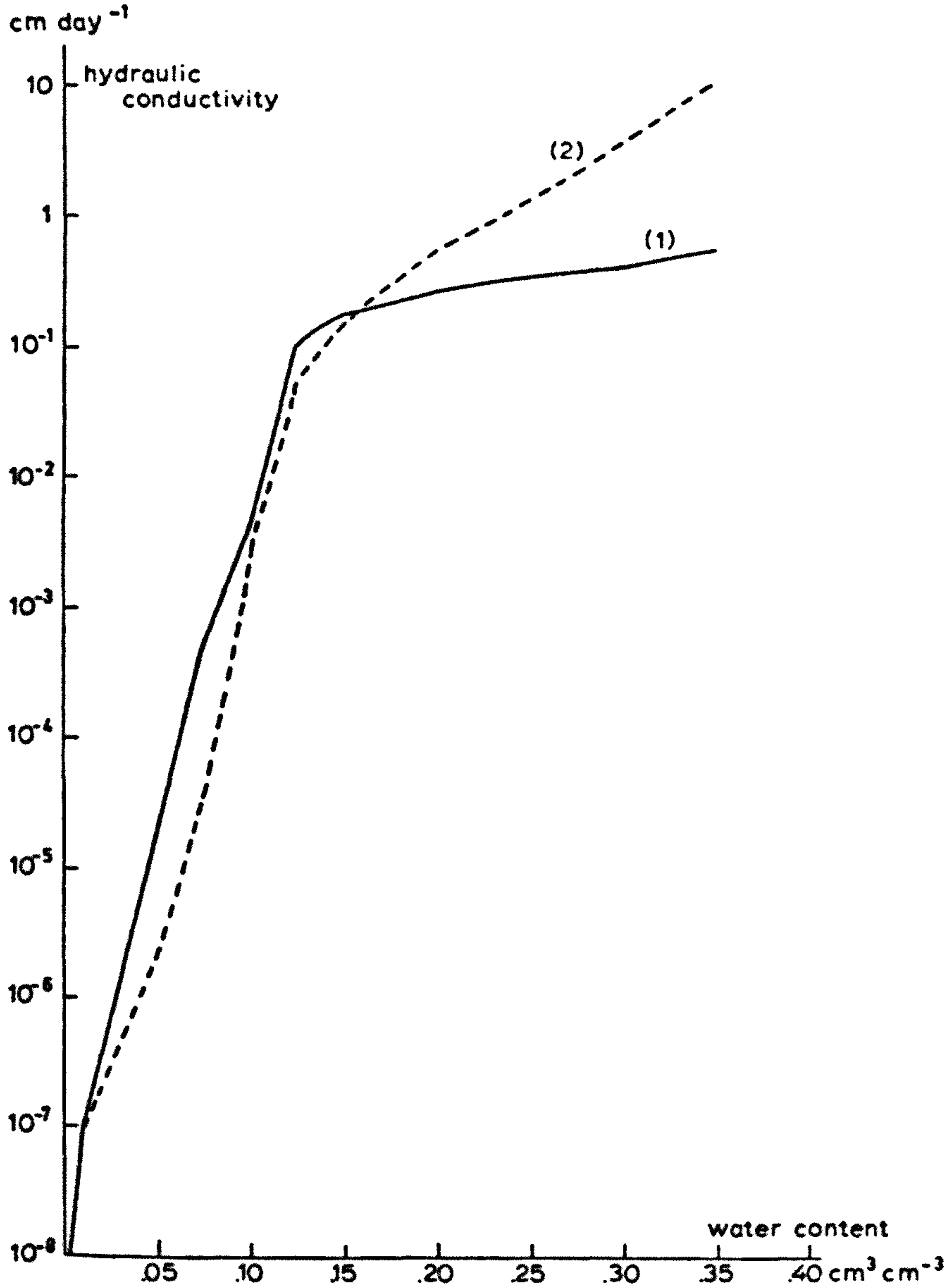

Fig. 27 | Different relations between moisture content and hydraulic conductivity of the soil used in the sensitivity test of the evaporation model.

through which a sinusoidal course was assumed with minimum at sunrise and maximum at 14h00. Measured daily total global radiation was divided over the day, dependent on the height of the sun and the cloudiness of the sky. Humidity was calculated from the measured dew point at 08h00. The wind speed was obtained from the measured daily wind run assuming the wind speed at daytime to be twice that at night time.

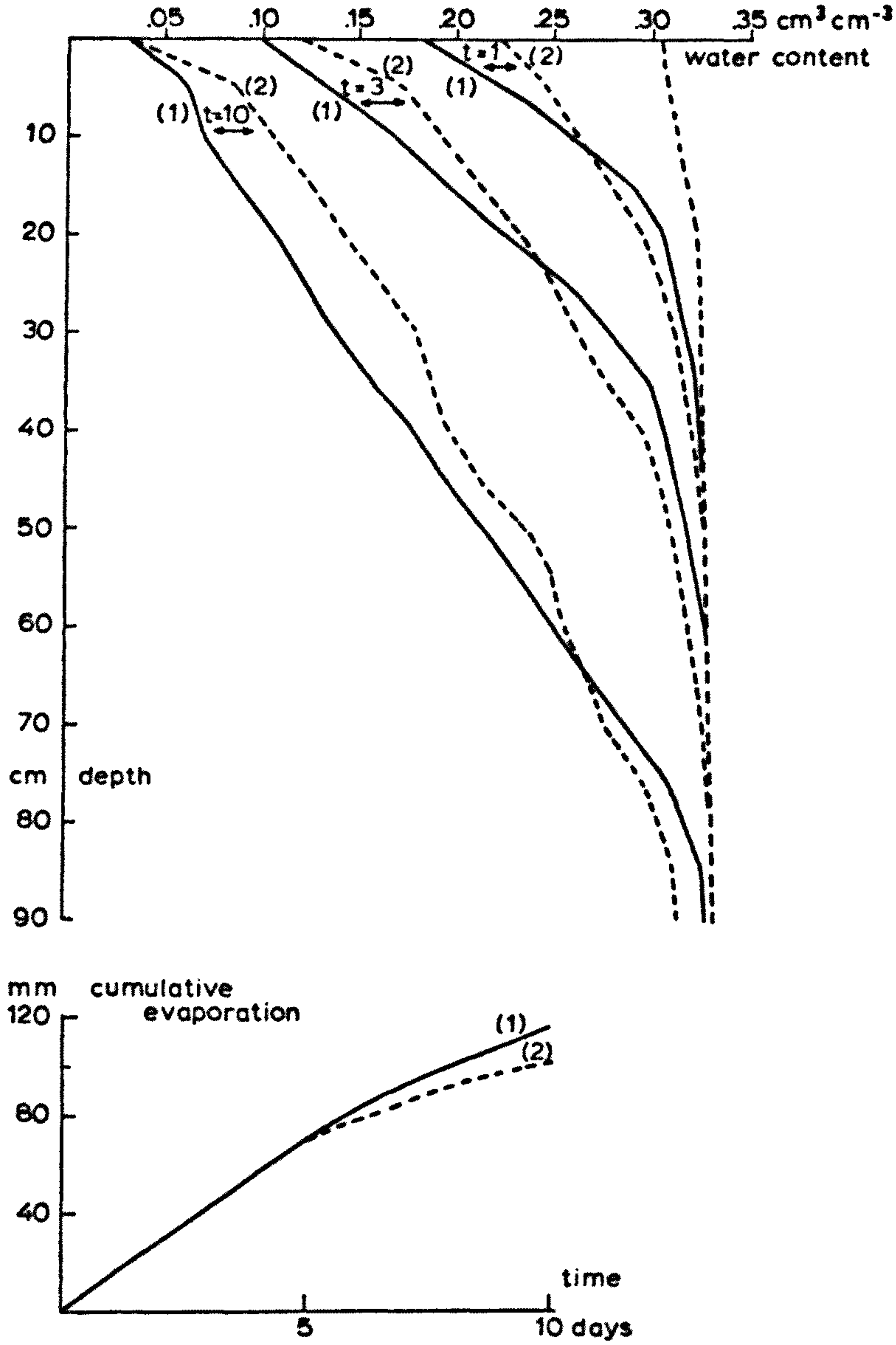

Fig. 28 | Influence of different relations between moisture content and hydraulic conductivity on moisture content profiles (top) and on cumulative evaporation (bottom) calculated with the simulation model.

Because the soil moisture below 30 cm was not measured, the moisture content at that depth was used as the boundary condition in the simulation.

In Fig. 29 the calculated cumulative evaporation is compared with the Penman evaporation. The conditions at the soil surface were always such, that potential evaporation could be maintained. The agreement between the two values is always within 10%, which is within the

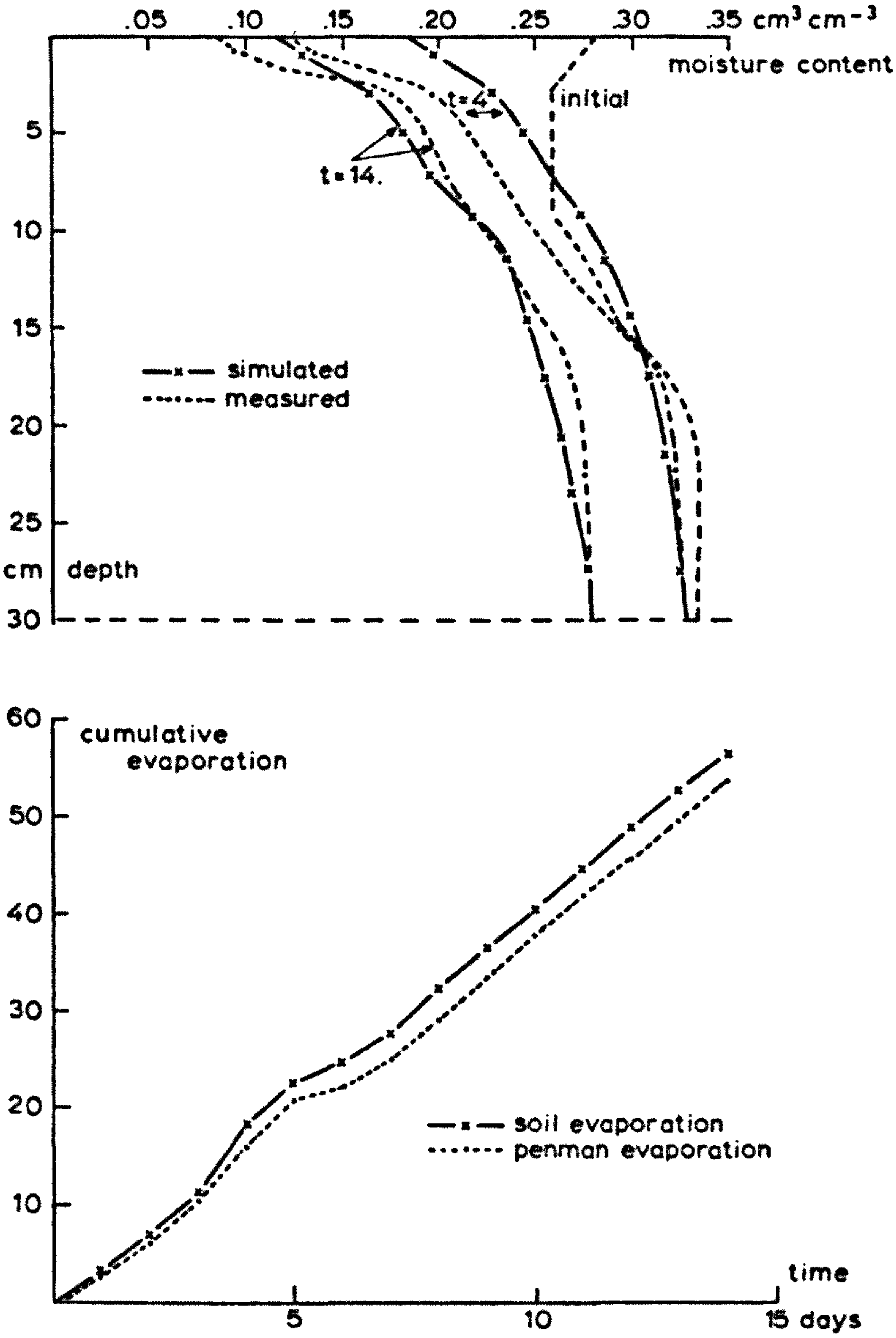

Fig. 29 | Comparison of measured and simulated moisture content profiles (top) and cumulative evaporation (bottom) from a field experiment in Avdat.

accuracy limits of the hydraulic properties of the soil. It is not an absolute proof for the correctness of the model, because the water loss could not be determined from the total soil moisture balance, but this agreement should give fair confidence in its results.
In the same figure the calculated and measured soil moisture profiles 4 days and 14 days after the start of the experiment are shown. The initial situation after the rain is also given. The measured result is

the average of eight replicates. These results also support the model, as the agreement between calculated and measured profiles is very good, if the inhomogeneity of the soil, and the difficulties in determining the hydraulic parameters in situ are taken into account. The results obtained with the model compared with the experimental results justify the conclusion that the model is an accurate enough representation of reality for the present objective.

In Fig. 30 the simulated temperature profiles are given for the Wageningen laboratory experiment (a) and the field experiment in Avdat (b). The numbers along the curve refer to days after the start of the experiment (a) or day and hour of that day (b).

In the laboratory experiment the temperature gradients are small, in the beginning reaching $\pm 0.3\,°C\,cm^{-1}$ and decreasing towards the end. Temperature gradients have hardly any effect on vapour transport in this case.

In the field experiment however under the high radiation regime, considerable temperature gradients may develop. Already at a moisture content of $\pm .09\ cm^3\,cm^{-3}$ (Fig. 29) at midday the gradient

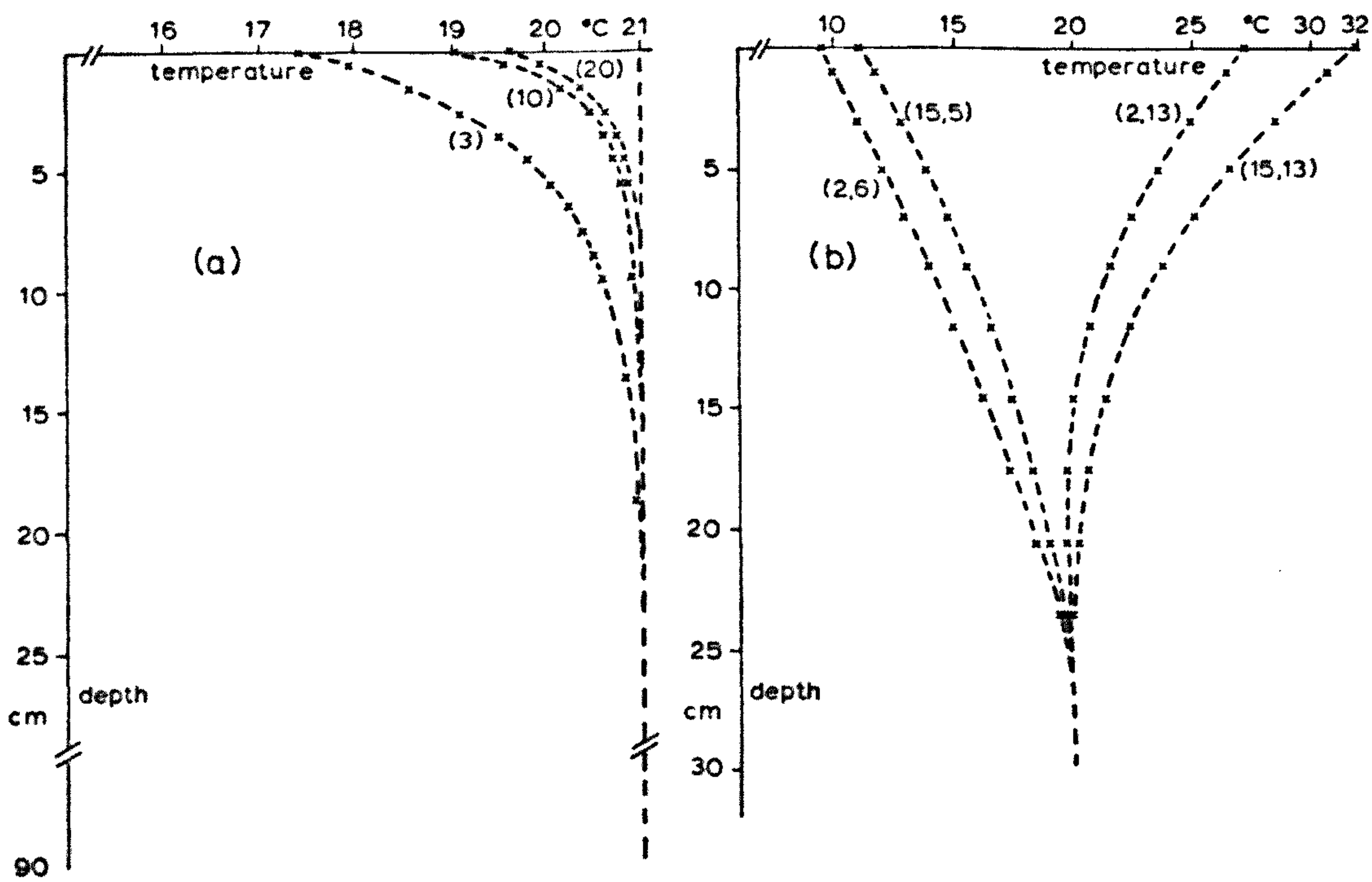

Fig. 30 | Simulated temperature profiles in the löss column in Wageningen (a, numbers refer to days) and the field experiment in Avdat (b, numbers refer to day + hour).

is 0.8 °C cm^{-1}. When the soil dries out further there may be still more heating. Under such conditions vapour transport can account for a considerable part of the total moisture transport. However during night time there is a tendency for vapour transport in the opposite direction. For a detailed treatment of soil moisture it is therefore necessary under such conditions to include temperature effects. However in terms of moisture availability for plant growth the amounts of water involved are so small that temperature influences may be neglected.

4.2.3 Application in the crop growth model

The simulation model as described in the previous section operates with time intervals of the order of minutes, and with compartments of 1 cm at the top, where the gradients are steep. It is, of course, impossible to apply this model in the crop growth model, where our period of interest is of the order of hundred days and the size of the compartments is much larger. Therefore a simplified procedure has been worked out.
The basis is the potential evaporation as calculated from the Penman equation. The actual evaporation rate is obtained by multiplying the potential rate with a depression factor dependent on the soil moisture potential in the top compartment, as given in Fig. 31. This curve is constructed from the data calculated with the evaporation model. It is striking that the evaporation drops considerably below the potential value only after the top compartment has dried out below wilting point (SSURF $\equiv 1.5 \times 10^4$ cm) which may seem contrary to many other reports (Lemon, 1956). In those cases, however, always some average moisture content of a soil slab is used, and the drop may occur at any point. This depends on the evaporation rate and the hydraulic properties of the soil, which are the important factors in determining the gradients that will occur.
The relation between the volumetric moisture content of the top compartment and the soil moisture potential may be introduced as a tabulated function, when it is available. If this relation is not known, an alternative may be used in which the reduction factor is directly related to the moisture content of the top compartment. For this purpose a dimensionless moisture number is defined:

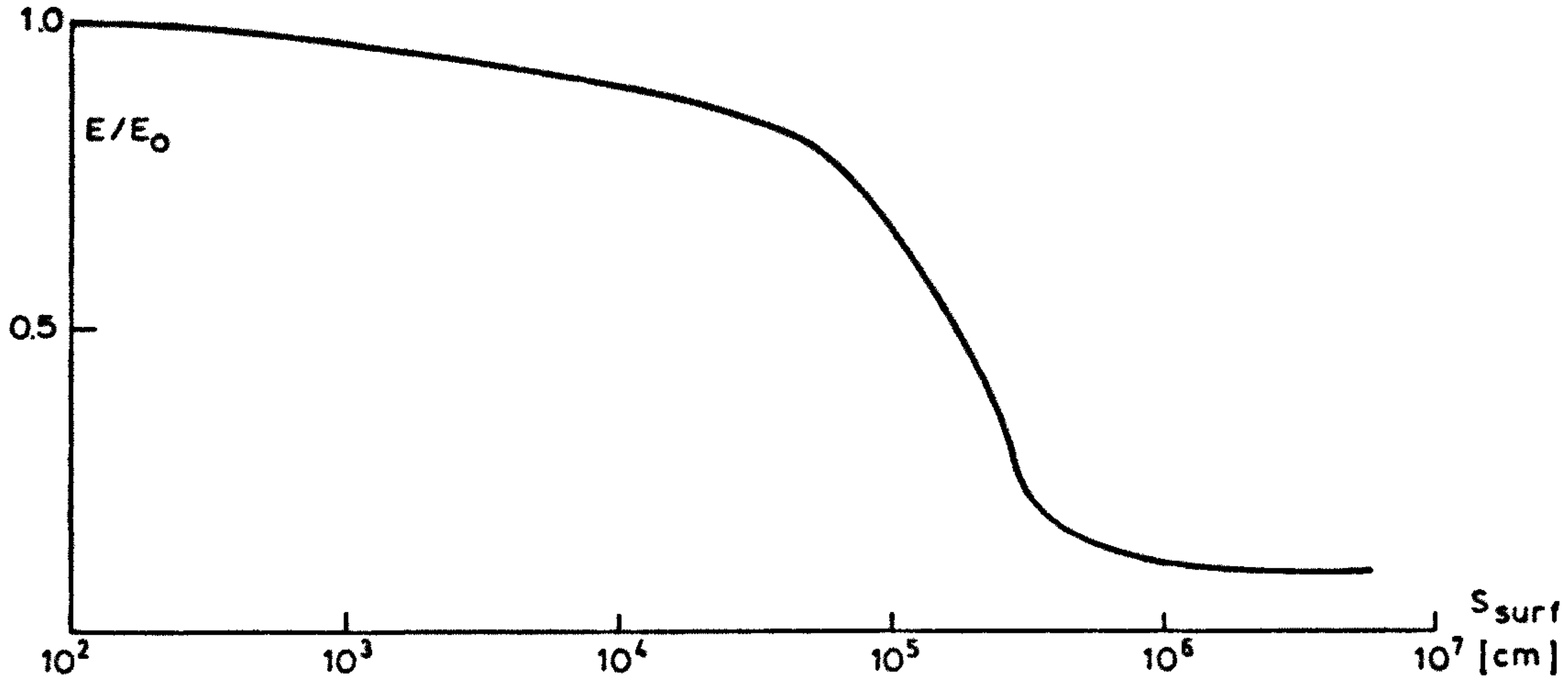

Fig. 31 | The relation between the ratio actual evaporation: potential evaporation (E/E_0) and the moisture potential at the surface (S_{surf}).

$$\theta' = \frac{\theta - \theta_a}{\theta_f - \theta_a}$$

in which

θ = actual moisture content in $cm^3\ cm^{-3}$
θ_a = moisture content at air dryness in $cm^3\ cm^{-3}$
θ_f = moisture content at field capacity in $cm^3\ cm^{-3}$

In a schematized situation, it seems reasonable to assume that the moisture content at wilting point is $\pm 1/3$ of that at field capacity and the moisture content at air dryness $\pm 1/3$ of that at wilting point (Bolt et al., 1965). When the soil surface is air dry, the evaporation rate is mainly determined by temperature gradients but is approximately 0.1 of the potential evaporation (Ritchie, 1971; Hillel, 1968). These assumptions enable the construction of a curve relating θ' and the moisture potential in the soil, as given in Fig. 32. Comparison with the experimental data plotted in the same figure shows reasonable agreement. Certainly for use under field conditions the proposed schematized relationship is good enough. When Figs. 31 and 32 are combined, the reduction factor for evaporation due to dryness of the top soil can directly be related to the moisture content in the upper soil compartment, for situations where the soil moisture retention curve is not known.

Evaporation takes place from the uppermost soil layer but because

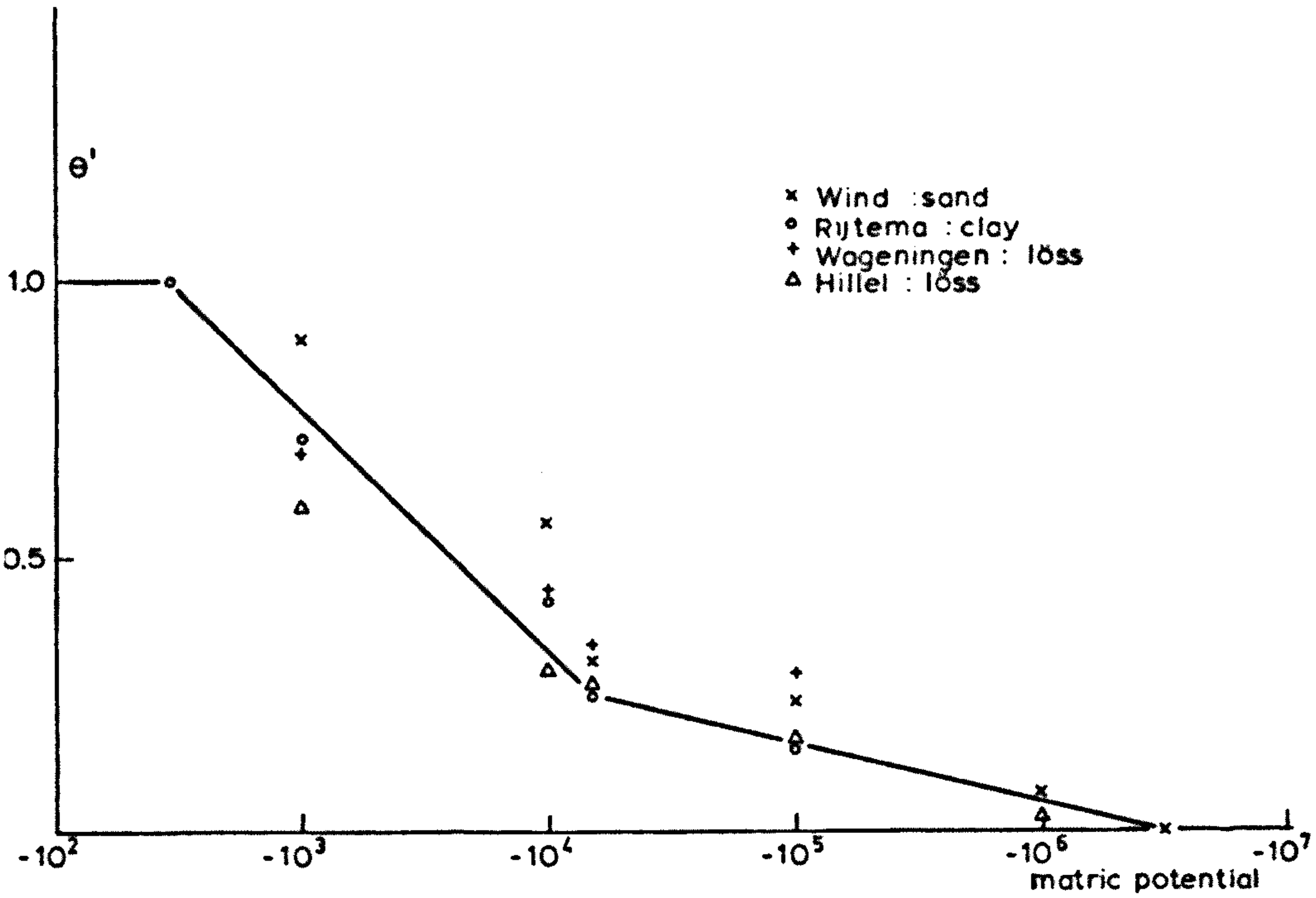

Fig. 32 | The relation between dimensionless moisture content (θ′) and matric potential of the soil for different soil types.

of developing potential gradients, soil moisture from deeper layers replaces the evaporated water. As this flow between compartments is not considered in the model the actual evaporation must be divided between the successive soil compartments. This is 'mimicked' with an exponential extinction of the soil moisture withdrawal according to the formulation:

$$E_x = F_x \times AE$$
$$F_x = d_x \times P_x / SUM$$
$$P_x = AMAX1(0., W_x - WLIM) \times e^{-K_e * Z_x}$$
$$SUM = \sum_{x=1}^{n} P_x \times d_x$$

in which

AE = actual rate of evaporation in mm day^{-1}
E_x = rate of water withdrawal from compartment x through evaporation in mm day^{-1}
d_x = thickness of compartment in cm
W_x = volumetric moisture content in cm^3 cm^{-3}

WLIM = volumetric moisture content at air dryness
Z_x = depth of centre of compartment below soil surface in m
K_e = extinction coefficient for moisture withdrawal.

For a given actual evaporation rate the steepness of the resulting gradients in the soil depends on the value of K_e. It is clear thus that this value is dependent on the moisture content-conductivity relation-

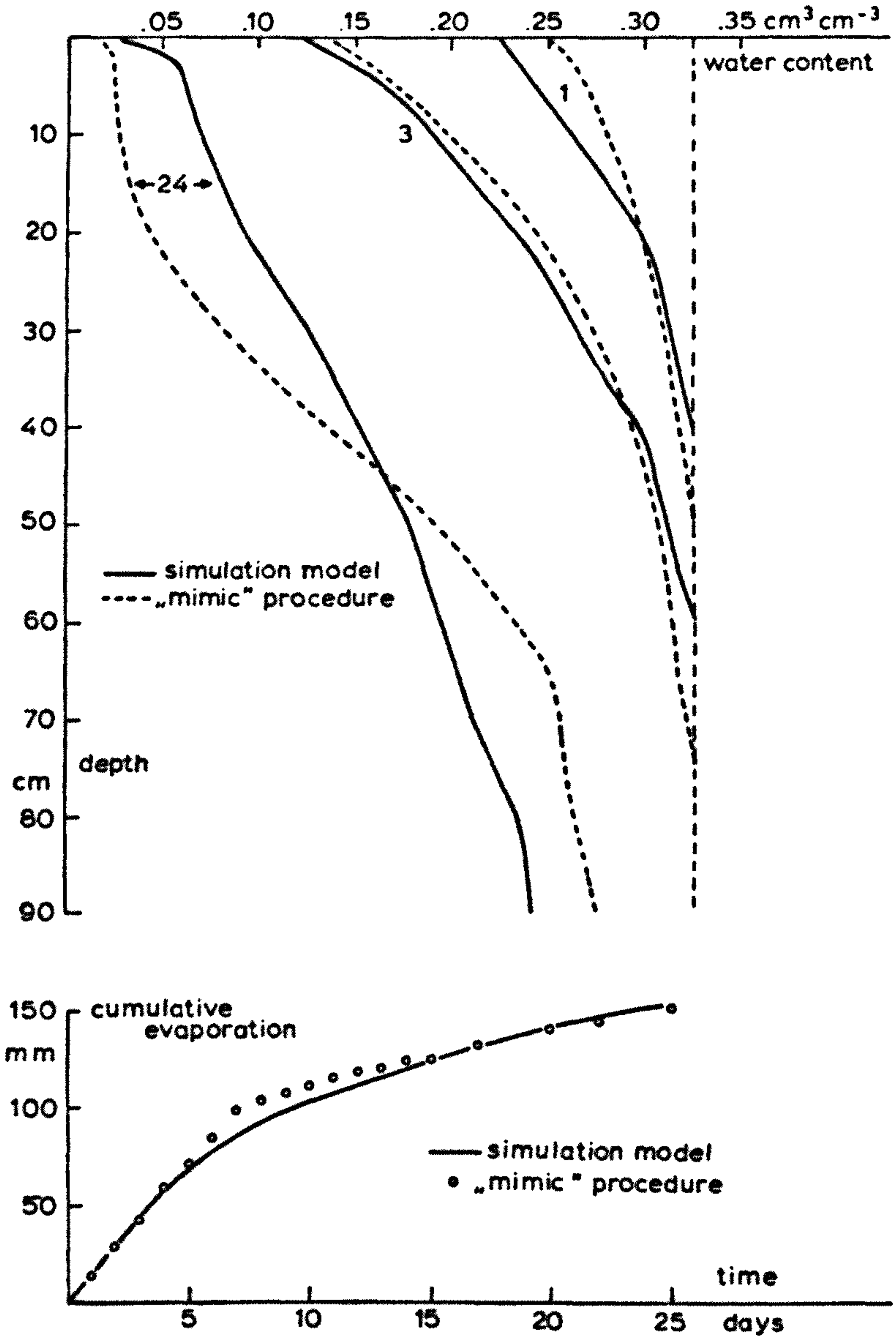

Fig. 33 | Comparison of moisture content profiles (top) and cumulative evaporation (bottom) calculated with the simulation model and the 'mimic' procedure for a löss column in the laboratory in Wageningen.

ship of the soil under consideration (compare Fig. 26). It is however difficult to relate the value of K_e directly to the conductivity value because both the actual value and the slope with respect to the moisture content are of importance.
The proposed procedure is therefore to use the simulation model for the calculation of the profiles and then to determine the appropriate

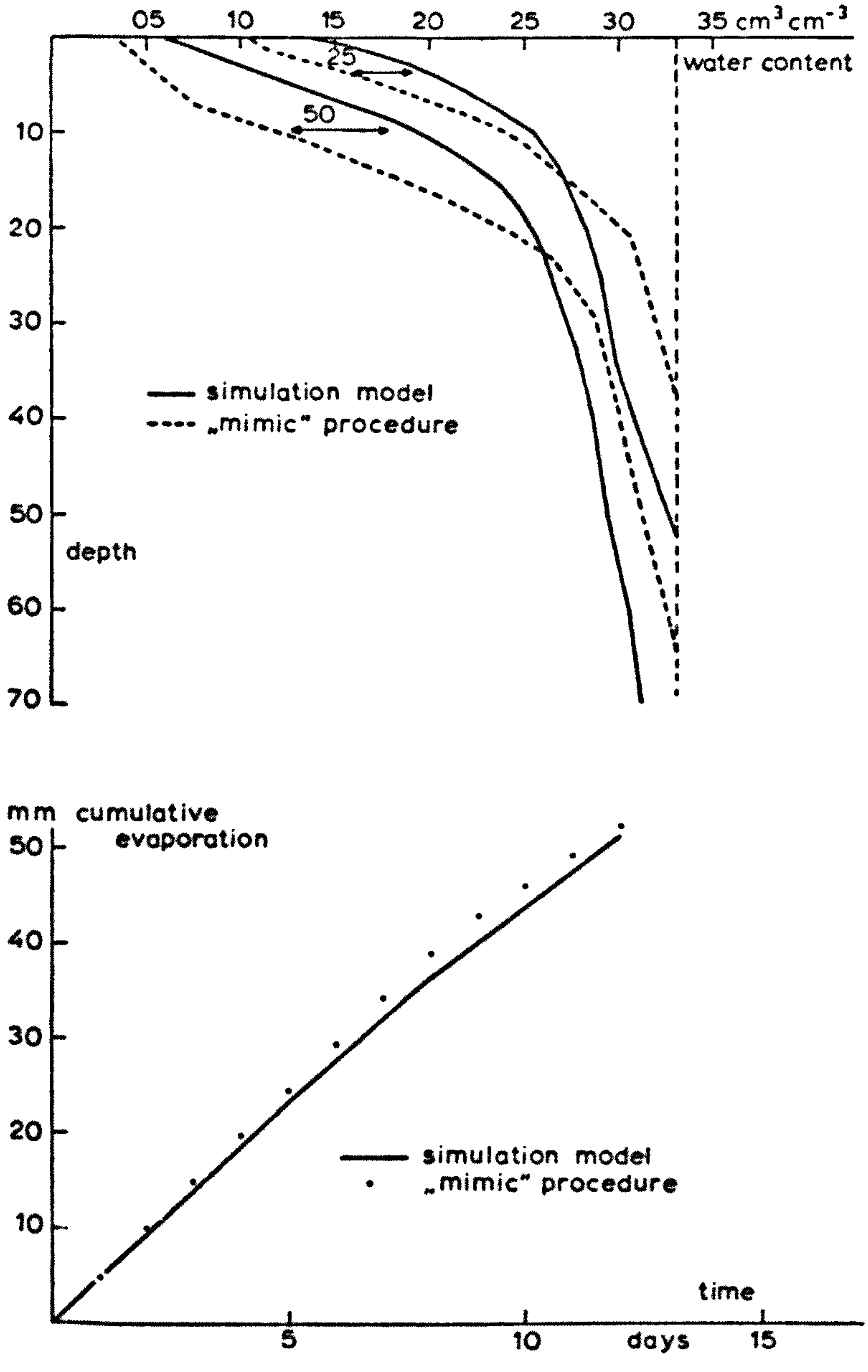

Fig. 34 | Comparison of moisture content profiles (top) and cumulative evaporation (bottom) calculated with the simulation model and the 'mimic' procedure for löss columns in the laboratory in Rehovot.

