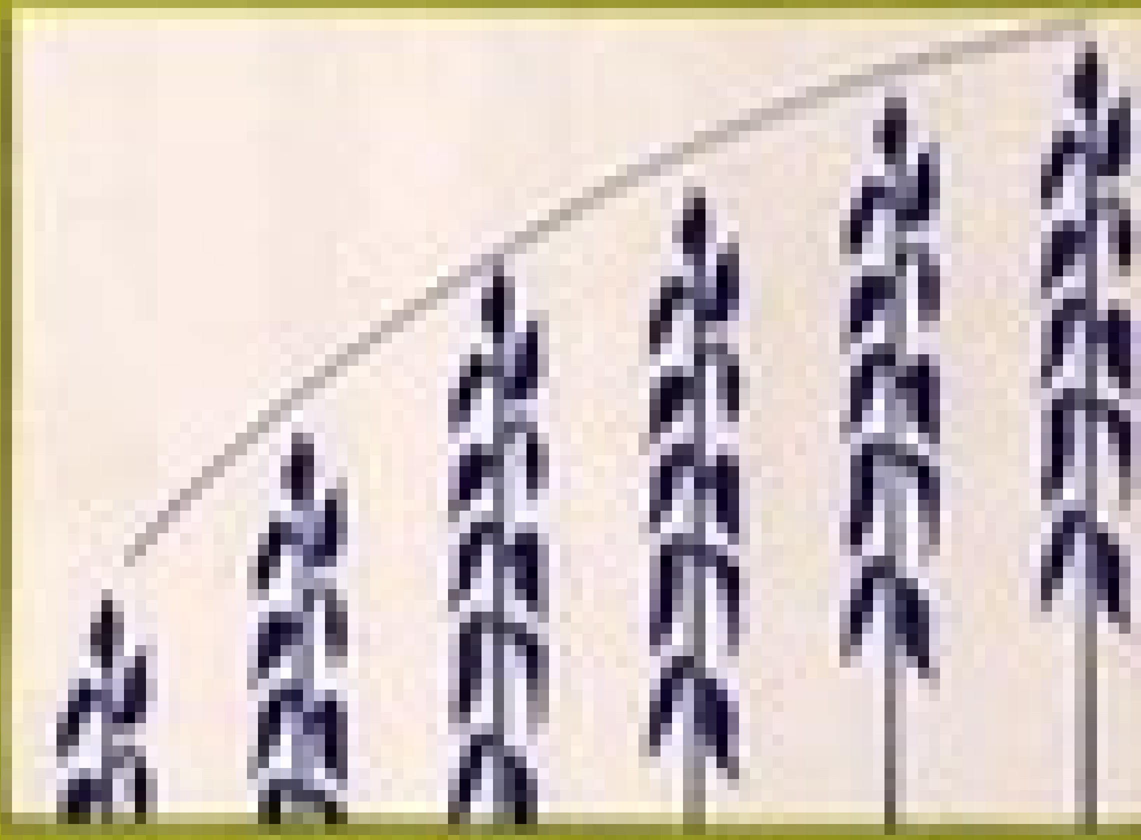
FAO IRRIGATION AND DRAINAGE PAPER 33

yield response to water



FOOD AND AGRICULTURE ORGANIZATION
OF THE UNITED NATIONS ROME

Yield response to water

FAO IRRIGATION ID DRAINAGE PAPER

33

by
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To: C.E. Houston

The role which water plays in the production of agricultural crops is complex and the interacting processes involved in crop growth do not easily lend themselves to quantification. This draft publication ambitiously presents the relationship between water and crop yields in a simplified and easy-to-use form. Comments and suggestions for improvement of the presented methodologies and their practical application to the field, to be included in a revised and possibly more complete edition, would be very welcome and should be forwarded to:

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PREFACE

Water is essential for crop production and best use of available water must be made for efficient crop production and high yields. This requires a proper understanding of the effect of water - rainfall and/or irrigation - on crop growth and yield under different growing conditions.

A great deal has been published on aspects of water relations in crop growth and attempts to understand crop response to water through crop growth modelling have met with success. However, for practical application, a method is required to measure yield response to water supply, which should be simple, require commonly available climatic, water, soil and crop data, be widely applicable with acceptable accuracy and allow easy verification through adaptive research. With this in mind, the Land and Water Development Division of FAO initiated a study to establish generalized crop yield and water use relationships of twenty-six important irrigated crops. An impressive amount of related research information was generously made available by scientists contacted in the course of the study (Appendix IV) and was further obtained by a review of literature (Appendix III). Valuable support was also received from the International Institute for Land Reclamation and Improvement (ILRI), Wageningen, The Netherlands, in formulating the presented approach and through their collection and analysis of data and testing of various water/crop yield models. The results of the work by ILRI are herein further simplified and expanded in an effort to present results in an easy-to-use form.

This publication presents a methodology to quantify yield response to water through aggregate components which form the 'handles' to assess crop yields under both adequate and limited water supply. The method is presented in Part A and takes into account maximum and actual crop yields as influenced by water deficits using yield response functions relating relative yield decrease and relative evapotranspiration deficits. Part B gives an account of water-related crop yield and quality information for twenty-six crops. Application of the method provides the user with:

- guidance in selection of irrigated crops under different growing conditions;
- assessment of crop yield under different water supply regimes;
- criteria, in terms of crop production, on which to base priorities for allocation of limited water to crops both between and within projects;
- directives for field water management for optimum crop production and water efficiency.

The publication lays down some of the important principles involved in water management in relation to crop production. However, improvement for site-specific conditions will be needed with respect to the accuracy offered by the methodology and verification through adaptive research is required.

It should be pointed out that:

THE UPPER LIMIT OF CROP PRODUCTION IS SET BY THE CLIMATIC CONDITIONS AND THE GENETIC POTENTIAL OF THE CROP. THE EXTENT TO WHICH THIS LIMIT CAN BE REACHED WILL ALWAYS DEPEND ON HOW FINELY THE ENGINEERING ASPECTS OF WATER SUPPLY ARE IN TUNE WITH THE BIOLOGICAL NEEDS FOR WATER IN CROP PRODUCTION. THEREFORE, EFFICIENT USE OF WATER IN CROP PRODUCTION CAN ONLY BE ATTAINED WHEN THE PLANNING, DESIGN AND OPERATION OF THE WATER SUPPLY AND DISTRIBUTION SYSTEM IS GEARED TOWARD MEETING IN QUANTITY AND TIME, INCLUDING THE PERIODS OF WATER SHORTAGES, THE CROP WATER NEEDS REQUIRED FOR OPTIMUM GROWTH AND HIGH YIELDS.

CONTENTS

PART B: CROP AND WATER

LIST OF TABLES

PART A

YIELD AND WATER

The relationships encountered between crop, climate, water and soil are complex and many biological, physiological, physical and chemical processes are involved. A great deal of research information on these processes in relation to water is available; however, for practical application this knowledge must be reduced to a manageable number of major components to allow a meaningful analysis of crop response to water at the field level.

For application in planning, design and operation of irrigation schemes, it is possible to analyse the effect of water supply on crop yields. The relationship between crop yield and water supply can be determined when crop water requirements and crop water deficits, on the one hand, and maximum and actual crop yield on the other can be quantified. Water deficits in crops, and the resulting water stress on the plant, have an effect on crop evapotranspiration and crop yield. Water stress in the plant can be quantified by the rate of actual evapotranspiration (ETa) in relation to the rate of maximum evapotranspiration (ETm). When crop water requirements are fully met from available water supply then ETa = ETm; when water supply is insufficient, ETa < ETm. For most crops and climates ETm and ETa can be quantified.

When the full crop water requirements are not met, water deficit in the plant can develop to a point where crop growth and yield are affected. The manner in which water deficit affects crop growth and yield varies with the crop species and crop growth period. To evaluate the effect of plant water stress on yield decrease through the quantification of relative evapotranspiration (ETa/ETm), an analysis of research results shows that it is possible to determine relative yield losses if information is available on actual yield (Ya) in relation to maximum yield (Ym) under different water supply regimes. Where economic conditions do not restrict production and in a constraint-free environment, Ya = Ym when full water requirements are met; when full water requirements are not met by available water supply, Ya < Ym.

In order to quantify the effect of water stress it is necessary to derive the relationship between relative yield decrease and relative evapotranspiration deficit given by the empirically-derived yield response factor (ky), or:

$$\left(1 - \frac{Ya}{Ym}\right) = ky\left(1 - \frac{ETa}{ETm}\right)$$

where:
- Ya = actual harvested yield
- Ym = maximum harvested yield
- ky = yield response factor
- ETa = actual evapotranspiration
- ETm = maximum evapotranspiration

The value of ky for different crops is based on the evaluation of numerous research results, given in the bibliography, which cover a wide range of growing conditions. Extensive use has also been made of related known yield responses to soil salinity, depth of groundwater table and crop management practices. Based on experimental evidence, the relationship is given for the total growing period and the individual growth periods of the crops. Other than for different crops and crop growth periods, attempts to separate crop response to water according to climate, magnitude of maximum evapotranspiration and soil did not add to the accuracy obtainable.

Since the relationship is also affected by factors other than water, such as crop variety, fertilizer, salinity, pests and diseases, and agronomic practices, the relationships presented refer to high producing varieties, well-adapted to the growing environment, growing in large fields where optimum agronomic and irrigation practices, including adequate input supply, except for water, are provided.

With the presented relationships it is possible to plan, design and operate irrigation supply systems taking into account the effect of different water regimes on crop production.

CALCULATION PROCEDURE

I. Determine maximum yield (Ym) of adapted crop variety, dictated by climate, assuming other growth factors (e.g. water, fertilizer, pests and diseases) are not limiting.

II. Calculate maximum evapotranspiration (ETm) when crop water requirements are fully met by available water supply.

III. Determine actual crop evapotranspiration (ETa) based on factors concerned with available water supply to the crop.

IV. Evaluate factors concerned with the interaction between water supply, crop water requirements and actual yield (Ya); through:

V. Selection of yield response factor (ky) to evaluate relative yield decrease as related to relative evapotranspiration deficit, or $(1 - Ya/Ym) = ky(1 - ETa/ETm)$, and obtain actual yield (Ya).

I. MAXIMUM YIELD (Ym)

The maximum yield level of a crop (Ym) is primarily determined by its genetic characteristics and how well the crop is adapted to the prevailing environment. Environmental requirements of climate, soil and water for optimum growth and yield vary with crop and crop variety. A careful selection of the crop and the variety most suited to a given environment is of paramount importance for obtaining high and efficient production.

Maximum yield of a crop (Ym) is defined as the harvested yield of a high-producing variety, well-adapted to the given growing environment, including the time available to reach maturity, under conditions where water, nutrients and pests and diseases do not limit yield. Information on yields indicates the maximum yields that are obtained under actual farming conditions, with a high level of crop and water management (Table 1).

Climatic factors which determine Ym are temperature, radiation and length of the total growing season in addition to any specific temperature and daylength requirements for crop development. In general, temperature determines the rate of crop development and consequently affects the length of the total growing period required for the crop to form yield; for example, a maize variety requiring 100 days to reach maturity at a mean daily temperature of 25 to 30°C may take 150 days at 20°C or 250 days or more at 15°C to reach maturity.

Some crops have specific temperature and/or daylength requirements for initiation of certain growth and development; for example, for tuber initiation in potato night temperature of below 15°C is normally required; in some sorghum varieties flowering is sensitive to short daylength, while in winter wheat flowering requires both a cold period and long days. Furthermore, in some crops the quality of yield is influenced by temperature; for example, in pineapple the sugar content of the fruit is determined by the temperature during yield formation. Also, many crops require appropriate climatic conditions for yield formation, ripening and harvest.

Crop growth and yield are affected by the total radiation received during the growing period. At a given radiation and temperature, crops differ in their response to how much of the total radiation received can be converted into growth and yield. This difference has an important effect on how efficiently water can be utilized by the crop for production. Crop selection must therefore consider the radiation requirement and response of crops in addition to temperature and daylength. For example, a good maize crop can convert 1 to 2 percent of total radiation received into growth, whereas groundnut can convert half as much, although for a given location both crops may be suitable for production from the viewpoint of other climatic requirements.

Most crops offer varieties which vary in their general and specific climatic requirements and in their length of total growing period from sowing to harvest. This variation allows the crop to be adapted to a wide range of climatic conditions and to the time period required and available for crop production. As an aid to crop selection, the length of the total growing period, the temperature, daylength and other specific requirements are given (Table 2). Soil and nutritional requirements for each crop are also summarized in Table 2.

In addition to climatic requirements, the available growing season is also determined by the duration of an assured water supply of good quality. Consideration must be given to available water supply and crop water requirements, using a crop calendar in which demands for water are synchronized with the water supply available; for example, with the variation in river discharge and reservoir release. For some crops the total growing period required for Ym must be manipulated by the level of water supply; for example, a reduction in water supply in the vegetative period of cotton hastens flowering and boll formation, in addition to bringing the crop to maturity at the required time. For other crops, the growth required for Ym must also be manipulated by the level of water supply during a particular growth period; for example, in citrus a reduction in water supply will assist in checking excess vegetative growth and at the same time enhance flower bud formation. The calculation of total crop water requirements (ETm) for maximum yield (Ym) is given in Chapter II and the level of water supply during the different growth periods to regulate crop development and yield is given for each crop in Part B. As an aid to crop selection in relation to total water required and maximum yield, the water utilization efficiency (Ey) or harvested yield per unit of water (kg/m^3) and the sensitivity of yield to water deficit are given (Table 2).

Other factors, particularly socio-economic, must also be considered in selection of crops and length of growing season, including, for example, farmers' preference in relation to market demand, storage facilities and availability of farm machinery and labour.

Maximum yield (Ym) can be calculated for different climatic conditions. The methods enable quantification of production potential of different areas and thereby identify the most suitable areas for production for a given crop. The complexity of interrelationships between many parameters makes the derivation of the methods complicated. However, their use is not, provided the essential data are available. Computation techniques are given for two selected methods:

1. An adaptation of the method evaluated by the International Institute for Land Reclamation and Improvement (ILRI), Wageningen, which is based on earlier work by De Wit, Bierhuizen, Rijtema, Feddes and Kowalik (see Slabbers, 1978).

2. The method developed by Kassam (1977) for the Agro-ecological Zone Project (see FAO World Soil Resources Report 48, Report of the Agro-ecological Zone Project I: Africa, 1978).

1. THE 'WAGENINGEN' METHOD (alfalfa, maize, sorghum, wheat)

Slabbers (1978) presents simplified water yield relationships which are calibrated and tested on extensive experimental data covering a wide range of climatic conditions. The so-called linear model is found to determine dry matter production adequately for alfalfa, maize, sorghum and wheat. Mathematical relationships are given to convert dry matter production to yield of marketable product depending on water shortages during different crop growth periods. A further simplification of the linear model is given herein by assuming, amongst other assumptions, that maximum dry matter production occurs at maximum evapotranspiration, and by applying simplified corrections for dry matter production to obtain marketable yield. The possible production potential for a given climate is calculated for a standard crop by the concept of De Wit (1965), using radiation and evapotranspiration data; for application to agricultural crops corrections are required using crop-dependent constants and expressions of the effect of temperature, growth efficiency (respiration), and for the harvested part on final yield. Since experimental field data were used for calibration of the method, the calculated 'experimental' yield in dry weight (Yme) must be adjusted to the yield level obtainable under actual farming conditions. However, Yme presents, for a given area, the reference yield level obtainable under a high standard of crop and water management, where water and nutrients are not limited and pests and diseases are minimal.

Table 1 Good Yields of High-producing Varieties adapted to the Climatic Conditions of the Available Growing Season under Adequate Water Supply and High Level of Agricultural Inputs under Irrigated Farming Conditions (ton/ha)

<table>
<tr><th rowspan="3" colspan="2">CROP</th><th colspan="6">Climatic Regions</th></tr>
<tr><th colspan="2">Tropics 1/</th><th colspan="2">Subtropics 2/</th><th colspan="2">Temperate 3/</th></tr>
<tr><th><20°C 4/</th><th>>20°C</th><th><20°C</th><th>>20°C</th><th><20°C</th><th>>20°C</th></tr>
<tr><td>Alfalfa</td><td>hay</td><td colspan="2">15</td><td colspan="2">25</td><td colspan="2">10</td></tr>
<tr><td>Banana</td><td>fruit</td><td></td><td>40-60</td><td></td><td>30-40</td><td></td><td></td></tr>
<tr><td>Bean: fresh</td><td>pod</td><td>6-8</td><td></td><td>6-8</td><td></td><td>6-8</td><td></td></tr>
<tr><td>dry</td><td>grain</td><td>1.5-2.5</td><td></td><td>1.5-2.5</td><td></td><td>1.5-2.5</td><td></td></tr>
<tr><td>Cabbage</td><td>head</td><td>40-60</td><td></td><td>40-60</td><td></td><td>40-60</td><td></td></tr>
<tr><td>Citrus:</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>grapefruit</td><td>fruit</td><td></td><td>35-50</td><td></td><td>40-60</td><td></td><td></td></tr>
<tr><td>lemon</td><td>fruit</td><td></td><td>25-30</td><td></td><td>30-45</td><td></td><td></td></tr>
<tr><td>orange</td><td>fruit</td><td></td><td>20-35</td><td></td><td>25-40</td><td></td><td></td></tr>
<tr><td>Cotton</td><td>seed cotton</td><td></td><td>3-4</td><td></td><td>3-4.5</td><td></td><td></td></tr>
<tr><td>Grape</td><td>fruit</td><td colspan="2">5-10</td><td colspan="2">15-30</td><td colspan="2">15-25</td></tr>
<tr><td>Groundnut</td><td>nut</td><td></td><td>3-4</td><td></td><td>3.5-4.5</td><td></td><td>1.5-2</td></tr>
<tr><td>Maize</td><td>grain</td><td>7-9</td><td>6-8</td><td>9-10</td><td>7-9</td><td></td><td>4-6</td></tr>
<tr><td>Olive</td><td>fruit</td><td colspan="2"></td><td colspan="2">7-10</td><td colspan="2"></td></tr>
<tr><td>Onion</td><td>bulb</td><td>35-45</td><td></td><td>35-45</td><td></td><td>35-45</td><td></td></tr>
<tr><td>Pea: fresh</td><td>pod</td><td>2-3</td><td></td><td>2-3</td><td></td><td>2-3</td><td></td></tr>
<tr><td>dry</td><td>grain</td><td>0.6-0.8</td><td></td><td>0.6-0.8</td><td></td><td>0.6-0.8</td><td></td></tr>
<tr><td>Fresh pepper</td><td>fruit</td><td colspan="2">15-20</td><td colspan="2">15-25</td><td colspan="2">15-20</td></tr>
<tr><td>Pineapple</td><td>fruit</td><td></td><td>75-90</td><td></td><td>65-75</td><td></td><td></td></tr>
<tr><td>Potato</td><td>tuber</td><td>15-20</td><td></td><td>25-35</td><td></td><td>30-40</td><td></td></tr>
<tr><td>Rice</td><td>paddy</td><td></td><td>6-8</td><td></td><td>5-7</td><td></td><td>4-6</td></tr>
<tr><td>Safflower</td><td>seed</td><td colspan="2"></td><td colspan="2">2-4</td><td colspan="2"></td></tr>
<tr><td>Sorghum</td><td>grain</td><td>3-4</td><td>3.5-5</td><td>3-4</td><td>3.5-5</td><td></td><td>2-3</td></tr>
<tr><td>Soybean</td><td>grain</td><td colspan="2">2.5-3.5</td><td colspan="2">2.5-3.5</td><td colspan="2"></td></tr>
<tr><td>Sugarbeet</td><td>beet</td><td colspan="2"></td><td colspan="2">40-60</td><td colspan="2">35-55</td></tr>
<tr><td>Sugarcane</td><td>cane</td><td></td><td>110-150</td><td></td><td>100-140</td><td></td><td></td></tr>
<tr><td>Sunflower</td><td>seed</td><td colspan="2">2.5-3.5</td><td colspan="2">2.5-3.5</td><td colspan="2">2-2.5</td></tr>
<tr><td>Tobacco</td><td>leaf</td><td></td><td>2-2.5</td><td></td><td>2-2.5</td><td></td><td>1.5-2</td></tr>
<tr><td>Tomato</td><td>fruit</td><td colspan="2">45-65</td><td colspan="2">55-75</td><td colspan="2">45-65</td></tr>
<tr><td>Water melon</td><td>fruit</td><td></td><td>25-35</td><td></td><td>25-35</td><td></td><td></td></tr>
<tr><td>Wheat</td><td>grain</td><td>4-6</td><td></td><td>4-6</td><td></td><td>4-6</td><td></td></tr>
</table>

1/ Semi-arid and arid areas only
2/ Summer and winter rainfall areas
3/ Oceanic and continental areas
4/ Mean temperature

Table 2 CLIMATIC, SOIL AND WATER REQUIREMENTS FOR CROPS

Crop	Total growing period (days)	Temperature requirements for growth, °C optimum[1] (range)	Daylength requirements for flowering	Specific climatic constraints/ requirements	Soil requirements
Alfalfa	100-365	24-26 (10-30)	Day neutral	Sensitive to frost; cutting interval related to temp.; requires low RH in warm climates	Deep, medium-textured, well-drained, pH = 6.5-7.5
Banana	300-365	25-30 (15-35)	Day neutral	Sensitive to frost; temp. <8°C for longer periods causes serious damage; requires high RH, wind < 4 m/sec	Deep, well-drained loam without stagnant water; pH = 5-7
Bean	fresh: 60-90 dry : 90-120	15-20 (10-27)	Short day/ day neutral	Sensitive to frost; excessive rain, hot weather	Deep, friable soil, well-drained and aerated; opt. pH = 5.5-6.0
Cabbage	100-150+	15-20 (10-24)	Long day	Short periods of frost (-6 to -10°C) are not harmful; opt. RH = 60-90%	Well-drained; opt. pH = 6.0-6.5
Citrus	240-365	23-30 (13-35)	Day neutral	Sensitive to frost (dormant trees less), strong wind, high humidity; cool winter or short dry period preferred	Deep, well-aerated, light to medium-textured soils, free from stagnant water; pH = 5-8
Cotton	150-180	20-30 (16-35)	Short day/ day neutral	Sensitive to frost; strong or cold winds; temp. req. for boll development: 27-32°C (18-38); dry ripening period required	Deep, medium to heavy-textured soils; pH = 5.5-8.0 with opt. pH = 7.0-8.0
Grape	180-270	20-25 (15-30)		Resistant to frost during dormancy (down to -18°C) but sensitive during growth; long, warm to hot, dry summer and cool winter preferred/ required	Well-drained, light soils are preferred
Groundnut	90-140	22-28 (18-33)	Day neutral	Sensitive to frost; for germination temp. >20°C	Well-drained, friable, medium-textured soil with loose top soil; pH = 5.5-7.0
Maize	100-140+	24-30 (15-35)	Day neutral/ short day	Sensitive to frost; for germination temp. >10°C; cool temp. causes problem for ripening	Well-drained and aerated soils with deep water table and without waterlogging; opt. pH = 5.0-7.0
Olive	210-300	20-25 (15-35)		Sensitive to frost (dormant trees less); low winter temp. required (< 10°C) for flower bud initiation	Deep, well-drained soils free from waterlogging
Onion	100-140 (+30-35 in nursery)	15-20 (10-25)	Long day/ day neutral	Tolerant to frost; low temp. (< 14-16°C) required for flower initiation; no extreme temp. or excessive rain	Medium-textured soil; pH = 6.0-7.0
Pea	fresh: 65-100 dry : 85-120	15-18 (10-23)	Day neutral	Slight frost tolerance when young	Well-drained and aerated soils; pH = 5.5-6.5
Pepper	120-150	18-23 (15-27)	Short day/ day neutral	Sensitive to frost	Light to medium-textured soils; pH = 5.5-7.0
Pineapple	365	22-26 (18-30)	Short day	Sensitive to frost; requires high RH; quality affected by temperature	Sandy loam with low lime content; pH = 4.5-6.5
Potato	100-150	15-20 (10-25)	Long day/ day neutral	Sensitive to frost; night temp.< 15°C required for good tuber initiation	Well-drained, aerated and porous soils; pH = 5-6
Rice	90-150	22-30 (18-35)	Short day/ day neutral	Sensitive to frost; cool temp. causes head sterility; small difference in day and night temp. is preferred	Heavy soils preferred for percolation losses, high tolerance to O_2 deficit; pH = 5.5-6.0
Safflower	spring: 120-160 autumn: 200-230	early growth: 15-20 later growth: 20-30 (10-35)		Tolerant to frost; cool temp. req. for good establishment and early growth	Fairly deep, well-drained soils, preferably medium-textured; pH = 6-8
Sorghum	100-140+	24-30 (15-35)	Short day/ day neutral	Sensitive to frost; for germination temp. > 10°C; cool temp. causes head sterility	Light to medium/heavy soils relatively tolerant to periodic waterlogging, pH = 6-8
Soybean	100-130	20-25 (18-30)	Short day/ day neutral	Sensitive to frost; for some var. temp. >24°C required for flowering	Wide range of soil except sandy, well-drained; pH = 6-6.5
Sugarbeet	160-200	18-22 (10-30)	Long day	Tolerant to light frost; toward harvest mean daily temp. <10°C for high sugar yield	Medium to slightly heavy-textured soils, friable and well-drained; pH = 6-7
Sugarcane	270-365	22-30 (15-35)	Short day/ day neutral	Sensitive to frost; during ripening cool (10-20°C), dry, sunny weather is required	Deep, well aerated with ground water deeper than 1.5-2 m but rel. tolerant to periodic high water tables and O_2 deficit; pH = 5-8.5; opt pH = 6.5
Sunflower	90-130	18-25 (15-30)	Short day/ day neutral	Sensitive to frost	Fairly deep soils; pH = 6-7.5
Tobacco	90-120 (+40-60 in nursery)	20-30 (15-35)	Short day/ day neutral	Sensitive to frost	Quality of leaf depends on soil texture; pH = 5-6.5
Tomato	90-140 (+25-35 in nursery)	18-25 (15-28)	Day neutral	Sensitive to frost, high RH, strong wind; opt. night temp. 10-20°C	Light loam, well-drained without waterlogging; pH = 5-7
Watermelon	80-110	22-30 (18-35)	Day neutral	Sensitive to frost	Sandy loam is preferred; pH = 5.8-7.2
Wheat	spring: 100-130 winter: 180-250	15-20 (10-25)	Day neutral/ long day	Spring wheat: sensitive to frost; Winter wheat: resistant to frost during dormancy (> -18°C), sensitive during post-dormancy period; requires a cold period for flowering during early growth. For both, dry period required for ripening	Medium-texture is preferred; relatively tolerant to high water table; pH = 6-8