K_e value by running the simplified model with a number of K_e values. In Fig. 33 the results of the simplified model with a K_e-value of 5 are compared with the results of the simulation model for the Wageningen löss-experiment. The cumulative evaporation is predicted within ±15%, with the greatest deviations around the tentht day, when the moisture content in the top layer differs most. After 24 days the moisture distribution shows marked differences. However in terms of moisture availability to plant roots this difference is admissible. In Fig. 34 the results of a run with a K_e-value of 12.5 are compared with the simulated results of the second laboratory experiment. The same remark as above applies here.
These results show that this 'mimicking' procedure gives results which are good enough for the purpose of predicting evaporative losses under field conditions.

4.3 Water uptake by the roots

4.3.1 Introduction

The process of water uptake by the root system of a plant is rather complicated. Water moves from the soil to the roots along potential gradients and then passes through the root membrane probably again in a passive physical process. There is, however, evidence (Kuiper, 1964) that the conductivity of the root system for water is determined by active processes, and that it is thus dependent on the amount of reserves available in the roots. Much research has been carried out on functioning of the plant root system (Kramer, 1940; Brouwer, 1961, 1965; Weatherley, 1963; Barrs, 1971). For obvious reasons, however, these studies are mainly restricted to plants growing in nutrient solutions and under laboratory conditions. These circumstances are so different from the situation to which plant roots in the field are exposed, that it is questionable whether the results may be applied there.
Studies on root systems in the soil have the disadvantage that most phenomena are hidden from observation and that conclusions are drawn from circumstantial evidence. When roots are sampled and washed from the soil, parts are lost even when it is done carefully, especially the very thin root hairs, which may be important in the uptake processes. It is also practically impossible to relate the activity

of the root system to any measurable quantity like root length or root weight, even assuming that living and dead roots can be distinguished. Any information on the spatial distribution of the roots is completely lost. Experiments in which this technique was applied have usually added little to our understanding of root functioning. Only recently so-called 'rhizotrons' have been developed (Taylor, 1969) in which soil-root systems are studied in their natural environment. They consist of underground laboratories with transparant walls. At these walls the dynamic behaviour of root systems is followed by counting or with photography (Taylor et al., 1970). Although anomalies in behaviour are still observed, caused by the presence of the walls, this technique yields a large amount of information on the dynamics of root growth.

In recent years several models, describing the behaviour of a soil-root system have been developed (Gardner, 1960; Cowan, 1965; Lambert & Penning de Vries, 1973; Huck et al., 1974). Except for the last one, these models deal with non-growing root systems, thus using assumptions that seriously hamper the use of their results under field conditions. Moreover there are practically no experimental data to validate these models a limitation which restricts their applicability.

4.3.2 Experimental results

The models of water uptake by the roots all predict that withdrawal of water from the soil creates large potential differences around the root, which in turn hamper moisture flow as a result of the rapidly decreasing hydraulic conductivity in the soil. The potential gradients, or water content gradients extend over distances of the order of centimetres around the root. In an experiment to verify such models, plants were grown in perspex containers with dimensions $20 \times 50 \times 1$ cm, γ-ray equipment was adapted, such that the measuring resolution was 1 mm. Water content profiles were measured daily by the gamma-ray technique, which, with proper counting times, reaches an accuracy of $\pm 0.02\ cm^3\ cm^{-3}$. Under different conditions no water content gradients around the roots could be shown (Stroosnijder & van Keulen, 1972). It seems, that with growing root systems, the plant is able to grow its root towards the water, rather than transport the water over some distance towards the root. In the crop growth model it is therefore assumed that water uptake by the roots is not restricted by horizontal gradients in the soil, so that the average water content of a compartment is the variable determining the rate of withdrawal.

4.3.3 Water flux towards the roots and in the soil

As mentioned in Section 3.3 water flow between soil compartments, resulting from differences in moisture content is neglected in the crop growth model. In general, the change in water content due to uptake by the roots is much larger than that caused by redistribution in the soil under the influence of developing potential gradients (Gardner & Ehlig, 1962; Feddes, 1971). To check on the relative importance of this soil water flux as compared to root water uptake, some simulation experiments have been carried out. The simulation model for water transport in soils, described by van Keulen & van Beek (1971) has been used as a basis. In the equation for the net flow rate, a term is added, describing the withdrawal of water by an (existing) root system. The uptake of water by the roots from a particular compartment is governed by the external evaporative conditions and a forcing function, giving the distribution of root activity in the soil dependent on depth. In this way, both changes in weather and differences in root distribution can be taken into account. The simulations were carried

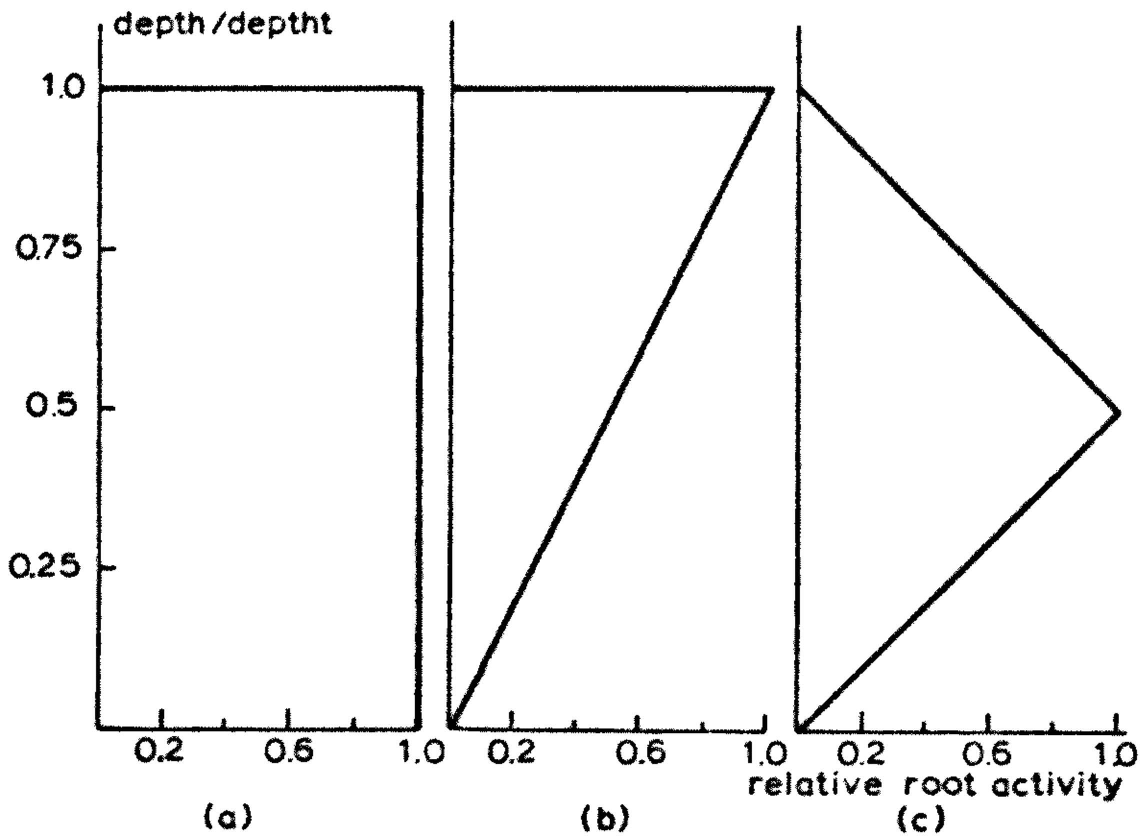

Fig. 35 | Schematized root activity functions used in the simulation experiments on the influence of soil moisture flow.

out with three schematized root activity distribution functions, as given in Fig. 35, assuming either constant activity throughout, or a peak activity in the top or the middle of the profile. The total rooted depth is in one case 60 cm, a situation existing in the field in the early stage of growth with a high moisture content in the soil and a relatively low evaporative demand. In the following simulation the rooted depth was 180 cm, resembling the conditions at peak growth, when the water content in the soil has already dropped and the evaporative demand of the atmosphere is high. For simplicity the initial moisture content of the profile was assumed to be constant throughout.

In Figs. 36 and 37 some results of these experiments are shown. Positive values for the root water flux always indicate depletion of soil water. Positive values for the soil water flux indicate addition of water through the soil towards a compartment, while negative values indicate additional depletion. In the situation, typical for the beginning of the growing season, the flux through the soil has a clear influence on the moisture distribution in the profile. With an uneven root distribution (Fig. 35c), flux through the soil can replace ±45% of the water

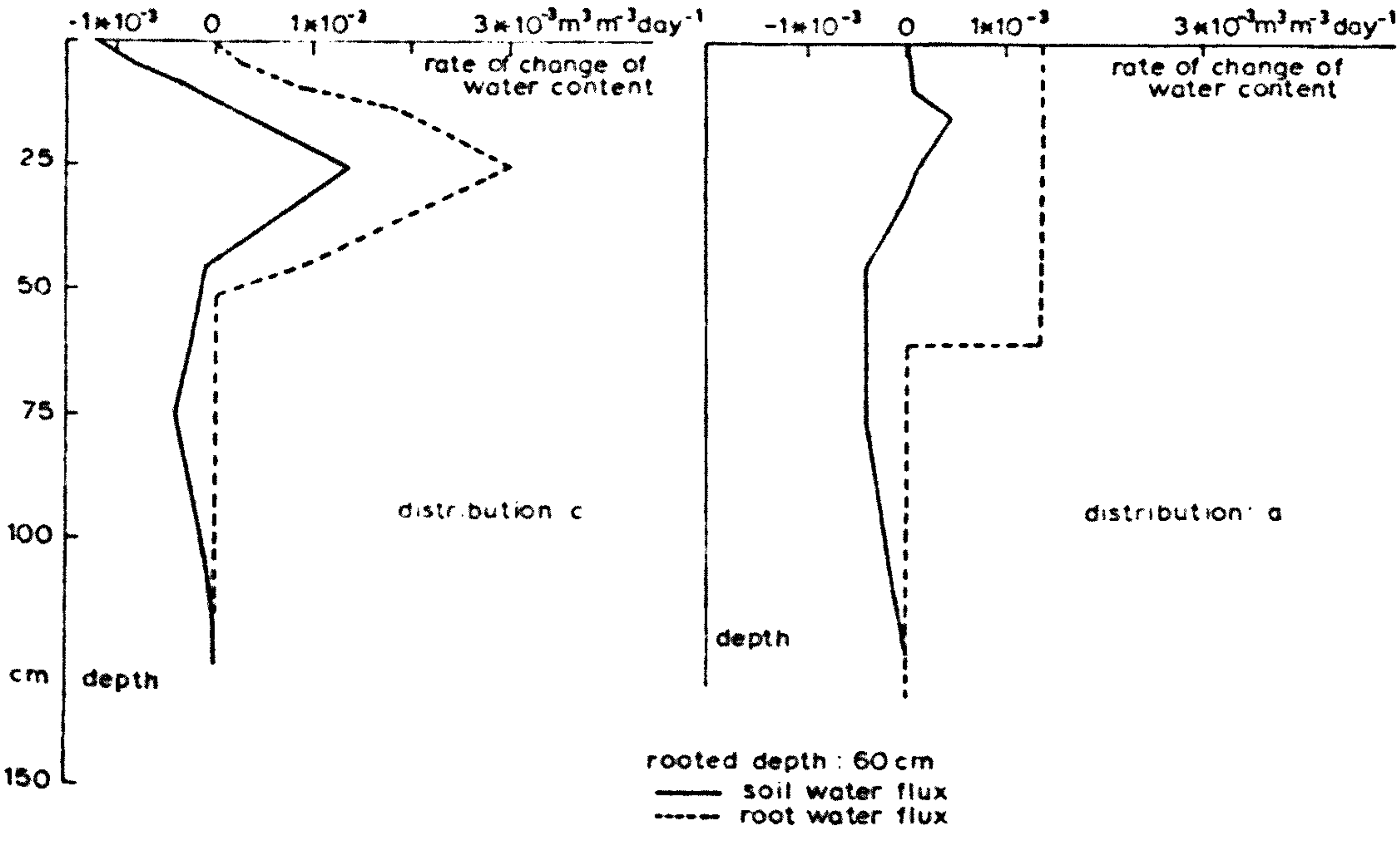

Fig. 36 | Relative contribution of water uptake by the roots and soil moisture flux to the change in moisture content in the soil, with shallow root system for different root distributions.

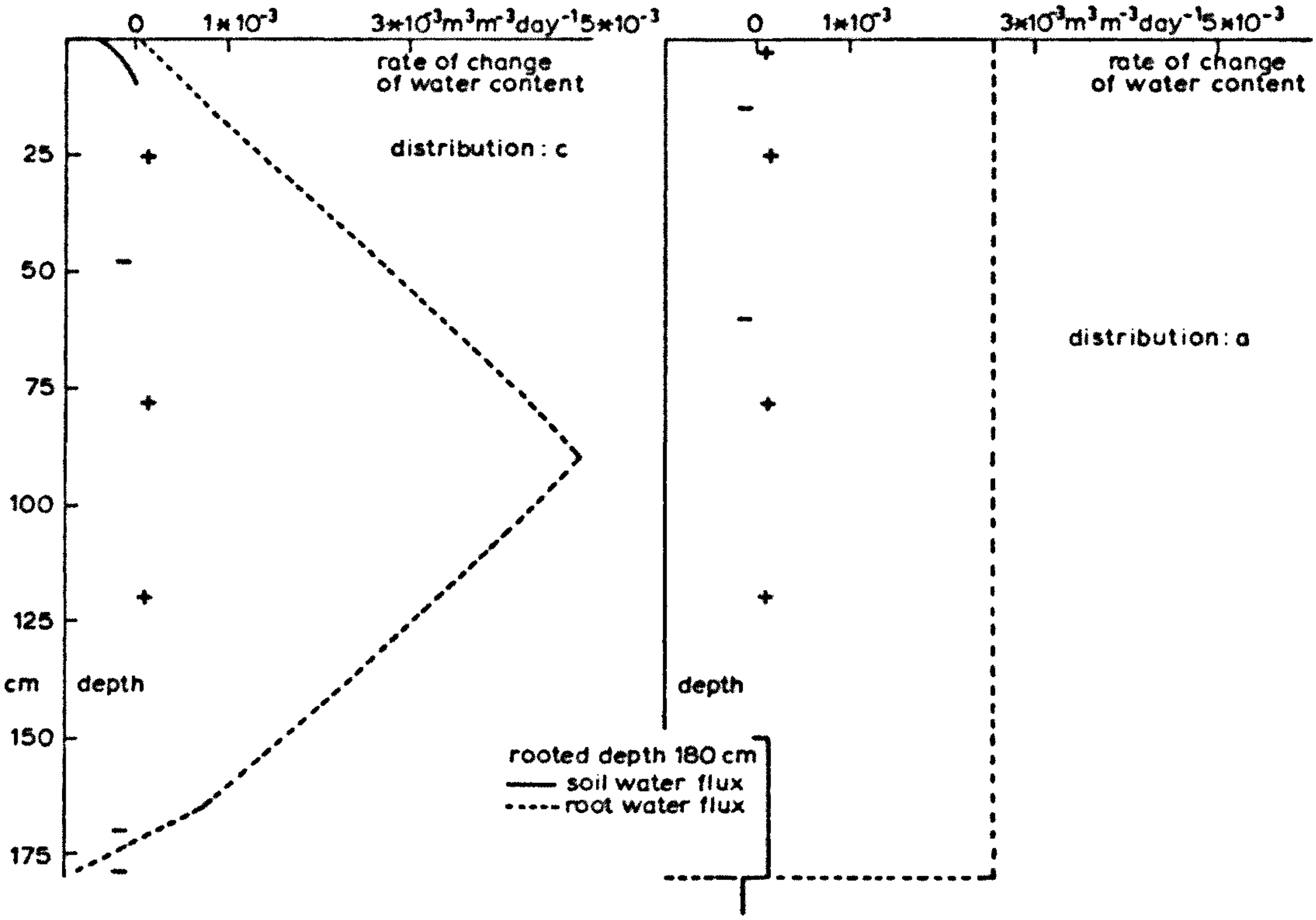

Fig. 37 | Relative contribution of water uptake by the roots and soil moisture flux to the change in moisture content in the soil, with deep root system for different root distributions.

removed by the roots, while additional water is added from below the root zone. Later in the season, when the water content in the profile is lower (0.15 m^3 m^{-3} as compared to 0.23 m^3 m^{-3}) and the evaporative demand higher, the influence of soil water flux is negligible. The fluxes are too small to be drawn on this scale and it is only indicated whether supply (+) or depletion (−) occurs.
In general it can be concluded that neglecting the soil water flux hardly influences the water availability to plant roots. This will even be less when a growing root system is considered, rather than a static one.

5 Plant submodels

5.1 The concept of the transpiration ratio

Since the classical work by Briggs & Shantz (1913) on the relation between dry matter production and water use of plants, many experiments have been done throughout the world on this subject. A major breakthrough in this field was achieved by the analysis of de Wit (1958), who showed that on the basis of physical and physiological processes, governing the transpiration and the photosynthesis of plants, there is a relation between both processes, dependent on the prevailing radiation intensity.
The free water evaporation and the water loss from crop surfaces increase almost linearly with increasing radiation intensity. The amount of available energy is practically always the main factor determining the evaporation and transpiration. Photosynthesis on the other hand approaches a maximum, as eventually the rate of CO_2 diffusion towards the active sites becomes the rate limiting factor.
In the arid regions, situated around the equatorial deserts (Section 1.1), the radiation intensity is in general high during the growing season. Photosynthesis is light saturated and the ratio of transpiration to assimilation is more or less proportional to radiation intensity or free water evaporation.
Since the standard error of the measured production in growth experiments was shown to be constant, de Wit arrived at the relation

$$P = MWE_0^{-1}$$

in which P is the dry matter production, W is the measured transpiration, E_0 is the average daily free water evaporation, and M is a proportionality factor, depending on plant species only. This relation satisfactorily described the results of water use experiments, both for plants grown in containers and for crops grown in the field. Values of the proportionality factor M calculated from the experiments of Briggs and Shantz in the Great Plains are: 207, 115 and 55 kg ha^{-1} day^{-1} for sorghum, wheat and alfalfa, respectively.

The above mentioned concepts have been used in various experiments to describe the relation between water use and dry matter production. Janssen (1972) investigating this relation for wheat, grown in the field in different years and under various rotational schemes in the arid region of Asian Turkey found a value for M of 106 kg ha^{-1} day^{-1}. In irrigation experiments with alfalfa and a number of pasture plants in the Central Negev of Israel, Tadmor et al. (1972) showed that the concept applied to these conditions. An M value of 105 kg ha^{-1} day^{-1} was found for alfalfa, while for the perennial range plants values of about 80 were established.

The remarkable difference between the M values for alfalfa obtained by Briggs and Shantz and by Tadmor et al. is probably due to varietal differences. In the Great Plains a hardy variety (ADI-E23) showing winter hardiness was used, while in the experiments in the Negev a non-hardy type (Hairy Peruvian) was grown. The latter variety shows a higher growth rate in summer and earlier flowering and may exhibit a more efficient use of water (A. Dovrat, pers. commun.).

The results of experiments with several crops in the Central Great Plains by Hanks et al. (1969) strongly supported the idea of de Wit. They calculated values of 125 kg ha^{-1} day^{-1} for winterwheat, 135–160 kg ha^{-1} day^{-1} for millet, and 140 kg ha^{-1} day^{-1} for grain sorghum. Recalculation of the results of irrigation experiments in Thorsby, Alabama, by Doss et al. (1964) yielded a value of 210 kg ha^{-1} day^{-1} for Sart sorghum. If the constancy of the proportionality factor M is considered, a number of difficulties arise however. De Wit already restricted the use to conditions where nutrients are not 'too low', the availability of water is not 'too high' and the leaf mass is not 'too dense'. Under these circumstances, assimilation and transpiration are not affected in the same way so that their relation changes.

Differences in the proportionality factor may occur during the growing season, caused by changes in daylength. The same amount of available energy spread out over a longer light period hardly influences the total transpiration of a canopy, but it may affect the assimilation through a more favourable distribution of the energy. The consequence is a lower value of M with a shorter daylength.

Another phenomenon which could change the relations as presented before is the fact that, even in climates with a high radiation intensity, a considerable portion of the dry matter is produced at times when photosynthesis is not saturated. However, the above mentioned considerations do not take into account the feedback of photosynthesis to the stomatal opening. There exists evidence (Takakura, 1974), that the stomata are regulated in such a way, that the CO_2 concentration in the stomatal cavity is kept constant within certain limits. Experiments carried out at IBS (Louwerse and van Laar, unpublished) also show that the internal CO_2 concentration remains constant over a considerable range of CO_2 concentrations in the air outside. Hence the stomata close, when the rate of photosynthesis decreases as a consequence of lower light intensities. Then the transpiration rate is more than proportionally reduced as the radiation intensity decreases. The qualitative consequences of this process are indicated in Fig. 38. It is clear that the ratio EA^{-1} does not change as much as shown by de Wit. Therefore the concept of the constant proportionality factor is not influenced so strongly by the period at lower light intensities.

When during the growing season the temperatures change considerably, the value of the proportionality factor may also be affected. The

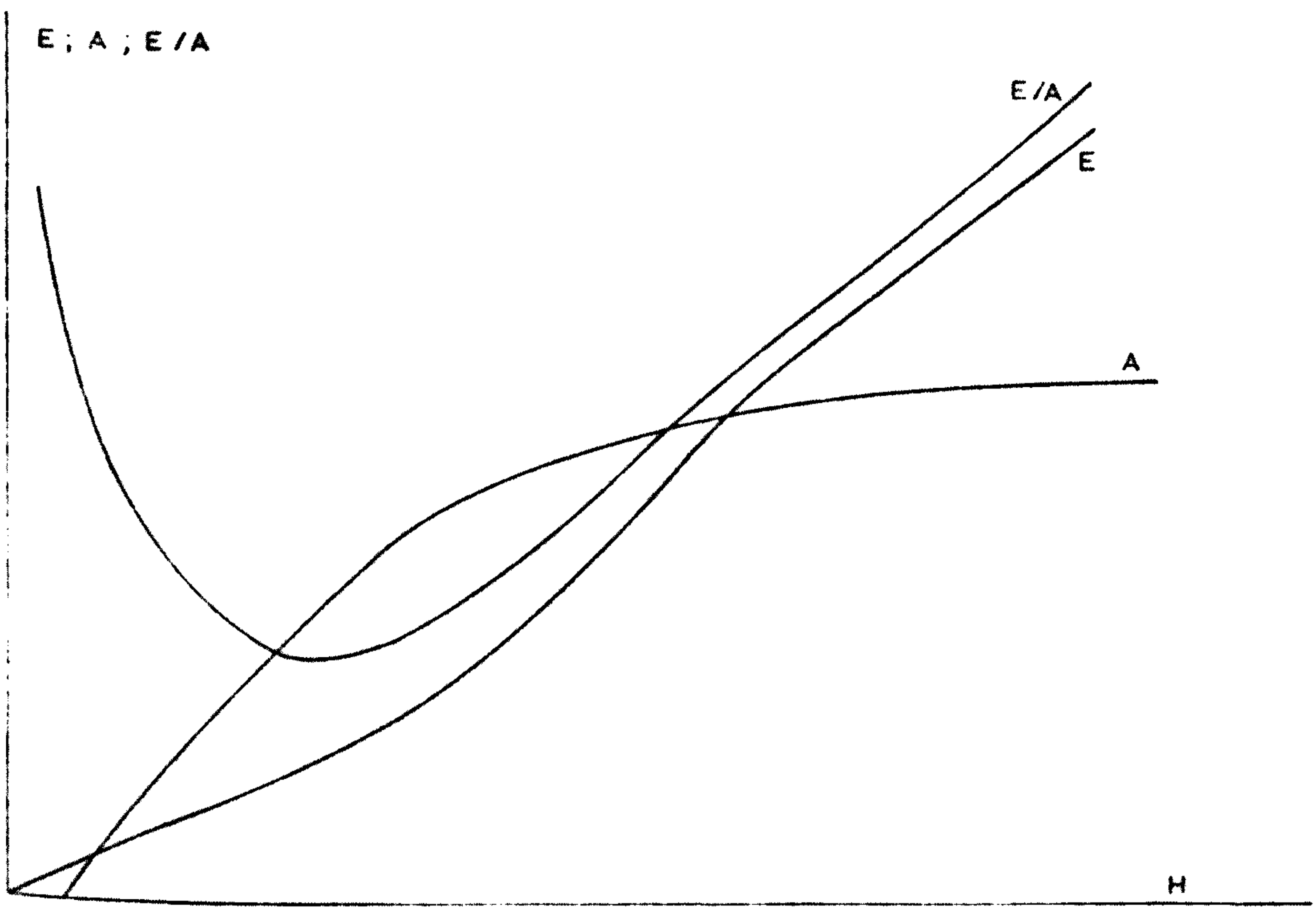

Fig. 38 | The relation between radiation intensity (–H–), transpiration (–E–), net assimilation (–A–) and their ratio (E/A), respectively.

temperature may be so low, that the enzymatic reactions in the photosynthetic process are affected, thus causing a sharp decline or even a complete standstill in assimilation. This will also cause the stomata to close, resulting in a lower transpiration rate at the same radiation intensity. Therefore the proportionality factor is not very sensitive to changes in temperature either.
From comparisons by de Wit and others, it appears that transpiration ratios determined from plants grown in containers can be applied to the field situation. The differences in general do not exceed 10%, which is within the limits of the accuracy obtained in these experiments.

5.2 The crop growth model

To use the concept of transpiration ratio in the model for the prediction of crop growth in areas where no investigations have been carried out, this ratio must be calculated. This can be done with the model, mentioned in Section 2.2, which calculates the photosynthesis, the respiration and the transpiration of a crop under optimum conditions, from physiological, physical and weather data. These weather data also provide the free water evaporation so that the proportionality factor also can be calculated. From validation experiments with this model, it is evident that the influence of stomatal behaviour on photosynthesis yields results, in good agreement with the measurements. The feedback of photosynthesis to the stomatal response however, is not (yet) included, causing differences between measured and calculated transpiration, especially under conditions, where photosynthesis is not light saturated. The model can thus be used to calculate the transpiration ratio, and relative differences between periods and between regions can be established. The absolute values, however, are not (yet) reliable, so that experiments to check the calculations are still necessary.
The BAsic CROp growth Simulator is a simulation model developed at the Department of Theoretical Production Ecology, and is based on the ELementary CROp growth Simulator, as described by de Wit et al. (1970). The model calculates the dry matter production and the transpiration of a growing canopy in the vegetative stage, optimally supplied with water and nutrients. Inputs are basic physical, physiological and chemical plant properties and macro-meteorological data from standard weather stations. The morphology of the canopy

is not simulated, but at present the LAI is given as a forcing function. In this section only a brief description of the model will be given, but a detailed report on the model and its validation will be published in another monograph of this series (de Wit et al., in prep.).

Weather

The weather data used as inputs are: daily total global radiation, daily minimum and maximum temperatures, daily wind speed and average dew point temperature. The current weather is calculated by sinusoidal interpolation for the temperature, assuming the minimum temperature to occur at sunrise and the maximum at 14h00, and from comparison of the measured radiation with standard values depending on time and place on earth. The dew point is assumed to be constant throughout the day.

Photosynthesis

The total crop photosynthesis is calculated by adding the photosynthetic rates of a number of leaf layers with known leaf area. In the separate leaf layers, allowance is made to distinguish between leaves at different angles with the sun and between sunlit and shadowed leaves. The intensity of the visible light in each layer – divided into direct and diffuse – is calculated from the intensity at screen height, depending on the scattering coefficient of the leaves, and assuming an exponential extinction with depth in the canopy, the extinction coefficient being dependent on the leaf angle distribution. From this light intensity and the CO_2 assimilation-light response curves of individual leaves, characterized by the quantum efficiency at low light intensities and a saturation value at high intensities, the rate of photosynthesis is calculated. The rate is dependent on the CO_2 concentration in the ambient air and the total resistance to CO_2 diffusion, which is the sum of the internal resistance, the stomatal resistance, the resistance of the laminar layer around the leaves and the resistance to turbulent transport in and above the canopy. To calculate the internal resistance, the temperature and the age of the leaves is taken into account. Allowance is made for the adaptation of the photosynthetic system to varying temperatures. The stomatal resistance is derived from the water status of the canopy and the light intensity. A simple function is used, in which stomatal opening is limited by either of the two driving variables. As

indicated above this is an oversimplification, which is at present being improved. The laminar resistance around the leaves is derived from the wind speed and the average size of the leaves. The resistance to turbulent transport from the canopy to the atmosphere is calculated from the wind speed, taking into account the aerodynamic properties of the crop and the stability of the atmosphere. A constant CO_2-concentration is assumed throughout the canopy.
The primary photosynthetic products are accumulated in the reserves, consisting of soluble carbohydrates.

Transpiration
Analogous to the photosynthesis, the total transpiration is calculated by adding the transpiration rates of individual leaf layers. In each layer this rate is derived from the absorbed radiation, being the sum of visible and near infrared light, the vapour pressure deficit in the ambient air and the resistance to vapour transport towards the atmosphere. This resistance includes the same elements as the resistance to CO_2 diffusion, except for the internal resistance. In the other elements the difference in molecular size between CO_2 and H_2O is taken into account. The vapour pressure deficit is again assumed to be constant throughout the canopy. The heat balance of the leaf layer also provides the leaf temperature, used in the photosynthesis calculation. From this an average canopy temperature is derived, used in the temperature dependent growth processes.

Crop water balance
The water status of the canopy is calculated from the balance between transpiration and water uptake from the soil. The uptake is dependent on the difference in potential between the water in the soil and in the plants and on the resistance of the roots to water flow. The resistance to water flow in the stem is of minor importance. The root resistance is calculated from the amount of roots and their degree of suberization. Soil temperature is taken into account, assuming that the temperature of the main root zone follows the air temperature with a delay of four hours and an appropriate decrease in amplitude. In the model, optimum soil water conditions are assumed, the potential being always 0.1 bar.

Crop growth
Growth is defined as increase in dry weight of the structural plant material. The growth rate is calculated from the amount of reserves present, assuming a constant relative consumption rate of these reserves modified by the temperature and the water status of the crop. Respiratory losses: growth respiration, caused by the conversion of primary products into structural material and maintenance respiration, caused by continuous rebuilding of enzymes and leakage through cell membranes are taken into account. Both processes are temperature-dependent and allowance is made for the chemical composition of the material.
The division of the newly formed material between shoot and root is governed by the functional balance principle of Brouwer (1963) and depends on the water status of the canopy.

Roots
As indicated before, the processes playing a role in root growth are not fully understood and these are being studied at present. Until now intelligent guesses have been used to define the lifetime of roots, their suberization rate and their decay rate. The last two processes depend on soil temperature.

Evaluation
Some of the above described processes are fast and require short-term experiments with a high resolution in time to be validated, while others have a much greater time constant and must be checked in long term experiments.
The short-term experiments are being carried out with crop enclosures in the field using mobile equipment (Louwerse & Eikhoudt, 1974). Especially the rate of CO_2 exchange and the transpiration rate are evaluated. Some results from a number of experiments with a wheat crop are given in Table 6. These experiments are treated more extensively by van Keulen & Louwerse (1974). The long-term experiments, validating the aerial dry matter production are carried out with periodic harvests.
To compare the results with measurements on single plants grown in containers, additional assumptions have to be made, especially with respect to the radiation climate and the transport of CO_2 and water vapour, away from or to the leaf surfaces.

Table 6 Comparison of measured and simulated values from enclosure experiments with wheat.

Date	transpiration mm day^{-1}	net photosynthesis kg CO_2 ha^{-1} day^{-1}	
73-05-22			
meas.	10.8	850	high temperature
simul.	9.9	892	
meas.	10.0	886	low temperature
simul.	8.6	925	
73-06-20			
meas.	14.5	793	high temperature
simul.	13.9	898	
meas.	10.4	853	low temperature
simul.	11.4	946	

5.3 Experimental results

5.3.1 Material and methods

To determine the water use efficiency of various plant species from the natural vegetation in Israel, growing in containers, experiments were carried out at the Avdat Desert Research Centre (30°47′ NL, 35°46′ EL, at 550 m altitude) of the Hebrew University, in the Negev desert of Israel. The complete series of experiments ran from October 1971 to July 1973, with only slight differences between successive treatments.

The plants were grown in plastic buckets with a content of 12 l. The buckets were filled with 13.5 kg of dry local löss (lössial sierozem), with a 'field capacity' of ±25% and a 'wilting point' of ±10% by volume. The soil was mixed with sufficient fertilizer, 7 g N, 12 g K and 10 g P per bucket, before filling. In the first series, when this mixing was omitted, the plants were watered with nutrient solution to ensure adequate mineral supply. Most species were sown directly in the buckets, but because of poor germination in the pots of some of the local species seedlings were transplanted from the field. To prevent direct soil surface evaporation, the surface was covered with ±5 cm of coarse gravel. This gravel layer also prevented crust formation as a result of repeated watering, which could cause aeration problems. To check on the effectiveness of the layer of gravel, 'control buckets' were installed, in which no plants grew. The direct evaporation, determined in this way which was in general less than 10% of the water lost by the transpiring plants, was used to adjust the transpiration data. When direct soil surface loss is a considerable proportion of the total water loss, the transpiration data are not reliable. If this situation occurred then the buckets were not taken into account.

Because of the prolific tillering of most of the native species, the containers could not be sealed by lids as done by Briggs and Shantz.

The soil in the pots was kept at approximately field capacity by adding known amounts of water each day, or with larger plants and under high evaporative conditions twice a day. The amount to be added was determined by weighing a few buckets to estimate the water loss. Approximately once a week all pots were weighed to determine the total evapotranspiration; then they were refilled to the original weight. These weights were adjusted a few times during the growing period to account for the increase in weight of the plant material.

To account for the influence of rain, the pots were, if possible, weighed before and after a shower. The average annual rainfall in Avdat is 90 mm and only occasional showers occur. In later series buckets and plants were covered with plastic at the onset of a shower.

The plants were preferably harvested in the vegetative stage, which was, however, impossible with some of the local species that flowered very soon after sprouting. The fresh weight of the shoot was determined and the dry weight after drying for some days at

70 °C. The roots were washed from the soil over a narrow sieve and after removal of stones, also dried at 70 °C to determine the dry weight. Some of the smaller roots were lost in this procedure, but the error is not too large, as the weight of these fine branches is negligible.