1/ mean daily temperatures

2/ ky of the total growing period:

low	:	ky <0.85
medium-low	:	ky 0.85 - 1.0
medium-high	:	ky 1.0 - 1.15
high	:	ky >1.15

Sensitivity to salinity	Fertilizer requirements N : P : K kg/ha/growing period	Water requirements mm/growing period	Sensitivity to water supply (ky)[2]	Water utilization efficiency for harvested yield, Ey, kg/m³ (% moisture)	Crop
moderately sensitive	0-40 : 55-65 : 75-100	800-1600	low to medium-high (0.7-1.1)	1.5 - 2.0 hay (10-15%)	Alfalfa
sensitive	200-400 : 45-60 : 240-480	1200-2200	high (1.2-1.35)	plant crop : 2.5-4 ratoon : 3.5-6 fruit (70%)	Banana
sensitive	20-40 : 40-60 : 50-120	300-500	medium-high (1.15)	lush : 1.5-2.0 (80-90%) dry : 0.3-0.6 (10%)	Bean
moderately sensitive	100-150 : 50-65 : 100-130	380-500	medium-low (0.95)	12-20 head (90-95%)	Cabbage
sensitive	100-200 : 35-45 : 50-160	900-1200	low to medium-high (0.8-1.1)	2-5 fruit (85%, lime: 70%)	Citrus
tolerant	100-180 : 20-60 : 50-80	700-1300	medium-low (0.85)	0.4-0.6 seed cotton (10%)	Cotton
moderately sensitive	100-160 : 40-60 : 160-230	500-1200	medium-low (0.85)	2-4 fresh fruit (80%)	Grape
moderately sensitive	10-20 : 15-40 : 25-40	500-700	low (0.7)	0.6-0.8 unshelled dry nut (15%)	Groundnut
moderately sensitive	100-200 : 50-80 : 60-100	500-800	high (1.25)	0.8-1.6 grain (10-13%)	Maize
moderately tolerant	200-250 : 55-70 : 160-210	600-800	low	1.5-2.0 fresh fruit (30%)	Olive
sensitive	60-100 : 25-45 : 45-80	350-550	medium-high (1.1)	8-10 bulb (85-90%)	Onion
sensitive	20-40 : 40-60 : 80-160	350-500	medium-high (1.15)	fresh: 0.5-0.7 shelled (70-80%) dry: 0.15-0.2 (12%)	Pea
moderately sensitive	100-170 : 25-50 : 50-100	600-900 (1250)	medium-high (1.1)	1.5-3.0 fresh fruit (90%)	Pepper
	230-300 : 45-65 : 110-220	700-1000	low	plant crop : 5-10 ratoon : 8-12 fruit (85%)	Pineapple
moderately sensitive	80-120 : 50-80 : 125-160	500-700	medium-high (1.1)	4-7 fresh tuber (70-75%)	Potato
moderately sensitive	100-150 : 20-40 : 80-120	350-700	high	0.7-1.1 paddy (15-20%)	Rice
moderately tolerant	60-110 : 15-30 : 25-40	600-1200	low (0.8)	0.2-0.5 seed (8-10%)	Safflower
moderately tolerant	100-180 : 20-45 : 35-80	450-650	medium-low (0.9)	0.6-1.0 grain (12-15%)	Sorghum
moderately tolerant	10-20 : 15-30 : 25-60	450-700	medium-low (0.85)	0.4-0.7 grain (6-10%)	Soybean
tolerant	150 : 50-70 : 100-160	550-750	low to medium-low (0.7-1.1)	beet : 6-9 (80-85%) sugar : 0.9-1.4 (0%)	Sugarbeet
moderately sensitive	100-200 : 20-90 : 125-160	1500-2500	high (1.2)	cane : 5-8 (80%) sugar : 0.6-1.0 (0%)	Sugarcane
moderately tolerant	50-100 : 20-45 : 60-125	600-1000	medium-low (0.95)	0.3-0.5 seed (6-10%)	Sunflower
sensitive	40-80 : 30-90 : 50-110	400-600	medium-low (0.9)	0.4-0.6 cured leaves (5-10%)	Tobacco
moderately sensitive	100-150 : 65-110 : 160-240	400-600	medium-high (1.05)	10-12 fresh fruit (80-90%)	Tomato
moderately sensitive	80-100 : 25-60 : 35-80	400-600	medium-high (1.1)	5-8 fruit (90%)	Water melon
moderately tolerant	100-150 : 35-45 : 25-50	450-650	medium-high (spring: 1.15 winter: 1.0)	0.8-1.0 grain (12-15%)	Wheat

1 kg P = 2.4 kg P_2O_5

1 kg K = 1.2 kg K_2O

CALCULATION PROCEDURE

To calculate 'experimental' yield (Yme) the steps needed are:

a. Calculate gross dry matter production of a standard crop (Yo).

b. Apply correction for climate (ETm/(ea-ed)).

Apply correction for crop species (K).

Apply correction for temperature (cT).

Apply correction for harvested part (cH).

a. Calculation of Gross Dry Matter Production of Standard Crop (Yo)

To calculate Yo in kg/ha/day for a given location, the method of De Wit (1965) is used. This method is based on the level of incoming active shortwave radiation for standard conditions:

$$Yo = F\,yo + (1 - F)\,yc$$

where:

Yo = gross dry matter production of a standard crop, kg/ha/day

F = fraction of the daytime the sky is clouded, fraction; or F = (Rse - 0.5Rs)/0.8Rse where Rse is the maximum active incoming shortwave radiation on clear days in cal/cm²/day (Table 3) and Rs is the actual measured incoming shortwave radiation in cal/cm²/day [1]

yo = gross dry matter production rate of a standard crop for a given location on a completely overcast day, kg/ha/day (Table 3)

yc = gross dry matter production rate of a standard crop for a given location on a clear (cloudless) day, kg/ha/day (Table 3)

b. Correction for Effect of Climate (ETm/(ea-ed))

In addition to radiation, the rate of crop growth for a given climate is closely related to the ratio mean maximum evapotranspiration (ETm) in mm/day and the vapour pressure deficit (ea-ed) in mean daily mbar over the total growing period (Bierhuizen and Slatyer, 1965). [2] Calculation of ETm is given in Chapter II; for calculation of mean saturation vapour pressure (ea) and mean actual vapour pressure (ed), both in mbar (Table 9), see Chapter II, 1.1 Penman Method.

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[1] Rs is also expressed in mm/day equivalent evaporation; conversion is 59 cal/cm² = 1 mm equivalent evaporation. When only sunshine duration data are available, Rs can also be calculated from Rs = (0.25 + 0.50 n/N)Ra, where Ra is the extra-terrestrial radiation in mm/day (Table 10), N is the maximum possible sunshine duration in hours/day (Table 11) and n is the actual measured sunshine duration in hours/day.

[2] When expressed in mm Hg conversions, 1 mbar = 0.75 mm Hg.

Table 3 Maximum Active Incoming Shortwave Radiation (Rse in cal/cm^2/day) and Gross Dry Matter Production on Overcast (yo) and Clear Days (yc) (in kg/ha/day) for a Standard Crop (De Wit, 1965)

North South		Jan July	Feb Aug	Mar Sept	Apr Oct	May Nov	June Dec	July Jan	Aug Feb	Sept Mar	Oct Apr	Nov May	Dec June
0°	Rse	343	360	369	364	349	337	343	357	368	365	349	337
	yc	413	424	429	426	417	410	413	422	429	427	418	410
	yo	219	226	230	228	221	216	218	225	230	228	222	216
10°	Rse	299	332	359	375	377	374	375	377	369	345	311	291
	yc	376	401	422	437	440	440	440	439	431	411	385	370
	yo	197	212	225	234	236	235	236	235	230	218	203	193
20°	Rse	249	293	337	375	394	400	399	386	357	313	264	238
	yc	334	371	407	439	460	468	465	451	425	387	348	325
	yo	170	193	215	235	246	250	249	242	226	203	178	164
30°	Rse	191	245	303	363	400*	417*	411*	384*	333	270	210	179
	yc	281	333	385	437	471*	489*	483*	456*	412	356	299	269
	yo	137	168	200	232	251*	261*	258*	243*	216	182	148	130
40°	Rse	131	190	260	339	396	422	413	369	298	220	151	118
	yc	219	283	353	427	480	506	497	455	390	314	241	204
	yo	99	137	178	223	253	268	263	239	200	155	112	91

* Values used in calculation example

c. Correction for Crop Species (K)

To relate gross dry matter production of a standard crop (Yo) to gross dry matter production of alfalfa, maize, sorghum and wheat (Yo . ETm/ea-ed)), empirically-derived crop constants (K) are used with a value for alfalfa equal 0.9, for maize equal 1.9, for sorghum equal 1.6, for spring wheat equal 1.17 and for winter wheat equal 0.65.

d. Correction for Temperature (cT)

The production of a standard crop (Yo) is presented for standard temperature conditions. For actual mean daily temperature during the total growing period, a crop-specific temperature correction (cT) is applied to obtain net dry matter production (Ydm) taking into account the 40 percent of total energy required by the plant for growth and maintenance processes (respiration). For a crop with optimum plant density, Ydm = K . cT . G . Yo . ETm/(ea-ed) in kg/ha/period, where Yo is taken as the average over a total growing period of G days.

Table 4 Correction for Temperature (cT)

	Mean temperature over the total growing period, °C						
	5	10	15	20	25	30	35
Alfalfa	0	0.2	0.4	0.55	0.6	0.6	0.5
Maize	0	0.1	0.35	0.5	0.6*	0.6*	0.6
Sorghum	0	0.1	0.3	0.45	0.55	0.6	0.6
Wheat	0.05	0.3	0.55	0.6	0.35	0.1	0

e. Correction for Harvested Part (cH)

In general, only a part of the total dry matter is harvested. For alfalfa, about 50 percent of the net total dry matter is formed in the roots during the first year of growth and about 10 percent for the subsequent years. When maize, sorghum and wheat are grown for grain, only a fraction of the total dry matter is harvested. The ratio between net total dry matter and harvested yield is given by the harvest index (cH) for high-producing varieties under irrigation:

	cH	
Alfalfa	0.4 - 0.[illegible]	first year
	0.8 - 0.9	subsequent years
Maize	0.4 - 0.5	
Sorghum	0.35 - 0.45	
Wheat	[illegible]	

In summary, the production (Yme) under experimental conditions of a high-producing, climatically adapted variety, grown under optimum climatic conditions is:

Alfalfa	Yme = 0.9 . cH . cT . G . Yo . ETm/(ea-ed)	kg/ha/period
Maize	Yme = 1.9 . cH . cT . G . Yo . ETm/(ea-ed)	kg/ha/period
Sorghum	Yme = 1.6 . cH . cT . G . Yo . ETm/(ea-ed)	kg/ha/period
Spring wheat	Yme = 1.17 . cH . cT . G . Yo . ETm/(ea-ed)	kg/ha/period
Winter wheat	Yme = 0.65 . cH . cT . G . Yo . ETm/(ea-ed)	kg/ha/period

EXAMPLE

Given: Maize, with optimum plant density; location 30°N; altitude 95 m; total growing period 123 days from 1 May to 31 August; mean incoming shortwave radiation (Rs) over the total growing period 650 cal/cm²/day; mean temperature 27.5°C; mean relative humidity 55%; mean maximum evapotranspiration (ETm) is 6.8 mm/day; harvest index (cH) is 0.45.

Calculation:

yo	mean		Table 3	253	kg/ha/day
yc	mean		Table 3	475	kg/ha/day
Rse	mean		Table 3	403	cal/cm²/day
F	mean	(403 - 0.5 x 650)/(0.8 x 403)	calc	0.24	
Yo	mean	(0.24 x 253) + (1 - 0.24)475	calc	422	kg/ha/day
ETm	mean		Chap. 2	6.8	mm/day
ea	mean	at 27.5°C	Table 9	36.8	mbar
ed	mean	ea x RH/100	calc	20.2	mbar
ea-ed	mean		calc	16.6	mbar
cT	fraction	at 27.5°C	Table 4	0.6	
Yme	total period	$\frac{1.9 \times 0.45 \times 0.6 \times 123 \times 422}{6.8/16.6}$	calc	10910	kg/ha grain dry weight

2. THE AGRO-ECOLOGICAL ZONE METHOD

The methodology to calculate crop production was developed to suit the assessment on a continental basis. However, the method can also be applied to a degree of detail required to suit specific locations. For a given climate, the possible potential yield is calculated for a standard crop using the concept of De Wit (1965) using radiation data; for agricultural crops, corrections are made for the genetically-controlled growth processes of the crop under the given climate. It is assumed that the climatic requirements of the crop are met and that water, nutrients, salinity, pests and diseases do not affect crop growth and potential yield (Ymp).

Under actual farming conditions, yield losses will occur due to adverse climatic conditions over short periods, limited water and nutrient supply, and problematic farm operations including land preparation, weeding and harvesting. These constraints are complex and it is difficult to quantify their effect on yield. However, when compared to actual farmers' yields, the calculated potential yield (Ymp) will give an indication of the efficiency in agricultural production.

CALCULATION PROCEDURE

To calculate potential yield (Ymp) the steps needed are:

a. Calculate gross dry matter production of a standard crop (Yo).

b. Apply correction for crop species and temperature.

c. Apply correction for crop development over time and leaf area (cL).

d. Apply correction for net dry matter production (cN).

e. Apply correction for harvested part (cH).

a. Calculation of Gross Dry Matter Production of a Standard Crop (Yo)

As in 1, Yo in kg/ha/day is calculated for a given location applying the concept of De Wit (1965):

$$Yo = F \cdot yo + (1-F)yc$$

where:

- Yo = gross dry matter production of a standard crop, kg/ha/day
- F = fraction of the daytime the sky is clouded, fraction; or $F = (Rse - 0.5Rs)/\ 0.8Rse$ where Rse is the maximum active incoming shortwave radiation on clear days in cal/cm²/day (Table 3) and Rs is the actual measured incoming shortwave radiation in cal/cm²/day. Rs can also be calculated from measured sunshine duration data (n) in hours/day
- yo = gross dry matter production rate of a standard crop for a given location on a completely overcast day, kg/ha/day (Table 3)
- yc = gross dry matter production rate of a standard crop for a given location on a clear (cloudless) day, kg/ha/day (Table 3)

b. Correction for Crop Species and Temperature

The gross dry matter production is crop species and temperature dependent. The production rate (ym) can be larger or smaller than 20 kg/ha/hour as assumed for the standard crop. Production rates (ym) in kg/ha/hour for groups of crops are given in Table 5.

Table 5 Production Rates (ym in kg/ha/hour) for Crop Groups and Mean Temperatures

Crop group	Mean temperature, °C								
	5	10	15	20	25	30	35	40	45
I cool	5	15	20	20	15	5	0	0	0
I warm	0	0	15	32.5	35	35	32.5	5	0
II cool	0	5	45	65	65	65	45	5	0
II warm	0	0	5	45	65	65	65*	45	5

I cool: alfalfa, bean, cabbage, pea, potato, tomato, sugarbeet, wheat
I warm: alfalfa, citrus, cotton, groundnut, pepper, rice, safflower, soybean, sunflower, tobacco, tomato
II cool: some maize and sorghum varieties
II warm: maize, sorghum, sugarcane

Applying De Wit's concept, the value of yo and yc can be adjusted for different crop groups:

a. when ym > 20 kg/ha/hour

$$Yo = F(0.8 + 0.01\ ym)yo + (1-F)(0.5 + 0.025\ ym)yc \quad kg/ha/day$$

when ym < 20 kg/ha/hour

[illegible].025 ym)yo + (1-F)(0.05 ym)yc kg/ha/day

c. Correction for Crop Development over Time and Leaf Area (cL)

In relation to the maximum growth rate during the middle of the total growing period, crop growth will be small at the start and the end of the growing period or the average rate over the growing period is about 50 percent of the rate during the maximum growth. Also for the standard crop an active leaf area of five times the ground surface is assumed (LAI = 5). When leaf area is smaller a correction must be applied; when greater than 5 the effect is small (Table 6).

Table 6 Correction for Crop Development over Time and Leaf Area (cL)

LAI	1	2	3	4	>5
Correction cL	0.2	0.3	0.4	0.48	0.5*

d. Correction for Net Dry Matter Production (cN)

To maintain dry matter production, energy is required by the plant for the within-plant growth processes (also called respiration). Only the remaining energy can be used to produce new growth which is about 0.6 for cool (mean temp. < 20°C) and 0.5 for warm (mean temp. >20°C) conditions, or cN = 0.5 to 0.6.

e. Correction for Harvested Part (cH)

In general, only a part of the total dry matter such as grain, sugar or oil is harvested. The ratio between net total dry matter and harvested yield is given by the harvest index (cH) for high-producing varieties under irrigation (Table 7).

Table 7 Harvest Index (cH) of High-producing Varieties under Irrigation (on Dry Weight Basis)

Crop	Product	cH	Crop	Product	cH
Alfalfa	hay	0.4-0.5[1/]	Potato	tuber	0.55-0.65
		0.8-0.9[1/]	Rice	grain	0.4-0.5
Bean	grain	0.25-0.35	Sorghum	grain	0.3-0.4
Cabbage	head	0.6-0.7	Soybean	grain	0.3-0.4
Cotton	lint	0.08-0.12	Sugarbeet	sugar	0.35-0.45
Groundnut	grain	0.25-0.35	Sugarcane	sugar	0.2-0.3
Maize	grain	0.35-0.45*	Sunflower	seed	0.2-0.3
Onion	bulb	0.7-0.8	Tobacco	leaf	0.5-0.6
Pea	grain	0.3-0.4	Tomato	fruit	0.25-0.35
Pepper	fruit	0.2-0.4	Wheat	grain	0.35-0.45
Pineapple	fruit	0.5-0.6			

[1/] first and second year

In summary, potential yield (Ymp) of a high-producing, climatically adapted variety grown under constraint-free conditions over a growing period of G days is:

a. when ym >20 kg/ha/hour

$$Ymp = cL . cN . cH . G\ [F(0.8 + 0.01\,ym)yo + (1-F)(0.5 + 0.025\,ym)yc]$$ kg/ha/period

b. when ym <20 kg/ha/hour

$$Ymp = cL . cN . cH . G\ [F(0.5 + 0.025\,ym)yo + (1-F)(0.05\,ym)yc]$$ kg/ha/period

where:

cL = correction crop development and leaf area (Table 6)
cN = correction for dry matter production, 0.6 for cool and 0.5 for warm conditions
cH = correction for harvest index (Table 7)
G = total growing period (days)
F = fraction of the daytime the sky is clouded
ym = maximum leaf gross dry matter production rate of a crop for a given climate, kg/ha/day (Table 5)
yo = gross dry matter production of a standard crop for a given location on a completely overcast (clouded) day, kg/ha/day (Table 3)
yc = gross dry matter production rate of a standard crop for a given location on a clear (cloudless) day, kg/ha/day (Table 3)

EXAMPLE

Given: Maize; location 30°N; total growing period (G) 123 days from 1 May to 31 August; LAI is 5; average incoming shortwave radiation (Rs) over growing period 650 cal/cm²/day; average mean temperature 27.5°C.

Calculation:

yo	mean		Table 3	253 kg/ha/day
yc	mean		Table 3	475 kg/ha/day
Rse	mean		Table 3	403 cal/cm²/day
F	mean	403 - 0.5 x 650/0.8 x 403	calc	0.24
ym		at 35°C	Table 5	65 kg/ha/h
cL		at LAI = 5	Table 6	0.5
cH			Table 7	0.4
cN		at 27.5°C	given	0.5
G			given	123
Ymp		0.5 x 0.5 x 0.4 x 123 [0.24(0.8 + 0.01 x 65) 253 + (1-0.24)(0.5 + 0.025 x 65)475]	calc	10520 kg/ha grain dry weight

NB: The derived yield using the two methods to calculate the 'experimental' (Yme) and 'potential' yield (Ymp) would seem high in relation to actual field production. However, for the location in question (Giza, UAR), the measured grain yield of maize with irrigation at 50 percent depletion of available soil water, and with measured crop water use of 6 850 m³/ha, was 10.3 ton/ha (El Maghraby, 1969).

II. MAXIMUM EVAPOTRANSPIRATION (ETm)

Climate is one of the most important factors determining the crop water requirements needed for unrestricted optimum growth and yield. Crop water requirements are normally expressed by the rate of evapotranspiration (ET) in mm/day or mm/period. The level of ET has been shown to be related to the evaporative demand of the air. The evaporative demand can be expressed as the reference evapotranspiration (ETo) which, when calculated, predicts the effect of climate on the level of crop evapotranspiration; ETo represents the rate of evapotranspiration of an extended surface of an 8 to 15 cm tall green grass cover, actively growing, completely shading the ground and not short of water. Methods to calculate ETo are given, i.e. the Penman, Radiation and Pan Evaporation Methods. Approximate values for ETo in mm/day for different agro-climatic regions are given in Table 8.

Empirically-determined crop coefficients (kc) can be used to relate ETo to maximum crop evapotranspiration (ETm) when water supply fully meets the water requirements of the crop. The value of kc varies with crop, development stage of the crop, and to some extent with windspeed and humidity. For most crops, the kc value increases from a low value at time of crop emergence to a maximum value during the period when the crop reaches full development, and declines as the crop matures. Values of kc for different crops are given in Table 18 and in Part B.

For a given climate, crop and crop development stage, the maximum evapotranspiration (ETm) in mm/day of the period considered is:

$$ETm = kc \cdot ETo$$

Maximum evapotranspiration (ETm) refers to conditions when water is adequate for unrestricted growth and development; ETm represents the rate of maximum evapotranspiration of a healthy crop, grown in large fields under optimum agronomic and irrigation management.

The methods presented allow prediction of ETm within 10 to 20 percent accuracy provided the meteorological data are reliable and obtained from a representative agricultural environment, and provided total growing period and lengths of development stages are known. For details see Doorenbos and Pruitt (1977).

Meteorological data used in the calculation of ETm should preferably be collected at stations situated within an agricultural (irrigated) area. When data are collected at stations in dry, bare areas, at airports or even on rooftops, the calculated ETm values should be corrected since the data do not represent the different micro-climates found within the irrigation schemes. In arid and semi-arid areas with moderate wind, ETm calculated with data obtained outside the irrigated area may need to be adjusted downward by 20 to 25 percent.

CALCULATION PROCEDURE

1. Reference Evapotranspiration (ETo)
   Collect and evaluate available meteorological and crop data; based on meteorological data available, select method of calculation. Compute ETo in mm/day for each 30 or 10-day period using mean meteorological data.

2. Crop Coefficient (kc)
   Determine growing period and length of crop development stages and select kc values.

Table 8 **Reference Evapotranspiration (ETo in mm/day) for Different Agro-climatic Regions**

Regions	Mean daily temperature, °C <10 ——— 20 ——— >30 (cool)	(moderate)	(warm)
TROPICS			
humid	3 - 4	4 - 5	5 - 6
subhumid	3 - 5	5 - 6	7 - 8
semi-arid	4 - 5	6 - 7	8 - 9
arid	4 - 5	7 - 8	9 - 10
SUBTROPICS			
Summer rainfall:			
humid	3 - 4	4 - 5	5 - 6
subhumid	3 - 5	5 - 6	6 - 7
semi-arid	4 - 5	6 - 7	7 - 8
arid	4 - 5	7 - 8	10 - 11
Winter rainfall			
humid - subhumid	2 - 3	4 - 5	5 - 6
semi-arid	3 - 4	5 - 6	7 - 8
arid	3 - 4	6 - 7	10 - 11
TEMPERATE			
humid - subhumid	2 - 3	3 - 4	5 - 7
semi-arid - arid	3 - 4	5 - 6	8 - 9

3. Maximum Evapotranspiration (ETm)
Calculate ETm in mm/day for each 30 or 10-day period from ETm = kc . ETo.
If needed, adjust ETm according to data source.

1. REFERENCE EVAPOTRANSPIRATION (ETo)

1.1 Penman Method

Climatic data required are: mean temperature (T in °C), mean relative humidity (RH in %), total windrun (U in km/day at 2 m height) and mean actual sunshine duration (n in hour/day) or mean radiation (Rs or Rn equivalent evaporation in mm/day). Also measured or estimated data on mean maximum relative humidity (RHmax in %) and mean daytime windspeed (Uday in m/sec at 2 m height) must be available. Reference evapotranspiration (ETo) representing the mean value in mm/day, over the period considered, is obtained by:

$$ETo = c\,[W \cdot Rn + (1-W) \cdot f(U) \cdot (ea-ed)]$$

where:

(ea-ed)	=	vapour pressure deficit i.e. the difference between saturation vapour pressure (ea) at Tmean in mbar (Table 9) and actual vapour pressure (ed) in mbar where ed = ea . RH/100
f(U)	=	wind function of f(U) = 0.27 (1 + U/100) with U in km/day measured at 2 m height
Rn	=	total net radiation in mm/day or Rn = 0.75Rs - Rnl where Rs is incoming shortwave radiation in mm/day either measured or obtained from Rs = (0.25 + 0.50 n/N)Ra. Ra is extra-terrestrial radiation in mm/day (Table 10), n is the mean actual sunshine duration in hour/day and N is maximum possible sunshine duration in hour/day (Table 11). Rnl is net longwave radiation in mm/day and is a function of temperature, f(T), of actual vapour pressure, f(ed) and sunshine duration, f(n/N), or Rnl = f(T) . f(n/N) . f(ed) (Tables 12, 13 and 14)
W	=	temperature and altitude dependent weighting factor (Table 15)
c	=	adjustment factor for ratio Uday/Unight, for RHmax and for Rs (Table 16)

EXAMPLE

Given: Location 30°N; altitude 95 m; July; Tmean 28.5°C; RHmean 55%; Umean 232 km/day; n mean 11.5 hour/day; (RHmax 80%, Uday 3 m/sec, Uday/Unight 1.5).