A standard weather station of the Israeli Meteorological Service is situated at the research centre and the meteorological data were collected there: daily radiation, daily minimum and maximum temperature, daily dew point temperature and daily wind run. These data were used in the calculation of the Penman evaporation as well as in the simulation model.
A similar set of experiments was carried out in Wageningen in the summers of 1972 and 1973. The water use efficiency of wheat and maize growing in Mitscherlich pots was determined. Here the soil was covered with ±5 cm of perlite to prevent direct soil evaporation. The pots were placed in the so-called 'mussenkooi', a construction with a glass roof and sides of wire netting to prevent bird damage. The plants are sheltered from rain at the same time. The soil used was a local sandy soil, kept at field capacity by watering every two or three days. The meteorological data were supplied by the Department of Physics and Meteorology of the Agricultural University, taken from their field about three kilometers from the experimental site.

5.3.2 Results and discussion

The average measured dry matter yields of shoot and root per pot and the transpiration coefficients obtained by dividing the total amount of water transpired by the total dry matter harvested are given in Tables 7 and 8 for the seasons 1971/1972 and 1972/1973 respectively, in both years for several growth periods.
It is striking that the first series in the '71/'72 season (oats and barley) have shoot:root ratios below 1. It is likely that annual plants form a rather vigorous root system in the early stages of development on which they can rely later for adequate supply of water and nutrients. However, these results were not repeated in the second year, where also the total amount of dry matter produced in about the same period was much higher. The growth conditions must have been more favourable in the second season, although it is not clear, what the adverse circumstances in the first season were. The general trend

Table 7 Measured transpiration coefficients in pots in Avdat 1971/1972.

Species	No of pots	dry shoot g/pot	dry root g/pot	total dry weight g/pot	TRC g H_2O/g DM
	71-10-08/71-11-22				
Avena sativa	4	10.3	17.0	27.3	170
Hordeum sativum	4	7.7	15.7	23.4	173
	71-10-08/72-01-25				
Avena sativa	8	175	79	254	79
Hordeum sativum	8	98	71	169	104
Triticum sativum	6	110	47	157	129
Reboudia pinnata	6	35	7	42	146
Medicago hispida	10	47	17	64	157
Hordeum murinum	10	47	31	78	129
Avena sterilis	10	75	65	140	124
	72-02-29/72-04-13				
Avena sativa	6	85	20	105	211
Hordeum sativum	6	93	25	118	187
Triticum sativum	6	81	19	100	220
Reboudia pinnata	6	54	6	60	275
Medicago hispida	5	27	7	34	226
Triticum durum	6	92	21	113	194
Trigonella arabica	6	92	8	60	222
	71-10-08/72-03-09				
Avena sativa	6	256	93	349	112
Hordeum sativum	7	218	85	303	118

Table 8 Measured transpiration coefficient in pots in Avdat 1972/1973.

Species	growing period	Nr. pots	dry shoot g/pot	dry root g/pot	total dry weight g/pot	TRC g H_2O/ g DM
Avena						
sativa	72-10-04/72-11-17	2	123	52	175	235
(oats)	72-10-04/72-12-08	2	156	57	213	233
	72-10-04/73-01-05	2	280	87	367	194
	72-10-04/73-01-26	2	341	73	414	221
Hordeum						
sativum	72-10-05/72-11-17	3	118	63	181	217
(barley)	72-10-05/72-12-08	3	167	98	256	191
	72-10-05/72-12-29	3	270	90	360	187
	72-10-05/73-02-23	3	373	136	509	224
Triticum						
sativum	72-10-17/72-11-27	3	122	44	166	217
(wheat)	72-10-17/72-12-08	3	161	70	231	190
	72-11-17/73-02-16	3	161	51	212	131
	72-15-12/73-03-16	3	128	61	189	100
	73-01-05/73-03-16	6	80	41	121	166
Reboudia						
pinnata	72-11-09/73-01-12	2	50	15	65	155
	72-12-10/73-02-16	3	37	4	41	168
Medicago						
hispida	72-10-18/73-03-02	3	72	11	83	192
	72-11-28/73-03-02	3	48	12	60	169
Hordeum						
murinum	72-10-20/72-12-22	2	69	26	95	144
	72-10-27/73-01-19	2	128	38	166	159
	72-10-27/73-02-16	2	220	68	288	178

Table 8 (continued)

Species	growing period	Nr pots	dry shoot g/pot	dry root g/pot	total dry weight g/pot	TRC g H_2O/ g DM
Avena						
sterilis	72-11-01/73-12-22	3	43	29	72	111
	72-11-01/73-01-26	3	96	45	141	129
	72-11-01/73-03-02	3	201	63	263	154
	72-11-01/73-03-16	2	216	93	309	164
Trigonella						
arabica	72-12-08/73-02-16	3	22	4	26	154
	72-12-08/73-03-02	3	44.5	5.5	50	131
Stipa						
capensis	72-10-27/73-01-12	2	48	15	63	181
	72-10-27/73-02-16	2	110	24	134	169
	72-10-27/73-03-02	2	106	11	117	165
Phalaris						
minor	72-11-01/72-12-22	2	52	30	83	157
	72-11-01/73-02-16	2	89	27	116	190
	72-11-01/73-02-16	2	178	105	283	162
Erucaria						
boveana	72-12-22/73-03-02	2	55	16	71	207
Malva						
sylvestris	72-10-27/73-02-16	6	105	34	139	142

is in both years, however, that the shoot:root ratio increases, when the growing period lengthens thus indicating that progressively less of the photosynthates are transferred to the underground plant parts. Comparison of the values of the transpiration coefficient for the various growing periods shows that they are rather high in early autumn, when the temperatures and the radiation intensity are high. This is followed by the real winter period (Dec.-Febr.) with low temperatures and a low radiation level leading to decreasing transpiration coefficients. In spring the values go up again, reflecting the rising evaporative demand from the atmosphere.

The measured water use efficiencies for the cultivated species (wheat, barley, oats) and the species from the natural vegetation (Reboudia, Hordeum murinum, Phalaris, Trigonella etc.) show very little difference when grown in the same periods. In comparison it should be born in mind, that the somewhat faster germination of the cultivated species may lead to a different water use pattern and thus to differences in the overall efficiency. These variations can cause differences of the order of 10% for plants grown during the same period. These results show again that whatever plant breeding may have changed in the properties of present-day cereals, no basic increase in efficiency of water use has been achieved.

The very low values for Avena and Hordeum in the second period of '71/'72 cannot be explained. In general there is not much difference between wheat, barley and oats. However in this period the oats produced considerably more than the wheat at about the same transpirational loss, while the barley had a much lower transpiration with the same production. For the oats there may be some speculation about a better adaptation of this cultivar to the low temperatures encountered during this period, compared with wheat. This does not seem very likely, however, because the wheat cultivars usually do not have such an extreme response to low temperatures and it is to be expected that the local species would at least be equally well adapted to these conditions. The explanation becomes even more difficult as the phenomenon did not reoccur in the second season, and literature data do not suggest such differences.

In the third period (02-29–04-13) Reboudia is the only exceptional case. The data indicate, however, that here a substantial part of the root system, which consists of a large number of very fine roots, must have been lost during harvest. The other values are all within 10%

of the average, as good an accuracy as can be obtained with these experiments.

In Figs. 39 and 40 the average dry matter yield per pot is plotted against the ratio of total transpiration to average free water evaporation. For each period that the actual water loss is known, the ratio is calculated and these ratios are added, weighted to the number of days of that particular period. The slope of the eye-fitted lines gives the value of the proportionality factor M. In Fig. 39 it is evident that the value of M has a drift in time, leading to higher values in the spring experiments, although here also the oats (Avena) behave exceptionally.

There are a number of reasons for this variation. Firstly the transpiration and the calculated free water evaporation do not react in the same way to differences in evaporative demand of the atmosphere. At lower humidities and higher radiation intensities generally prevailing in spring, plants may react by closing their

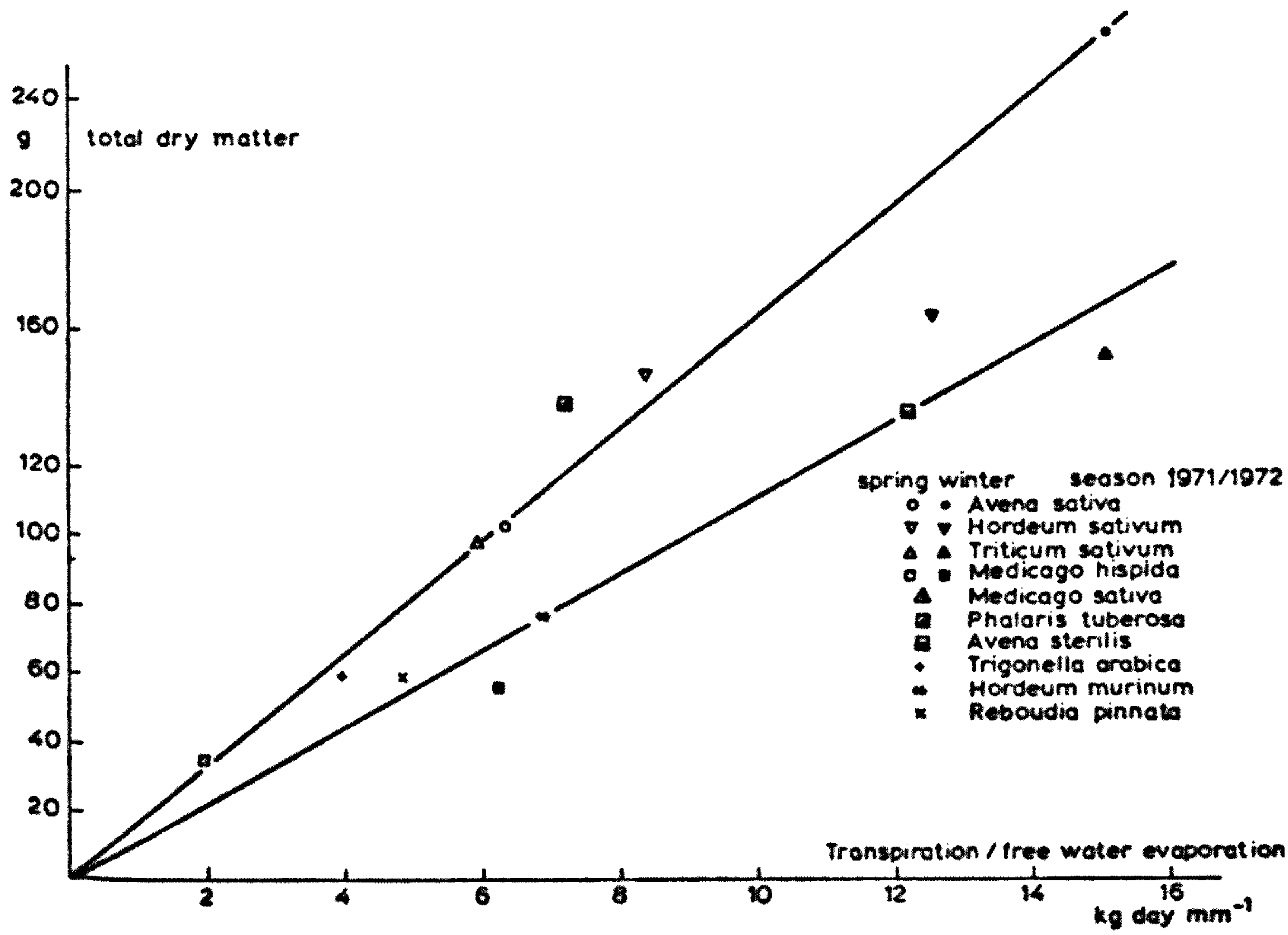

Fig. 39 | The relation between total dry matter production and the ratio transpiration: free water evaporation as determined in pot trials in Avdat in '71/'72.

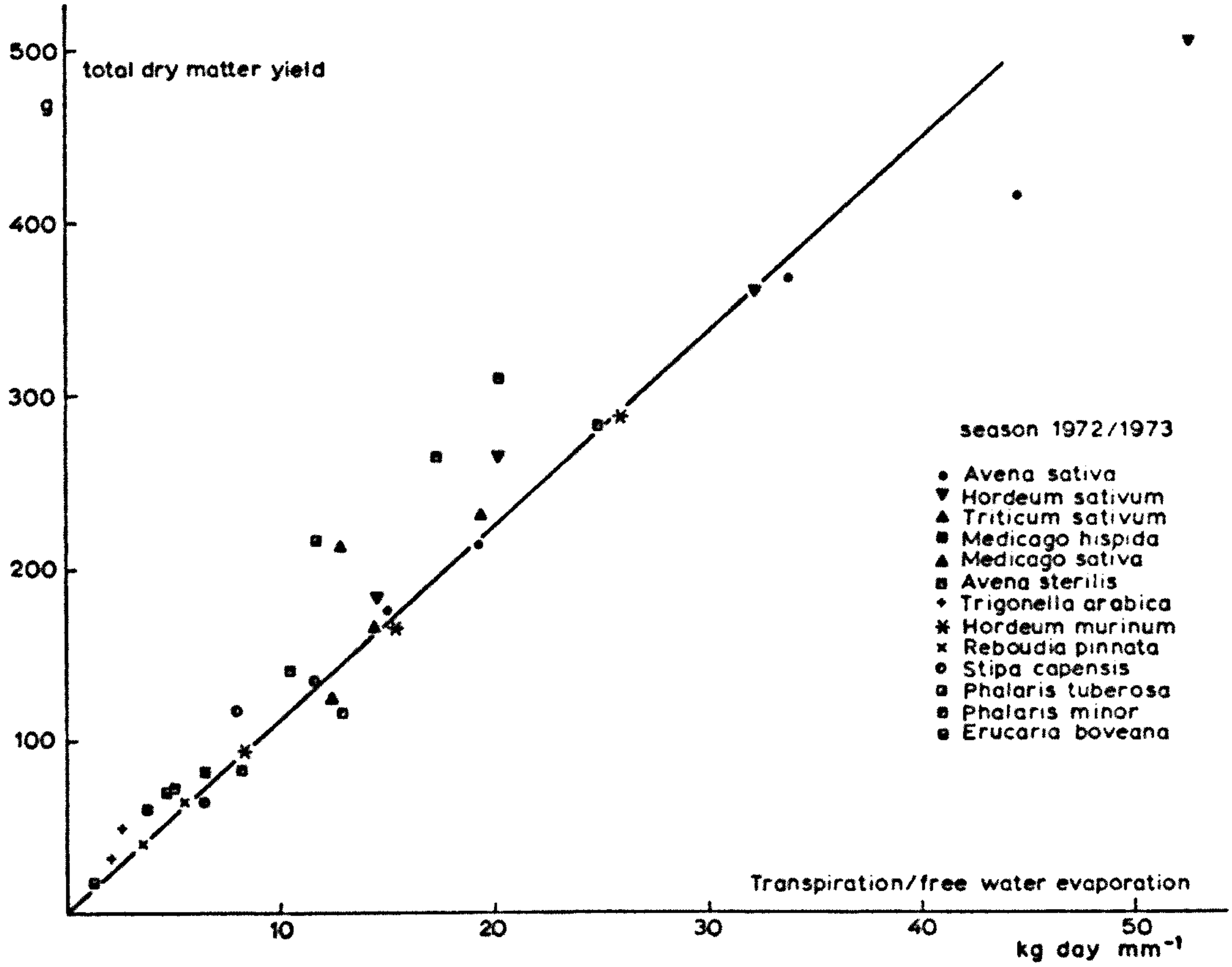

Fig. 40 | The relation between total dry matter production and the ratio transpiration: free water evaporation as determined in pot trials in Avdat in '72/'73.

stomata during the midday period, thus leading to lower calculated M-values. Also the increasing daylength creates more favourable conditions for assimilation through a better light distribution. This causes higher production at the same transpirational loss. There may finally be some influence of the temperature, which was probably more suitable for assimilation in the spring period.

In the second season (Fig. 40) the growing periods were not so clearly separated, but here the same tendency is visible, i.e. an increasing value for the proportionality factor for plants grown in the spring period.

It is thus obvious, that although the concept of the constant proportionality factor gives satisfactory results in a number of situations and interspecific differences are small, it is not possible to calculate the dry matter production during a whole growing season on basis of a single constant value.

5.3.3 *Comparison of measured and simulated results*

To test whether it is possible to calculate the transpiration coefficients with BACROS, a number of the experimental periods were simulated. Application of the model to single plants grown in containers is, however, difficult. Both transpiration and production are strongly dependent on the leaf area index which is entered in the model as a forcing function. In the pot trials, these values lose their meaning as the radiation climate calculated on basis of the exponential extinction does not apply here because the plants receive light from the sides as well. The same holds for the extinction of the wind speed, which in these pots is certainly different from the field situation. To adopt a uniform procedure, the model has been run during the whole period with a constant leaf area index of 2, thus creating conditions in which part of the leaf area is shaded. This value is chosen rather arbitrarily, but for the sake of comparison of different periods it is not very important. The model was fed with the physiological properties of wheat, as determined in the laboratory, or from literature. The properties are the same as those used in the simulation of the enclosure experiments shown in Table 6.

To calculate the transpiration coefficient for a certain experiment the following procedure was used: For each period that the actual transpiration from the pots is known, the ratio between dry matter production and water loss is calculated with the model. These values are then multiplied by the measured transpiration thus giving an amount of dry matter produced. These productions are added for the complete period between germination and harvest. Finally the total measured transpiration is divided by the calculated dry matter production yielding the calculated transpiration coefficient.

In Table 9 the measured and calculated values are compared. Only the experiments with the cultivated species are given, because the differences with the local species are negligible. In general the calculated and measured coefficients agree within 25%, with a general tendency for the calculated values to be higher. It is very difficult to pinpoint the reason for the discrepancies. The problems mentioned before concerning the radiation climate and the exchange with the atmosphere of single plants may play a role, as the illumination on all sides could lead to a more efficient use of the available energy in the assimilation process. Another difficulty is the determination of

Table 9 Comparison between measured and simulated transpiration coefficients.

Species	growing period	measured gH_2O/gDM	simulated gH_2O/gDM	ratio sim:meas.
Avena sativa	71-10-08/71-11-22	170	165	0.97
(oats)	71-10-08/72-25-01	79	147	1.86*
	71-10-08/72-03-03	112	146	1.31
	72-02-29/73-04-13	211	250	1.19
	72-01-04/72-11-17	235	257	1.10
	72-10-04/72-12-08	233	243	1.05
	72-10-04/73-01-05	194	206	1.07
	72-10-04/73-01-26	221	197	0.90
Triticum				
sativum	71-10-08/72-01-25	129	147	1.14
(wheat)	72-02-29/72-04-13	220	242	1.10
	72-10-17/72-11-27	217	228	1.05
	72-10-17/72-12-08	190	229	1.21
	72-11-17/73-02-16	131	218	1.67*
	72-12-15/73-03-16	160	198	1.24
	73-01-05/73-03-16	166	202	1.22
Hordeum				
sativum	71-10-08/71-11-22	173	185	1.07
(barley)	71-10-08/72-01-25	104	149	1.44*
	71-10-08/72-02-09	118	147	1.25
	72-02-29/72-04-13	187	228	1.22
	72-10-05/72-11-17	217	246	1.14
	72-10-05/72/12-08	191	231	1.21
	72-10-05/72-12-29	187	206	1.11
	72-10-05/73-02-23	224	209	0.94

the respiration rate, especially the maintenance respiration. These losses are proportional to the biomass present and it is not possible to determine them in relation to the actual amounts of plant in the buckets. Probably a certain radiation climate leading to a given assimilation:transpiration ratio is achieved at lower biomass values per unit surface in buckets than in the field, where the plants are forced into a limited space by the surrounding plants. Then the respiratory losses would be reduced, which is also so when a greater portion of the leaves is at high radiation intensities, thus enabling the utilization of part of the sun energy directly for growth and maintenance (Penning de Vries, 1974). With the present knowledge it seems very speculative to attribute the discrepancies to one of the above mentioned factors.

Three values, marked with an asterisk are well outside the range. The values for oats and barley (1.86 and 1.44 respectively) have been discussed in Section 5.3.2 and the simulation gave no additional clue to explain these results. Also the very low value for the wheat measured from 72–11–17 – 73–02–16 cannot be explained, although there is no indication that any mistake occurred during the experiment.

The agreement between simulated and measured results is in general satisfactory, and it may be argued that the discrepancies will be even smaller when the stomatal behavior is programmed according to the ideas which are being developed at present in the Department (Section 5.2). It seems therefore admissable to use calculated values of the transpiration coefficient when new areas have to be explored and the production potential must be calculated. In the next section a simplified procedure to calculate the transpiration coefficients will be worked out, based on the results of the simulation model.

5.4 Application in the crop growth model

Introduction

Although the value of the proportionality factor is approximately constant when calculated for a particular plant species for a whole growing period in different years, considerable fluctuations may occur over shorter periods of time. In Fig. 41 the values for weekly periods are given, obtained from the transpiration coefficients calculated with the method given in Section 5.3.3 and the free water evaporation

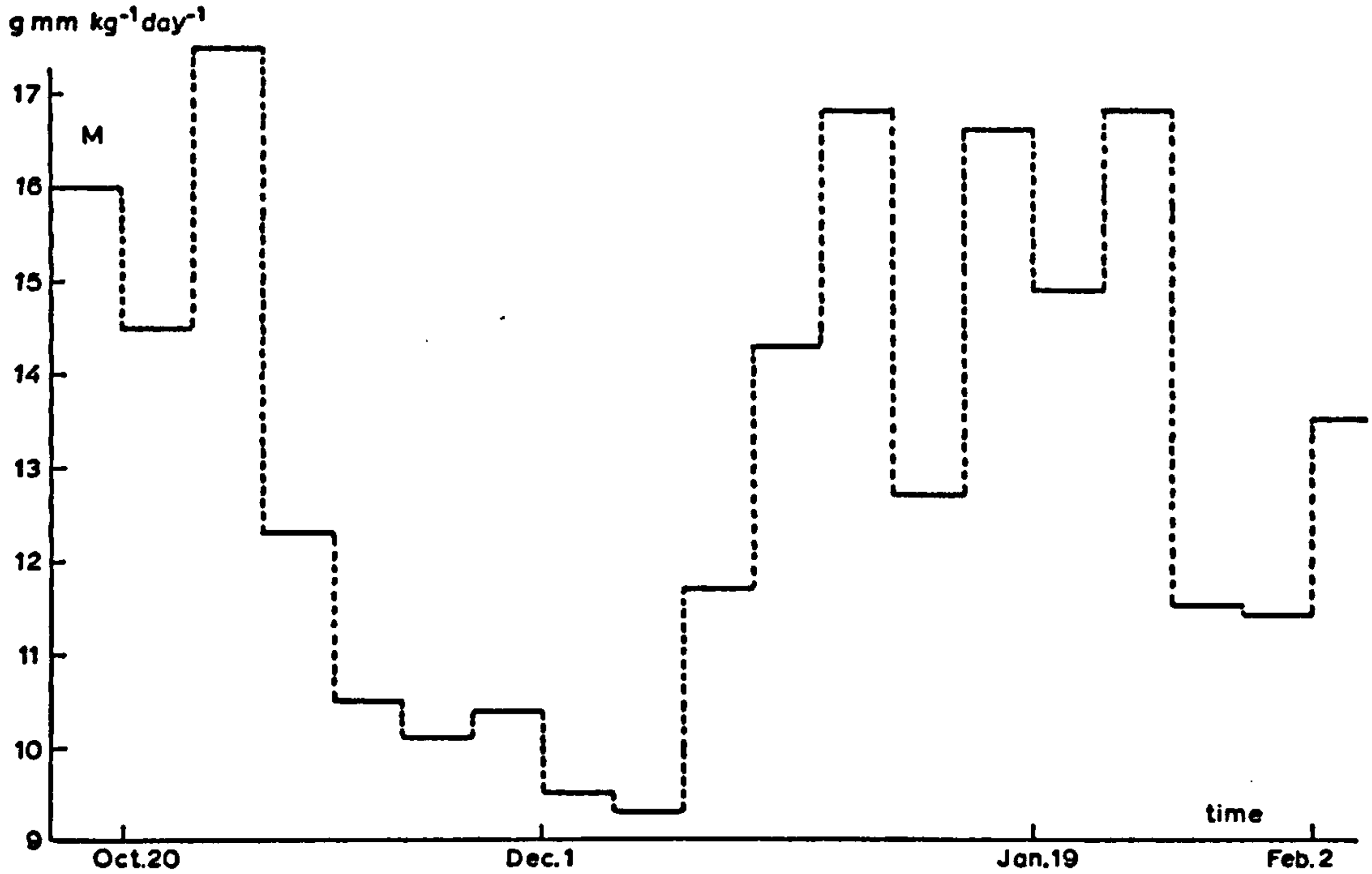

Fig. 41 | The variation in the calculated proportionality factor M for weekly periods in Avdat '72/'73.

from the Penman equation (Section 3.2). The data apply to the 1972/1973 experimental season in Avdat. There is practically a twofold difference in these weekly values during the growing season. These fluctuations may have a major influence on dry matter production, especially in semi-arid regions with a very erratic rainfall pattern, where the actual production may take place in various periods in different years. It is therefore important to be able to predict the efficiency of water use for shorter periods of time. The fluctuations in the calculated M-values are caused by different influences of the wind function term on crop transpiration and free water evaporation. For a crop canopy the evaporating surface may be a multiple of the surface area, namely the value of the leaf area index. Each of these leaf layers reacts practically independently to the vapour pressure deficit in the atmosphere and the transpiration increases linearly with increasing leaf area index as long as the opening of the stomata in the deeper layers is not prevented by a too low radiation intensity. Thus when the vapour pressure deficit increases, the crop transpiration will increase more strongly than the free water evaporation and consequently the ratio W:E will go up, leading to lower values for M. When the ratio between the radiation term and the wind function term in the formula to calculate potential evapotranspiration is approximately constant (Makkink, as cited by de Wit, 1958), crop transpiration will be proportional to the radiation intensity. But when this ratio shows great fluctuations, it is to be expected that the relation between radiation and crop transpiration will be blurred by the effect of wind speed and humidity. This is clearly shown in Fig. 42 where the measured evapotranspiration from an alfalfa crop, grown under optimum moisture conditions in Gilat, about 4 km from the experimental site in Migda, is plotted against the radiation intensity (Cohen, 1968). The evapotranspiration data are averages of 15-day periods, obtained from daily measurements of soil moisture by the neutron moderation technique. The alfalfa was harvested regularly and the crosses are periods just after harvests, when probably the vegetation did not form a complete soil cover. The dots refer to periods when a complete cover was established. From these data it can be concluded that at the same radiation intensity, the transpiration of a canopy can vary twofold, as a result of differences in air

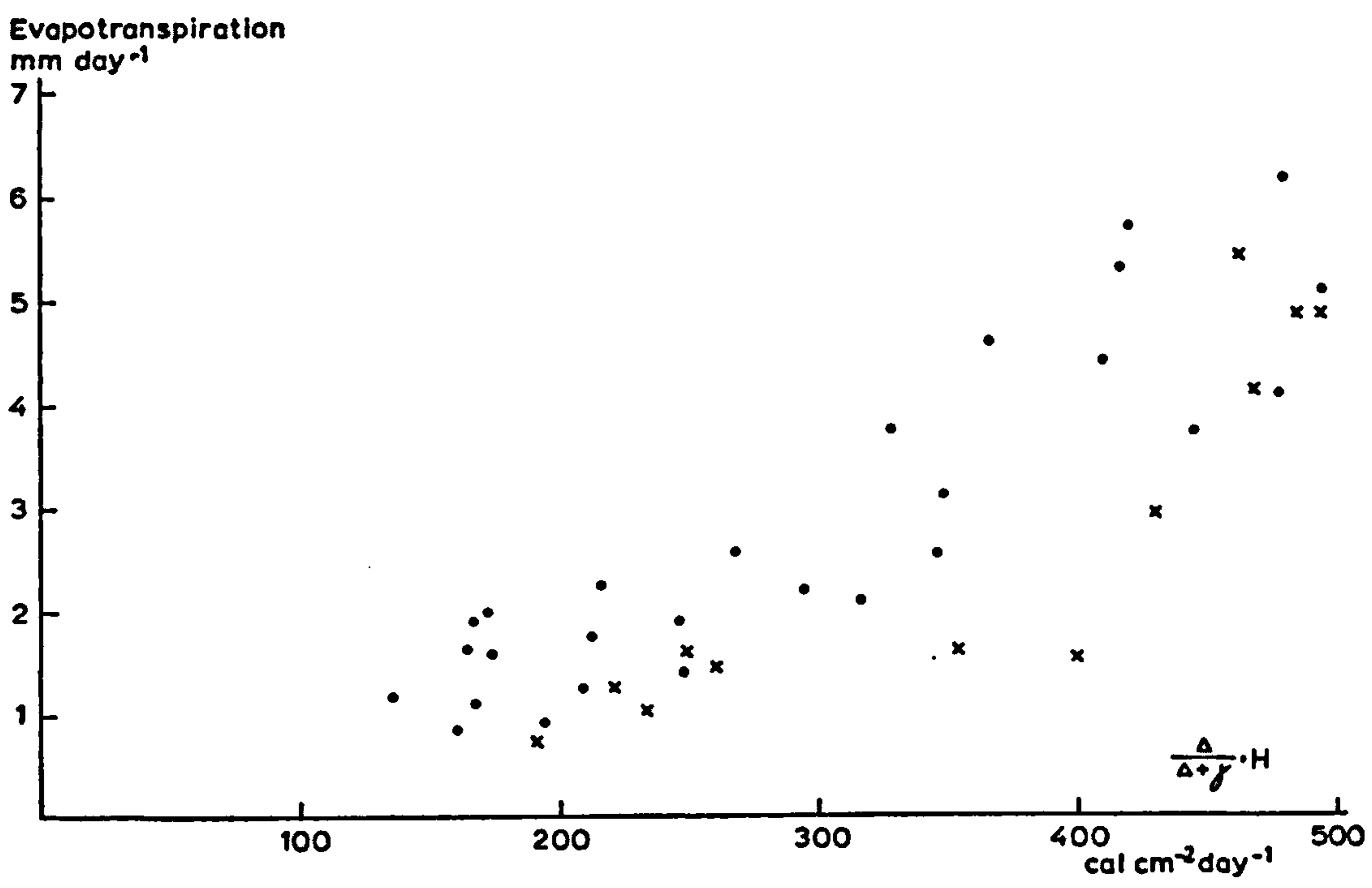

Fig. 42 | The relation between two-weekly potential evapotranspiration and the factor $\Delta(\Delta+\gamma)^{-1}$ H for alfalfa in Gilat.

humidity and wind speed. And because of the above mentioned different reaction of free water evaporation, the calculated M-value may also vary by a factor two.
It is therefore more accurate to use the calculated transpiration coefficients than the proportionality factor M. This coefficient expressed in g dry matter produced per g water transpired under optimum conditions may be calculated by the crop growth model (Section 5.3). It is, however, very expensive to apply this detailed program for all periods in which we are interested.
Therefore a simplified procedure has been worked out to calculate the transpiration coefficient directly from the meteorological data that are available. To obtain that value the potential crop transpiration must be known and the potential dry matter production. Both are calculated independently from the data.

Potential crop transpiration
In Section 3.2 the formula for the calculation of the evaporative heat loss of leaves is given, based on the combination method:

$$\begin{aligned} EHL = {} & (SLOPE \times ASWR + (ES - EA)/RA \times RHOCP)/ \\ & ((RA + SRW)/RA \times PSCH + SLOPE) \qquad J\,m^{-2}\,sec^{-1} \quad (5.1) \end{aligned}$$

in which

SLOPE = slope of the saturated vapour pressure curve mbar $°C^{-1}$

ASWR = absorbed short-wave radiation $J\,m^{-2}\,sec^{-1}$

ES = saturated vapour pressure in the atmosphere mbar

EA = actual vapour pressure in the atmosphere mbar

RHOCP = volumetric heat capacity of the air $J\,m^{-3}\,°C^{-1}$

RA = resistance to water vapour diffusion from the leaf to the atmosphere including laminar resistance above the leaf and turbulent resistance in and above the canopy $sec\,m^{-1}$

SRW = stomatal resistance $sec\,m^{-1}$

PSCH = psychrometric constant mbar $°C^{-1}$

This formula is valid at any moment for an individual leaf or a leaf layer in a canopy with the appropriate values for the parameters substituted. The aim is now to calculate an integrated value for the water loss of a canopy from average daily weather data.
For this purpose Eqn (5.1) is rewritten as:

$$PTR = \int^{day} \frac{SLOPE \times HNOT}{SLOPE + \frac{(RA+RS)}{RA} \times PSCH} dt +$$

$$+ \int^{day} \frac{(ES-EA) \times \frac{RHOCP}{RA}}{SLOPE + \frac{(RA+RS)}{RA} \times PSCH} dt \qquad (5.2)$$

in which PTR is the potential daily crop transpiration, and the two terms represent the contribution of absorbed radiation and of the wind speed and humidity to the total transpiration.
The individual variables in this expression are now considered: HNOT is the total absorbed radiant energy available for transpiration. It may be calculated from the measured daily global radiation with:

$$HNOT = ((1.-REFLC) \times DGRAD - LWR) \times$$
$$\times (1.-EXP(-0.5 \times LAI)) \qquad (5.3)$$

in which

REFLC = the reflection coefficient of the vegetation. For a normal crop surface it is about 0.25 (Goudriaan, 1973).

DGRAD = daily total global radiation

LWR = net outgoing long-wave radiation

The long-wave radiation is calculated from the formula given by Brunt (Section 3.2). Most of the transpiration occurs at daytime because the stomata are closed at night and the cuticular resistance is a factor 10 higher. The loss of long-wave radiation to be considered here is thus only the fraction that is emitted during daylight hours. The expression given in Section 3.2 is therefore multiplied by DAYL/24, DAYL being the effective daylength.
Finally the expression is multiplied by $(1-e^{(-0.5 \times LAI)})$ to account

for that part of the incoming radiation transmitted towards the soil surface. Goudriaan (1973) showed that it is justified to use an exponential extinction of the radiation, the value of 0.5 for the extinction coefficient being valid for a spherical leaf angle distribution.

RA: the resistance to heat and vapour exchange from the leaf surface to the bulk of the atmosphere consists of two resistances in series: a laminar directly above the leaf, and a turbulent resistance in and above the canopy.
The laminar resistance can be calculated from the wind speed using semi-empirical formulas (Section 4.2). If the average leaf size is assumed to be 1 cm, the formula is

$$RAL = 3.5 \times 10^{-3} \times \sqrt{(1./WS)} \quad \text{in day cm}^{-1} \quad (5.4)$$

To calculate the turbulent resistance the Thornthwaite-Holtzmann formula, based on an aerodynamic theory is applied. Assuming neutral atmospheric conditions throughout, an average crop height of 0.75 m and appropriate values for zero plane displacement and roughness, the resistance can be calculated with

$$RAT = 63/WS \quad \text{in day cm}^{-1} \quad (5.5)$$

At low values of the leaf area index this formula tends to overestimate the resistance because part of the transport is then in the horizontal direction. Therefore RAT is multiplied by LAI for values below 1, this value being chosen rather arbitrarily.
The wind speed WS is read from the measured daily wind run. The effective wind speed is taken as 1.33 × the average, assuming that the wind speed in daytime is twice that at night.

RS: the stomatal resistance is assumed to be at the minimum value. For the calculation of potential crop transpiration, optimum soil moisture conditions are assumed, thus no stomata close because of water stress. The influence of stomatal closure in the deeper layers of the canopy due to low light intensities is accounted for in the wind term of the formula. For wheat the minimum value determined under laboratory conditions is 18.5×10^{-6} day cm^{-1}.