Calculation:

ea	T = 28.5°C	Table 9	38.9 mbar
ed	ea . RH/100	calc	21.4 mbar
ea-ed		calc	17.5 mbar
f(U)	0.27(1 + U/100): U = 232 km/day	calc	0.9
Ra	30°N, July	Table 10	16.8 mm/day
N	30°N, July	Table 11	13.9 hour/day
Rs	(0.25 + 0.50 n/N) Ra	calc	11.2 mm/day
Rnl	f(T) . f(ed) . f(n/N)	Tables 12, 13, 14	1.8 mm/day
Rn	0.75Rs - Rnl	calc	6.6 mm/day
W	T = 28.5°C; 95 m	Table 15	0.77
c	RHmax 80%; Rs 11.2; Uday/Unight 1.5	Table 16	1.01
ETo	c [W . Rn + (1-W) . f(U) . (ea-ed)]	calc	8.8 mm/day

1.2 Radiation Method

Climatic data required are mean temperature (T in °C) and mean actual sunshine duration (n in hour/day) or mean incoming shortwave radiation (Rs in mm/day equivalent evaporation). Estimated values of mean relative humidity (RH in %) and mean daytime windspeed (Uday in m/sec at 2 m height) must be available.

Reference evapotranspiration (ETo in mm/day) representing the mean daily value over the period considered is obtained by:

$$ETo = c(W \cdot Rs)$$

where:

Rs = measured mean incoming shortwave radiation in mm/day or is obtained from Rs = (0.25 + 0.50 n/N) Ra where Ra is extra-terrestrial radiation in mm/day (Table 10), N is maximum possible sunshine duration in hour/day (Table 11) and n is measured mean actual sunshine duration in hour/day

W = temperature and altitude dependent weighting factor (Table 15)

c = adjustment factor made graphically on W . Rs using estimated values of RHmean and Udaytime (Figure 1).

EXAMPLE

Given: Location 30°N; altitude 95 m; July; Tmean 28.5°C; n mean 11.5 hour/day; Uday mean = moderate (2 to 5 m/sec); RHmean = medium (about 55%).

Calculation:

Ra	30°N; July	Table 10	16.8	mm/day
N	30°N; July	Table 11	13.9	mm/day
Rs	(0.25 + 0.50 n/N) Ra	calc	11.2	mm/day
W	T = 28.5°C; 95 m	Table 15	0.77	
W . Rs		calc	8.6	mm/day
ETo	RH 55%; U = 2 to 5 m/sec	Fig. 1	8.4	mm/day

1.3 Pan Evaporation Method

Data required are mean pan evaporation (Epan in mm/day), estimated values of mean relative humidity (RH in %) and mean windrun (U in km/day at 2 m height) and information on whether the pan is surrounded by a cropped or dry fallow area.

Reference evapotranspiration (ETo) representing the mean value in mm/day over the period considered is obtained by:

$$ETo = k_{pan} \cdot Epan$$

where:

Epan = evaporation in mm/day from an unscreened class A evaporation pan
kpan = pan coefficient (Table 17)

EXAMPLE

Given: July; E class A pan 11.3 mm/day; RHmean = medium; Umean = moderate; pan surrounded by cropped area of several hectares.

Calculation:

kpan	RH = medium; U = moderate; cropped	Table 17	0.75
ETo	kpan . Epan	calc	8.5 mm/day

2 CROP COEFFICIENT (kc)

Information required on crops is:

- the date of sowing
- the length of the total growing season, including
- the duration of initial stage (germination to 10 percent ground cover)
- the duration of crop development stage (from 10 percent to 80 percent ground cover)
- the duration of the mid-season stage (from 80 percent ground cover to start of ripening)
- the duration of late season stage (from start of ripening to harvest).

General information on crop development stages is given for different crops in Part B. For crop coefficients see Table 18. Climatic data required for the selection of kc values are windspeed and humidity.

The value of the crop coefficient (kc) varies with the development stages of the crop. For most crops the kc value for the total growing period is between 0.85 and 0.9 with the exception of a higher value for banana, rice, coffee and cocoa and a lower value for citrus, grape, sisal and pineapple.

EXAMPLE

Given: Maize; planted 1 May; harvested 31 August; initial stage is 20 days; development stage 35 days; mid-season stage 40 days; late season stage 28 days; windspeed is light to moderate; minimum mean relative humidity is low.

Calculation: From Part B, Maize, or from Table 18:

kc May = 0.4; June = 0.75; July = 1.15; August = 0.85

3. MAXIMUM EVAPOTRANSPIRATION (ETm)

Data required are monthly mean ETo in mm/day and the kc values for the given crop over each 30 or 10-day period. Maximum evapotranspiration ETm = kc . ETo.

EXAMPLE

Given: Climatic data collected at station located within an irrigated area:

	May	June	July	August	
ETo mm/day	8.9	9.4	8.8	7.6	
kc	0.4	0.75	1.15	0.85	
Calculation:					
ETm mm/day	3.6	7.1	10.1	6.5	
mm/month	110	212	314	201	840

Table 9 **Saturation Vapour Pressure (ea) in mbar as Function of Mean Air Temperature (T) in °C** [1]

Temperature °C	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
ea mbar	6.1	6.6	7.1	7.6	8.1	8.7	9.3	10.0	10.7	11.5	12.3	13.1	14.0	15.0	16.1	17.0	18.2	19.4	20.6	22.0

Temperature °C	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
ea mbar	23.4	24.9	26.4	28.1	29.8	31.7	33.6	35.7*	37.8*	40.1*	42.4	44.9	47.6	50.3	53.2	56.2	59.4	62.8	66.3	69.9

[1] Also actual vapour pressure (ed) can be obtained from this table using available Tdewpoint data.
(Example: Tdewpoint is 18°C; ed is 20.6 mbar)

Table 10 **Extra-terrestrial Radiation (Ra) expressed in equivalent evaporation in mm/day**

Northern Hemisphere													Southern Hemisphere											
Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Lat	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
6.4	8.6	11.4	14.3	16.4	17.3	16.7	15.2	12.5	9.6	7.0	5.7	40°	17.9	15.7	12.5	9.2	6.6	5.3	5.9	7.9	11.0	14.2	16.9	18.3
6.9	9.0	11.8	14.5	16.4	17.2	16.7	15.3	12.8	10.0	7.5	6.1	38	17.9	15.8	12.8	9.6	7.1	5.8	6.3	8.3	11.4	14.4	17.0	18.3
7.4	9.4	12.1	14.7	16.4	17.2	16.7	15.4	13.1	10.6	8.0	6.6	36	17.9	16.0	13.2	10.1	7.5	6.3	6.8	8.8	11.7	14.6	17.0	18.2
7.9	9.8	12.4	14.8	16.5	17.1	16.8	15.5	13.4	10.8	8.5	7.2	34	17.8	16.1	13.5	10.5	8.0	6.8	7.2	9.2	12.0	14.9	17.1	18.2
8.3	10.2	12.8	15.0	16.5	17.0	16.8	15.6	13.6	11.2	9.0	7.8	32	17.8	16.2	13.8	10.9	8.5	7.3	7.7	9.6	12.4	15.1	17.2	18.1
8.8	10.7	13.1	15.2	16.5	17.0	16.8*	15.7	13.9	11.6	9.5	8.3	30	17.8	16.4	14.0	11.3	8.9	7.8	8.1	10.1	12.7	15.3	17.3	18.1
9.3	11.1	13.4	15.3	16.5	16.8	16.7	15.7	14.1	12.0	9.9	8.8	28	17.7	16.4	14.3	11.6	9.3	8.2	8.6	10.4	13.0	15.4	17.2	17.9
9.8	11.5	13.7	15.3	16.4	16.7	16.6	15.7	14.3	12.3	10.3	9.3	26	17.6	16.4	14.4	12.0	9.7	8.7	9.1	10.9	13.2	15.5	17.2	17.8
10.2	11.9	13.9	15.4	16.4	16.6	16.5	15.8	14.5	12.6	10.7	9.7	24	17.5	16.5	14.6	12.3	10.2	9.1	9.5	11.2	13.4	15.6	17.1	17.7
10.7	12.3	14.2	15.5	16.3	16.4	16.4	15.8	14.6	13.0	11.1	10.2	22	17.4	16.5	14.8	12.6	10.6	9.6	10.0	11.6	13.7	15.7	17.0	17.5
11.2	12.7	14.4	15.6	16.3	16.4	16.3	15.9	14.8	13.3	11.6	10.7	20	17.3	16.5	15.0	13.0	11.0	10.0	10.4	12.0	13.9	15.8	17.0	17.4
11.6	13.0	14.6	15.6	16.1	16.1	16.1	15.8	14.9	13.6	12.0	11.1	18	17.1	16.5	15.1	13.2	11.4	10.4	10.8	12.3	14.1	15.8	16.8	17.1
12.0	13.3	14.7	15.6	16.0	15.9	15.9	15.7	15.0	13.9	12.4	11.6	16	16.9	16.4	15.2	13.5	11.7	10.8	11.2	12.6	14.3	15.8	16.7	16.8
12.4	13.6	14.9	15.7	15.8	15.7	15.7	15.7	15.1	14.1	12.8	12.0	14	16.7	16.4	15.3	13.7	12.1	11.2	11.6	12.9	14.5	15.8	16.5	16.6
12.8	13.9	15.1	15.7	15.7	15.5	15.5	15.6	15.2	14.4	13.3	12.5	12	16.6	16.3	15.4	14.0	12.5	11.6	12.0	13.2	14.7	15.8	16.4	16.5
13.2	14.2	15.3	15.7	15.5	15.3	15.3	15.5	15.3	14.7	13.6	12.9	10	16.4	16.3	15.5	14.2	12.8	12.0	12.4	13.5	14.8	15.9	16.2	16.2
13.6	14.5	15.3	15.6	15.3	15.0	15.1	15.4	15.3	14.8	13.9	13.3	8	16.1	16.1	15.5	14.4	13.1	12.4	12.7	13.7	14.9	15.8	16.0	16.0
13.9	14.8	15.4	15.4	15.1	14.7	14.9	15.2	15.3	15.0	14.2	13.7	6	15.8	16.0	15.6	14.7	13.4	12.8	13.1	14.0	15.0	15.7	15.8	15.7
14.3	15.0	15.5	15.5	14.9	14.4	14.6	15.1	15.3	15.1	14.5	14.1	4	15.5	15.8	15.6	14.9	13.8	13.2	13.4	14.3	15.1	15.6	15.5	15.4
14.7	15.3	15.6	15.3	14.6	14.2	14.3	14.9	15.3	15.3	14.8	14.4	2	15.3	15.7	15.7	15.1	14.1	13.5	13.7	14.5	15.2	15.5	15.3	15.1
15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8	0	15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8

Table 11 Mean Daily Duration of Maximum Possible Sunshine Hours (N) for Different Months and Latitudes

Northern Latitudes	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Southern Latitudes	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
40	9.6	10.7	11.9	13.3	14.4	15.0	14.7	13.7	12.5	11.2	10.0	9.3
35	10.1	11.0	11.9	13.1	14.0	14.5	14.3	13.5	12.4	11.3	10.3	9.8
30	10.4	11.1	12.0	12.9	13.6	14.0	13.9*	13.2	12.4	11.5	10.6	10.2
25	10.7	11.3	12.0	12.7	13.3	13.7	13.5	13.0	12.3	11.6	10.9	10.6
20	11.0	11.5	12.0	12.6	13.1	13.3	13.2	12.8	12.3	11.7	11.2	10.9
15	11.3	11.6	12.0	12.5	12.8	13.0	12.9	12.6	12.2	11.8	11.4	11.2
10	11.6	11.8	12.0	12.3	12.6	12.7	12.6	12.4	12.1	11.8	11.6	11.5
5	11.8	11.9	12.0	12.2	12.3	12.4	12.3	12.3	12.1	12.0	11.9	11.8
0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0

Table 12 Effect of Temperature f(T) on Longwave Radiation (Rnl)

T°C	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
$f(T) = \delta Tk^4$	11.0	11.4	11.7	12.0	12.4	12.7	13.1	13.5	13.8	14.2	14.6	15.0	15.4	15.9	16.3*	16.7	17.2	17.7	18.1

Table 13 Effect of Vapour Pressure f(ed) on Longwave Radiation (Rnl)

ed mbar	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
$f(ed) = 0.34 - 0.044\sqrt{ed}$	0.23	.22	.20	.19	.18	.16	.15	.14	.13*	.12	.12	.11	.10	.09	.08	.08	.07	.06

Table 14 Effect of the Ratio Actual and Maximum Bright Sunshine Hours f(n/N) on Longwave Radiation (Rnl)

n/N	0	.05	.1	.15	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8	.85	.9	.95	1.0
$f(n/N) = 0.1 + 0.9n/N$	0.10	.15	.19	.24	.28	.33	.37	.42	.46	.51	.55	.60	.64	.69	.73	.78	.82*	.87	.91	.96	1.0

Table 15 **Values of Weighting Factor (W) for the Effect of Radiation on ETo at Different Temperatures and Altitudes**

Temperature °C	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
W at altitude m																				
0	0.43	.46	.49	.52	.55	.58	.61	.64	.66	.69	.71	.73	.75	.77*	.78	.80	.82	.83	.84	.85
500	.45	.48	.51	.54	.57	.60	.62	.65	.67	.70	.72	.74	.76	.78	.79	.81	.82	.84	.85	.86
1000	.46	.49	.52	.55	.58	.61	.64	.66	.69	.71	.73	.75	.77	.79	.80	.82	.83	.85	.86	.87
2000	.49	.52	.55	.58	.61	.64	.66	.69	.71	.73	.75	.77	.79	.81	.82	.84	.85	.86	.87	.88
3000	.52	.55	.58	.61	.64	.66	.69	.71	.73	.75	.77	.79	.81	.82	.84	.85	.86	.88	.88	.89

Table 16 **Adjustment Factor (c) in Presented Penman Equation**

	RHmax = 30%				RHmax = 60%				RHmax = 90%			
Rs mm/day	3	6	9	12	3	6	9	12	3	6	9	12
Uday m/sec	Uday/Unight = 4.0											
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.79	.84	.92	.97	.92	1.00	1.11	1.19	.99	1.10	1.27	1.32
6	.68	.77	.87	.93	.85	.96	1.11	1.19	.94	1.10	1.26	1.33
9	.55	.65	.78	.90	.76	.88	1.02	1.14	.88	1.01	1.16	1.27
	Uday/Unight = 3.0											
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.76	.81	.88	.94	.87	.96	1.06	1.12	.94	1.04	1.18	1.28
6	.61	.68	.81	.88	.77	.88	1.02	1.10	.86	1.01	1.15	1.22
9	.46	.56	.72	.82	.67	.79	.88	1.05	.78	.92	1.06	1.18
	Uday/Unight = 2.0											
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.69	.76	.85	.92	.83	.91	.99*	1.05*	.89	.98	1.10*	1.14*
6	.53	.61	.74	.84	.70	.80	.94	1.02	.79	.92	1.05	1.12
9	.37	.48	.65	.76	.59	.70	.84	.95	.71	.81	.96	1.06
	Uday/Unight = 1.0											
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.64	.71	.82	.89	.78	.86	.94*	.99*	.85	.92	1.01*	1.05*
6	.43	.53	.68	.79	.62	.70	.84	.93	.72	.82	.95	1.00
9	.27	.41	.59	.70	.50	.60	.75	.87	.62	.72	.87	.96

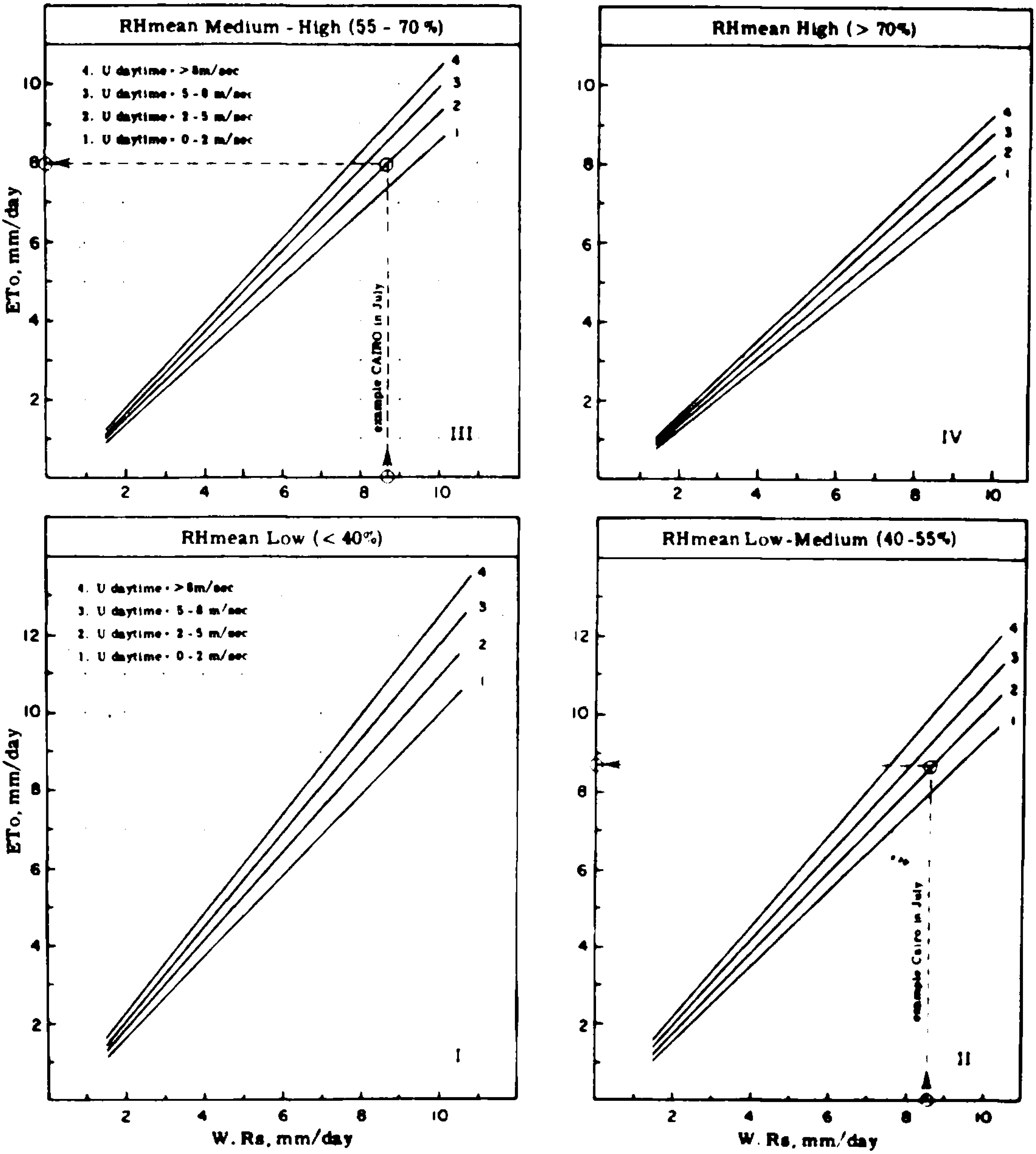


Fig. 1 Prediction of ETo from W. RS for different conditions of mean relative humidity and day time wind.

Table 17 Pan Coefficient (kpan) for Class A Pan for Different Groundcover and Levels of Mean Relative Humidity and 24-hour Windrun

	Pan placed in short green cropped area				Pan placed in dry fallow area			
RHmean %		low <40	med. 40-70	high >70		low <40	med. 40-70	high >70
Wind km/day	Windward side distance of green crop m				Windward side distance of dry fallow m			
Light <175	1	.55	.65	.75	1	.7	.8	.85
	10	.65	.75	.85	10	.6	.7	.8
	100	.7	.8	.85	100	.55	.65	.75
	1 000	.75	.85	.85	1 000	.5	.6	.7
Moderate 175 - 425	1	.5	.6	.65	1	.65	.75	.8
	10	.6	.7	.75	10	.55	.65	.7
	100	.65	.75*	.8	100	.5	.6	.65
	1 000	.7	.8	.8	1 000	.45	.55	.6
Strong 425-700	1	.45	.5	.6	1	.6	.65	.7
	10	.55	.6	.65	10	.5	.55	.65
	100	.6	.65	.7	100	.45	.5	.6
	1 000	.65	.7	.75	1 000	.4	.45	.55
Very strong >700	1	.4	.45	.5	1	.5	.6	.65
	10	.45	.55	.6	10	.45	.5	.55
	100	.5	.6	.65	100	.4	.45	.5
	1 000	.55	.6	.65	1 000	.35	.4	.45

Table 18 — Crop Coefficients (kc)

CROP	Crop Development stages					Total growing period
	Initial	Crop development	Mid-season	Late season	At harvest	
Banana						
tropical	0.4 -0.5	0.7 -0.85	1.0 -1.1	0.9 -1.0	0.75-0.85	0.7 -0.8
subtropical	0.5 -0.65	0.8 -0.9	1.0 -1.2	1.0 -1.15	1.0 -1.15	0.85-0.95
Bean						
green	0.3 -0.4	0.65-0.75	0.95-1.05	0.9 -0.95	0.85-0.95	0.85-0.9
dry	0.3 -0.4	0.7 -0.8	1.05-1.2	0.65-0.75	0.25-0.3	0.7 -0.8
Cabbage	0.4 -0.5	0.7 -0.8	0.95-1.1	0.9 -1.0	0.8 -0.95	0.7 -0.8
Cotton	0.4 -0.5	0.7 -0.8	1.05-1.25	0.8 -0.9	0.65-0.7	0.8 -0.9
Grape	0.35-0.55	0.6 -0.8	0.7 -0.9	0.6 -0.8	0.55-0.7	0.55-0.75
Groundnut	0.4 -0.5	0.7 -0.8	0.95-1.1	0.75-0.85	0.55-0.6	0.75-0.8
Maize						
sweet	0.3 -0.5	0.7 -0.9	1.05-1.2	1.0 -1.15	0.95-1.1	0.8 -0.95
grain	0.3 -0.5*	0.7 -0.85*	1.05-1.2*	0.8 -0.95	0.55-0.6*	0.75-0.9*
Onion						
dry	0.4 -0.6	0.7 -0.8	0.95-1.1	0.85-0.9	0.75-0.85	0.8 -0.9
green	0.4 -0.6	0.6 -0.75	0.95-1.05	0.95-1.05	0.95-1.05	0.65-0.8
Pea, fresh	0.4 -0.5	0.7 -0.85	1.05-1.2	1.0 -1.15	0.95-1.1	0.8 -0.95
Pepper, fresh	0.3 -0.4	0.6 -0.75	0.95-1.1	0.85-1.0	0.8 -0.9	0.7 -0.8
Potato	0.4 -0.5	0.7 -0.8	1.05-1.2	0.85-0.95	0.7 -0.75	0.75-0.9
Rice	1.1 -1.15	1.1 -1.5	1.1 -1.3	0.95-1.05	0.95-1.05	1.05-1.2
Safflower	0.3 -0.4	0.7 -0.8	1.05-1.2	0.65-0.7	0.2 -0.25	0.65-0.7
Sorghum	0.3 -0.4	0.7 -0.75	1.0 -1.15	0.75-0.8	0.5 -0.55	0.75-0.85
Soybean	0.3 -0.4	0.7 -0.8	1.0 -1.15	0.7 -0.8	0.4 -0.5	0.75-0.9
Sugarbeet	0.4 -0.5	0.75-0.85	1.05-1.2	0.9 -1.0	0.6 -0.7	0.8 -0.9
Sugarcane	0.4 -0.5	0.7 -1.0	1.0 -1.3	0.75-0.8	0.5 -0.6	0.85-1.05
Sunflower	0.3 -0.4	0.7 -0.8	1.05-1.2	0.7 -0.8	0.35-0.45	0.75-0.85
Tobacco	0.3 -0.4	0.7 -0.8	1.0 -1.2	0.9 -1.0	0.75-0.85	0.85-0.95
Tomato	0.4 -0.5	0.7 -0.8	1.05-1.25	0.8 -0.95	0.6 -0.65	0.75-0.9
Water melon	0.4 -0.5	0.7 -0.8	0.95-1.05	0.8 -0.9	0.65-0.75	0.75-0.85
Wheat	0.3 -0.4	0.7 -0.8	1.05-1.2	0.65-0.75	0.2 -0.25	0.8 -0.9
Alfalfa	0.3 -0.4				1.05-1.2	0.85-1.05
Citrus						
clean weeding						0.65-0.75
no weed control						0.85-0.9
Olive						0.4 -0.6

First figure : Under high humidity (RHmin >70%) and low wind (U <5 m/sec).
Second figure: Under low humidity (RHmin <20%) and strong wind (>5 m/sec).

III. ACTUAL EVAPOTRANSPIRATION (ETa)

The demand for water by the crop must be met by the water in the soil, via the root system. The actual rate of water uptake by the crop from the soil in relation to its maximum evapotranspiration (ETm) is determined by whether the available water in the soil is adequate or whether the crop will suffer from stress inducing water deficit.

In order to determine actual evapotranspiration (ETa), the level of the available soil water must be considered. Actual evapotranspiration (ETa) equals maximum evapotranspiration (ETm) when available soil water to the crop is adequate, or ETa = ETm. However, ETa < ETm when available soil water is limited. Available soil water can be defined as the fraction (p) to which the total available soil water can be depleted without causing ETa to become less than ETm. The magnitude of ETa can be quantified for periods between irrigation or heavy rain, and for monthly periods.

Total available soil water (Sa) is defined here as the depth of water in mm/m soil depth between the soil water content at field capacity (Sfc or at soil water tension of 0.1 to 0.2 atmosphere) and the soil water content at wilting point (Sw or at soil water tension of 15 atmosphere). Total available soil water (Sa) can vary widely for soils having a similar texture. Also, most soils are layered and integrated values of Sa over soil depth should be selected; dense layers restrict water distribution.

As a general indication, Sa mm/m for different soil textures is:

heavy textured soil	200 mm/m
medium textured soil	140 mm/m
coarse textured soil	60 mm/m

Local information on total available soil water in the root zone will be required. The need for field measurements is evident.