SLOPE: the slope of the saturated vapour pressure curve varies considerably when going from the minimum to the maximum temperature (ranging from 0.5 mbar °C^{-1} at 0°C to 2.5 mbar °C^{-1} at 30°C). If we take into account that at midday it has its strongest influence, it is calculated at AVT = TMAX − 0.25 × (TMAX − TMIN), TMAX and TMIN being the daily maximum and minimum temperature, respectively.

The contribution of the wind function to the transpiration of one leaf layer, which will be called here the drying power of the atmosphere, is equal to:

$$\text{DRYP} = \text{RHOCP/RA} \times$$
$$\times (\text{SVPA} - \text{VPA}) \Big/ \left(\text{SLOPE} + \frac{(\text{RA}+\text{RS})}{\text{RA}} \times \text{PSCH}\right) \qquad (5.6)$$

The value of the saturated vapor pressure is calculated at the same temperature as used for SLOPE, with an analytical expression:

$$\text{SVPA} = 6.11 \times e^{(17.4 \times \text{AVT}/(\text{AVT}+239.))} \quad \text{in mbar}$$

Actual vapour pressure is obtained from the measured dew point temperatures at 08h00 and 14h00 with:

$$\text{DPTA} = (\text{DPT08}+\text{DPT14})/2. \quad \text{and}$$
$$\text{VPA} = 6.11 \times e^{(17.4 \times \text{DPTA}/(\text{DPTA}+239))}$$

Here again it is clear that the drying power is only effective when the stomata are open and the expression must be multiplied by DAYL/24. Eqn (5.6) refers to one leaf layer, and to integrate over the whole canopy it must be multiplied by the leaf area index. However when the leaf area is high, the light does not penetrate to the deeper layers of the canopy and the stomata will not or only partly open, so that part of the leaves do not contribute to the transpiration. It is obvious that the degree of opening also depends on the light intensity above the canopy because at lower light intensities the intensity in the canopy earlier reaches a value below which the stomata will partially close. Thus for these circumstances RS will not have the minimum value for all leaf layers. To account for this Eqn (5.6) is multiplied by

$$\text{LAI} \times \alpha$$

in which α is a reduction factor depending both on leaf area index and on the average radiation intensity. In Fig. 43 α, is plotted as a function of the global radiation per daylight hour for various values of the

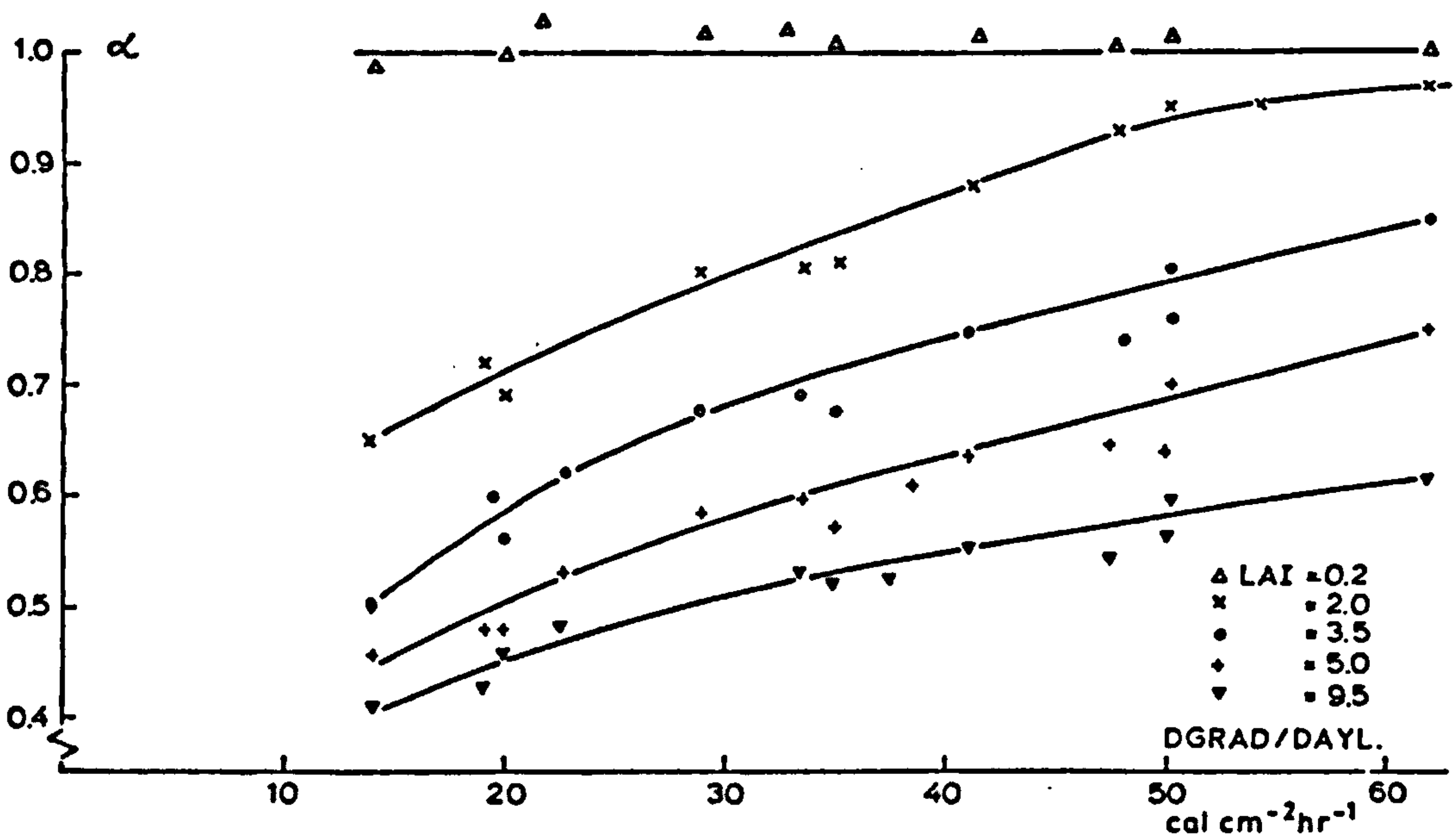

Fig. 43 | The relation between the reduction factor for transpiration (-α-) and the average light intensity for various values of the leaf area index (LAI).

leaf area index. The values were obtained by substituting the daily transpiration values calculated with BACROS in Eqn 5.1 and solving it for α. In this way, the daily transpiration rates calculated with Eqn (5.1) are equal to the ones calculated with BACROS. From Table 6 it may be concluded that for normal circumstances BACROS gives accurate transpiration values. Thus, by applying Eqn (5.1) the potential daily crop transpiration may be calculated from average daily weather data.

Potential growth

The potential growth rate of a canopy expressed as the increase in dry weight is determined by the rate of gross photosynthesis, the efficiency of conversion of primary photosynthetic products into structural material and the rate of maintenance respiration.

For given optical (reflection and transmission) and geometrical (leaf angle distribution) properties of the leaves of a canopy, the rate of photosynthesis is determined by the leaf area per unit of soil surface, the photosynthesis function of the leaves and the radiation intensity (de Wit, 1965).

The photosynthesis functions of individual leaves of several species from the natural vegetation from Migda were determined in the laboratory (H. Lof, pers. commun.). Between the species not much difference was observed and the curves were very similar to the ones determined for wheat under identical conditions. Under the assumption that the optical and geometrical properties of the leaves are also approximately equal to those of wheat, the gross rate of photosynthesis under different meteorological conditions can be calculated with the simulation model. The results of these calculations are given in Fig. 44. Radiation is again expressed here as an average intensity during daylight hours, because the same total radiation distributed over a shorter period of time may lead to partial light saturation i.e. photosynthesis diffusion limited and hence to a lower total gross assimilation. The gross photosynthesis rate is expressed in kg CH_2O ha^{-1} h^{-1}. From this graph the daily total gross assimilation can be obtained for various values of radiation, leaf area index and daylength. The scatter of the points around the solid lines is mainly caused by

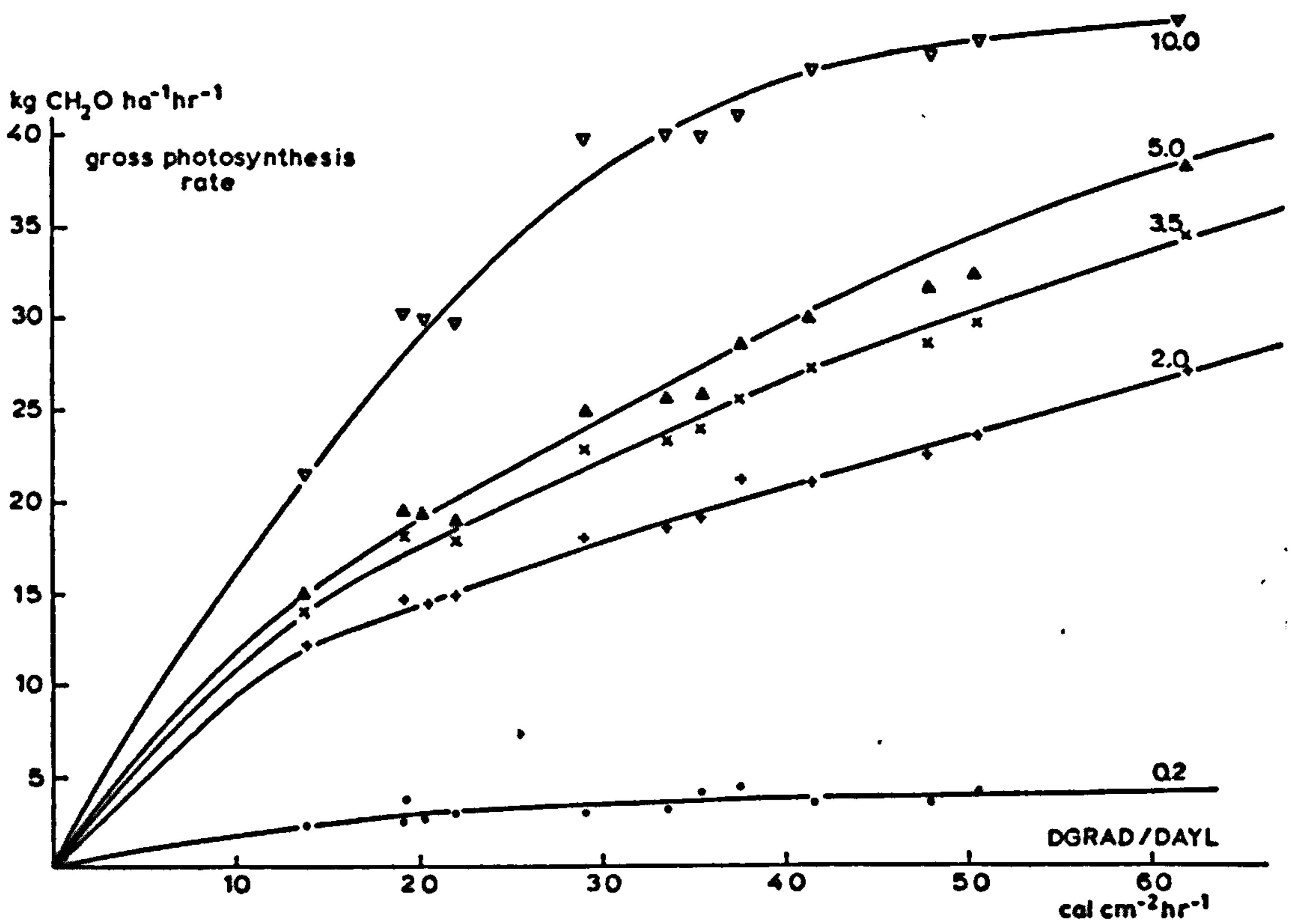

Fig. 44 | The relation between gross rate of photosynthesis and the average light intensity for various values of the leaf area index.

differences in temperature, which has an influence on the enzymatic process. This effect is however so small in the range of temperatures normally encountered that it may be neglected here. If crops with a different photosynthesis function are considered the graphs will have to be recalculated of course.

Part of the energy fixed by photosynthesis is used for maintenance of the canopy. The most important processes that play a role are the continuous recycling of enzymes and the maintenance of ionic balance of the cells. In a recent article Penning de Vries (1974) showed that the maintenance costs range between 1.5 and 4.5% of the dry matter per day, depending mainly on the level of proteins in the plant. It is however still difficult to relate the actual value to any of the measurable crop characteristics. An average value of 2% per day is therefore used throughout the growing season.

The efficiency of conversion of primary photosynthetic products into plant biomass depends mainly on the chemical composition of the biomass that is formed (Penning de Vries, 1974). This composition changes during the growing season as most of the proteins are formed in the early stages of crop growth, while later on the percentage of proteins in the total biomass gradually decreases. The exact chemical composition is not known and therefore a constant value of 0.75 for the whole growing season is applied.

From the above described variables, the daily total growth rate under optimum conditions can be calculated as:

(DAYL × HOURLY GROSS ASSIMILATION –
MAINTENANCE) × CONVERSION FACTOR

Efficiency of water use

From the potential crop transpiration calculated according to the method described above and the potential crop growth a daily value for efficiency of water use is obtained. The efficiency is expressed then in kg dry matter produced per mm of water transpired. This value is used in the program to calculate the dry matter production by multiplication with the actual rate of transpiration. As both the transpiration and the dry matter production calculation give the same results as those obtained with BACROS, the agreement between calculated and measured transpiration coefficients remains as given in Table 9.

6 The simulation model Arid Crop

6.1 Description of the model

A complete listing of the CSMP text of the model is given in Table 10. In Section 0 of the program, TITLE specifications are given, like the name of the model and details on place and time of a particular run. This text appears on top of each page with printed output.

Macro definitions
Section 1 contains the MACRO definitions, each one with its specific name, defined on the right side of the equal sign of the line starting with the word MACRO. Each time a MACRO is invoked in the model, the complete text defined between the line starting with MACRO and the line ENDMAC is written out, the specific names defined in the MACRO call statement being assigned to the variables in the MACRO.
The MACRO COMP describes the processes occurring in one soil compartment and calculates the variables for each layer according to an identical procedure.
WATER is the total amount of moisture in a compartment expressed in mm. The initial value is not introduced in the integral but added as a term to the right side of the expression. In this way it is not necessary to calculate the initial values separately in the program.
The rate of change of the integral in mm day^{-1} equals the difference between the Rate of Water Flow at the Top (positive downwards) and at the bottom minus the TRanspiration Rate minus the Rate of Evaporation. The Rate of Water Flow at the Top is set equal to the Rate of Water Flow at the Bottom of the preceding compartment through transposition of the appropriate terms in the MACRO call statements, except for the first compartment, where it is equal to the INFiltration Rate. The Rate of Flow at the Bottom is found by subtracting the amount that can be stored additionally in the compartment, divided by the time interval DELT. Through this procedure the compartments are filled till field capacity from the top one down (Section 4.2). Division by the time interval

DELT is a common technique to convert amounts into rates, that can be applied with integration methods using a fixed integration interval. The Rate of TRanspiration from a compartment is calculated from the TRanspiration rate Per MM of root length, times the vertical rooting length; the influence of the temperature (TEC) and of the water content in the compartment (WRED) are included. The Evaporation Rate from a compartment equals the Actual EVAPoration rate times a distribution Factor. This factor governs the distribution of the total evaporative water loss (AEVAP) over the various compartments, through 'mimicking' of the redistribution along developing potential gradients. The relative contribution of each compartment depends on the water content in that layer, a proportionality factor (PROP) and the depth of the centre of the compartment below the soil surface (Section 4.2). Intermediate variables for these calculations are also obtained in the MACRO. The Maximum amount of WATER that can be stored in mm depends on the FieLD CaPacity of the soil and the THiCKNess of the compartment; Available WATER for plant growth, being the amount of water in mm present above wilting point; the vertical RooTing Length in a compartment in mm equals the difference between the RooTed Depth, i.e. the depth of the root front and the Total Depth to the Top of the compartment limited on one side to zero, when the 'root front' has not yet reached the compartment and on the other side to the THiCKNess when the front already passed the bottom; a SWitch Parameter for root growth which assumes the value 1 if the root front is in a compartment with a moisture content above wilting point and is otherwise equal to zero; the Relative Amount of Water available for the Roots, which governs the relative death rate of the vegetation as a result of water shortage is obtained from the vertical rooting length, the available water in the compartment and the Maximum amount of Water that can be stored in the RooTed Depth.
The Effective DePTh Factor accounting for the compensatory effect on water uptake when part of the root system is under unfavourable moisture conditions is obtained from a tabulated function, with the fraction of available water as the independent variable. When a compartment is too dry the vertical rooting length in that compartment is only partly effective, thus increasing the potential rate of transpiration per mm of rooting length.

A number of variables are totalled, like TRanspiration Rate, to yield, for instance total TRANspiration. The values at the bottom of the tenth compartment are used further in the program. Here again the values at the top of a compartment are set equal to the ones at the bottom of the preceding one by transposition of the arguments in the MACRO call statements.

INITIAL *section*

The initial values of integrals have to be defined in the INITIAL section. Here only the value of the Temperature of the Soil is calculated and set equal to the average air temperature on the STarting DAY.
The location is defined by its LATitude, which is used in the determination of the radiation climate. The geometry of the soil system is defined by given parameter values for the thickness of the consecutive compartments.
The parameter values DRF1 ... DRF11 define the initial soil moisture content per compartment as a fraction of the water present at wilting point.

DYNAMIC *section*

The DYNAMIC section of the program starts with the definition of the TIME variables. The time units in this model are days, and TIME itself is tracked by CSMP. By changing the parameter STDAY the simulation may be started at any moment during the growing season. The value of 273 in the definition of the DAY of the Year is connected with the layout of the weather functions, which start with 1 October (the 274th day of the year) as day 1. When a different set up is chosen this value should be changed.

Weather section

In Section 3 the relevant weather data are calculated from the inputs. Daily Total global Radiation is read from a tabulated function. The Fraction OVercast of the sky, which is needed in the calculation of the outgoing long-wave radiation is obtained by comparing the measured daily radiation with the daily totals on perfectly clear and completely overcast days (de Wit, 1965).
Daily Global Radiation on CLear days is read from a series of tabulated functions relating this value to the day of the year for

various latitudes. The TWOVAR function provides linear interpolation in two-entry tables. A factor 2 is introduced because in the tables only the photosynthetic active radiation (400–700 mμ) has been taken into account. The Daily Global Radiation on OVercast days is equal to 20% of that on clear days. When global radiation is not measured but only the duration of sunshine or the relative cloudiness have been recorded, the data may first be transformed into incident amounts of light (Bernhardt & Phillips, 1958; Stanhill, 1965).

Daily MiNimum Temperature and MaXimum Temperature are recorded and the TeMPerature of the Air is calculated as the average of the two. The AVerage Temperature during Daytime is assumed to be the maximum temperature minus one quarter of the difference between minimum and maximum temperature.

Daily Wind Run is read again from a tabulated function. The humidity of the air is characterized by the recorded Dew Point Temperatures at 08h00 and 14h00. The Vapour Pressure of the Air is calculated with an analytical expression from the average Dew Point Temperature. The Saturated Vapour Pressure of the Air is obtained from the same equation substituting the average air temperature, and the same is done for the Saturated Vapour Pressure in Daytime.

The RAINfall intensity in mm day^{-1} is read from a tabulated function, which gives daily rainfall in mm as a function of time. By integrating the rainfall the Total seasonal RAINfall is obtained.

Penman evaporation

The potential soil evaporation is calculated following the procedure as described by Penman (1956). Average daily weather data are used along with the coefficients from the original paper. Comparison with the simulated evaporation (Section 4.2) showed good agreement.

Soil water section

First the parameters, characterizing the hydraulic properties of the soil are defined. WiLTing PoinT and FieLD CaPacity may be read from the soil moisture retention curve if available at ±15 bar and ±0.3 bar, respectively. Or they can be obtained experimentally: field capacity through measurement of the moisture content in the soil after cessation of drainage from an initially saturated soil column; wilting point from the moisture content in a pot at the moment plants under moderate evaporative conditions start wilting.

The PROPortionality factor for soil water evaporation is obtained from successive sampling for soil moisture of a bare soil after initial wetting.
The LIMiting Water Content can be obtained from determination of the moisture content after a prolonged drying period, or may be set equal to 1/3 of the moisture content at wilting point (Section 4.2).

Infiltration
The Rate of INFiltration in mm day^{-1} is the difference between the intensity of the rain and the Rate of RUN-OFF. When the area is sloping and run-off may occur, empirical equations may be introduced, relating the rate of run-off to slope, rain intensity and vegetative cover (Tadmor & Shanan, 1969). For the Migda situation the slope is too small to cause water loss through surface flow and the factor A is therefore set to zero. The TOTal amount of water INFiltrated is found by integration of the infiltration rate.
The amount of water lost by deep DRAINage is obtained by integration of the Rate of Water Flow at the Bottom of the 10th compartment. Here a maximum rooted depth of 180 cm is assumed but by changing the thickness of the compartments this can easily be adapted to different circumstances.

MACRO call statements
The number of times the MACRO is called determines the number of soil compartments that are considered. Here ten relevant compartments to a depth of 180 cm are considered while the 11th compartment is used as a 'storage' for deep drainage.
The meaning of the variable names is found by comparing identical positions in the MACRO-definition and MACRO-call statements. As can be seen in the call statement both variable names and numerical values may be introduced. Variables that do not occur in the MACRO definition are replaced by the program with variable names starting with ZZ and having four numerical characters (e.g. ZZ0001). It should be noted that invocation of a MACRO is not a structural statement, which calls on a subroutine but an order to write a section of the simulation model, which is then subject to sorting.

Transpiration

To obtain the loss of water by transpiration, first the Potential TRANspiration rate is calculated, according to the procedure worked out in Section 5.4.

The Saturated Vapour Pressure and the Actual Vapour Pressure of the Atmosphere in mbar are obtained from the measured Average Air Temperature in Daytime and the dew point, respectively. The Resistance of the Atmosphere is calculated from the measured wind run, assuming that the average velocity in daytime is twice that at night. The Effective outgoing Long-Wave Radiation is obtained from the Brunt formula taking into account the vapour pressure, the cloudiness of the sky and the daylength.

The effective DAYLength is read from a tabulated two-entry function, with the day of the year and the latitude of the location as independent variables. The functions are taken from the Smithonian Tables, (1956) while corrections are made for twilight periods, in which light intensity is too low for the stomata to open.

The correction factor ALPHA for the drying power is also obtained from a two entry table with independent variables average Hourly RADiation intensity and Leaf Area Index (see Fig. 43).

The calculated potential transpiration refers to a vegetative canopy, well supplied with water. However when the vegetation matures the rate of transpiration decreases. The Actual Potential rate of TRANspiration is found by multiplying PTRAN by a Reduction Factor for the DeVelopment Stage of the crop. This factor is read from a tabulated function (RFDVST), which indicates that there is no reduction up to DVS = 0.9, after which a gradual decrease in potential transpiration follows, ending in a complete standstill at ripeness. The shape of the function is rather arbitrary as no definite data could be found or determined.

To calculate the TRanspiration Per MM of rooting length the actual potential transpiration is divided by the cumulative effective rooting length till the bottom of the last compartment (ERLB10). The function EDPTFT, relating the fraction of available water to the relative root activity is compiled from Lawlor (1973) with a fair proportion of personal interpretation (Fig. 45).

The relation between the fraction of moisture content in a compartment and the reduction factor for the withdrawal of water by the roots (Fig. 46) is according to the concept of Viehmeyer (1955).

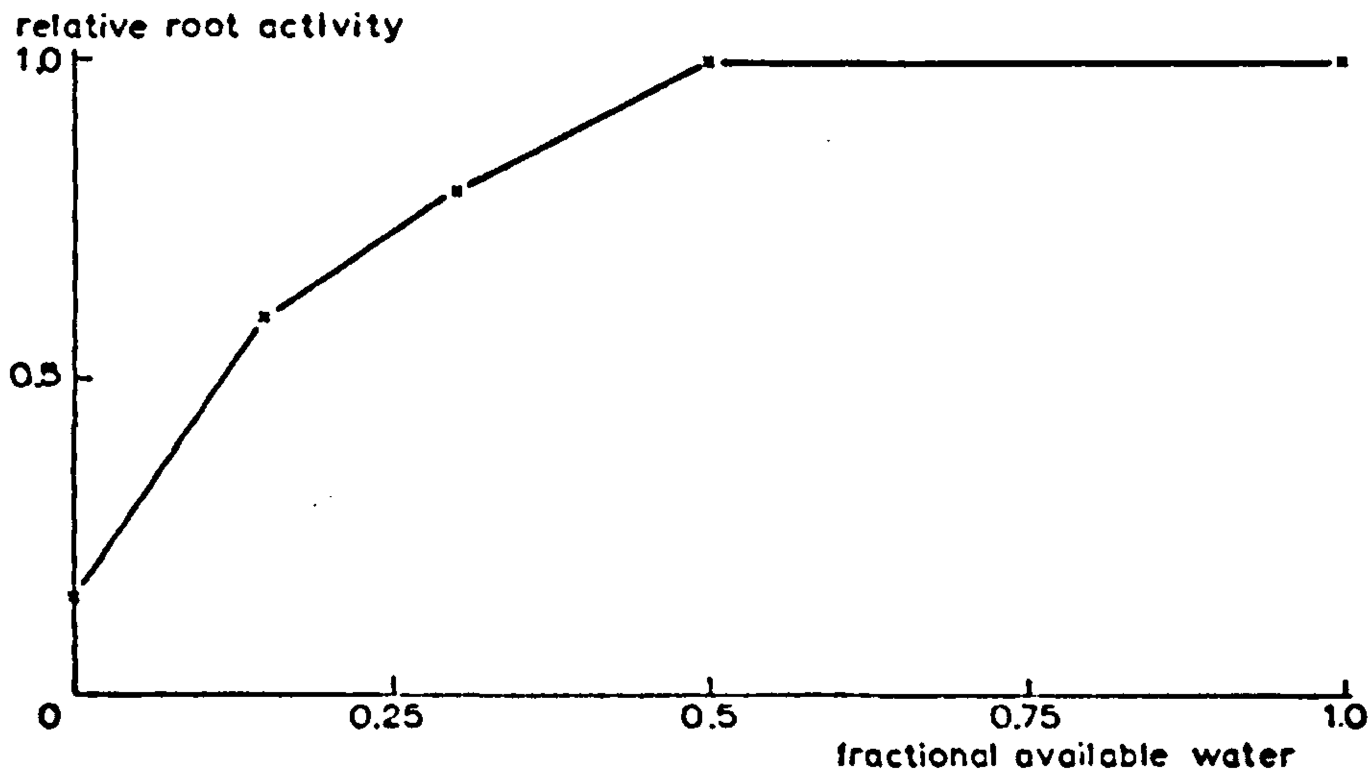

Fig. 45 | The relation between the fraction of available water and the relative activity of the root.

It should be mentioned however that this relation was never established for parts of a root system in a particular environment. In fact Viehmeyer's approach gives a combined effect of the relations depicted in Figs. 45 and 46 as practically all the other available experimental work does. For a better understanding of the dynamic functioning of the root system, however, efforts should be made to

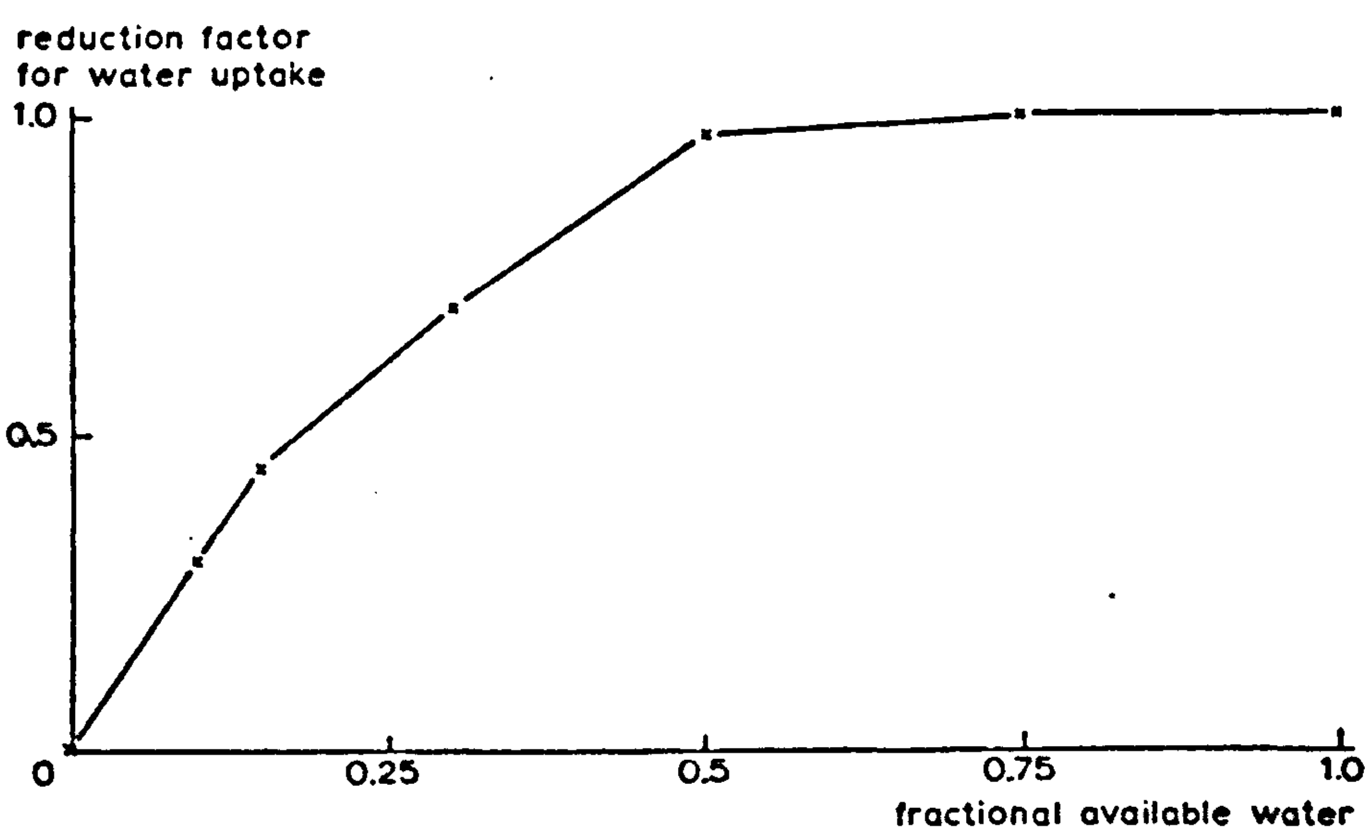

Fig. 46 | The reduction factor for water uptake by the root as a function of the fraction of available water.

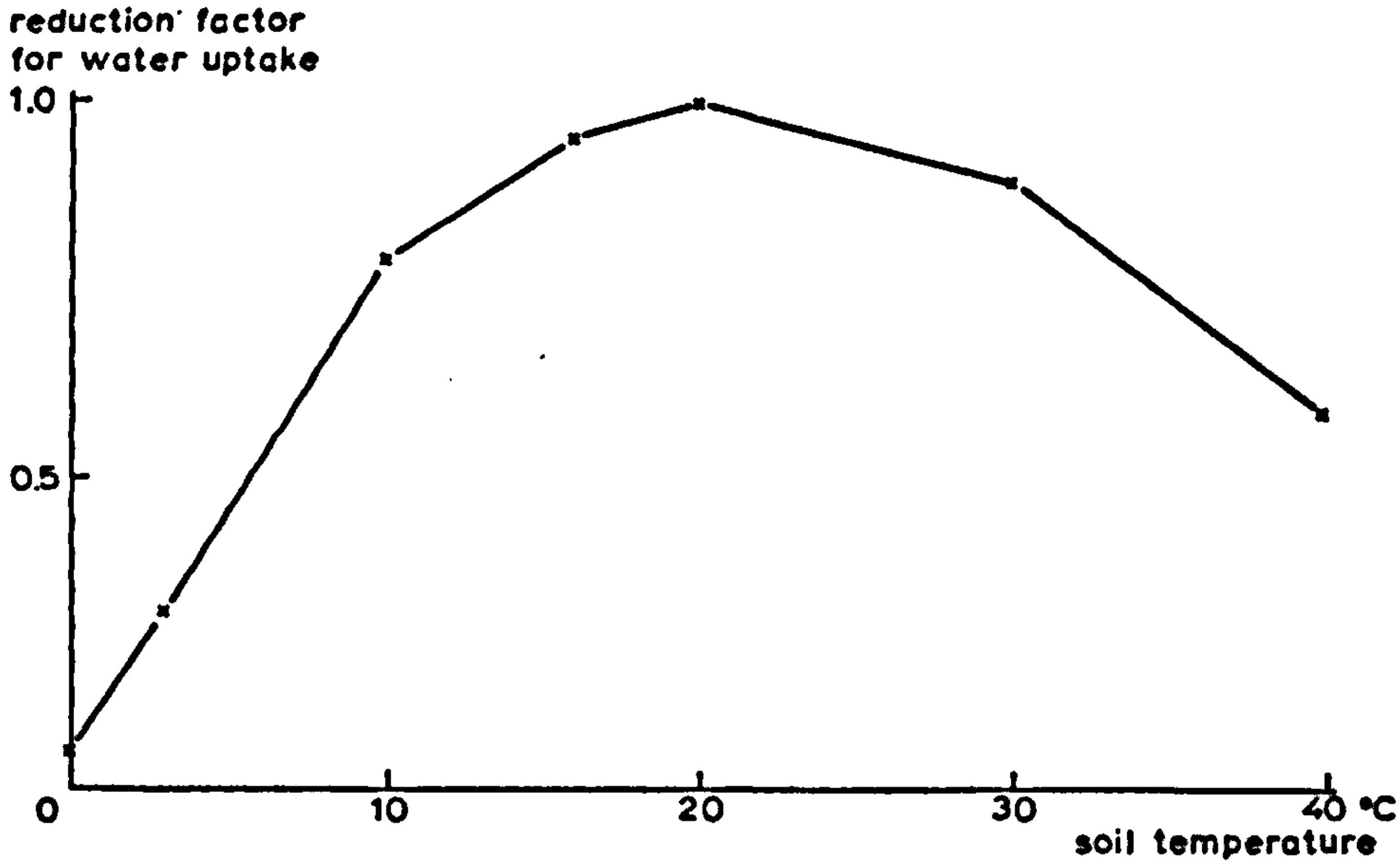

Fig. 47 | The relation between soil temperature and the reduction factor for water uptake by the roots.

establish the above mentioned relations for different soil types and root systems.

The water uptake by the roots is affected by the temperature in the root zone. The temperature has an effect on the mobility of the water through changes in viscosity, as well as on the conductivity of the root system (Kuiper, 1964). These effects are combined in the Temperature Effect Table, as given in Fig. 47. This curve has been constructed from measurements by Penning de Vries (unpublished data) with maize. The temperatures were decreased by 15 °C in accordance with the optimum temperature for photosynthesis. For this relation again more experimental work should be carried out to improve our insight. The above described relations are applied to each of the compartments and the amount of water extracted from that compartment is calculated. The cumulative amount is then transferred to the variable TRAN, giving the actual crop transpiration in mm day^{-1}.

Evaporation

The Potential EVAPoration rate from the soil in mm day^{-1} is calculated from the Penman evaporation and the FRaction of Light that is Transmitted through the canopy. The Actual rate of EVAPoration is then obtained by multiplying the potential rate by a REDuction Factor due to Dryness of the upper compartment.