1. ADEQUATE SOIL WATER, ETa = ETm

Immediately following irrigation or heavy rain, the actual rate of evapotranspiration (ETa) equals maximum evapotranspiration (ETm) where ETm for a given crop is dictated by the evaporative demand of the air. As the available soil water is depleted, ETa at some point will become less than ETm. The proportion of the total available soil water that can be depleted without causing ETa to become less than ETm is defined by the fraction (p) of the total available soil water (Sa). The value of the fraction (p) will depend on (i) the crop; (ii) the magnitude of ETm; and (iii) the soil:

(i) Some crops, such as most vegetables, continuously need relatively wet soils to maintain ETa = ETm; others, such as cotton and sorghum, can deplete soil water much further before ETa falls below ETm. Crops can be grouped according to the fraction (p) to which the available soil water (Sa) can be depleted while maintaining ETa equal to ETm (Table 19). The tolerable range of the fraction (p) is narrow for crops where the harvested part is in the fleshy or fresh form, such as fruit, vegetable or forage, but it is wider for crops where the harvested part is in the dry form, such as cereals for dry grain, cotton and oil seeds. The value of p may vary with the growth period and in general will be greater during the ripening period due to the low evapotranspiration (ETm) level caused by a low value of kc. In general, lower depletion levels than calculated are required during the establishment period.

(ii) For conditions where ETm is high, p is smaller and the soil is comparatively wet when ETa becomes less than ETm in comparison to when ETm is low. Consequently, the fraction (p) of available soil water over which ETa is equal ETm varies with the level of ETm (Table 20).

(iii) Soil water is more easily transmitted to and taken up by the plant roots in light textured than in heavy textured soils. Somewhat higher values of p would seem to apply to light textured soils than than to heavy textured soils. However, considerations of soil texture would add little to accuracy.

CALCULATION PROCEDURE

a. Total available soil water (D.Sa)
from field data or general soil information, determine total available soil water (Sa in mm/m) over the root depth (D in m) or D.Sa in mm/root depth.

b. Soil water depletion (p.D.Sa) when ETa = ETm
select soil water depletion fraction (p) for given crop and ETm (Table 19). Calculate available soil water over root depth (D) or p.Sa.D in mm/root depth when ETa = ETm.

c. Irrigation interval (i) when ETa = ETm
calculate number of days when ETa = ETm by p.Sa.D/ETm.

EXAMPLE

Given: Maize; July; ETm is 10.1 mm/day; soil is medium textured with Sa 140 mm; root depth (D) in July is 1.2 m.

Calculation:

fraction p	Tables 19, 20		0.40
Sa over root depth	Sa.D	calc	170
available soil water over root depth, ETa = ETm	p.Sa.D	calc	68 mm
irrigation interval (i) when ETa = ETm	p.Sa.D/ETm	calc	7 days

2. LIMITED SOIL WATER, ETa < ETm

Maximum evapotranspiration (ETm) will be maintained until the fraction (p) of the available soil water has been depleted. Beyond this depletion level actual evapotranspiration (ETa) becomes increasingly smaller than ETm until the next irrigation or heavy rain. When ETa < ETm, the magnitude of ETa will depend on the remaining available soil water (1-p)Sa.D, and on ETm. The remaining available soil water is related to the crop group (Table 19), to ETm (i.e. the fraction p) and to the total available soil water over the root depth (Sa.D). Applying an adaptation of the formulation by Rijtema and Aboukhaled (1975) given in Appendix I, ETa can be quantified for the interval between irrigation or heavy rain (Table 21) and for monthly periods (Table 22).

For practical application, the information can be used to calculate the effect of available soil water on ETa, and also to determine ETa for the period since last irrigation or heavy rain and for monthly periods when monthly irrigation supply and rainfall are known. The calculated results are relevant to predict the effect of irrigation schedules on ETa. The need to check the presented information through local available field data and comparison with other methods to determine ETa is stressed.

Table 19 Crop Groups according to Soil Water Depletion

Group	Crops
1	onion, pepper, potato
2	banana, cabbage, grape, pea, tomato
	alfalfa, bean, citrus, groundnut, pineapple, sunflower, watermelon, wheat
-	cotton, maize*, olive, safflower, sorghum, soybean, sugarbeet, sugarcane, tobacco

Table 20 Soil Water Depletion Fraction (p) for Crop Groups and Maximum Evapotranspiration (ETm)

Crop Group	ETm mm/day								
	2	3	4	5	6	7	8	9	10
1	0.50	0.425	0.35	0.30	0.25	0.225	0.20	0.20	0.175
2	0.675	0.575	0.475	0.40	0.35	0.325	0.275	0.25	0.225
3	0.80	0.70	0.60	0.50	0.45	0.425	0.375	0.35	0.30
-	0.875	0.80	0.70	0.60	0.55	0.50	0.45	0.425	0.40*

2.1 <u>ETa over Irrigation Interval</u>

CALCULATION PROCEDURE

a. **Total available soil water (D.Sa)**
from field data or general information on crop and soil determine total available soil water (Sa) over the root depth (D) or D.Sa in mm/root depth.

b. **Soil water depletion fraction (p) when ETa = ETm**
select p for given crop and level of ETm (Table 20).

c. **Actual evapotranspiration (ETa)**
select mean ETa over irrigation interval for value of ETm, p and D.Sa (Table 21).

EXAMPLE

Given: Maize; July; ETm = 10.1 mm/day; soil is medium textured with Sa = 140 mm/m; root depth (D) in July is 1.2 m.

Calculation:

total available soil water	D.Sa	calc	170 mm/root depth
fraction p		Table 20	0.40
ETa	by interpolation	Table 21	

irrigation interval, days	8	10	12	16	20	24	30
mean ETa maize, mm/day	9.8	9.4	9.0	8.0	7.1	6.2	5.3

Similar calculations are made for when ETm maize is 7 and 4 mm/day. Results of calculating ETa and available soil water depletion for different durations of the irrigation interval are given in the figure below. This shows that at lower ETm values the irrigation interval with ETa = ETm can be extended (Figure 2).

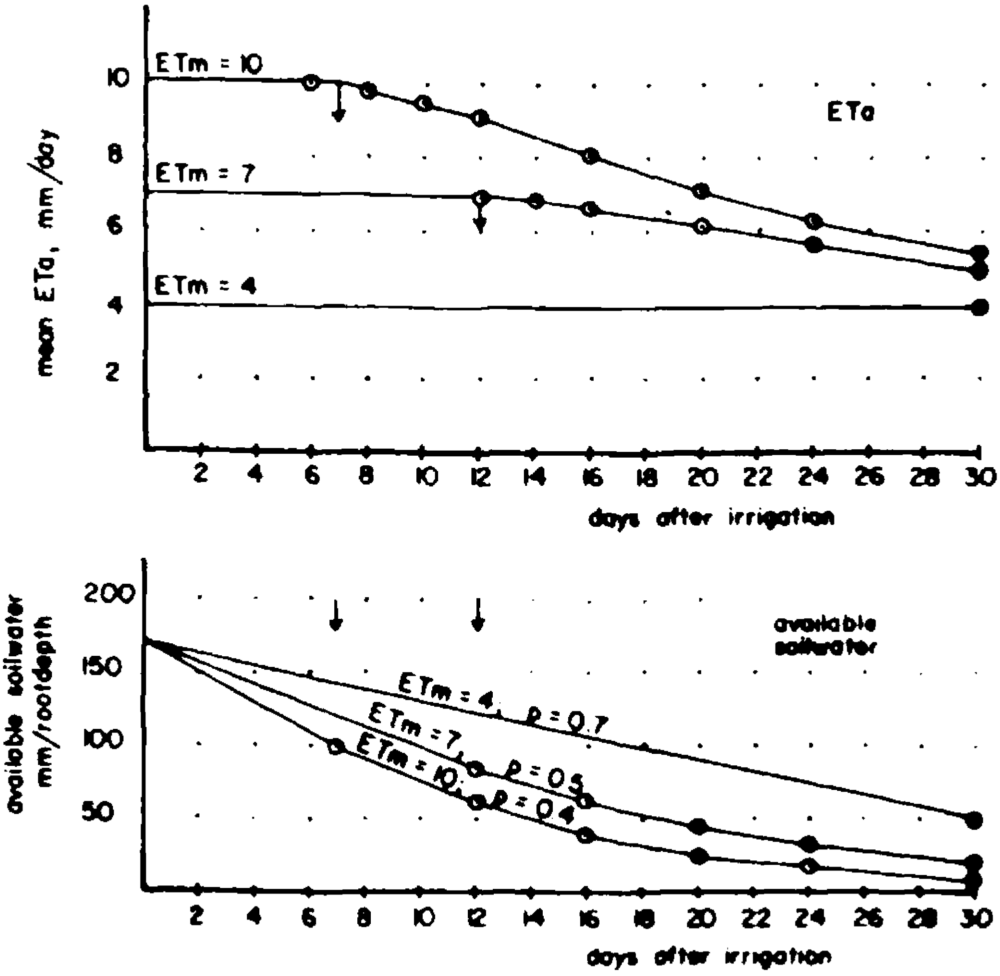


Fig. 2 Mean actual evapotranspiration (ETa) and available soil water (Sa.D) over time after irrigation for different values of maximum evapotranspiration (ETm)

Table 21 Mean Actual Evapotranspiration (ETa) in mm/day over the Irrigation Interval for Different Yields of ETm (mm/day), D.Sa (mm) and p (fraction)

									ETm = 2.0 mm/day									
D.Sa	p	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	35	40
25	0.2	2.0	2.0	1.8	1.7	1.6	1.4	1.3	1.2	1.2	1.1	1.0	0.9	0.9	0.8	0.8	0.7	0.6
	0.4	2.0	2.0	2.0	1.9	1.7	1.6	1.5	1.4	1.2	1.2	1.1	1.0	0.9	0.9	0.8	0.7	0.6
	0.6	2.0		2.0	2.0	1.9	1.7	1.6	1.5	1.3	1.2	1.1	1.0	1.0	0.9	0.8	0.7	0.6
	0.8	2.0			2.0	2.0	1.9	1.7	1.5	1.4	1.3	1.1	1.0	1.0	0.9	0.8	0.7	0.6
50	0.2	2.0	2.0	2.0	2.0	1.9	1.8	1.8	1.7	1.6	1.6	1.5	1.4	1.4	1.3	1.3	1.2	1.1
	0.4	2.0			2.0	2.0	2.0	1.9	1.9	1.8	1.7	1.7	1.6	1.5	1.5	1.4	1.3	1.1
	0.6	2.0					2.0	2.0	2.0	2.0	1.9	1.8	1.7	1.7	1.6	1.5	1.4	1.2
	0.8	2.0								2.0	2.0	2.0	1.9	1.8	1.7	1.6	1.4	1.2
100	0.2	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.9	1.9	1.9	1.8	1.8	1.7	1.7	1.6	1.6
	0.4	2.0							2.0	2.0	2.0	2.0	2.0	2.0	1.9	1.9	1.8	1.7
	0.6	2.0												2.0	2.0	2.0	2.0	1.9
	0.8	2.0														2.0	2.0	2.0
150	0.2	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.9	1.9	1.9	1.8	1.8
	0.4	2.0											2.0	2.0	2.0	2.0	2.0	1.9
	0.6	2.0															2.0	2.0
	0.8	2.0																2.0
200	0.2	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.9	1.9
	0.4	2.0														2.0	2.0	2.0
	0.6	2.0																2.0
	0.8	2.0																2.0
300	0.2	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	0.4	2.0																2.0
	0.6	2.0																2.0
	0.8	2.0																2.0
									ETm = 4.0 mm/day									
25	0.2	3.9	3.4	2.9	2.5	2.2	1.9	1.7	1.5	1.4	1.2	1.1	1.0	0.9	0.9	0.8	0.7	0.6
	0.4	4.0	3.7	3.2	2.7	2.3	2.0	1.7	1.5	1.4	1.3	1.1	1.0	1.0	0.9	0.8	0.7	0.6
	0.6	4.0	4.0	3.5	2.9	2.4	2.1	1.8	1.6	1.4	1.3	1.1	1.0	1.0	0.9	0.8	0.7	0.6
	0.8	4.0	4.0	3.8	3.1	2.5	2.1	1.8	1.6	1.4	1.3	1.1	1.0	1.0	0.9	0.8	0.7	0.6
50	0.2	4.0	3.9	3.6	3.4	3.1	2.9	2.7	2.5	2.3	2.2	2.0	1.9	1.8	1.7	1.6	1.4	1.2
	0.4	4.0	4.0	4.0	3.7	3.5	3.2	2.9	2.7	2.5	2.3	2.1	2.0	1.9	1.7	1.6	1.4	1.2
	0.6	4.0		4.0	4.0	3.8	3.5	3.2	2.9	2.6	2.4	2.2	2.1	1.9	1.8	1.6	1.4	1.2
	0.8	4.0			4.0	4.0	3.8	3.4	3.1	2.8	2.5	2.3	2.1	1.9	1.8	1.6	1.4	1.2
100	0.2	4.0	4.0	4.0	3.9	3.8	3.6	3.5	3.4	3.2	3.1	3.0	2.9	2.8	2.7	2.6	2.3	2.2
	0.4	4.0		4.0	4.0	4.0	4.0	3.9	3.7	3.6	3.5	3.3	3.2	3.1	2.9	2.8	2.5	2.3
	0.6	4.0					4.0	4.0	4.0	3.9	3.8	3.6	3.5	3.3	3.2	3.0	2.7	2.4
	0.8	4.0							4.0	4.0	4.0	3.9	3.8	3.6	3.4	3.2	2.8	2.5
150	0.2	4.0	4.0	4.0	4.0	4.0	3.9	3.8	3.7	3.6	3.5	3.5	3.4	3.3	3.2	3.1	2.9	2.7
	0.4	4.0				4.0	4.0	4.0	4.0	4.0	3.9	3.8	3.7	3.7	3.6	3.5	3.2	3.0
	0.6	4.0								4.0	4.0	4.0	4.0	3.9	3.9	3.8	3.5	3.3
	0.8	4.0											4.0	4.0	4.0	4.0	3.8	3.6
200	0.2	4.0	[illegible]	[illegible]	[illegible]	4.0	4.0	3.9	3.9	3.8	3.8	3.7	3.6	3.6	3.5	3.4	3.3	3.1
	0.4	4.0					4.0	4.0	4.0	4.0	4.0	4.0	4.0	3.9	3.9	3.8	3.6	3.5
	0.6	4.0											4.0	4.0	4.0	4.0	3.9	3.8
	0.8	4.0														4.0	4.0	4.0
300	0.2	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	3.9	3.9	3.9	3.8	3.8	3.7	3.5
	0.4	4.0									4.0	4.0	4.0	4.0	4.0	4.0	4.0	3.9
	0.6	4.0															4.0	4.0
	0.8	4.0																4.0