This reduction factor is read from the tabulated function REDFDT with the relative Water Content WCPR as the independent variable. This graph is constructed through combination of Figs. 30 and 31, taking into account that the upper compartment is here 2 cm, which means that the actual evaporation deviates from the potential rate at a somewhat higher value of WCPR, than for the 1 cm thick compartments. The value of EB10, the accumulated Evaporation rate at the Bottom of the 10th compartment equals, of course, AEVAP and the Total water loss through direct soil EVAPoration is their integrated value.

Soil temperature
The Temperature of the Soil is assumed to be constant throughout and equal to a ten-day running average of the air temperature. This is achieved by changing the value each day by the temperature difference between that day and ten days ago. The latter value is found from the DELAY function and because this function assumes the value 0 when time is less than the delay period, in the first 10 days one tenth of the initial value is removed.

Growth of the crop

Germination
Germination proceeds when the water content in one of the three upper compartments is above wilting point (i.e. SW is positive). Then the TeMPerature SUM accumulates and the seedlings reach the stage of establishment when the temperature sum passes the Temperature SUM needed for Germination. At that moment the PUSH for Germination assumes the value 1 during one time-step and the integrals for Living BIOMass, LeaF AREA, RooTed Depth and RooT WeiGHT attain their initial values.
When SW is negative, the current content of the temperature sum is removed at each time-interval through the rate of Emptying if No seeds are GeRminating.

Growth of the vegetation
The Living BIOMass in kg ha^{-1} is kept in a integral. The Initial BIOMass is added at the moment of establishment, when PUSHG has the value 1.

The GROWTH Rate is calculated from the TRANspiration rate and the daily Water USe EFFiciency. This efficiency is the ratio between Potential Daily Total GRowth and Potential TRANspiration, as explained in Section 5.4. Potential growth in kg dry matter ha^{-1} day^{-1} depends on the Potential Daily Total Gross ASsimilation, the respiratory losses due to MAINTenance processes and the efficiency of CONVersion of primary photosynthates into structural material. Gross assimilation values are obtained from a tabulated two-entry function, using the average hourly radiation and the leaf area index as the independent variables. These data were obtained from the simulation model BACROS (Section 5.4), by substituting the physiological data for wheat. When crops with distinctly different physiological characteristics are considered these functions should be recalculated. The main rate-determining factors are the stomatal resistance and the internal resistance to CO_2 diffusion.
Maintenance respiration is calculated from the Total DRy WeighT, assuming a constant maintenance RESpiration Factor of 0.02 g g^{-1} day^{-1} and taking into account the EFfect of Temperature with a Q10 value of 2.0.
The conversion efficiency from primary photosynthates into structural material is set at a constant value of 0.75, reflecting an average chemical composition of the plant biomass. When the vegetation consists of species forming either very protein-rich or fat-rich material, this factor must be lower (Penning de Vries, 1974).
The total amount of dry matter produced is then divided over aerial and underground parts, according to the Current Shoot to Root Ratio. This ratio is read from a tabulated function, with the development stage of the canopy as the independent variable. This function is compiled from data measured in the pot trials (Section 5.3) and shows that progressively less of the dry matter is transferred to the root system, as development continues. The Rate of DyiNG depends on the Relative Death Rate and the amount of biomass present. The relative death rate is either determined by the moisture status of the soil (RDRW) or by the development stage of the vegetation (RDRD). When favourable conditions exist the relative death rate assumes the value 0.005 day^{-1}, while the maximum value is 0.10 day^{-1} causing a reduction of $\pm 50\%$ in standing crop in a week. The function RDRWT relating the relative death rate to the moisture status of the soil is derived from the Viehmeyer (1955) approach and

is also based on the experience that the vegetation dies at a fast rate only when the soil is practically at wilting point i.e. when the Relative amount of Water available to the Roots till the Bottom of the 10th compartment equals 0.
The function RDRDT which relates the relative death rate and the development stage of the canopy is based on intelligent guess work on basis of field knowledge, because quantitative data are lacking. When the value of the living biomass drops below the LiMiting BIOMass, it is assumed that the vegetation is completely dead. Then the PUSH for Dying assumes the value 1 during one time-step and all integrals connected with crop growth are emptied. Growth will only start again after a new wave of germination. After the beginning of March (Day 180) no germination will occur.

Leaf area
The leaf area of the vegetation is used in the calculation of the efficiency of water use as well as in the determination of the division of energy between the soil surface and the vegetative cover. The LeaF AREA in m^2 ha^{-1} is kept in an integral, the Leaf Area GRowTh Rate being calculated from the growth rate of the vegetation by multiplication by the LeaF ARea Ratio in m^2 kg^{-1}. This ratio is governed by the air temperature and read from the function LeaF ARea Ratio Table. This function is taken from growth analysis data for wheat (Friends, 1966). The Leaf Area Index in ha ha^{-1} follows from the calculated leaf area, and this in turn determines the FRaction of Light that is Transmitted. The function relating both was calculated using a light extinction coefficient of 0.6, which holds for slightly planofile leaf angle distributions (Goudriaan, 1973).

Development of the vegetation
The DeVelopment Stage of the vegetation is an integral, with a rate of change, the DeVelopment Rate, which is dependent on the air temperature. It is assumed that the development stage has the value 0 at establishment. The function DVRT relating the rate of development to the air temperature is constructed as explained in Section 3.3. Switch functions are built in to prevent development when no vegetation is present and to stop the development when DVS = 1 is reached.

Root growth

The rate of vertical extension of the root system, GRRT in mm day^{-1} is obtained from the Daily Growth Rate of the RooTs, taking into account the effect of soil temperature (RFRGT). This factor is read from the function REDTTB, which was set equal to the temperature effect on the growth of aerial organs for wheat. The SWitch Parameter at the Bottom of the 10th compartment assumes the value 1, when the root front is in a wet compartment and is otherwise zero.

The RooT WeiGHT is calculated by multiplying the total growth rate of the crop by 1 – current shoot to root ratio. The initial value of the weight is assumed to be equal to the initial weight of the aerial plant material. The weight is an acceptor of dry matter that is produced but does not have any feedback to the system.

Output and run control

The program is finished when at some moment after Day 200 (18th of April) the living biomass drops below the limiting value. There will be no regrowth after that time and further calculation is useless. So that moment is considered as the ENd of the GRowing Season.

Besides the normal PRINTed output, which is obtained at each PRDEL here DEBUG is requested at certain interesting moments. With this facility a print of all variables appearing in the program may be obtained.

In this model the simple RECTilinear METHOD of integration is used, which is sufficiently accurate here. The time interval of integration, DELT, is chosen as 1 day. The time constant for the growth of the vegetation, which is equal to 1/relative growth rate is at the minimum about 10 days, when the relative growth rate is 0.1 day^{-1}. A value of 1 for the time interval is thus small enough. Changing this value to 0.5 does hardly influence the results. Moreover the available weather data are daily values and although it is possible to simulate the daily course from these data (Section 4.2), it is not worthwhile to do so for this model.

Finally the relevant weather functions are added to the program. These functions will replace the earlier defined dummy functions.

The program is finished with the lines

END

STOP

Table 10

```
************************ SECTION 0 ******
TITLE ARID CROP
TITLE SIMULATION OF CROP GROWTH UNDER ARID CONDITIONS

************************* SECTION 1 ************


**               MACRO DEFINITIONS

*  MACRO DLYTOT CALCULATES DAILY TOTALS OF INTEGRALS
*
MACRO DTOT = DLYTOT(DTOTI,RATE)
      DTOT1 = INTGRL(DTOTI,RATE)
      DTOT = DTOT1-ZHOLD(IMPULS(DELT,1.)*KEEP,DTOT1)
ENDMAC
*
*
*  MACRO COMP  DESCRIBES THE PROCESSES IN ONE SOIL COMPARTMENT
*
MACRO EB,ERLB,TDB,RWFB,WATER,RAWRB,SWPB,TRB,SUMB = COMP(ET,ERLT,TDT, ...
        RWFT,THCKN,F,RAWRT,SWPT,DRF,TRT,SUMT)
      WATER = DRF*WLTPT*THCKN+INTGRL(0.,RWFT-RWFB-TRR-ER)
      MWATER = FLDCP*THCKN
      AWATER = AMAX1(0.,WATER-THCKN*WLTPT)
      ER = F*AEVAP
      F = THCKN*VAR/(SUM10+NOT(SUM10))
      VAR=AMAX1(WATER/THCKN-WCLIM,0.)*EXP(-PROP*0.001*(TDT+0.5*THCKN))
      SUMB = SUMT+VAR*THCKN
      EB = ET+ER
      TRR = TRPMM*RTL*TEC*WRED
      RTL = LIMIT(0.,THCKN,RTD-TDT)
      WRED = AFGEN(WREDT,AWATER/(MWATER-THCKN*WLTPT))
      TEC = AFGEN(TECT,TS)
      TRB = TRT+TRR
      RWFB = AMAX1(0.,RWFT-(MWATER-WATER)/DELT)
      SWP = FCNSW(AWATER,0.,0.,AND(RTD-TDT,TDB-RTD))
      SWPB = SWPT+SWP
      EDPTF = AFGEN(EDPTFT,AWATER/(MWATER-THCKN*WLTPT))
      ERLB = ERLT+RTL*EDPTF
      RAWR = RTL/THCKN*AWATER/MWRTD
      RAWRB = RAWRT+RAWR
      TDB = TDT+THCKN
ENDMAC




*************** SECTION 2 *******


INITIAL                                                            ARCRSYS1
PARAMETER PI = 3.1416,LAT = 31.
*  LAT = LATITUDE OF LOCATION
      SNLT = SIN(2*PI*LAT/360.)
*  SINE OF LATITUDE
      CSLT = COS(2*PI*LAT/360.)
*  COSINE OF LATITUDE

      TSI = 5.*(AFGEN(MXTT,STDAY)+AFGEN(MNTT,STDAY))
*  TSI = INITIAL VALUE OF SOIL TEMPERATURE

PARAMETER TCK1=20.,TCK2=30.,TCK3=50.,TCK4=100.,TCK5=100.,TCK6=300.
PARAMETER TCK7=300.,TCK8=300.,TCK9=300.,TCK10=300.,TCK11=1.E4
*  THICKNESS OF CONSECUTIVE COMPARTMENTS IN MM

PARAM DRF1=0.5,DRF2=0.75,DRF3=0.8,DRF4=0.9,DRF5=1.0,DRF6=1.0,DRF7=1.0
PARAM DRF8=1.2,DRF9=1.2,DRF10=1.2,DRF11=1.0
*  INITIAL DRYNESS FACTOR OF CONSECUTIVE COMPARTMENTS AS A FRACTION
*  OF MOISTURE CONTENT AT WILTING POINT

DYNAMIC                                                            ARCRSYS2
```

```
***          TIMER VARIABLES *********
*  TIME IS EXPRESSED IN DAYS

      DAY = AINT(STDAY+TIME)
PARAMETER STDAY = 1.
*  FIRST OF OCTOBER IS FIRST DAY OF SIMULATION
      DAYY = AMOD(DAY+FDAYY,365.)
PARAM FDAYY=273.
* DAYY = NUMBER OF CALENDER DAY


********************  SECTION 3 ********


******************** WEATHER ****************

**        RADIATION
      DTR  = AFGEN(DTRT,DAY)
*  DTR = DAILY TOTAL RADIATION IN CAL/CM**2
FUNCTION DTRT = 0.,450.,   90.,250.,      200.,450.                        DUMMY

********** RADIATION VALUES FOR STANDARD SKIES **************

*  TOTAL DAILY VISIBLE RADIATION AS A FUNCTION OF LATITUDE AND
*                   DAY OF THE YEAR

FUNCTION RADTB, 0.0=   0.,340.,               ...
        15.,343.,46.,360.,74.,369.,105.,364.,135.,349.,166.,337.,    ...
         196.,342.,227.,357.,258.,368.,288.,365.,319.,349.,349.,337.,...
         365.,340.
FUNCTION RADTB,10.0=  0.,295.,                ...
         15.,299.,46.,332.,74.,359.,105.,375.,135.,377.,166.,374.,   ...
 196.,375.,227.,377.,258.,369.,288.,345.,319.,311.,349.,291.,365.,294.
FUNCTION RADTB,20.0=    0.,243.,              ...
         15.,249.,46.,293.,74.,337.,105.,375.,135.,394.,166.,400.,   ...
 196.,399.,227.,386.,258.,357.,288.,313.,319.,264.,349.,239.,365.,241.

FUNCTION RADTB,30.0=  0.,185.,                ...
          15.,191.,46.,245.,74.,303.,105.,363.,135.,400.,166.,417.,  ...
 196.,411.,227.,384.,258.,333.,288.,270.,319.,210.,349.,179.,365.,183.
FUNCTION RADTB,40.0=    0.,124.,              ...
          15.,131.,46.,190.,74.,260.,105.,339.,135.,396.,166.,422.,  ...
 196.,413.,227.,369.,258.,298.,288.,220.,319.,151.,349.,117.,365.,122.
FUNCTION RADTB,50.0=    0.,67.,               ...
         15., 73.,46.,131.,74.,207.,105.,304.,135.,380.,166.,418.,   ...
 196.,405.,227.,344.,258.,254.,288.,163.,319., 92.,349., 61.,365., 66.
FUNCTION RADTB,60.0=      0., 18.,            ...
          15., 22.,46., 72.,74.,149.,105.,260.,135.,356.,166.,408.,  ...
 196.,389.,227.,309.,258.,201.,288.,103.,319., 37.,349., 14.,365., 17.
FUNCTION RADTB,70.0=    0.,0.,                ...
         15.,  0.,46., 20.,74., 89.,105.,209.,135.,331.,166.,408.,   ...
 196.,380.,227.,269.,258.,142.,288., 45.,319.,  2.,349.,  0.,365.,  0.
FUNCTION RADTB,80.0=          0.,0.,          ...
         15.,  0.,46.,  0.,74., 28.,105.,162.,135.,334.,166.,424.,   ...
 196.,380.,227.,248.,258., 81.,288.,  3.,319.,  0.,365.,  0.
FUNCTION RADTB,90.0=   0.,0.,                 ...
         15.,  0.,46.,  0.,74.,  0.,105.,154.,135.,339.,166.,428.,   ...
 196.,393.,227.,252.,258., 40.,288.,0.,               365.,0.

      DGRCL = 2*TWOVAR(RADTB,DAYY,LAT)
*  DAILY TOTAL GLOBAL RADIATION WITH CLEAR SKY
      DGROV = 0.2*DGRCL
*  DAILY TOTAL GLOBAL RADIATION WITH OVERCAST SKY
      FCL = (DTR-DGROV)/(DGRCL-DGROV+NOT(DGRCL-DGROV))
*  FRACTION OF THE DAY THAT IS CLEAR
      FOV = 1.-FCL
      LFOV= LIMIT(0.,1.,FOV)
```

```
      TMPA =(MNT+MXT)/2.
*  TMPA = AVERAGE DAILY AIR TEMPERATURE
      MNT = AFGEN(MNTT,DAY)
*  MNT = MINIMUM TEMPERATURE IN DEGR C
FUNCTION MNTT = 0.,10.,    90.,5.,      200.,10.                          DUMMY
      MXT = AFGEN(MXTT,DAY)
*  MXT = MAXIMUM TEMPERATURE IN DEGR C
FUNCTION MXTT = 0.,30.,      90.,15.,      200.,30.                       DUMMY


**    WINDSPEED

      WSR = AFGEN(WSTB,DAY)
*  WSR = MEASURED WIND RUN IN KM/DAY
FUNCTION WSTB = 0.,120.,360.,120.                                         DUMMY

**    HUMIDITY

      DPT8 = AFGEN(DP8T,DAY)
*  DPT8 = DEW POINT AT 8 IN THE MORNING
FUNCTION DP8T = 0.,10.,      90.,5.,       200.,10.                       DUMMY
      DPT2 = AFGEN(DP2T,DAY)
*  DPT2 = DEW POINT AT 2 IN THE AFTERNOON
FUNCTION DP2T = 0.,11.,      90.,6.,       200.,11.                       DUMMY

      DPT = (DPT8+DPT2)/2.
*  DPT = AVERAGE DEW POINT TEMPERATURE IN DEGR C
      VPA = 4.58*EXP(17.4*DPT/(DPT+239.))
*  VPA = AVERAGE VAPOR PRESSURE IN THE AIR IN MM HG
      SVPA = 4.58*EXP(17.4*TMPA/(TMPA+239.))
*  SVPA = AVERAGE SATURATED VAPOR PRESSURE IN THE AIR IN MM HG

*****         RAINFALL    ****

      RAIN = AFGEN(RAINTB,DAY)
*  RAINFALL INTENSITY IN MM/DAY
FUNCTION RAINTB = 0.,0.,10.,0.,11.,5.,15.,5.,16.,0.,20.,0.,21.,100.,  ...
          21.99,100.,22.,0.,365.,0.
      TRAIN = INTGRL(0.,RAIN)
*  TRAIN = TOTAL SEASONAL RAINFALL IN MM

***    CALCULATION OF PENMAN EVAPORATION


      HZERO = DTR*(1.-REFCF)-LWR
*  HZERO = ENERGY AVAILABLE FOR EVAPORATION IN CAL/CM**2,DAY
PARAMETER REFCF = 0.05
*  REFCF = REFLECTION COEFFICIENT OF WATER
      LWR = 1.178E-7*(TMPA+273.)**4*(0.58-0.09*SQRT(VPA))*(1.0-0.9*LFOV)
*     LWR = OUTGOING LONG WAVE RADIATION IN CAL/CM**2,DAY
      WSM = WSR/1.6
*  WSM = AVERAGE WIND SPEED IN MILES/DAY
      EA = 0.35*(SVPA-VPA)*(0.5+WSM/100.)*LHVAP
*  EA = CONTRIBUTION OF DRYING POWER OF THE ATMOSPHERE TO EVAPORATIVE
*  DEMAND IN CAL/CM**2,DAY
      EVAP = (HZERO*DELTA/GAMMA+EA)/(1.+DELTA/GAMMA) *1./LHVAP
*  EVAP = PENMAN EVAPORATION IN MM/DAY
      DELTA = 17.4*SVPA*(1.-TMPA/(TMPA+239))/(TMPA+239)
*  DELTA = SLOPE OF  SATURATED VAPOR PRESSURE CURVE AT AIR TEMPERATURE
      GAMMA = 0.49
*     GAMMA = PSYCHROMETER CONSTANT IN MBAR/DEGR C
PARAMETER LHVAP = 59.
*  LHVAP = HEAT OF VAPORISATION OF WATER IN CAL/MM


**************************** SECTION 4 *************************

****************** SOIL WATER SECTION ********************************

* DEFINITION OF SOIL PARAMETERS
PARAMETER WLTPT = .075,FLDCP = .23
```

```
*  FIELD CAPACITY AND WILTING POINT IN CM**3/CM**3 , DATA GILAT LOAM
PARAM WCLIM = .0375
*  WCLIM = LOWEST WATER CONTENT THAT CAN BE REACHED IN A COMPARTMENT
*  IS EQUIVALENT TO AIR DRY
PARAM PROP = 15.
*  PROP = PROPORTIONALITY FACTOR FOR DIVISION OF SOIL WATER EVAPORATION
*  OVER VARIOUS COMPARTMENTS


*******************INFILTRATION***********

      INFR = RAIN-RRNOFF+LRNON
*  INFR = RATE OF INFILTRATION IN MM/DAY

      RRNOFF = AMAX1(0.,A*(RAIN-B))
*  RRNOFF = RATE OF RUN OFF IN MM/DAY
PARAMETER B = 5.
*  B = SURFACE STORAGE CAPACITY IN MM
      A = AFGEN(ATB,BIOM)
FUNCTION ATB = 0.,0.,             10000.,0.
*  ATB = RELATION BETWEEN SOIL COVER AND RUN OFF COEFFICIENT
*  SET AT 0. HERE TO PREVENT THE OCCURENCE OF RUN OFF
      LRNON = LRF*RAIN
*  LRNON = EFFECT OF LOCAL RUN-OFF/RUN-ON SITUATIONS
*  LRF = FACTOR ACCOUNTING FOR LOCAL RUNOFF/RUNON
* LRF POSITIVE IS ON RUN ON AREA
*  LRF NEGATIVE IS ON LOCAL RUNOFF AREA

      TOTINF = INTGRL(0.,INFR)
*  TOTAL AMOUNT OF WATER INFILTRATED IN MM

      TDRAIN = INTGRL(0.,RWFB10)
*  TDRAIN = WATER LOST BY DEEP DRAINAGE BELOW DEPTH OF 180. CM

*  CALL OF MACRO COMP FOR THE SOIL COMPARTMENTS


   EB1 ,ERLB1 ,TDB1 ,RWFB1 ,W1 ,RWRB1 ,SWPB1 ,TRB1 ,SUM1 =COMP(  0., ...
         0.,   0.,  INFR,TCK1,F1 ,    0.,    0.,DRF1 ,   0.,   0.)
   EB2 ,ERLB2 ,TDB2 ,RWFB2 ,W2 ,RWRB2 ,SWPB2 ,TRB2 ,SUM2 =COMP(EB1 , ...
       ERLB1 ,TDB1 ,RWFB1 ,TCK2,F2 ,RWRB1 ,SWPB1 ,DRF2 ,TRB1 ,SUM1 )
   EB3 ,ERLB3 ,TDB3 ,RWFB3 ,W3 ,RWRB3 ,SWPB3 ,TRB3 ,SUM3 =COMP(EB2 , ...
       ERLB2 ,TDB2 ,RWFB2 ,TCK3,F3 ,RWRB2 ,SWPB2 ,DRF3 ,TRB2 ,SUM2 )
   EB4 ,ERLB4 ,TDB4 ,RWFB4 ,W4 ,RWRB4 ,SWPB4 ,TRB4 ,SUM4 =COMP(EB3 , ...
       ERLB3 ,TDB3 ,RWFB3 ,TCK4,F4 ,RWRB3 ,SWPB3 ,DRF4 ,TRB3 ,SUM3 )
   EB5 ,ERLB5 ,TDB5 ,RWFB5 ,W5 ,RWRB5 ,SWPB5 ,TRB5 ,SUM5 =COMP(EB4 , ...
       ERLB4 ,TDB4 ,RWFB4 ,TCK5,F5 ,RWRB4 ,SWPB4 ,DRF5 ,TRB4 ,SUM4 )
   EB6 ,ERLB6 ,TDB6 ,RWFB6 ,W6 ,RWRB6 ,SWPB6 ,TRB6 ,SUM6 =COMP(EB5 , ...
       ERLB5 ,TDB5 ,RWFB5 ,TCK6,F6 ,RWRB5 ,SWPB5 ,DRF6 ,TRB5 ,SUM5 )
   EB7 ,ERLB7 ,TDB7 ,RWFB7 ,W7 ,RWRB7 ,SWPB7 ,TRB7 ,SUM7 =COMP(EB6 , ...
       ERLB6 ,TDB6 ,RWFB6 ,TCK7,F7 ,RWRB6 ,SWPB6 ,DRF7 ,TRB6 ,SUM6 )
   EB8 ,ERLB8 ,TDB8 ,RWFB8 ,W8 ,RWRB8 ,SWPB8 ,TRB8 ,SUM8 =COMP(EB7 , ...
       ERLB7 ,TDB7 ,RWFB7 ,TCK8,F8 ,RWRB7 ,SWPB7 ,DRF8 ,TRB7 ,SUM7 )
   EB9 ,ERLB9 ,TDB9 ,RWFB9 ,W9 ,RWRB9 ,SWPB9 ,TRB9 ,SUM9 =COMP(EB8 , ...
       ERLB8 ,TDB8 ,RWFB8 ,TCK9,F9 ,RWRB8 ,SWPB8 ,DRF9 ,TRB8 ,SUM8 )
   EB10,ERLB10,TDB10,RWFB10,W10,RWRB10,SWPB10,TRB10,SUM10=COMP(EB9 , ...
       ERLB9 ,TDB9 ,RWFB9 ,TCK10,F10,RWRB9 ,SWPB9 ,DRF10,TRB9 ,SUM9 )
   EB11,ERLB11,TDB11,RWFB11,W11,RWRB11,SWPB11,TRB11,SUM11=COMP(EB10, ...
       ERLB10,TDB10,RWFB10,TCK11,F11,RWRB10,SWPB10,DRF11,TRB10,SUM10)

      WTOT=W1+W2+W3+W4+W5+W6+W7+W8+W9+W10
*  TOTAL AMOUNT OF WATER IN THE PROFILE IN MM

***********TRANSPIRATION***********


*  CALCULATION OF POTENTIAL CROP TRANSPIRATION

      PTRAN = CC*((1.-EXP(-0.5*LAI))*HNOT+ALPHA*LAI*RHOCP/RA*(SVPAM- ...
        VPAM)*DAYL/24.)/LHVAP
*  PTRAN = POTENTIAL TRANSPIRATION  RATE IN MM/DAY
      APTRAN = PTRAN*RFDVS
*  ACTUAL POTENTIAL TRANSPIRATION,CORRECTED FOR DEVELOPMENT STAGE
      RFDVS = AFGEN(RFDVST,DVS)
```

```
      VPAM = 1.33*VPA
      SVPAM = 6.11*EXP(17.4*EAVT/(EAVT+239.))
*  SVPAM AND VPAM ARE SATURATED AND ACTUAL VAPOR PRESSURE IN MBAR
      EAVT = MXT-0.25*(MXT-MNT)
      RA = 3.045E-3*SQRT(1./WSA)+63./WSA
      WSA = 1.333E5*AFGEN(WSTB,DAY)
PARAM RHOCP = 2.86E-4
      HNOT = 0.75*DTR-ELWR
      ELWR = 1.175E-7*(EAVT+273.)**4*(0.58-0.09*SQRT(VPA))*(1.0-0.9  ...
          *LFOV)*DAYL/24.
      CC = 1./(SLOPE+S*PSCH)
      S = (RA+RS)/RA
PARAM RS = 18.5E-6,PSCH=0.67
      SLOPE=17.4*SVPAM*(1.-EAVT/(EAVT+239.))/(EAVT+239.)

      ALPHA = TWOVAR(ALPHAT,HRAD,LAI)


*  PROPORTIONALITY FACTOR ALPHA AS FUNCTION OF LAI AND RADIATION
*  INTENSITY

FUNCTION ALPHAT,0. = 0.,1.,100.,1.
FUNCTION ALPHAT,0.2 = 0.,1.,   100.,1.
FUNCTION ALPHAT,2.0= 0.,0.,10.,0.6,15.,.66,20.,.715,25.,.76,30.,.795,...
      35.,.835,40.,.87,45.,.91,50.,.94,60.,.97,100.,1.
FUNCTION ALPHAT,3.5=0.,0.,10.,.425,15.,.515,20.,.585,25.,.64,30.,.68,...
      35.,.715,40.,.745,45.,.77,50.,.795,60.,.845,100.,.875
FUNCTION ALPHAT,5.0=0.,0.,10.,.39,15.,.455,20.,.505,25.,.545,30.,.58,...
      35.,.61,40.,.635,45.,.66,50.,.685,60.,.74,100.,.775
FUNCTION ALPHAT,10.0=0.,0.,10.,.35,15.,.41,20.,.45,25.,.485,30.,.51, ...
      35.,.53,40.,.55,45.,.565,50.,.585,60.,.61,100.,.65


      DAYL = TWOVAR(DAYLT,DAYY,LAT)
*  EFFECTIVE DAYLENGTH AS A FUNCTION OF DAYY AND LATITUDE

FUNCTION DAYLT,0. = 0.,10.5,        365.,0.
FUNCTION DAYLT,10. =0.,10.1,40.,10.25,54.,10.4,67.,10.5,80.,10.6,      ...
   94.,10.75,107.,10.85,122.,11.0,141.,11.1,173.,11.2,206.,11.1,      ...
   226.,11.0,241.,10.85,254.,10.75,267.,10.6,280.,10.5,293.,10.4,     ...
   308.,10.25,357.,10.05,365.,10.1
FUNCTION DAYLT,20.=0.,9.5,40.,9.9,54.,10.15,67.,10.35,80.,10.6,       ...
   94.,10.85,107.,11.1,122.,11.4,141.,11.65,173.,11.85,206.,11.65,    ...
   226.,11.4,241.,11.1,254.,10.85,267.,10.6,280.,10.35,293.,10.15,    ...
   308.,9.9,357.,9.4,365.,9.5
FUNCTION DAYLT,30.0=0.,8.8,40.,9.3,54.,9.85,67.,10.25,80.,10.63,      ...
      93.,11.0,106.,11.4,121.,11.8,140.,12.25,172.,12.6,205.,12.55,   ...
       225.,11.8,240.,11.4,253.,11.0,266.,10.63,279.,10.25,292.,9.85,...
      307.,9.3,357.,8.7,365.,8.8
FUNCTION DAYLT,40.=0.,8.05,40.,8.95,54.,9.5,67.,10.1,80.,10.65,       ...
   94.,11.2,107.,11.75,122.,12.4,141.,13.05,173.,13.5,206.,13.05,     ...
   226.,12.4,241.,11.75,254.,11.2,267.,10.65,280.,10.1,293.,9.5,      ...
   308.,8.95,357.,7.85,365.,8.05
FUNCTION DAYLT,50.=0.,6.9,40.,8.2,54.,8.75,67.,9.9,80.,10.7,94.,11.5,...
   107.,12.3,122.,13.15,141.,14.15,173.,14.9,206.,14.15,226.,13.15,  ...
   241.,12.3,254.,11.5,267.,10.7,280.,9.9,293.,8.75,308.,8.2,         ...
   357.,6.6,365.,6.9
FUNCTION DAYLT,55=0.,6.1,40.,7.75,54.,8.75,67.,9.75,80.,10.7,         ...
   94.,11.7,107.,12.65,122.,13.7,141.,14.9,173.,15.9,209.,14.9,       ...
   226.,13.7,241.,12.65,254.,11.7,267.,10.7,280.,9.75,293.,8.75,      ...
   308.,7.75,357.,5.7,365.,6.1
FUNCTION DAYLT,60.=0.,4.9,40.,7.15,54.,8.4,67.,9.55,80.,10.75,        ...
   94.,11.9,107.,13.1,122.,14.4,141.,16.0,173.,17.4,206.,16.0,        ...
   226.,14.4,241.,13.1,254.,11.9,267.,10.75,280.,9.55,293.,8.4,       ...
   308.,7.15,357.,4.35,365.,4.9
FUNCTION DAYLT,65.=0.,2.9,40.,6.2,54.,7.85,67.,9.35,80.,10.8,         ...
   94.,13.25,107.,13.85,122.,15.45,141.,17.85,173.,20.55,206.,17.85, ...
   226.,15.45,241.,13.85,254.,13.25,267.,10.8,280.,9.35,293.,7.85,    ...
   308.,6.2,357.,2.05,365.,2.9

      TRPMM = APTRAN/(ERLB10+NOT(ERLB10))
*  TRPMM =POTENTIAL TRANSPIRATION RATE PER MM OF ROOT LENGTH IN WET SOIL
```

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FUNCTION WREDT = 0.,0.,.1,.30,.15,.45,.3,.7,.5,.975,.75,1.,1.,1.
*  RELATION BETWEEN MOISTURE CONTENT OF THE SOIL AND THE REDUCTION
*  IN WATER UPTAKE , RESULTING IN A REDUCED TRANSPIRATION

FUNCTION TECT = 0.,0.06, 3.,0.29, 10.,0.85,                          ...
                               16.,0.94,20.,1.,31.,0.87,40.,0.6,50.,0.3
*  TECT IS THE RELATION BETWEEN SOIL TEMPERATURE AND ROOT CONDUCTIVITY
*  HERE USED AS A FACTOR TO REDUCE POTENTIAL TRANSPIRATION
*  TABLE IS DERIVED FROM MAIZE MEASUREMENTS IN PHOTOSROOM(72)
*  ALL TEMPERATURES ARE DECREASED BY 15 DEGREES


FUNCTION EDPTFT = 0.,.15,.15,.6,.3,.8,.5,1.,1.,1.
*  EDPTFT = RELATION BETWEEN SOIL MOISTURE AND EFFECTIVINESS OF ROOTS


      TRAN = TRB10
*  TRAN = ACTUAL RATE OF TRANSPIRATION IN MM/DAY

      TOTRAN = INTGRL(0.,TRAN)
*  TOTRAN = ACCUMULATED TRANSPIRATION OVER GROWING SEASON IN MM


*************EVAPORATION*************

      PEVAP = FRLT*EVAP
*  PEVAP = POTENTIAL EVAPORATION AS A FUNCTION OF SOIL COVER

      TPEVAP = INTGRL(0.,EVAP)
*  TPEVAP = TOTAL POTENTIAL EVAPOTRANSPIRATION IN MM
      AEVAP = PEVAP * REDFD
*  AEVAP = ACTUAL RATE OF EVAPORATION IN MM/DAY
      REDFD = AFGEN(REDFDT,WCPR)
*  REDFD = REDUCTION FACTOR FOR EVAPORATION DUE TO DRYING OF THE SOIL
FUNCTION REDFDT = 0.,.075,.05,.1,.1,.2,.2,.375,.3,.5,.4,.725,.5,.775,...
         .75,.9,1.,1.
*  REDFDT = RELATION BETWEEN FRACTION OF POTENTIAL EVAPORATION AND
*  DIMENSIONLESS WATER CONTENT IN TOP COMPARTMENT
      WCPR = (W1/TCK1-WCLIM)/(FLDCP-WCLIM)
*  WCPR = DIMENSIONLESS WATER CONTENT IN THE TOP COMPARTMENT

      TEVAP = INTGRL(0.,ER10)
*  TEVAP = TOTAL SURFACE EVAPORATION IN MM

      AEPER = (TRB10+ER10)/(PEVAP+PTRAN+NOT(PEVAP+PTRAN))
* AEPER = RATIO OF ACTUAL AND POTENTIAL EVAPOTRANSPIRATION


**      SOIL TEMPERATURE


      TS = 0.1*INTGRL(TSI,RCST)
*  TS = AVERAGE SOIL TEMPERATURE IN DEGR C
*  EQUAL TO TEN DAY RUNNING AVERAGE OF AIR TEMPERATURE
      RCST = (TMPA-DTMPA)/DELT
*  RCST = RATE OF CHANGE OF SOIL TEMPERATURE IN DEGR C/DAY
      DTMPA = DELAY(20,10.,TMPA)+INSW(TIME-10.,0.1*TSI,0.)
*  DTMPA = AIR TEMPERATURE 10 DAYS AGO


**************************** SECTION 5 ***********************


****************** GROWTH OF THE CROP**********


***      GERMINATION

PARAMETER IBIOM = 100.
*  IBIOM = INITIAL AMOUNT OF BIOMASS PRESENT AFTER ESTABLISHMENT
PARAMETER TSUMG = 150.
*  TSUMG = TEMPERATURE SUM NEEDED FOR GERMINATION
      TMPSUM = INTGRL(TMPSMI,TS-ENGR-TMPSUM*PUSHD/DELT)
*  TMPSUM = TEMPERATURE SUM IN DEGR C * DAYS FROM THE ONSET OF
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PARAM TMPSMI = 0.
      ENGR = INSW(TSUMG-TMPSUM,0.,INSW(SW,TMPSUM/DELT,0.))
*  ENGR = RATE OF EMPTYING OF TEMPERATURE SUM WHEN NO SEEDS ARE
*  GERMINATING
      SW = W1+W2+W3-WLTPT*TDB3
*  SW = AMOUNT OF AVAILABLE WATER IN UPPER 10 CM OF SOIL
      PUSHG = AND(TMPSUM-TSUMG,0.5*IBIOM-LBIOM)*INSW(TIME-180.,1.,0.)
*  PUSHG = VARIABLE TO INITIALISE BIOMASS AT MOMENT OF ESTABLISHMENT

***         GROWTH OF STANDING VEGETATION


      LBIOM = INTGRL(0.,GROWTR+IBIOM*PUSHG/DELT-LBIOM*PUSHD/DELT-RDNG)
*  LBIOM = LIVING BIOMASS IN KG/HA

*    CALCULATION OF CROP PRODUCTION

      PDTGR = (PDTGAS-MAINT)*CONFS
*  POTENTIAL DAILY GROWTH IN KG DRY MATTER PER HA
      MAINT = TDRWT*MRESF*TEFR
* LOSS BY MAINTENANCE RESPIRATION
      TEFR = 10**((TMPA-REFT)*ALOG10(2.)/10.)
PARAM MRESF = 0.02,REFT = 25.
PARAM CONFS = 0.75
      HRAD = DTR/DAYL
      PDTGAS = DAYL*TWOVAR(DTGAST,HRAD,LAI)
*  POTENTIAL DAILY GROSS ASSIMILATION IN KG CH2O/HA


*  HOURLY TOTALS OF GROSS ASSIMILATION IN KG CH2O/HA AS A FUNCTION OF
*  RADIATION INTENSITY AND LEAF AREA INDEX(WHEAT)


FUNCTION DTGAST,0. = 0.,0.,   100.,0.
FUNCTION DTGAST,0.2=0.,0.,5.,1.25,10.,2.,15.,2.5,20.,3.,25.,3.25,     ...
    30.,3.5,40.,3.75,50.,4.,60.,4.25,65.,4.3,75.,4.5
FUNCTION DTGAST,2.0=0.,0.,5.,5.,10.,9.5,15.,12.5,20.,15.,25.,16.25,  ...
    30.,17.5,40.,20.5,50.,23.75,60.,26.25,65.,27.75,75.,28.5
FUNCTION DTGAST,3.5=0.,0.,5.,6.25,10.,10.75,15.,14.75,20.,17.5,      ...
    25.,20.,30.,22.25,40.,26.5,50.,30.,60.,33.75,65.,35.,75.,36.
FUNCTION DTGAST,5.0=0.,0.,5.,6.5,10.,11.5,15.,15.75,20.,18.75,       ...
    25.,21.75,30.,24.25,40.,29.5,50.,34.25,60.,37.5,65.,39.5,75.,41.
FUNCTION DTGAST,10.0 = 0.,0.,5.,8.75,10.,16.25,15.,22.75,20.,28.75,  ...
      25.,33.75,30.,38.,40.,43.25,50.,45.,60.,46.25,65.,47.5,75.,50.


      WUSEFF = PDTGR/(PTRAN+NOT(PTRAN))
*  WATER USE EFFICIENCY IN KG DRY MATTER PER MM WATER TRANSPIRED
      TGRWTH = TRAN*WUSEFF
      GROWTR = TGRWTH*CSRR
*****     SHOOT/ROOT RATIO

      CSRR = AFGEN(CSRRT,DVS)
*  CURRENT SHOOT TO ROOT RATIO I.E. DIVISION OF NEW MATERIAL
*  BETWEEN ABOVE AND BELOW GROUND PARTS
FUNCTION CSRRT= 0.,0.3,0.1,0.4,0.25,0.5,0.5,0.65,0.75,0.75,1.,0.975, ...
      1.1,0.975
      TDRWT= LBIOM+RTWGHT
      DBIOM = INTGRL(0.,RDNG+LBIOM*PUSHD/DELT)
*  DBIOM = DEAD BIOMASS IN KG/HA
      RDNG = RDR*LBIOM*(1.-PUSHD)
*  RDNG = RATE OF DYING OF BIOMASS IN KG/HA,DAY
      RDR = AMAX1(RDRW,RDRD)
*  RDR = RELATIVE DEATH RATE IN DAY**(-1)
      RDRW = AFGEN(RDRWT,RWRB10)
*  RDRW = RELATIVE DEATH RATE OF CANOPY AS A RESULT OF WATER SHORTAGE
FUNCTION RDRWT = -0.25,0.10, 0.,0.10, .1,.015, .25,.005,1.,0.005
      RDRD = AFGEN(RDRDT,DVS)

*  RDRD = RELATIVE DEATH RATE CAUSED BY COMPLETION OF DEVELOPMENT
FUNCTION RDRDT = 0.,0.005, 0.90,0.005, 1.,0.10,1.1,0.1
      PUSHD = AND(PLBIOM-LMBIOM,LMBIOM-LBIOM)*INSW(TIME-180.,1.,0.)
      LMBIOM = IBIOM-0.5
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*  LMBIOM = LIMITING BIOMASS TO BE CONSIDERED IN KG/HA
*  PUSHD = VARIABLE TO KILL THE VEGETATION AFTER DROUGHT PERIOD
      PLBIOM = DELAY(10,DELT,LBIOM)
*  PLBIOM = LIVING BIOMASS ONE TIME STEP AGO IN KG/HA
*
      BIOM = LBIOM+DBIOM
*  BIOM = TOTAL AMOUNT OF VEGETATION IN KG/HA

***              LEAF AREA

*
      LFAREA = INTGRL(0.,LAGRTR+LFI*PUSHG/DELT-LFAREA*PUSHD/DELT)
*  LFAREA = LEAF AREA IN M**2/HA
      LFI = IBIOM/750.*1.E4
*  LFI = INITIAL LEAF AREA IN M**2/HA
      LAGRTR = GROWTR*LFARR
*  LAGRTR = RATE OF LEAF AREA GROWTH ON M**2/HA,DAY
      LFARR = AFGEN(LFARRT,TMPA)
*  LFARR = LEAF AREA RATIO IN M**2/KG
FUNCTION LFARRT = 5.,11.5,10.,12.5,15.,13.0,20.,14.0,25.,15.0,30.,13.2
*  LFARRT = RELATION BETWEEN LEAF AREA RATIO AND TEMPERATURE
      LAI = 1.E-4*LFAREA
*  LAI = LEAF AREA INDEX IN HA/HA
      FRLT = AFGEN(FLTRT,LAI)
*  FRLT = FRACTION OF LIGHT TRANSMITTED THROUGH VEGETATION
FUNCTION FLTRT = 0.,1.,0.5,.705,1.,0.496,1.5,0.384,2.,0.248,3.,0.134,...
         5.,0.03,8.,0.004,10.,0.001,15.,0.0001
*  FLTRT = RELATION BETWEEN LAI AND FRACTION OF ENERGY REACHING THE
*  SOIL SURFACE
*  CALCULATED ACCORDING TO INTERCEPTION = 1.-EXP(-0.5*LAI)
*  THIS HOLDS FOR SPHERICAL LEAF DISTRIBUTIONS

***         DEVELOPMENT OF THE VEGETATION

      DVS = INTGRL(0.,DVR-DVS*PUSHD/DELT)
*  DVS = DEVELOPMENT STAGE OF THE VEGETATION AS A FRACTION, DVS = 1.
*  IS RIPENESS
      DVR = AFGEN(DVRT,TMPA)*INSW(LBIOM-IBIOM,0.,1.)*(1.-PUSHD)*     ...
         INSW(DVS-1.,1.,0.)
*  DVR = RATE OF DEVELOPMENT IN DAY**(-1)
*  ONLY EFFECTIVE WHEN VEGETATION IS PRESENT
FUNCTION DVRT = 0.,0., 3.75,0., 16.,0.01, 25.,0.0175, 40.,0.02
*  DVRT = RELATION BETWEEN DEVELOPMENT RATE AND TEMPERATURE


*********** ROOT GROWTH*******

      RTWGHT = INTGRL(0.,GRRWT+IRWT*PUSHG/DELT-RTWGHT*PUSHD/DELT)
*  WEIGHT OF THE ROOTS IN KG/HA
      GRRWT = TGRWTH*(1.-CSRR)
PARAM IRWT = 25.

      RTD = INTGRL(0.,GRRT+IRTD*PUSHG/DELT-RTD*PUSHD/DELT)
*  RTD = ROOTING DEPTH IN MM
PARAMETER IRTD = 101.

*  IRTD = INITIAL ROOTING DEPTH IN MM
      GRRT = SWPB10*DGRRT*RFRGT*INSW(LBIOM-IBIOM,0.,1.)              ...
                   *INSW(RTD-MXRTD,1.,0.)
*  GRRT = GROWTH RATE OF THE ROOT IN MM/DAY
PARAM MXRTD = 1800.
*  MXRTD = MAXIMUM DEPTH OF ROOTING IN MM
PARAMETER DGRRT = 12.
*  DGRRT = DAILY GROWTH RATE OF THE ROOTS UNDER OPTIMAL CONDITIONS
      RFRGT = AFGEN(REDTTB,TS)
*  RFRGT = REDUCTION FACTOR FOR ROOT GROWTH DUE TO TEMPERATURE
FUNCTION REDTTB = 5.,.8,10.,.9,15.,1.,20.,.97,25.,.97,30.,.97,50.,.97
      MWRTD = RTD*(FLDCP-WLTPT)+NOT(RTD)
*  MWRTD = MAXIMUM AMOUNT OF WATER TO BE STORED IN ROOTED DEPTH
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******************   SECTION 6 *********************

*********************     OUTPUT AND RUN CONTROL ***************

      ENGRS = AND(TIME-200.,LMBIOM-LBIOM)
*  ENGRS = SWITCH PARAMETER TO INDICATE END OF GROWING SEASON
FINISH ENGRS = 0.5

*
PRINT   W1,W2,W3,W4,W5,W6,W7,W8,W9,W10,WTOT,TS,                    ...
      TRAIN,EVAP,PTRAN,EB10,TRAN,AEPER,TRPMM,TOTRAN,TEVAP,          ...
      TPEVAP,LBIOM,DBIOM,FRLT,RTD,LAI,F1,F2,F3,F5,F7,TMPA,DPT,TMPSUM,...
       SWPB10,DVS,RWRB10,ERLB10,FOV,RDR,HRAD,MAINT,PDTGAS,PLBIOM,   ...
      RTWGHT,WUSEFF,PDTGR,GROWTR
      XX = DEBUG(3,0.)
      YY = DEBUG(2,10.)
      AA = DEBUG(5,30.)
METHOD RECT
TIMER FINTIM = 245.,PRDEL=1.,DELT=1.0
*  TIMER VARIABLES ARE IN DAYS
TITLE MIGDA,ISRAEL,1972/1973
FUNCTION RAINTB =                                    ...
     0., 0. , 20.99, 0. , 21.,11.1, 21.99,11.1, 22., 0. , 40.99, 0. ,...MIGDAVER
    41.,12.0, 41.99,12.0, 42., 0. , 50.99, 0. , 51.,12.0, 51.99,12.0,...MIGDAVER
    52., 0. , 60.99, 0. , 61.,12.0, 61.99,12.0, 62., 0. , 67.99, 0. ,...MIGDAVER
    68.,12.7, 68.99,12.7, 69., 0. , 74.99, 0. , 75.,12.7, 75.99,12.7,...MIGDAVER
    76., 0. , 81.99, 0. , 82.,12.7, 82.99,12.7, 83., 0. , 88.99, 0. ,...MIGDAVER
    89.,12.7, 89.99,12.7, 90., 0. ,101.99, 0. ,102.,21.0,102.99,21.0,...MIGDAVER
   103., 0. ,108.99, 0. ,109.,21.0,109.99,21.0,110., 0. ,115.99, 0. ,...MIGDAVER
   116.,21.0,116.99,21.0,117., 0. ,126.99, 0. ,127.,10.1,127.99,10.1,...MIGDAVER
   128., 0. ,133.99, 0. ,134.,10.1,134.99,10.1,135., 0. ,140.99, 0. ,...MIGDAVER
   141.,10.1,141.99,10.1,142., 0. ,147.99, 0. ,148.,10.1,148.99,10.1,...MIGDAVER
   149., 0. ,161.99, 0. ,162.,19.4,162.99,19.4,163., 0. ,171.99, 0. ,...MIGDAVER
   172.,19.4,172.99,19.4,173., 0. ,197.99, 0. ,198., 8.5,198.99, 8.5,...MIGDAVER
   199., 0. ,217.99, 0. ,218., 0.8,218.99, 0.8,219., 0. ,365.99, 0.     MIGDAVER
FUNCTION DTRT = 1.,631.,2.,535.,3.,475.,5.,467.,6.,535.,7.,523.,     ...GILOKT72
      8.,411.,9.,760.,10.,735.,11.,874.,12.,438.,13.,465.,           ...GILOKT72
      14.,485.,15.,501.,16.,862.,17.,455.,18.,469.,19.,479.,20.,431.,...GILOKT72
      21.,457.,22.,375.,23.,691.,24.,302.,25.,409.,26.,392.,27.,435.,...GILOKT72
      28.,519.,29.,548.,30.,660.,31.,423.,32.,433.,33.,361.,34.,441.,...
      35.,616.,36.,465.,37.,529.,38.,265.,39.,336.,40.,363.,41.,397.,...
      42.,382.,43.,436.,44.,449.,45.,414.,46.,297.,47.,343.,48.,348.,...
      49.,297.,50.,392.,51.,399.,52.,394.,53.,345.,54.,387.,55.,394.,...
      56.,370.,57.,399.,58.,623.,59.,399.,60.,294.,61.,435.,62.,426.,...
      63.,387.,64.,404.,65.,589.,66.,333.,67.,314.,68.,258.,69.,234.,...
      70.,343.,71.,380.,72.,545.,73.,361.,74.,199.,75.,292.,76.,219.,...
      77.,285.,78.,277.,79.,385.,80.,268.,81.,226.,82.,204.,83.,194.,...
      84.,339.,85.,275.,86.,491.,87.,180.,88.,194.,89.,185.,90.,194.,...
      91.,250.,92.,263.,93.,441.,94.,296.,95.,383.,96.,370.,97.,373.,...
      98.,363.,99.,329.,100.,641.,101.,399.,102.,365.,103.,395.,     ...
     104.,419.,105.,368.,106.,325.,107.,533.,108.,370.,109.,319.,    ...
     110.,436.,111.,419.,112.,270.,113.,319.,114.,489.,115.,373.,    ...
     116.,429.,117.,353.,118.,397.,119.,419.,120.,363.,121.,584.,    ...
     122.,426.,123.,475.,124.,411.,125.,448.,126.,329.,127.,258.,    ...
     128.,548.,129.,236.,130.,265.,131.,290.,132.,377.,133.,451.,    ...
     134.,443.,135.,621.,136.,460.,137.,465.,138.,502.,139.,467.,    ...
     140.,441.,141.,385.,142.,685.,143.,465.,144.,529.,145.,529.,    ...
     146.,513.,147.,551.,148.,482.,149.,624.,150.,533.,151.,513.,    ...
     152.,721.,153.,446.,154.,565.,155.,461.,156.,533.,157.,487.,    ...
     158.,438.,159.,590.,160.,461.,161.,511.,162.,509.,163.,608.,    ...
     164.,519.,165.,521.,166.,334.,167.,487.,168.,182.,169.,295.,    ...
     170.,521.,171.,511.,172.,550.,173.,345.,174.,375.,175.,513.,    ...
     176.,533.,177.,535.,178.,596.,179.,619.,180.,465.,181.,339.,    ...
     182.,585.,183.,572.,184.,519.,185.,611.,186.,579.,187.,604.,    ...
     188.,626.,189.,636.,190.,682.,191.,748.,192.,504.,193.,409.,    ...
     194.,604.,195.,786.,196.,397.,197.,619.,198.,570.,199.,604.,    ...
     200.,550.,201.,592.,202.,656.,203.,648.,204.,449.,205.,570.,    ...
     206.,601.,207.,648.,208.,482.,209.,655.,210.,745.,211.,548.,    ...
     212.,653.,213.,485.,214.,574.,215.,478.,216.,481.,217.,523.,    ...
     218.,488.,219.,612.,220.,312.,221.,626.,222.,499.,223.,614.,    ...
     224.,619.,225.,622.,226.,656.,227.,641.,228.,645.,229.,650.,    ...
     230.,696.,231.,637.,232.,612.,233.,644.,234.,642.,235.,644.,    ...
     236.,442.,237.,611.,238.,626.,239.,655.,240.,659.,241.,515.,    ...
     242.,679.,243.,690.,244.,678.
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*  NOTE THAT THE DATA TILL APRIL 30 ARE FROM GILAT, LATER DATA FROM
*  BETH DAGAN
FUNCTION MXTT  =                                                        ...
        1.,28.7,  2.,28.1,  3.,28.8,  4.,28.9,  5.,29.9,  6.,30.7,     ...MXGOKT72
        7.,31.1,  8.,31.7,  9.,29.6, 10.,33.0, 11.,33.0, 12.,30.8,     ...MXGOKT72
       13.,30.4, 14.,31.0, 15.,31.1, 16.,30.0, 17.,30.5, 18.,30.2,     ...MXGOKT72
     19.,27.0, 20.,25.7, 21.,27.0,  22.,29.0, 23.,32.4, 24.,36.1,      ...MXGOKT72
     25.,36.9, 26.,25.6, 27.,24.6, 28.,25.2, 29.,23.7, 30.,26.3,       ...MXGOKT72
     31.,27.7,                                                          ...MXGOKT72
    32.,25.1,33.,24.5,34.,21.4,35.,22.0,36.,21.4,37.,23.0,38.,22.2,     ...MIGNOV72
    39.,22.5,40.,26.5,41.,27.7,42.,27.1,43.,23.6,44.,22.5,45.,21.7,     ...MIGNOV72
    46.,22.2,47.,22.7,48.,22.8,49.,23.0,50.,23.3,51.,22.3,52.,23.4,     ...MIGNOV72
    53.,26.5,54.,31.2,55.,20.2,56.,21.0,57.,20.5,58.,21.2,59.,17.0,     ...MIGNOV72
    60.,18.1,61.,16.4,                                                  ...MIGNOV72
    62.,16.4,63.,18.0,64.,19.4,65.,16.0,66.,18.0,67.,20.3,68.,22.5,     ...MIGDEC72
    69.,21.0,70.,21.0,71.,18.7,72.,17.0,73.,19.0,74.,18.8,75.,20.5,     ...MIGDEC72
    76.,19.0,77.,19.5,78.,19.0,79.,18.0,80.,16.5,81.,16.6,82.,16.0,     ...MIGDEC72
    83.,13.7,84.,13.5,85.,13.6,86.,15.0,87.,16.5,88., 7.0,89.,16.4,     ...MIGDEC72
    90., 9.2,91., 5.0,92., 2.0,                                         ...MIGDEC72
    93.,15.0,  94.,15.6,  95.,19.2,  96.,21.4,  97.,21.8,  98.,21.0,    ...GMXJAN73
    99.,23.4, 100.,19.5, 101.,15.6, 102.,17.6, 103.,18.0, 104.,15.1,    ...GMXJAN73
   105.,13.0, 106.,14.2, 107., 8.0, 108.,11.3, 109.,14.0, 110.,16.7,    ...GMXJAN73
   111.,18.0, 112.,21.0, 113.,19.4, 114.,15.5, 115.,17.4, 116.,20.0,    ...GMXJAN73
   117.,22.3, 118.,21.7, 119.,18.0, 120.,17.1, 121.,20.5, 122.,20.0,    ...GMXJAN73
   123.,15.5,                                                           ...GMXJAN73
   124.,16.4, 125.,18.0, 126.,21.0, 127.,21.4, 128.,16.5, 129.,20.9,    ...GMXFEB73
   130.,18.7, 131.,17.6, 132.,17.7, 133.,18.5, 134.,21.4, 135.,22.0,    ...GMXFEB73
   136.,24.3, 137.,18.2, 138.,20.9, 139.,28.7, 140.,33.0, 141.,26.1,    ...GMXFEB73
   142.,20.2, 143.,20.4, 144.,26.0, 145.,19.0, 146.,16.5, 147.,18.5,    ...GMXFEB73
   148.,19.6, 149.,21.0, 150.,25.5, 151.,24.5,                          ...GMXFEB73
   152.,19.0, 153.,19.6, 154.,12.2, 155.,14.3, 156.,15.2, 157.,15.7,    ...GMXMRC73
   158.,15.0, 159.,15.6, 160.,21.7, 161.,21.2, 162.,19.2, 163.,26.2,    ...GMXMRC73
   164.,30.0, 165.,31.5, 166.,18.6, 167.,18.6, 168.,22.0, 169.,26.2,    ...GMXMRC73
   170.,30.2, 171.,18.0, 172.,17.8, 173.,16.3, 174.,16.6, 175.,19.0,    ...GMXMRC73
   176.,24.5, 177.,27.5, 178.,17.2, 179.,25.0, 180.,35.2, 181.,21.7,    ...GMXMRC73
   182.,22.2,                                                           ...MXGMRC73
       183.,27.0,184.,32.2,185.,22.7,186.,21.6,187.,24.6,188.,25.8,     ...MXGAPR73
       189.,21.5,190.,21.8,191.,21.0,192.,22.8,193.,25.9,194.,30.5,     ...MXGAPR73
       195.,27.7,196.,22.0,197.,20.4,198.,21.5,199.,29.5,200.,21.2,     ...MXGAPR73
       201.,33.6,202.,35.6,203.,23.8,204.,21.0,205.,24.0,206.,32.8,     ...MXGAPR73
       207.,32.1,208.,22.4,209.,23.2,210.,27.5,211.,21.8,212.,25.0,     ...MXGAPR73
       213.,29.0,214.,26.2,215.,25.6,216.,26.4,217.,26.5,218.,28.1,     ...MXGMAY73
       219.,27.1,220.,32.6,221.,30.0,222.,31.0,223.,29.1,224.,29.1,     ...MXGMAY73
       225.,28.7,226.,38.0,227.,24.0,228.,23.0,229.,23.5,230.,26.0,     ...MXGMAY73
       231.,26.0,232.,28.2,233.,32.1,234.,32.0,235.,33.2,236.,34.0,     ...MXGMAY73
       237.,35.3,238.,33.6,239.,28.0,240.,28.0,241.,26.0,242.,25.6,     ...MXGMAY73
       243.,26.2                                                           MXGMAY73
FUNCTION MNTT  =                                                        ...
        1.,21.1,  2.,17.7,  3.,16.8,  4.,18.1,  5.,17.5,  6.,16.4,     ...MNGOKT72
        7.,16.0,  8.,15.4,  9.,13.9, 10.,15.2, 11.,16.6, 12.,19.4,     ...MNGOKT72
     13.,13.0, 14.,18.8, 15.,19.8, 16.,17.0, 17.,15.0, 18.,16.2,       ...MNGOKT72
     19.,16.1, 20.,16.7, 21.,13.5, 22.,13.1, 23.,15.7, 24.,14.0,       ...MNGOKT72
     25.,22.1, 26.,16.9, 27.,15.0, 28.,10.4, 29.,13.0, 30.,15.0,       ...MNGOKT72
     31.,11.7,                                                          ...MNGOKT72
    32.,13.5,33.,11.1,34.,10.6,35.,15.3,36.,10.2,37.,10.6,38.,10.0,     ...MIGNOV72
    39.,13.5,40.,12.3,41.,12.6,42.,11.9,43.,11.7,44.,12.4,45.,13.0,     ...MIGNOV72
    46.,10.3,47.,10.2,48.,14.2,49.,11.9,50.,10.0,51., 9.0,52., 9.6,     ...MIGNOV72
    53., 8.9,54.,16.0,55.,15.0,56.,13.1,57.,13.0,58.,13.0,59.,11.3,     ...MIGNOV72
    60., 9.4,61., 9.0,                                                  ...MIGNOV72
    62., 6.1,63., 5.2,64., 2.5,65., 8.0,66., 7.8,67., 7.4,68., 8.1,     ...MIGDEC72
    69., 9.4,70., 8.5,71., 7.3,72., 7.2,73., 7.1,74., 6.9,75., 7.8,     ...MIGDEC72
    76., 4.4,77., 5.0,78., 4.8,79., 7.4,80.,10.2,81., 9.2,82., 9.7,     ...MIGDEC72
    83., 5.6,84., 4.2,85., 3.9,86., 3.8,87., 4.8,88., 2.0,89., 4.8,     ...MIGDEC72
    90., 4.0,91., 2.0,92., 1.5,                                         ...MIGDEC72
    93., 0.0,  94., 1.4,  95.,-0.4,  96., 3.0,  97., 6.0,  98., 8.0,    ...GMNJAN73
    99., 4.9, 100., 3.4, 101., 3.9, 102., 6.9, 103., 8.5, 104., 7.0,    ...GMNJAN73
   105., 7.0, 106., 7.6, 107., 1.6, 108., 5.0, 109., 5.8, 110., 5.2,    ...GMNJAN73
   111., 4.1, 112., 8.0, 113., 8.0, 114., 9.0, 115., 7.8, 116., 7.5,    ...GMNJAN73
   117.,10.4, 118., 9.4, 119., 8.0, 120., 7.3, 121., 5.1, 122., 6.8,    ...GMNJAN73
   123., 9.5,                                                           ...GMNJAN73
   124., 8.4, 125., 3.7, 126., 5.4, 127., 5.5, 128., 8.0, 129., 4.7,    ...GMNFEB73
   130., 8.0, 131., 7.5, 132., 5.4, 133., 4.6, 134., 4.9, 135., 4.2,    ...GMNFEB73
   136., 5.6, 137., 9.1, 138., 3.9, 139., 7.3, 140.,15.0, 141.,13.4,    ...GMNFEB73
   142., 7.2, 143., 9.5, 144.,14.3, 145.,12.2, 146., 9.6, 147., 8.4,    ...GMNFEB73
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148., 8.0, 149., 7.4, 150., 8.1, 151.,12.0,
152., 8.2, 153., 7.0, 154., 6.5, 155., 6.0, 156., 7.8, 157., 5.8,   ....GMNFEB73
158., 6.0, 159., 4.6, 160., 4.1, 161.,12.4, 162., 8.0, 163., 8.0,   ...GMNMRC73
164.,10.4, 165.,16.6, 166.,12.4, 167., 7.6, 168.,14.8, 169.,16.4,   ...GMNMRC73
170.,11.5, 171.,10.0, 172., 8.4, 173., 8.6, 174., 8.0, 175., 5.0,   ...GMNMRC73
176., 5.0, 177.,13.8, 178., 9.0, 179., 7.7, 180.,13.3, 181.,13.2,   ...GMNMRC73
182.,10.0,                                                          ...GMNMRC73
    183., 9.9,184.,12.1,185.,12.2,186.,10.3,187., 6.0,188., 9.2,    ...GMNMRC73
    189., 8.6,190., 9.5,191., 8.4,192., 6.3,193.,10.7,194.,10.2,    ...MNGAPR73
    195., 8.9,196.,13.0,197.,10.0,198., 8.2,199., 8.0,200., 8.0,    ...MNGAPR73
    201.,10.0,202.,16.0,203.,11.4,204., 9.8,205., 8.4,206., 6.3,    ...MNGAPR73
    207.,17.0,208.,14.0,209.,11.1,210., 8.0,211., 7.9,212., 8.0,    ...MNGAPR73
    213., 8.5,214., 8.3,215.,12.0,216.,12.0,217.,10.4,218., 9.8,    ...MNGAPR73
    219.,12.7,220.,12.6,221.,15.6,222.,14.7,223.,10.8,224.,15.0,    ...MNGMAY73
    225., 9.7,226.,12.6,227.,16.1,228.,14.5,229.,13.4,230.,11.8,    ...MNGMAY73
    231.,11.4,232.,10.6,233.,10.8,234.,14.0,235.,14.4,236.,14.0,    ...MNGMAY73
    237.,13.5,238.,13.4,239.,12.6,240.,16.1,241.,13.4,242.,14.0,    ...MNGMAY73
    243.,12.7                                                       ...MNGMAY73
FUNCTION DP2T =                                                        MNGMAY73
      1.,16.9,  2.,15.0,  3.,16.8,  4.,16.4,  5.,17.3,  6.,16.2,    ...
      7.,12.7,  8.,12.0,  9.,17.9, 10.,18.4,  5.,17.3,  6.,16.2,    ...D2GOKT72
   13.,18.5, 14.,19.4, 15.,19.6, 16.,17.0, 11.,20.8, 12.,17.7,      ...D2GOKT72
   19.,13.7, 20.,10.8, 21.,13.2, 22.,16.1, 17.,13.9, 18.,11.2,      ...D2GOKT72
   25.,15.3, 26.,13.5, 27., 9.9, 28., 8.8, 23., 5.7, 24., 3.4,      ...D2GOKT72
   31.,10.5,                     29., 6.8, 30., 9.5,                ...D2GOKT72
    32.,14.2, 33., 4.8, 34.,15.9, 35.,16.3, 36., 5.9, 37.,10.9,     ...D2GOKT72
    38.,11.2, 39., 9.9, 40.,10.5, 41.,10.9, 42.,17.6, 43.,13.5,     ...D2GNOV72
    44.,12.8, 45.,15.7, 46.,11.4, 47.,14.3, 48.,11.3, 49.,11.9,     ...D2GNOV72
    50., 7.7, 51.,10.7, 52., 9.2, 53.,11.4, 54.,10.4, 55.,15.1,     ...D2GNOV72
    56.,16.7, 57.,16.5, 58., 8.8, 59.,14.8, 60., 8.4, 61., 9.7,     ...D2GNOV72
    62., 4.0, 63., 0.2, 64., 0.1, 65.,12.9, 66., 8.6, 67., 6.5,     ...D2GNOV72
    68., 6.0, 69., 8.9, 70.,13.1, 71., 8.8, 72., 5.4, 73., 5.0,     ...D2GDEC72
    74., 5.5, 75., 2.3, 76., 3.4, 77., 9.0, 78., 8.9, 79.,11.1,     ...D2GDEC72
    80., 9.7, 81., 7.8, 82.,11.1, 83., 5.2, 84.,-0.3, 85.,-3.5,     ...D2GDEC72
    86.,-5.7, 87.,-5.7, 88., 8.3, 89., 1.4, 90., 6.3, 91., 0.9,     ...D2GDEC72
    92., 6.2,                                                       ...D2GDEC72
    93.,-4.0, 94., 1.1, 95.,-6.8, 96.,-8.1, 97.,-8.7, 98.,-9.8,     ...D2GDEC72
    99.,-4.4,100., 4.6,101.,10.8,102., 7.1,103., 8.8,104.,10.7,     ...D2GJAN73
   105., 7.4,106., 5.1,107., 5.1,108., 6.1,109., 1.6,110., 9.0,     ...D2GJAN73
   111., 8.6,112., 6.5,113., 7.5,114.,11.2,115., 8.0,116., 5.4,     ...D2GJAN73
   117., 4.2,118., 7.2,119., 4.2,120., 1.7,121.,-0.7,122.,-1.6,     ...D2GJAN73
   123., 6.3,                                                       ...D2GJAN73
   124., 5.8,125., 9.3,126., 6.5,127., 3.1,128., 0.2,129., 4.2,     ...D2GJAN73
   130.,10.8,131., 6.3,132., 7.8,133., 6.4,134., 3.1,135.,12.2,     ...D2GFEB73
   136., 3.8,137., 8.2,138., 6.2,139.,-3.7,140., 1.4,141.,12.5,     ...D2GFEB73
   142., 6.5,143.,13.0,144.,12.5,145., 8.3,146., 7.0,147., 4.1,     ...D2GFEB73
   148., 5.2,149., 1.5,150.,-1.1,151., 0.2,                         ...D2GFEB73
   152., 9.2,153., 4.6,154., 6.0,155., 6.0,156., 7.3,157., 3.4,     ...D2GFEB73
   158., 4.0,159., 6.3,160., 2.9,161.,10.9,162.,10.6,163.,-0.7,     ...D2GMRC73
   164., 5.5,165.,-2.5,166., 8.9,167., 9.0,168., 2.3,169., 2.0,     ...D2GMRC73
   170., 1.1,171., 8.2,172., 7.9,173., 7.2,174., 7.1,175., 3.7,     ...D2GMRC73
   176., 6.9,177., 5.8,178., 7.9,179., 6.5,180., 3.0,181.,10.3,     ...D2GMRC73
   182., 8.0,                                                       ...D2GMRC73
   183., 3.5,184., 1.0,185.,11.1,186., 7.0,187., 6.6,188.,13.5,     ...D2GMRC73
   189., 3.8,190., 6.1,191., 7.2,192.,10.5,193.,11.9,194.,13.4,     ...D2GAPR73
   195.,11.1,196.,10.8,197., 5.4,198., 5.0,199., 3.5,200., 6.0,     ...D2GAPR73
   201., 0.0,202., 9.4,203., 9.6,204., 6.9,205., 5.7,206.,-6.5,     ...D2GAPR73
   207.,12.9,208., 9.9,209., 9.2,210., 8.4,211., 9.9,212., 3.0,     ...D2GAPR73
   213.,-1.8,214.,-7.7,215.,10.3,216., 2.6,217.,-9.8,218., 5.7,     ...D2GAPR73
   219., 8.2,220., 2.2,221.,10.0,222., 0.7,223., 8.3,224.,13.0,     ...D2GMAY73
   225.,12.2,226.,-3.0,227.,11.4,228., 9.1,229.,10.4,230.,10.3,     ...D2GMAY73
   231.,12.7,232.,14.6,233.,14.1,234., 6.0,235., 7.2,236., 6.0,     ...D2GMAY73
   237., 8.1,238., 5.5,239.,14.8,240., 9.5,241., 9.1,242., 8.5,     ...D2GMAY73
   243., 8.5                                                        ...D2GMAY73
FUNCTION DP8T =                                                        D2GMAY73
      1.,18.1,  2.,16.2,  3.,16.0,  4.,17.1,  5.,16.6,  6.,18.1,    ...
      7.,18.7,  8.,10.7,  9.,17.7, 10.,17.0, 11.,19.6, 12.,21.2,    ...D8GOKT72
   13.,18.2, 14.,20.7, 15.,19.2, 16.,18.8, 17.,11.1, 18.,14.5,      ...D8GOKT72
   19.,15.6, 20.,10.1, 21.,13.8, 22.,12.9, 23.,11.7, 24.,10.5,      ...D8GOKT72
   25.,-0.2, 26.,13.2, 27.,12.1, 28.,12.5, 29.,11.2, 30., 9.1,      ...D8GOKT72
   31., 9.9,                                                        ...D8GOKT72
    32.,14.2, 33., 7.8, 34.,12.7, 35.,15.0, 36.,11.3, 37., 9.7,     ...D8GOKT72
    38.,14.6, 39.,12.8, 40., 9.6, 41.,11.3, 42.,10.6, 43.,14.2,     ...D8GNOV72
    44.,12.4, 45.,12.4, 46.,11.0, 47.,12.4, 48.,13.6, 49.,11.9,     ...D8GNOV72
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     50.,10.7, 51.,11.4, 52., 9.0, 53., 8.1, 54., 9.9, 55.,17.6,    ...DBGNOV72
     56.,15.3, 57.,15.7, 58.,14.2, 59.,11.9, 60., 9.2, 61.,10.3,    ...DBGNOV72
     62., 5.9, 63., 4.8, 64., 2.9, 65., 9.8, 66., 8.0, 67., 7.8,    ...DBGDEC72
     68., 6.2, 69., 5.9, 70., 9.1, 71., 8.6, 72., 9.1, 73., 6.1,    ...DBGDEC72
     74., 7.4, 75., 3.4, 76., 4.0, 77., 1.4, 78., 9.9, 79., 7.4,    ...DBGDEC72
     80., 9.2, 81., 7.4, 82., 9.6, 83., 4.9, 84., 2.6, 85.,-3.7,    ...DBGDEC72
     86.,-4.8, 87., 2.5, 88.,-7.7, 89.,-4.8, 90., 2.5, 91.,-2.5,    ...DBGDEC72
     92., 1.4,                                                      ...DBGDEC72
     93.,-2.7, 94.,-7.5, 95.,-3.5, 96.,-7.2, 97.,-9.8, 98.,-7.6,    ...DBGJAN73
     99.,-4.4,100.,-1.8,101., 3.1,102., 7.3,103., 7.5,104., 6.5,    ...DBGJAN73
    105., 8.1,106., 5.9,107.,-0.7,108., 5.3,109., 3.2,110., 5.5,    ...DBGJAN73
    111., 5.5,112., 7.6,113., 3.2,114., 9.4,115., 9.9,116., 2.9,    ...DBGJAN73
    117.,13.4,118., 6.9,119., 6.7,120., 4.6,121., 3.1,122., 1.9,    ...DBGJAN73
    123., 1.3,                                                      ...DBGJAN73
    124., 8.7,125., 6.9,126., 4.9,127., 4.8,128., 7.2,129., 8.1,    ...DBGFEB73
    130.,11.9,131., 9.7,132., 6.8,133., 5.0,134., 4.1,135., 3.8,    ...DBGFEB73
    136., 5.9,137., 8.3,138., 5.3,139., 3.2,140., 4.5,141.,-0.9,    ...DBGFEB73
    142., 8.1,143.,10.1,144.,10.3,145.,10.7,146., 7.4,147., 6.0,    ...DBGFEB73
    148., 3.7,149., 4.2,150., 2.9,151., 0.3,                        ...DBGFEB73
    152.,10.6,153., 7.9,154., 6.3,155., 4.8,156., 4.2,157., 3.9,    ...DBGMRC73
    158., 5.2,159., 4.8,160., 6.7,161.,10.7,162.,11.9,163., 2.6,    ...DBGMRC73
    164., 5.1,165.,-3.1,166.,12.0,167., 9.0,168., 1.5,169., 2.7,    ...DBGMRC73
    170.,-1.3,171.,11.4,172., 8.8,173., 6.8,174., 8.7,175.,12.9,    ...DBGMRC73
    176., 5.2,177., 3.1,178.,10.6,179., 9.1,180., 1.5,181.,11.5,    ...DBGMRC73
    182.,10.3,                                                      ...DBGMRC73
    183., 0.9,184., 9.0,185.,12.5,186.,11.3,187., 4.5,188.,13.3,    ...DBGAPR73
    189.,10.7,190., 7.8,191., 9.9,192.,10.6,193.,11.7,194.,13.3,    ...DBGAPR73
    195.,13.1,196.,12.7,197., 8.4,198., 9.6,199., 7.6,200.,10.5,    ...DBGAPR73
    201.,-1.8,202., 8.1,203.,10.6,204.,11.3,205., 8.3,206.,-5.7,    ...DBGAPR73
    207.,-6.3,208.,11.8,209., 9.8,210.,10.5,211., 9.6,212., 7.5,    ...DBGAPR73
    213., 3.4,214., 3.8,215.,13.7,216.,12.5,217.,13.5,218., 2.2,    ...DBGMAY73
    219.,16.8,220., 7.0,221.,12.8,222., 9.5,223.,11.0,224., 8.8,    ...DBGMAY73
    225.,11.1,226., 1.9,227.,14.5,228., 8.7,229.,10.1,230.,11.3,    ...DBGMAY73
    231.,11.2,232.,15.1,233.,12.6,234.,15.5,235., 2.9,236.,11.5,    ...DBGMAY73
    237., 6.6,238.,-6.2,239.,15.1,240.,13.7,241.,11.9,242.,12.6,    ...DBGMAY73
    243.,10.2                                                          DBGMAY73
FUNCTION WSTB =                                                     ...
       1.,138.,  2.,103.,  3.,112.,  4.,113.,  5.,132.,  6.,122.,   ...WGLOKT72
       7.,199.,  8.,138.,  9.,161., 10.,105., 11.,103., 12.,111.,   ...WGLOKT72
      13.,110., 14.,138., 15.,118., 16.,100., 17.,166., 18.,116.,   ...WGLOKT72
      19.,130., 20.,138., 21.,165., 22.,109., 23.,120., 24.,168.,   ...WGLOKT72
      25.,179., 26.,124., 27.,160., 28.,173., 29.,136., 30.,125.,   ...WGLOKT72
      31.,125.,                                                     ...WGLOKT72
  32.,150.0,33.,129.5,34.,207.3,35.,286.8,36.,115.1,37.,121.7,      ...MIGNOV72
  38., 63.0,39.,126.7,40.,116.6,41.,105.7,42.,219.0,43.,104.3,      ...MIGNOV72
  44.,111.1,45.,106.6,46.,154.6,47., 93.0,48.,114.0,49.,111.3,      ...MIGNOV72
  50., 99.2,51.,108.2,52.,106.7,53., 96.6,54., 96.2,55.,170.4,      ...MIGNOV72
  56.,184.9,57.,132.6,58.,106.1,59.,105.9,60.,170.4,61.,142.0,      ...MIGNOV72
  62., 78.7,63., 90.6,64., 85.2,65.,117.9,66., 58.6,67., 94.2,      ...MIGNOV72
  68., 89.2,69.,120.2,          70.,108.2,71., 69.1,72., 84.8,      ...MIGDEC72
  73., 99.1,74., 72.5,75., 74.5,76., 71.0,77.,104.8,78.,107.3,      ...MIGDEC72
  79., 99.1,80.,187.7,81.,190.0,82.,189.1,83., 93.2,84., 87.9,      ...MIGDEC72
  85.,120.5,86., 93.5,87., 98.1,88., 76.7,89.,106.1,90.,113.2,      ...MIGDEC72
  91., 78.7,92.,152.7,                                              ...MIGDEC72
  93., 74.8, 94., 57.9, 95.,122.6, 96.,204.7, 97.,241.5, 98.,140.0, ...GWSJAN73
  99., 94.4,100., 76.6,101.,125.2,102.,122.9,103., 99.7,104.,322.7, ...GWSJAN73
 105.,311.7,106.,546.6,107.,390.0,108.,259.3,109.,144.0,110., 80.9, ...GWSJAN73
 111., 96.0,112.,141.6,113.,165.8,114., 85.4,115., 92.4,116.,108.2, ...GWSJAN73
 117.,167.7,118.,123.0,119.,197.5,120.,140.7,121.,147.5,122.,325.7, ...GWSJAN73
 123.,327.1,                                                        ...GWSJAN73
 124., 88.0,125.,101.3,126., 85.2,127.,158.9,128.,149.9,129.,137.5, ...GWSFEB73
 130., 67.8,131., 99.0,132., 92.1,133., 93.4,134.,115.3,135., 78.6, ...GWSFEB73
 136.,102.1,137., 84.1,138.,108.7,139.,180.3,140.,211.1,141.,152.4, ...GWSFEB73
 142.,146.8,143.,112.6,144.,173.5,145.,327.6,146.,335.8,147.,168.1, ...GWSFEB73
 148.,172.1,149.,121.6,150.,169.0,151., 97.3,                       ...GWSFEB73
 152.,125.0,153.,333.7,154.,270.8,155., 84.8,156.,188.0,157.,301.9, ...GWSMRC73
 158.,323.8,159., 85.3,160.,131.8,161.,103.8,162.,140.3,163.,152.9, ...GWSMRC73
 164.,176.1,165.,194.7,166.,183.5,167.,117.6,168.,107.3,169.,180.4, ...GWSMRC73
 170.,150.8,171.,189.2,172.,173.3,173.,170.7,174.,112.9,175.,140.7, ...GWSMRC73
 176.,117.1,177.,152.4,178., 66.2,179., 62.2,180.,175.7,181.,154.2, ...GWSMRC73
 182.,120.0,                                                        ...GWSMRC73
   183.,178.,184.,140.,185.,130.,186.,125.,187.,133.,188.,137.,     ...WGLAPR73
   189.,297.,190.,243.,191.,127.,192.,135.,193.,136.,194.,121.,     ...WGLAPR73
   195.,121.,196.,130.,197.,157.,198.,167.,199.,202.,200.,118.,     ...WGLAPR73
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      201.,350.,202.,162.,203.,158.,204.,143.,205.,157.,206.,140.,       ...WGLAPR73
      207.,262.,208.,203.,209.,154.,210.,129.,211.,198.,212.,123.,       ...WGLAPR73
      213.,118.,214.,136.,215.,153.,216.,136.,217.,137.,218.,143.,       ...WGLMAY73
      219.,184.,220.,243.,221.,179.,222.,103.,223.,168.,224., 84.,       ...WGLMAY73
      225.,121.,226.,251.,227.,234.,228.,283.,229.,182.,230.,158.,       ...WGLMAY73
      231.,158.,232.,173.,233.,142.,234.,148.,235.,125.,236.,142.,       ...WGLMAY73
      237.,159.,238.,142.,239.,171.,240.,153.,241.,158.,242.,139.,       ...WGLMAY73
      243.,135.                                                             WGLMAY73
END
STOP
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6.2 Validation of the model

6.2.1 Introduction

In the growing stream of publications, dealing with models and model building in biological sciences, as a rule much more attention is paid to the structure and functioning of the models than to the validation. That part should however be strongly emphasized because the value of a model, both explanatory and predictive, is completely determined by the degree of fit between simulated and experimental results (van Keulen, 1974). This already shows that modelling must not replace experimentation, but present a framework, in which proper experiments, designed to test the hypothesis expressed in the model are carried out.

There are several pitfalls in the validation procedure: special care must be taken that the same data are not used in both the development of the model and in its validation. The only conclusion that can be drawn from such models is, that a calculation procedure has been developed which regenerates its own inputs. Especially when part of the structure contains (semi)-empirical relations, there is the danger of circular reasoning. Thus if possible completely independent data should be collected for validation.

But even when the structure of the model is completely based upon physical and physiological principles and no experimental data are used in program development, it is impossible to separate model and experiment completely. When both the model development and the experimentation are carried out by the same person or team, the model will always be influenced by the experimental results. Although the scientist may, to the best of his knowledge, try to be objective in both parts of his work, he will not be able to avoid continuous interaction. This will introduce subjective functions in the model, although these may be difficult to pinpoint.

The validation studies carried out with the model ARID CROP, whose results are given in Figs. 48, 49 and 50 may illustrate the effect of this phenomenon. During development of the model, the data collected in the season '71/'72 have always been used to test the model's behaviour. It is obvious that the agreement between measured and simulated results is best for that season. However, no attempt was made to obtain a better fit with the experimental data in the other seasons by changing either structure or parameters of the model. It would be easy to obtain a good fit for all three years with such a complex model. The existing differences show that there are processes playing a role which are either not described or not described accurately enough. A better agreement may be obtained by again studying the relevant processes and trying to improve their description. This is, however, not felt necessary for the present purpose. An attempt to improve the results by changing a few of the numerous parameter values would be "a disastrous way of working... and reduce the technique into the most cumbersome and subjective technique of curve fitting that can be imagined" (de Wit, 1970).

6.2.2 Comparison of simulated and measured results

In Figs. 48, 49 and 50 the measured and calculated values of aerial dry matter production and total moisture content of the soil are given for the three growing seasons.

The agreement between the two is excellent for the '71/'72 season, the differences being never greater than 5%.

There is a marked difference when these results are compared with the ones in Fig. 49. When the same initial biomass, the amount present after establishment, of 25 kg ha^{-1} is assumed, the calculated growth rate is much lower than the measured one. Already in Section 2.3.5 the opinion was expressed that in '71/'72 germination was poor due to disking. It seems therefore likely that more seeds germinated and that the initial biomass under normal conditions is about 100 kg ha^{-1}. Introduction of that value in the model yields results which are in better agreement with the measurements. Comparison of the two calculated curves shows that despite the different growing pattern, the final yields differ by only 10%. The difference is caused by a lower loss through direct soil evaporation when the vegetation forms a closed surface earlier in the season. Between days 130 and 145

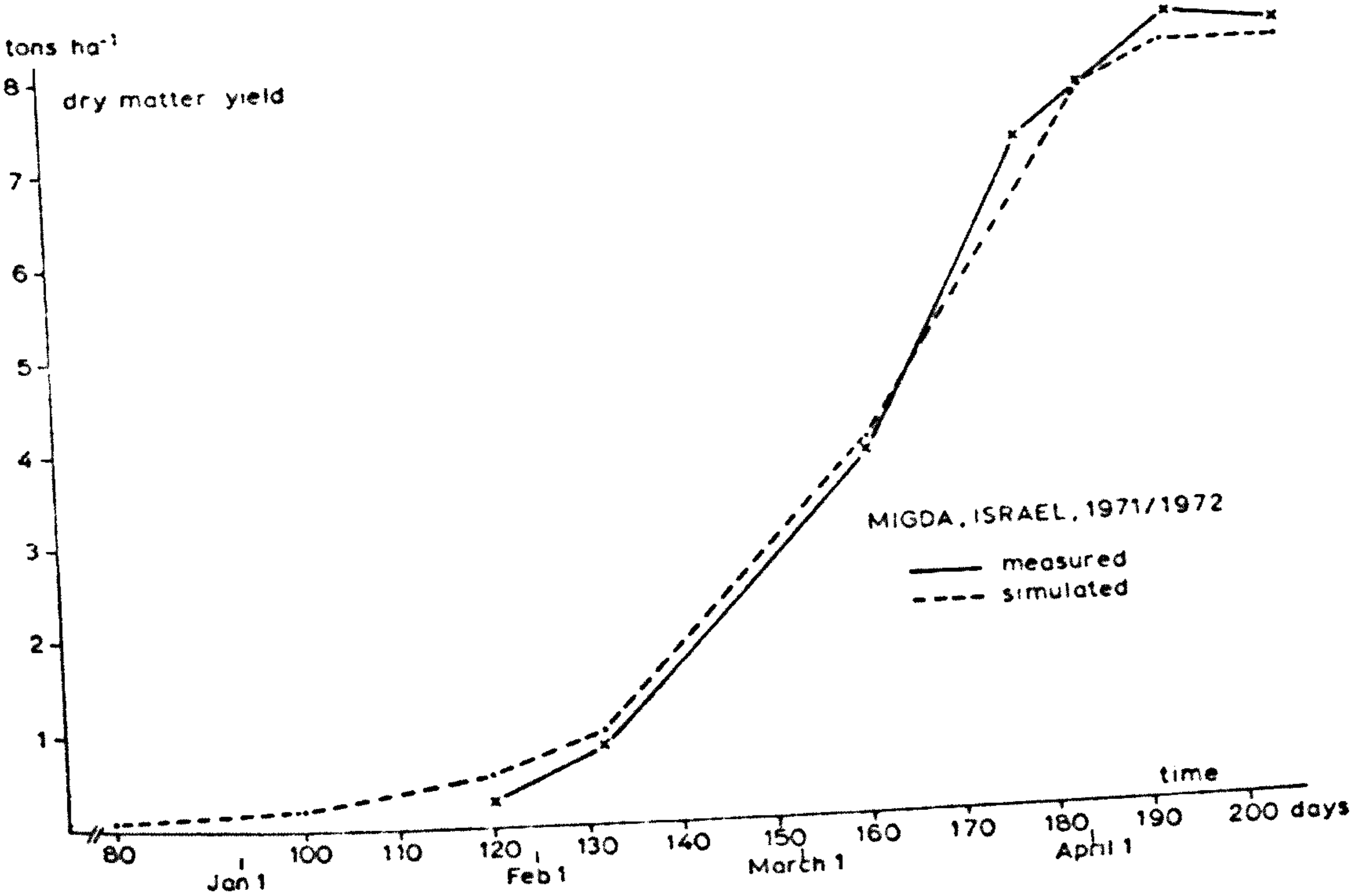

Fig. 48a | Comparison between measured and simulated dry matter production of natural vegetation in Migda '71/'72.

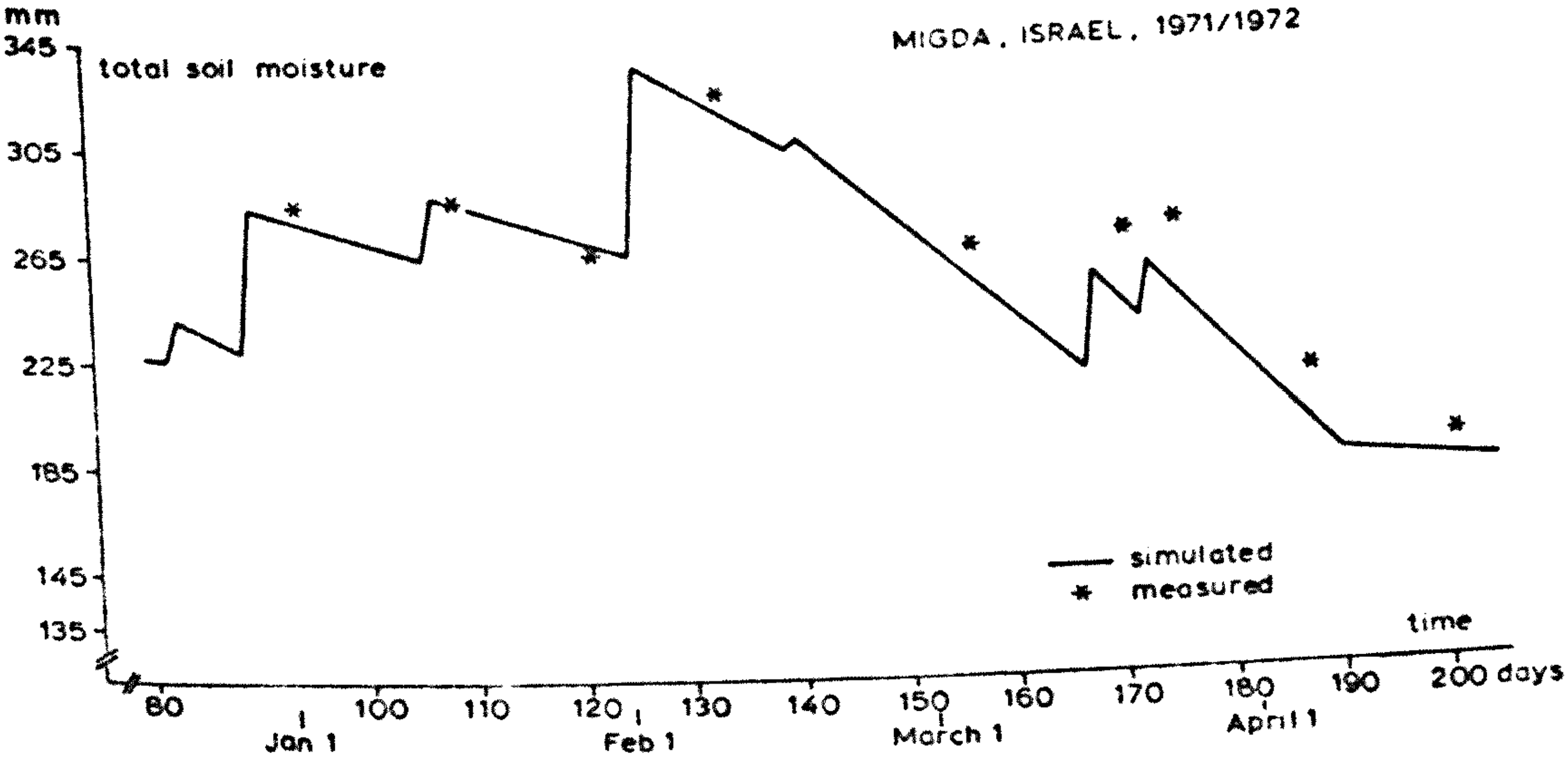

Fig. 48b | Comparison between measured and simulated course of total soil moisture under natural vegetation in Migda '71/'72.

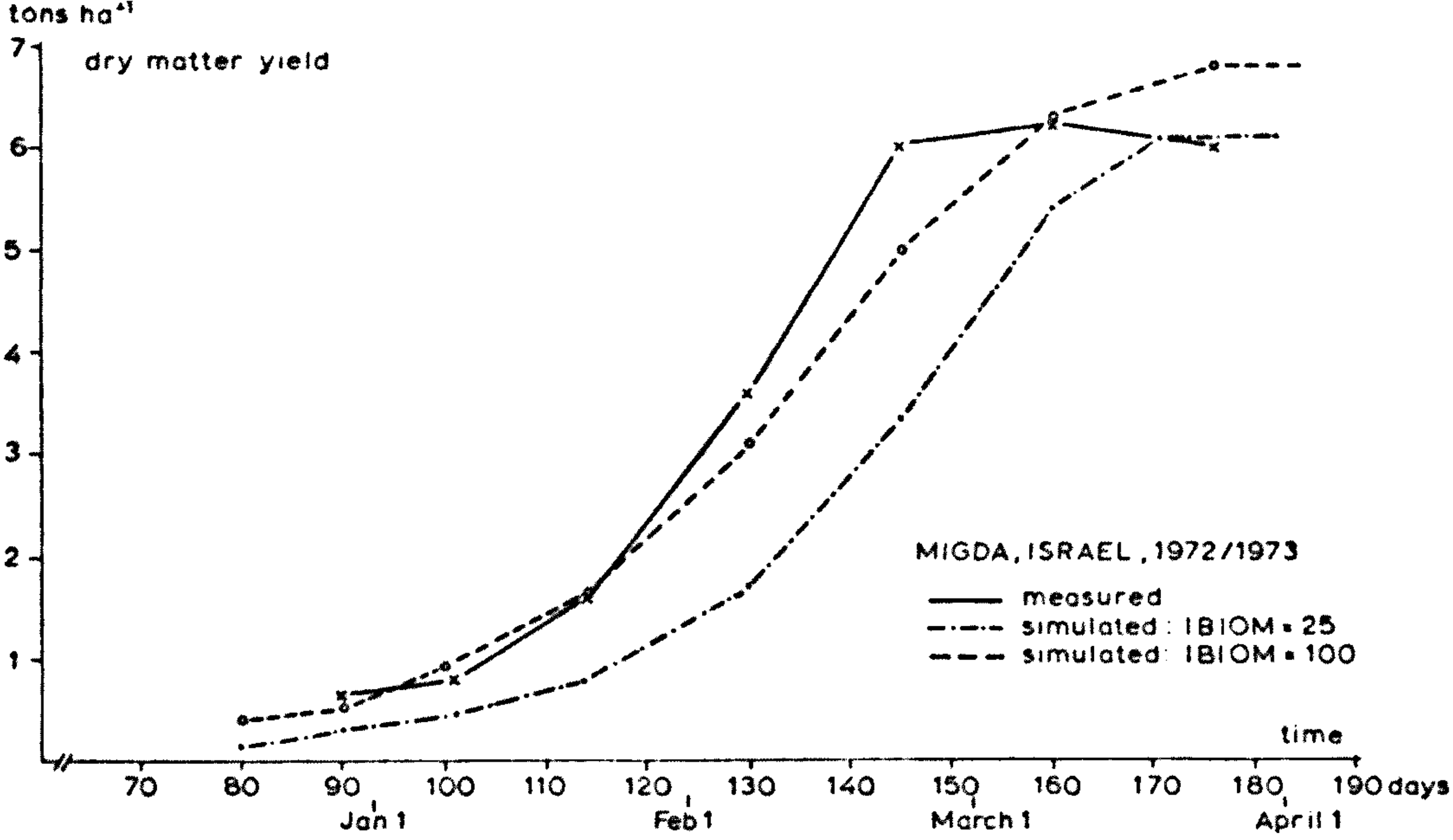

Fig. 49a | Comparison between measured and simulated dry matter production of natural vegetation in Migda '72/'73.

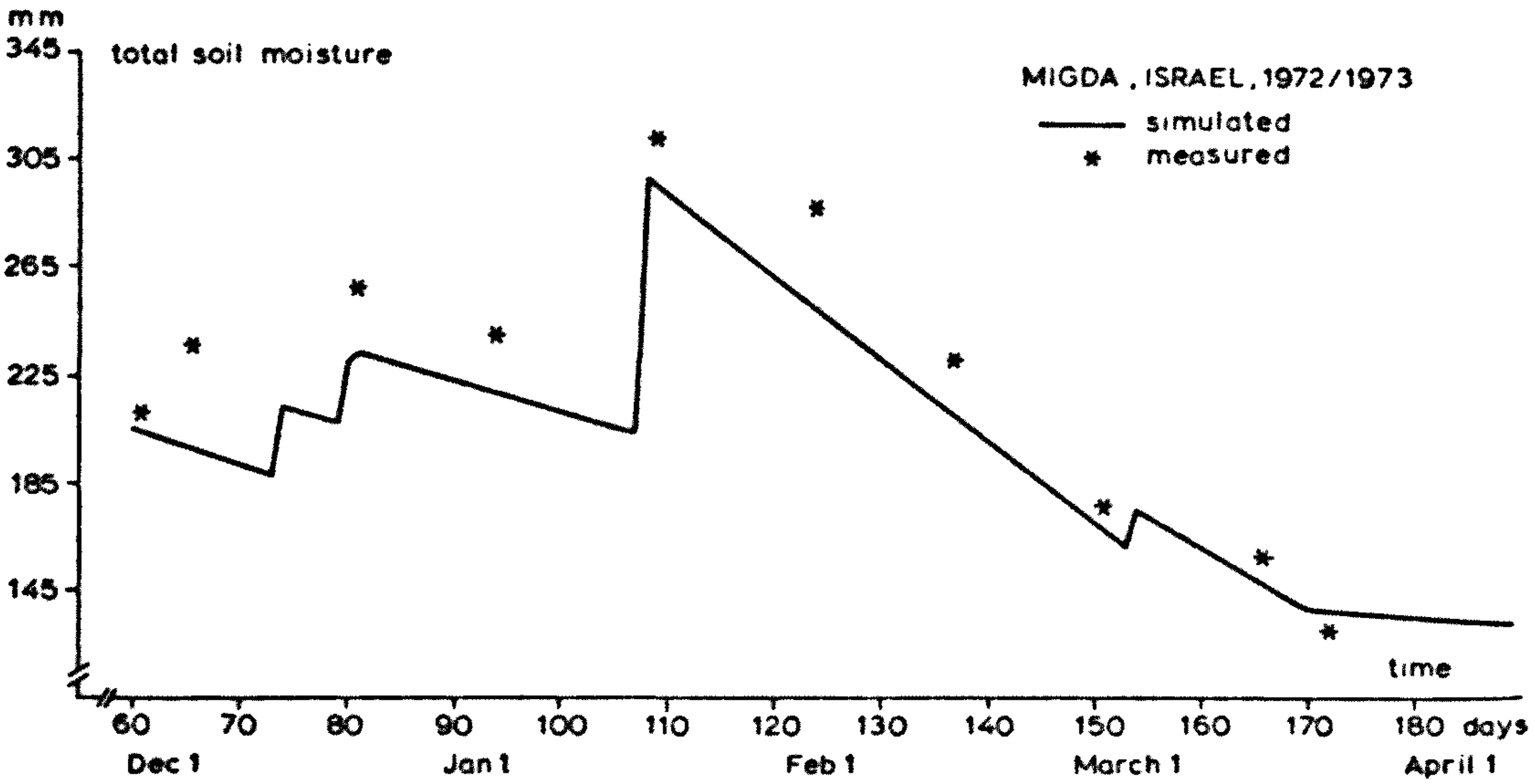

Fig. 49b | Comparison between measured and simulated course of total soil moisture under natural vegetation in Migda '72/'73.

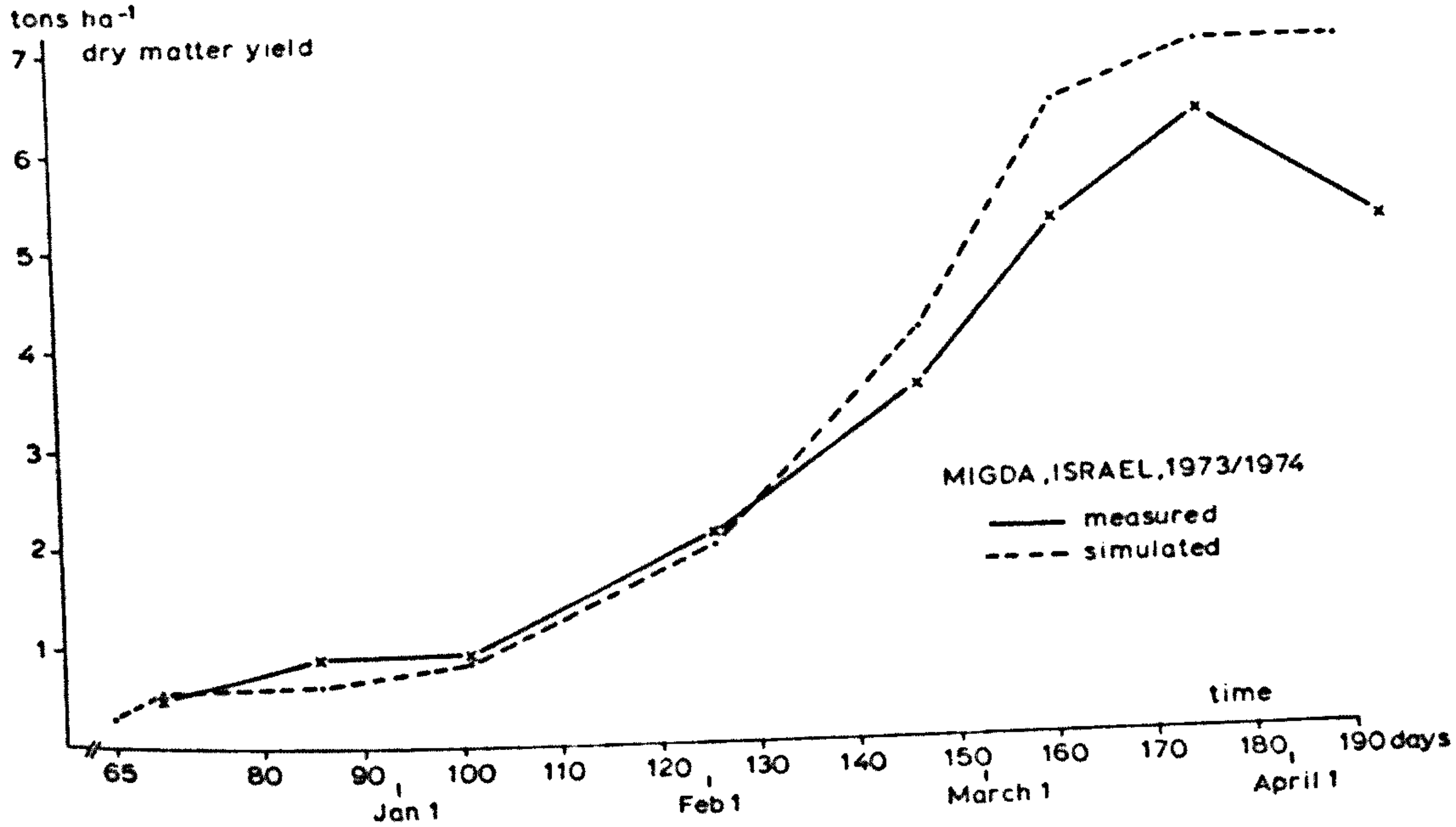

Fig. 50a | Comparison between measured and simulated dry matter production of natural vegetation in Migda '73/'74.

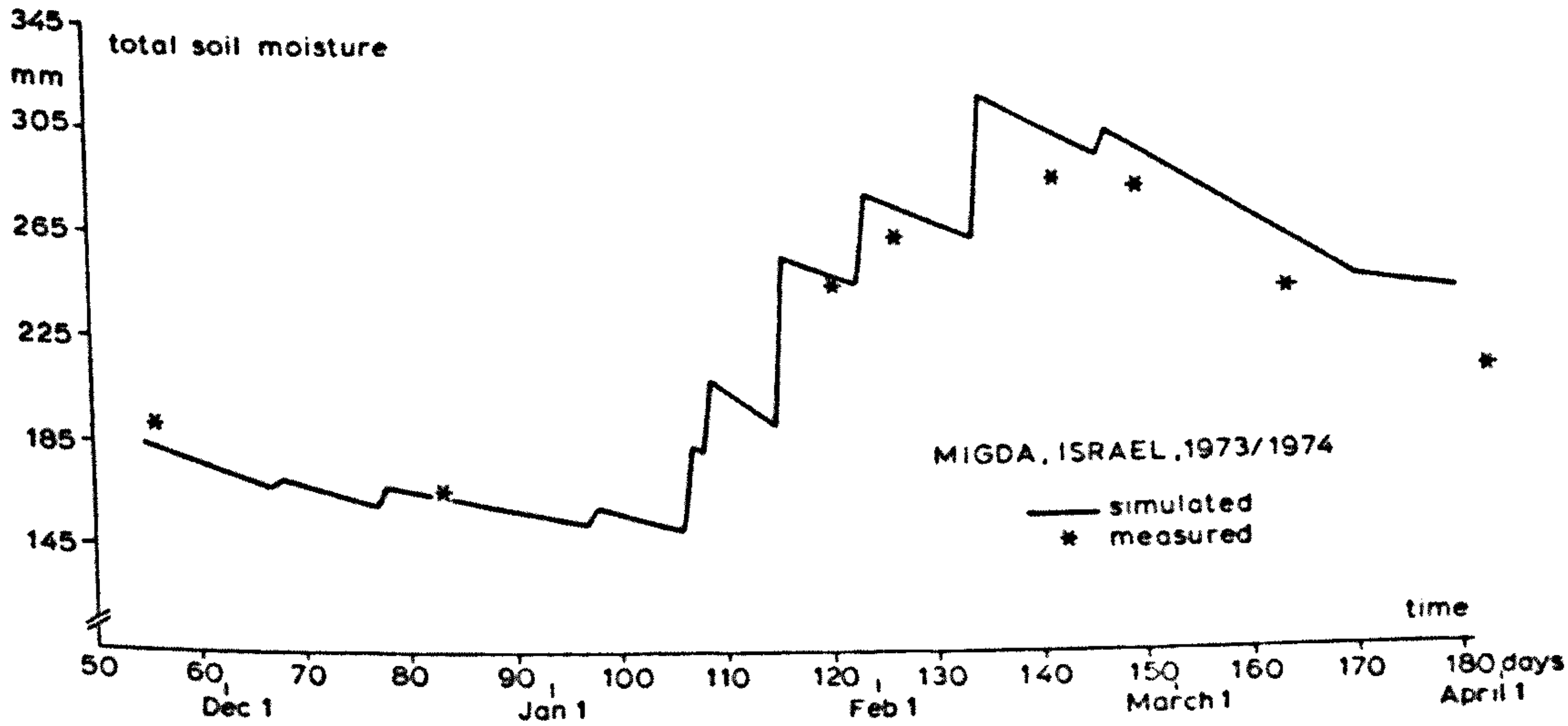

Fig. 50b | Comparison between measured and simulated course of total soil moisture under natural vegetation in Migda '73/'74.

the calculated growth rate is approximately 25% lower than the measured rate. There is no obvious reason for this discrepancy, although a possibility could be a different division of the dry matter between shoot and root. A definite statement about this question requires much more information about the processes governing root growth and decay. The peak yields differ ±12%, which is about the accuracy limit of the biomass determination.

The calculated moisture extraction pattern agrees very well with the measured one, although a tendency exists for the simulation to underestimate the amount of water in the soil. The differences are however well within the limits of the variation that exists in the field (Fig. 54).

In the '73/'74 season the initial biomass was also taken as 100 kg ha^{-1}. Early growth is simulated accurately, the influence of the dry spell being visible from the middle of December till mid January. After Day 130 the simulated growth rate is about 10% higher than the measured one. The simulated moisture use is somewhat lower than the measured one, so that the calculated water use efficiency is higher than the measured value. There may be some speculation about the nitrogen status of this field. The original application of 400 kg N ha^{-1} was given as ammonia and it is not certain what the efficiency of this application was. Unfortunately before the season '72/'73 only 40 kg ha^{-1} was given, while 170 kg N ha^{-1} had been removed in the previous winter. In that year another 180 kg ha^{-1} was taken up by the vegetation. It is thus possible that at the beginning of the season '73/'74 practically no nitrogen was left in the soil. The 100 kg N ha^{-1} added at that time would hardly be sufficient to maintain potential growth during the whole season. Thus the observed difference between simulated and measured efficiency of water use may be due to this effect.

As a result of the different growth rate the calculated peak yield is about 10% higher than the measured production, which is satisfactory compared with the accuracy of yield determination and the variability of the field.

In Table 11 a summary of the simulated results is given. It is striking, that despite the differences in growth pattern, the calculated proportionality factor is practically constant for the three seasons. It shows that this concept does work when applied for a whole growing season.

Table 11 Summary of the results of the simulation model ARID CROP.

season	rain (mm)	transp. (mm)	soil evap. (mm)	aerial yield kg ha^{-1}	root weight kg ha^{-1}	E_0 mm day^{-1}	M_{sh} kg ha^{-1} day^{-1}	M_{tot} kg ha^{-1} day^{-1}
71/72	348.5	230.5	114	8026	2880	2.5	98	132
72/73	245.0	191	79	6930	3021	2.4	87	125
73/74	351.0	136	149	6900	2528	1.8	92	123.5

In the season '73/'74 about 15% of the rain fell so late in the season, that it did not contribute to the crop production, because development was already completed. Part of that rain will be stored in the soil and may be used in the next season, as was the case with the surplus moisture of the 1971/1972 season.

6.2.3 Conclusions

From the overall comparison of simulated and measured results, it may be concluded that the model ARID CROP simulates rather accurately the dry matter production of the natural vegetation and the water balance of the soil below it. It is however also clear that the initialization is still a major difficulty. Differences in the value of the initial biomass affect the total yield only through secondary effects: different values of the ratio transpiration: evaporation and different water use efficiencies which do not have a strong influence on the final yield. However the growth curve has a distinctly different pattern, which may be of importance because it is the lamb-raising period and the availability of food is critical for their condition.

The actual value of the initial biomass in a certain year is not only dependent on the environmental conditions (soil and weather) whose influence is already difficult to quantify (Janssen, 1974) but also on the condition of the seed, which depends on the growing conditions over a number of previous seasons. It is beyond the scope of this model to go into more detail on this subject. When the model is to be used in an actual situation, the best solution is to measure the biomass in an early stage and to use this real value as a start to calculate the expected growth curve for a number of conditions to be expected. To calculate the yield potential of some new region an arbitary value somewhere between 25 and 100 kg ha^{-1} may be used.
From the description it is clear, that despite the reasonable behaviour of the model, there are still a number of relations, which need a more thorough investigation. Specially the root growth part is not very satisfactory in that the root weight does not have any feedback to the crop behaviour.
The simulation of crop morphology (leaf area) is very much simplified and here is certainly a problem area for plant physiologists. It would be worthwhile to know which internal or external factors

influence the morphogenesis of the plant species.
The interaction between root distribution and soil moisture distribution had to be deduced from fragmentary data and it is to be hoped that continuation of the experiments with rhizotrons will improve our knowledge about the behaviour of underground plant parts in their natural environment.
The relation between environmental and crop factors and the development pattern of the vegetation was constructed from circumstantial evidence and some more factual data on this subject would help in understanding plant behaviour towards the end of the growing period. Specially the interaction between soil water status and development needs more attention.
The model has shown that in terms of dry matter production, a mixture of species may be treated with single plant parameters, indicating that in this respect the differences between species are rather small.
It is a pity that the experimental period in Migda did not include a real drought year, so that the influence of prolonged periods of water shortage could not be verified in detail. It is, however, hoped that extension of this work will provide this information.

Finally it should be remarked, that although the results of the efforts to build and to validate a model should be made available as quickly as possible – however not overlooking the fact that the validity must have been proven – such a model should never remain static because the growing knowledge in different disciplines should lead to continuous adaptation of the model.

6.3 Examples of application of the model

The simulation model described in the previous section may be used to calculate the productivity of a specific region under given climatological conditions, assuming that the nutrient status of the soil is not limiting the yield.
To illustrate such use, the model was executed with historical weather data from Migda for the years 1961/1962 till 1969/1970. The weather data were collected at the station of the Israeli Meteorological Service in Gilat (Section 2.3) except for the rain data which were taken from the rain gauges located on the experimental area.

The results of these simulation runs are shown in Fig. 51, where the calculated peak yields of fertilized areas are given as a function of time, including the three experimental years. The broken line indicates the measured peak yields in non-fertilized experimental fields in the same area (Tadmor et al., 1974). On the upper axis the total seasonal rainfall, used in the model, is given.

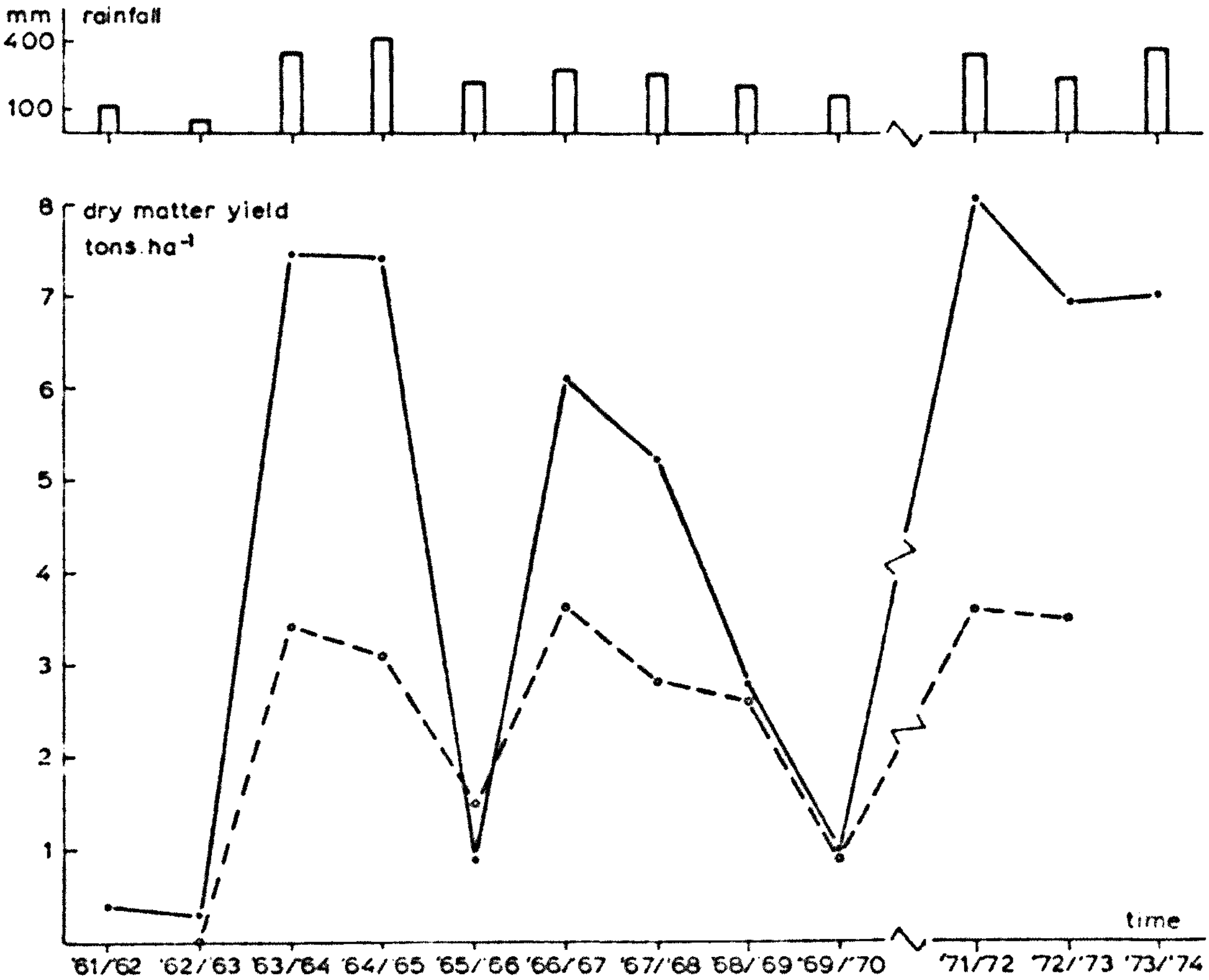

Fig. 51 | Calculated water limited dry matter yields of natural vegetation in Migda for the period '61/'62 till '73/'74 (solid line) and measured dry matter production for the same period (broken line).

6.3.1 Calculation of productivity

Comparison of the yield data with the total seasonal rainfall amounts shows, that not only the total precipitation determines the yield, but the distribution over the season is of equal importance. A different distribution – both the timing and the number of showers in which the rain falls – leads to a different ratio of transpiration/soil surface evaporation as well as to variations in water use efficiency. The influence of these factors is obvious when the seasons '68/'69 and '72/'73 are compared. The total rainfall in both seasons differs by only 15%, while there is a more than twofold difference in total dry matter production. In '68/'69 the division between transpiration and evaporation was 76/145, while in '72/'73 it was 1971/76, which explains the great yield difference.

For the twelve years recorded here, the average rainfall is ±250 mm, and the average calculated yield ±4450 kg ha^{-1} with a standard deviation for the single observation of 3000 kg ha^{-1}.

The effect of the distribution is again shown in Fig. 52, where the model was executed with rain data calculated from the average monthly rainfall over the 12-year period which was distributed over that month according to the average number of rainy days (Case 1). In Case 2 the same average monthly rainfall was used but distributed over about half the number of rainy days. For the other weather parameters the '72/'73 data were used, as that year had about the same rainfall. This decrease in number of rain-days already gives an increase in yield of ±40%, while with a still more favourable rain pattern almost 7000 kg ha^{-1} can be achieved ('72/'73). The erratic nature of the precipitation in these regions has such large consequences for their productivity that any attempt to characterize the climate in terms of averages and variances has very little meaning from an agricultural point of view.

Even with the present state of knowledge and insight as expressed in ARID CROP, it seems still much more promising to characterize the productivity of such regions in the way presented here: by simulating the yield over a historical period on basis of actual data on weather, soil and (perhaps) plants. As mentioned earlier (Section 2.1) we can distinguish then three levels of productivity: the potential level on which both water and nutrients are in optimum supply, the level where only water is the limiting factor and the lowest level, where production may also be limited by nutrient (nitrogen) deficiency. Only for the last level are the simulation programs not very much developed as yet, but progress in this field is being made in another part of this project (Section 2.2), even though one may argue that such models are probably the least needed as an estimate of the actual

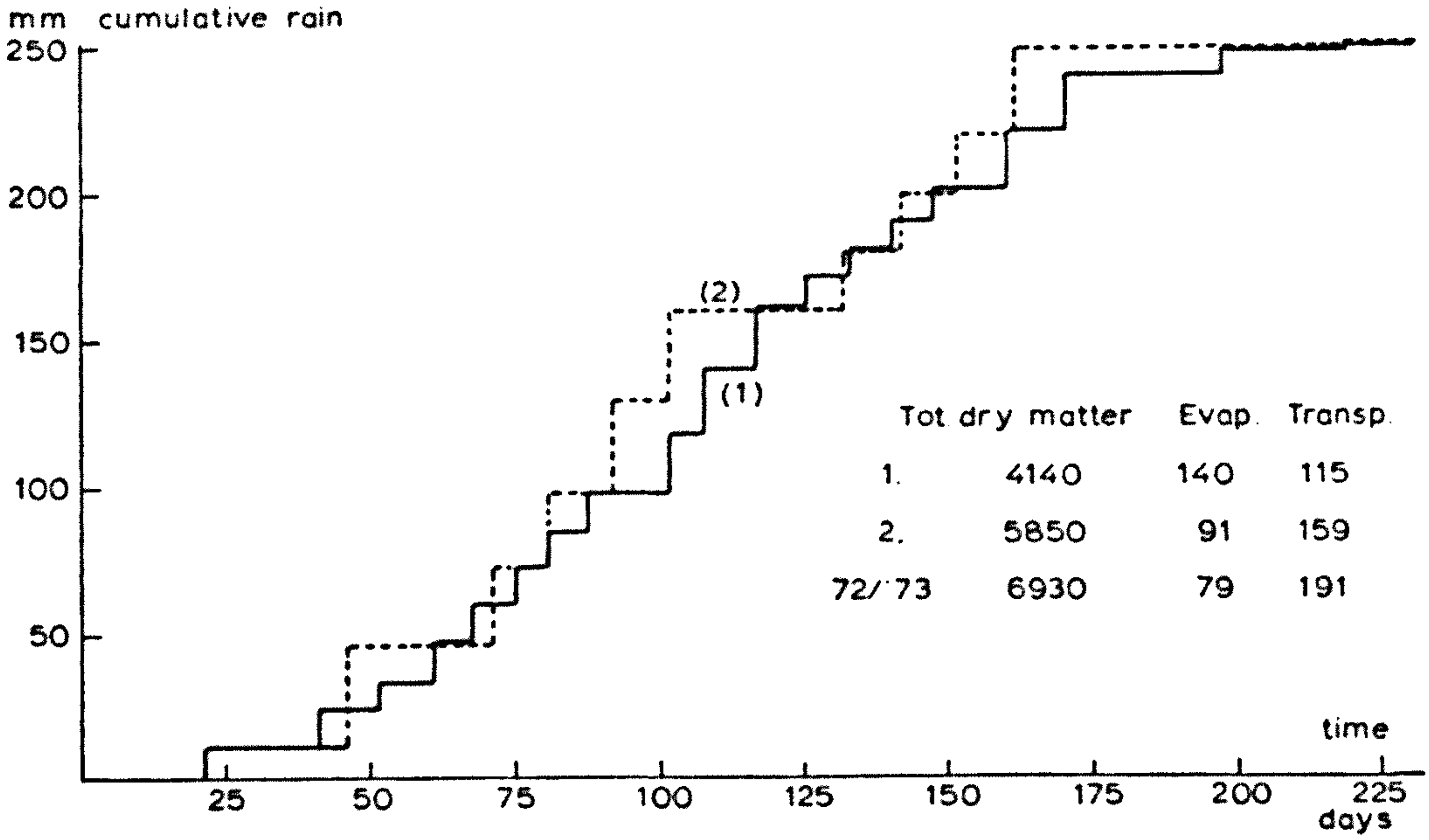

Fig. 52 | Cumulative rainfall functions, used in the sensitivity test of the simulation model.

yield on this level can be obtained without sophisticated experimental techniques.
Generally speaking thus one may say that the tools to calculate the productivity of such regions, the variation in yield that can be expected and the possibilities for improvement, through either fertilization or irrigation are available.

6.3.2 Influence of improved fertility

When comparing the yields calculated under the assumption that nitrogen is optimum, with the yields in the non-fertilized fields, the most striking phenomenon is the much greater fluctuation between seasons. In dry years, when water is really the limiting factor, the yields in fertilized and non-fertilized conditions are practically the same. However, in good rainfall years fertilization increases dry matter production up to a factor two. Hence annual differences are still more increased by fertilization than the average productivity. As practically all the dry matter produced in these regions is used for grazing, the greater fluctuations make it more difficult to fully exploit the yield increase, since stocking rates cannot be adapted so fast from year to year. A practical solution to this problem is suggested by some semi-nomadic Bedouins in the Negev area. Part of the grazing area is sown with small grains like wheat or barley, and the size of the herd is based on a normal stocking rate in the remaining area. In good years the animals live on the natural pasture and the small grains are harvested and sold. In unfavourable years, the seed yields are too low for harvesting and the arable crop, which is sown on the most advantageous places, is used for grazing. In this way the overall grazing pressure is considerably reduced in dry years. With such a management system and the application of nitrogen the productivity of semi-arid regions could increase considerably. However, fertilizers are likely to be too expensive anyhow for use under these conditions, so that considerable attention should be paid to the possibilities of introducing leguminous species, adapted to the local conditions to form stable grass-legume mixture as is successfully done in Australia.

Whatever possibility to increase the efficiency of the available water is chosen, the productivity in the dry years remains the problem that must be solved to arrive at a successful grazing management system in semi-arid regions.

6.3.3 Influence of soil variability

In many of the arid and semi-arid regions, even in the northern Negev which is considered as a very homogeneous area, there are small-scale differences in topography, for instance caused by animal activities. The effect of such phenomena is shown in Fig. 53, where the yields calculated as given in Section 6.3.1 are compared with the yields in a run-off/run-on situation where patches with a total area of half of the surface receive local run-on water from patches comprising the other half of the surface. In these calculations it is assumed that 30% of the rainfall is subject to local run-off/run-on irrespective of the intensity of the rain or the conditions of the vegetation. This 30% is based on the soil moisture measurements carried out in Migda. In Fig. 54 it is shown that the calculated differences in total soil moisture between the 'run-off part' and the 'run-on part' are of the same order as the standard deviation from the field measurements.

The dry years '65/'66 and '69/'70 show a twofold increase in average dry matter yield when this local run-off/run-on plays a role. The main reasons for this increase are the reduction in evaporation losses and a more successful germination on the run-on parts.

Although the influence of inhomogeneity is difficult to quantify exactly, as the area consists of a whole set of different microsites, which do interact through horizontal root extension and lateral moisture movement, it is clear from this example that the existence of small-scale differences which are so troublesome during experimentation are of primary importance for obtaining any yields at all in dry seasons. Since the main problem of the management system is the yield in dry years, it may be very worthwhile to promote any measure that increases local run-off/run-on.

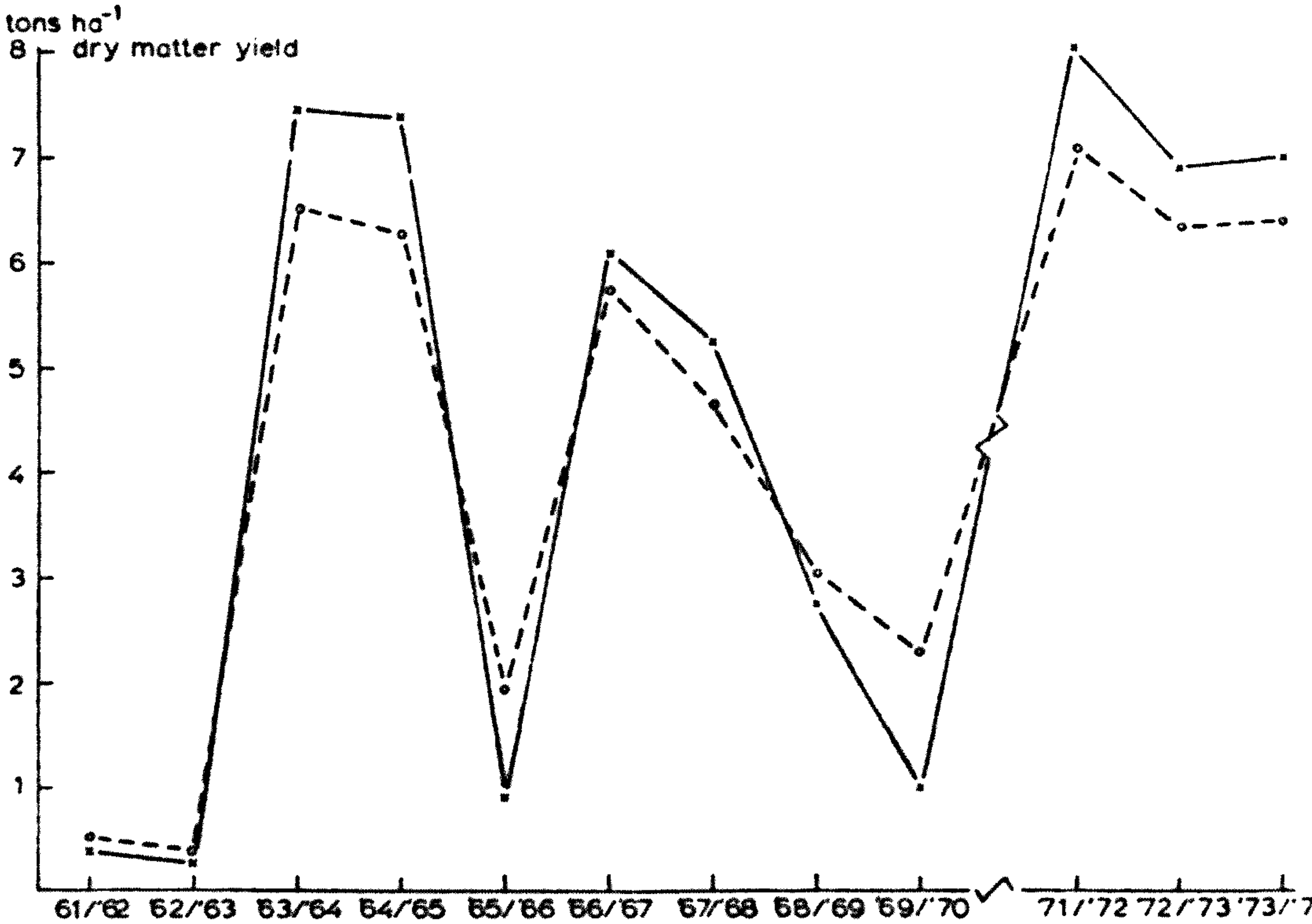

Fig. 53 | Simulated dry matter production of the natural vegetation in Migda for the period '61/'62 till '73/'74 in the absence (solid line) and in the presence (broken line) of local run-off.

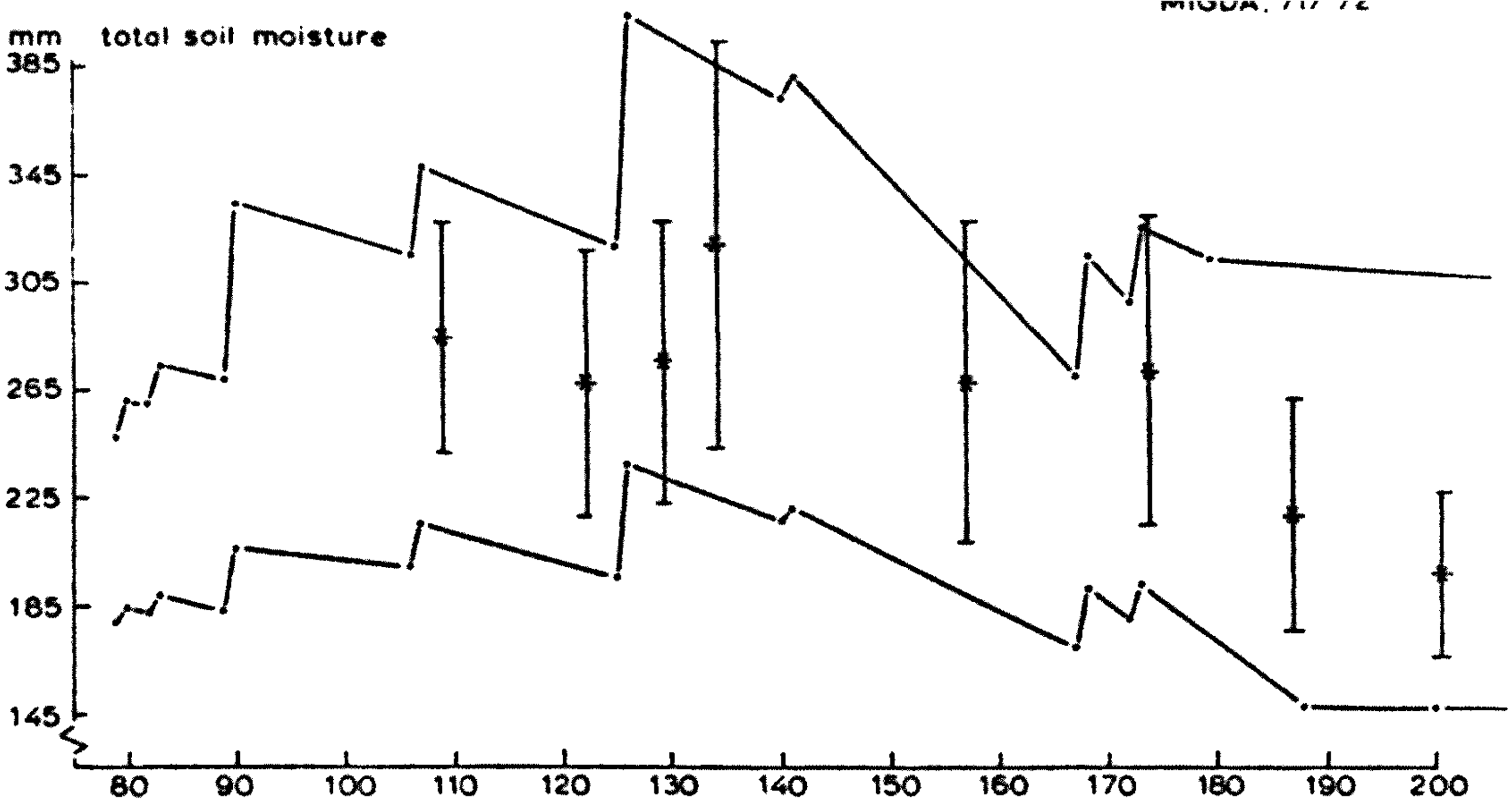

Fig. 54a | The influence of local run-off on calculated total soil moisture under the natural vegetation in Migda '71/'72, compared with the measured values.

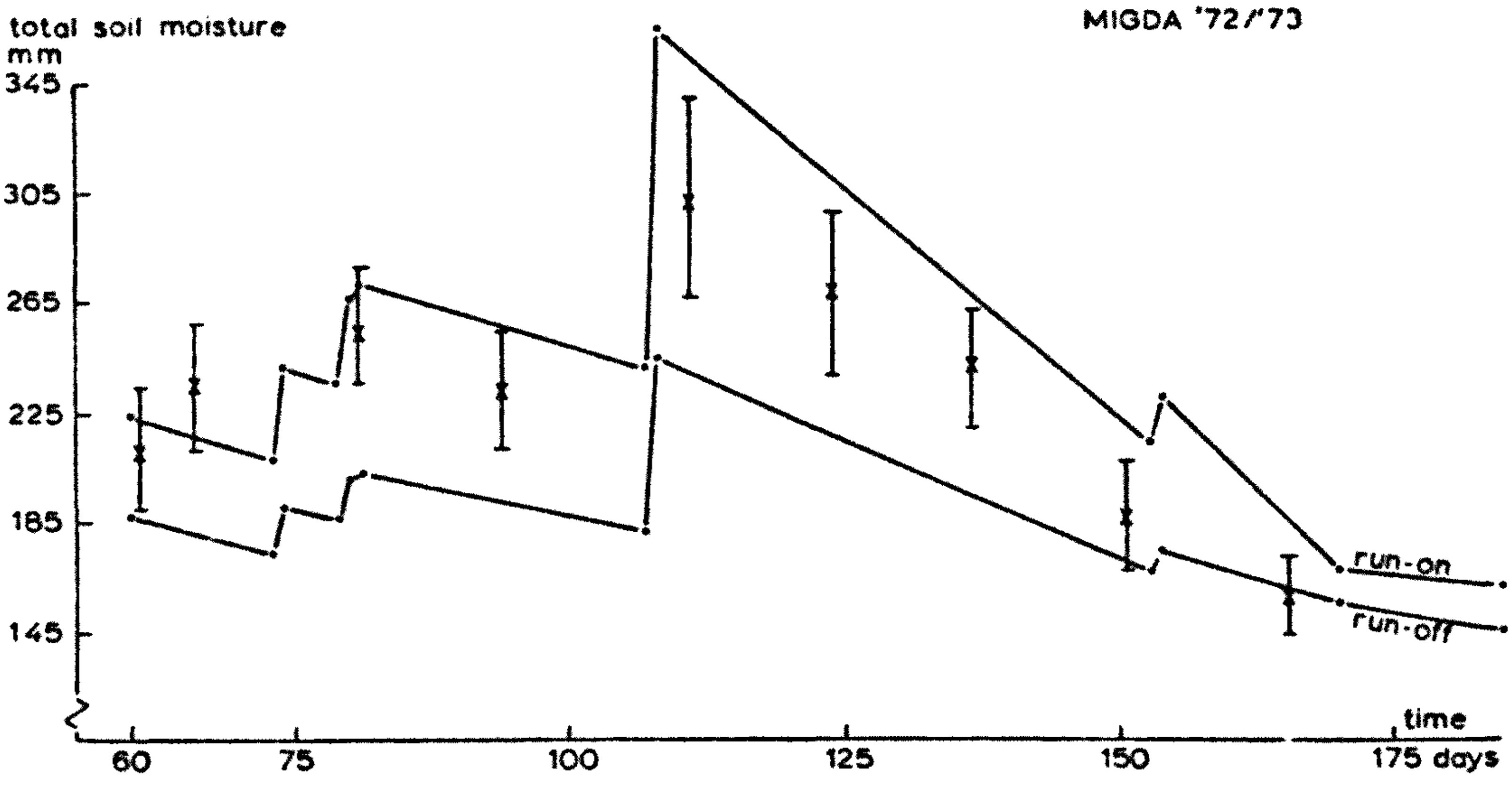

Fig. 54b | The influence of local run-off on calculated total soil moisture under the natural vegetation in Migda '72/'73, compared with the measured values.

Summary

The arid and semi-arid regions of the world, totalling about 30% of the land surface of the earth, are predominantly used for extensive grazing, as low and erratic rainfall presents too high a risk for arable farming. The population that can be sustained by the animal products —meat, milk or wool—is largely determined by the availability of primary production for fodder.
An increase in primary production in these areas is possible on two levels:

— without irrigation: either by an increase in the amount of available water or by a more efficient use of the moisture. The first may be achieved by controlling run-off or deep drainage. The latter through improvement of the botanical composition, mainly by legumes or by application of nitrogen fertilizer;
— with irrigation: when water and nutrients are non-limiting, very high production levels may be attained because the environmental conditions, radiation intensity, temperature and length of the growing season are favourable in these regions.

This study was done within the framework of the project 'Actual and potential herbage production under arid conditions'. This project aimed at summarizing existing knowledge on the functioning of agro-ecosystems in dynamic simulation models, describing plant growth under semi-arid conditions. Such models were developed on three levels of interest:

— optimum supply with water and nutrients;
— optimum supply of nutrients, but limited moisture;
— conditions where either water or nutrients were the limiting factor.

Validation data for the models were collected in the field and relevant processes were studied under controlled conditions.
This book deals mainly with the different aspects of the relation between water use and plant production under moisture limiting conditions.

The validation experiments were carried out at the Tadmor Experimental Farm in the northern Negev desert of Israel (34°25′ OL, 31°22′ NB. The average rainfall in this area is 250 mm $year^{-1}$, concentrated in winter (October-March); strong fluctuations between years occur with extremes of 42 mm in '61/'62 and 414 mm in '64/'65. Radiation intensity ranges from 1150 J m^{-2} day^{-1} in December to 2750 J m^{-2} day^{-1} in August, while average daytime temperatures range between 12.6 °C in January and 26.8 °C in August. The soil consists of a sierozem, developed in a 10–20 m thick mantle of löss. Its physical properties are favourable for plant growth: high water-holding capacity and low resistance to root growth.

The vegetation is an abandoned crop land vegetation and consists mainly of herbaceous annuals. The predominant species are the grasses *Phalaris minor*, *Hordeum murinum* and *Stipa capensis*, the crucifers *Erucaria boveana* and *Reboudia pinnata*, the compositae *Anthemis melaleuca* and *Centaurea iberica* and the legumes *Trigonella arabica* and *Medicago polymorpha*. The actual botanical composition shows a great variation both in time and place but this hardly influences the production potential.

Experiments were carried out to determine the course of above ground dry matter production and of available soil moisture during the growing season. Dry matter production was determined via a double-sampling technique of visual estimates. In each treatment 200-400 estimations were carried out and each fifth sample was also harvested and weighed. The harvested samples provide a calibration curve, which is used to give an estimate of the average yield of the field.

Soil moisture was measured with the neutron moderation technique. In each treatment 30–60 aluminium access tubes were installed and soil moisture was measured over two-weekly periods and after sufficiently heavy showers in 30 cm intervals. The upper 30 cm of the soil were at the same time sampled for gravimetric determination of the moisture content.

Meteorological observations were obtained from a standard weather station of the Israeli Meteorological Service, located in Gilat, about 8 km from the experimental site. Rainfall however was recorded in rain-gauges at the experimental site.

The results of the experiments, which were carried out in the fields fertilized with P and K as well as in fields that received NPK fertilization show that under the prevailing conditions actual production is more often limited by nitrogen shortage than by moisture availability. Nitrogen application increased the production up to 2-3 fold.

Maximum growth rates of the natural vegetation reached values of 170 kg ha^{-1} day^{-1} under optimum conditions. A local wheat variety, used in another experiment attained the same value, which is also equal to the theoretical optimum calculated for the conditions.

The efficiency of water use was also the same for the wheat and for the natural vegetation. However the nitrogen deficient fields showed a much lower efficiency of water use, due to either a lower photosynthetic capacity or greater losses through continuous break-down and rebuilding of nitrogenous compounds.

Experiments carried out to determine the influence of grazing on primary production showed that under normal grazing pressures, the consumption by animals during the growing season is negligible compared with the growth rates. Only heavy overgrazing may affect the level of primary production.

The simulation model 'ARID CROP' developed in the second part of this study, written in the simulation language CSMP/360, describes crop growth under water limiting conditions.

A hierarchical approach is applied to incorporate the various processes when their time constant is too small. A detailed model of evaporation from a bare soil is described and the results are compared with both laboratory and field measurements.

A simplified procedure to calculate the water use efficiency on a daily basis is worked out, based on the results of a detailed model, described elsewhere. The calculated values are compared with the results of pot trials carried out in the framework of the project. In practically all cases the agreement is within 20% which is considered reasonable in view of the assumptions.

Validation of the model shows that reasonable agreement between measured and simulated values is obtained, both for above ground dry matter production and for soil moisture in spite of the limitations of the model. Special difficulties arise from the initialization due to the gross simplifications with regard to germination. Some examples for the application of the model have been described: potential production under moisture limiting conditions is calculated for a 15-year period at the experimental site, based on historical weather data. Comparison with the measured yields shows that mostly actual production was limited by nitrogen availability. Fertilization would

not only increase the average yield, but also the fluctuations to about the same range as the rainfall. Management problems will then arise as short-term adaptation of herd size is not possible. These may either be overcome by adaptation of the grazing pressure to some average production level so that food reserves may be build up in good years or by adjustment of the size of the herd to a smaller grazing area. Part of the total available area may be sown with small grain, which will yield seed in favourable years, and may be used as additional grazing area in unfavourable years.
Another conclusion derived from this example is, that the distribution of the precipitation over the growing season is of equal importance for the production as the total amount of rainfall. An unfavourable pattern—many small showers—increases losses through direct soil evaporation and limits the amount of moisture available for plant growth.
Finally it is shown that spatial inhomogeneity of the soil, which is so troublesome during experimentation counteracts the fluctuations described earlier, mainly through increase of production in unfavourable years.

In conclusion it may be stated that the use of dynamic simulation models to establish the production potential of new areas is preferable to the application of correlation models. Simulation models provide a better insight into the relevant processes and have a much greater potential for extrapolation. Moreover they supply a useful tool for the design of relevant experiments when new regions have to be explored.

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