Table 21 Continued

D.Sa	p	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	35	40
ETm - 6.0 mm/day																		
25	0.2	5.5	4.3	3.5	2.8	2.4	2.0	1.8	1.6	1.4	1.2	1.1	1.0	1.0	0.9	0.8	0.7	0.6
	0.4	5.9	4.8	3.7	3.0	2.5	2.1	1.8	1.6	1.4	1.3	1.1	1.0	1.0	0.9	0.8	0.7	0.6
	0.6	6.0	5.2	4.0	3.1	2.5	2.1	1.8	1.6	1.4	1.3	1.1	1.0	1.0	0.9	0.8	0.7	0.6
	0.8	6.0	5.7	4.1	3.1	2.5	2.1	1.8	1.6	1.4	1.3	1.1	1.0	1.0	0.9	0.8	0.7	0.6
50	0.2	6.0	5.5	4.9	4.3	3.9	3.5	3.1	2.8	2.6	2.4	2.2	2.0	1.9	1.8	1.7	1.4	1.3
	0.4	6.0	5.9	5.4	4.8	4.2	3.7	3.3	3.0	2.7	2.5	2.2	2.1	1.9	1.8	1.7	1.4	1.3
	0.6	6.0	6.0	5.9	5.2	4.6	4.0	3.5	3.1	2.8	2.5	2.3	2.1	1.9	1.8	1.7	1.5	1.3
	0.8	6.0	6.0	6.0	5.7	4.9	4.1	3.6	3.1	2.8	2.5	2.3	2.1	1.9	1.8	1.7	1.4	1.3
100	0.2	6.0	6.0	5.8	5.5	5.2	4.9	4.6	4.3	4.1	3.9	3.7	3.5	3.3	3.1	3.0	2.6	2.4
	0.4	6.0	6.0	6.0	5.9	5.7	5.4	5.1	4.8	4.5	4.2	4.0	3.7	3.5	3.3	3.1	2.8	2.4
	0.6	6.0		6.0	6.0	6.0	5.9	5.6	5.2	4.9	4.6	4.3	4.0	3.7	3.5	3.3	2.8	2.5
	0.8	6.0				6.0	6.0	6.0	5.7	5.3	4.9	4.5	4.1	3.8	3.6	3.3	2.9	2.5
150	0.2	6.0	6.0	6.0	5.8	5.7	5.5	5.3	5.1	4.9	4.7	4.5	4.3	4.2	4.0	3.9	3.5	3.2
	0.4	6.0		6.0	6.0	6.0	5.9	5.8	5.6	5.4	5.2	5.0	4.8	4.6	4.4	4.2	3.8	3.3
	0.6	6.0				6.0	6.0	6.0	6.0	5.9	5.7	5.5	5.2	5.0	4.8	4.6	4.1	3.6
	0.8	6.0							6.0	6.0	6.0	5.9	5.7	5.4	5.1	4.9	4.2	3.7
200	0.2	6.0	6.0	6.0	6.0	5.9	5.8	5.6	5.5	5.3	5.2	5.0	4.9	4.7	4.6	4.4	4.1	3.9
	0.4	6.0			6.0	6.0	6.0	6.0	5.9	5.8	5.7	5.6	5.4	5.2	5.1	4.9	4.6	4.2
	0.6	6.0						6.0	6.0	6.0	6.0	6.0	5.9	5.7	5.6	5.4	5.0	4.6
	0.8	6.0										6.0	6.0	6.0	6.0	5.9	5.4	4.9
300	0.2	6.0	6.0	6.0	6.0	6.0	6.0	5.9	5.8	5.8	5.7	5.6	5.5	5.4	5.3	5.2	4.9	4.7
	0.4	6.0					6.0	6.0	6.0	6.0	6.0	6.0	5.9	5.9	5.8	5.7	5.4	5.2
	0.6	6.0										6.0	6.0	6.0	6.0	6.0	5.9	5.7
	0.8	6.0														6.0	6.0	6.0
ETm - 8.0 mm/day																		
25	0.2	6.7	5.0	3.8	3.0	2.5	2.1	1.8	1.6	1.4	1.3	1.1	1.0	1.0	0.9	0.8	0.7	0.6
	0.4	7.5	5.4	4.0	3.1	2.5	2.1	1.8	1.6	1.4	1.3	1.1	1.0	1.0	0.9	0.8	0.7	0.6
	0.6	8.0	5.8	4.1	3.1	2.5	2.1	1.8	1.6	1.4	1.3	1.1	1.0	1.0	0.9	0.8	0.7	0.6
	0.8	8.0	6.1	4.2	3.1	2.5	2.1	1.8	1.6	1.4	1.3	1.1	1.0	1.0	0.9	0.8	0.7	0.6
50	0.2	7.8	6.7	5.8	5.0	4.3	3.8	3.4	3.0	2.7	2.5	2.2	2.1	1.9	1.8	1.7	1.4	1.3
	0.4	7.9	7.5	6.4	5.4	4.6	4.0	3.5	3.1	2.8	2.5	2.2	2.1	1.9	1.8	1.7	1.4	1.3
	0.6	8.0	8.0	7.0	5.8	4.8	4.1	3.6	3.1	2.8	2.5	2.3	2.1	1.9	1.8	1.7	1.4	1.3
	0.8	8.0	8.0	7.6	6.1	5.0	4.2	3.6	3.1	2.8	2.5	2.3	2.1	1.9	1.8	1.7	1.4	1.3
100	0.2	8.0	7.8	7.3	6.7	6.2	5.8	5.3	5.0	4.6	4.3	4.0	3.8	3.6	3.4	3.2	2.8	2.5
	0.4	8.0	8.0	7.9	7.5	6.9	6.4	5.9	5.4	5.0	4.6	4.3	4.0	3.7	3.5	3.3	2.8	2.5
	0.6	8.0	8.0	8.0	8.0	7.6	7.0	6.4	5.8	5.3	4.9	4.5	4.1	3.8	3.6	3.3	2.9	2.5
	0.8	8.0			8.0	8.0	7.6	6.9	6.1	5.5	5.0	4.5	4.1	3.8	3.6	3.3	2.9	2.5
150	0.2	8.0	8.0	7.8	7.5	7.1	6.7	6.4	6.1	5.8	5.5	5.2	5.0	4.7	4.5	4.3	3.9	3.5
	0.4	8.0	8.0	8.0	8.0	7.8	7.5	7.1	6.7	6.4	6.0	5.7	5.4	5.1	4.8	4.6	4.1	3.6
	0.6	8.0			8.0	8.0	8.0	7.7	7.4	7.0	6.6	6.2	5.8	5.5	5.1	4.8	4.2	3.7
	0.8	8.0					8.0	8.0	7.9	7.6	7.1	6.6	6.1	5.7	5.3	5.0	4.3	3.7
200	0.2	8.0	8.0	8.0	7.8	7.5	7.2	7.0	6.7	6.5	6.2	6.0	5.7	5.5	5.3	5.1	4.7	4.3
	0.4	8.0		8.0	8.0	8.0	7.9	7.7	7.5	7.2	6.9	6.6	6.4	6.1	5.9	5.6	5.1	4.6
	0.6	8.0				8.0	8.0	8.0	8.0	7.8	7.6	7.3	7.0	6.7	6.4	6.1	5.4	4.8
	0.8	8.0							8.0	8.0	8.0	7.9	7.6	7.2	6.9	6.5	5.7	5.0
300	0.2	8.0	8.0	8.0	8.0	7.9	7.8	7.6	7.5	7.3	7.1	6.9	6.7	6.6	6.4	6.2	5.8	5.5
	0.4	8.0			8.0	8.0	8.0	8.0	8.0	7.9	7.8	7.6	7.5	7.3	7.1	6.9	6.5	6.0
	0.6	8.0							8.0	8.0	8.0	8.0	8.0	7.9	7.7	7.6	7.1	6.7
	0.8	8.0											8.0	8.0	8.0	8.0	7.7	7.1

Table 21 Continued

		ETm = 10.0 mm/day																
D.Sa		2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	35	40
25	0.2	7.8	5.4	4.0	3.1	2.5	2.1	1.8	1.6	1.4	1.3	1.1	1.0	1.0	0.9	0.8	0.7	0.6
	0.4	8.7	5.7	4.1	3.1	2.5	2.1	1.8	1.6	1.4	1.3	1.1	1.0	1.0	0.9	0.8	0.7	0.6
	0.6	9.5	6.0	4.2	3.1	2.5	2.1	1.8	1.6	1.4	1.3	1.1	1.0	1.0	0.9	0.8	0.7	0.6
	0.8	10.0	6.2	4.2	3.1	2.5	2.1	1.8	1.6	1.4	1.3	1.1	1.0	1.0	0.9	0.8	0.7	0.6
50	0.2	9.4	7.8	6.4	5.4	4.6	4.0	3.5	3.1	2.8	2.5	2.3	2.1	1.9	1.8	1.7	1.4	1.3
	0.4	10.0	8.7	7.0	5.7	4.8	4.1	3.5	3.1	2.8	2.5	2.3	2.1	1.9	1.8	1.7	1.4	1.3
	0.6	10.0	9.5	7.6	6.0	4.9	4.2	3.6	3.1	2.8	2.5	2.3	2.1	1.9	1.8	1.7	1.4	1.3
	0.8	10.0	10.0	8.1	6.2	5.0	4.2	3.6	3.1	2.8	2.5	2.3	2.1	1.9	1.8	1.7	1.4	1.3
100	0.2	10.0	9.4	8.6	7.8	7.1	6.4	5.9	5.4	5.0	4.6	4.3	4.0	3.7	3.5	3.3	2.8	2.5
	0.4	10.0	10.0	9.5	8.7	7.8	7.0	6.3	5.7	5.2	4.8	4.4	4.1	3.8	3.6	3.3	2.8	2.5
	0.6	10.0	10.0	10.0	9.5	8.5	7.6	6.8	6.0	5.4	4.9	4.5	4.2	3.8	3.6	3.3	2.9	2.5
	0.8	10.0		10.0	10.0	9.3	8.1	7.1	6.2	5.6	5.0	4.5	4.2	3.9	3.6	3.3	2.9	2.5
150	0.2	10.0	9.9	9.4	8.9	8.3	7.8	7.3	6.8	6.4	6.0	5.7	5.4	5.1	4.8	4.6	4.0	3.7
	0.4	10.0	10.0	10.0	9.7*	9.2*	8.7*	8.1*	7.5*	7.0	6.6*	6.1	5.7*	5.4	5.1	4.8*	4.2	3.7
	0.6	10.0		10.0	10.0	9.9	9.5	8.9	8.2	7.6	7.0	6.5	6.0	5.6	5.3	4.9	4.3	3.7
	0.8	10.0			10.0	10.0	10.0	9.6	8.9	8.1	7.4	6.8	6.2	5.8	5.4	5.0	4.3	3.7
200	0.2	10.0	10.0	9.8	9.4	9.0	8.6	8.2	7.8	7.4	7.1	6.7	6.4	6.1	5.9	5.6	5.1	4.6
	0.4	10.0	10.0	10.0	10.0*	9.8*	9.5*	9.1*	8.7*	8.2	7.8*	7.4	7.0*	6.7	6.3	6.0*	5.4	4.8
	0.6	10.0			10.0	10.0	10.0	9.8	9.5	9.0	8.5	8.1	7.6	7.2	6.8	6.4	5.6	4.9
	0.8	10.0					10.0	10.0	10.0	9.8	9.3	8.7	8.1	7.6	7.1	6.6	5.7	5.0
300	0.2	10.0	10.0	10.0	9.9	9.7	9.4	9.2	8.9	8.6	8.3	8.0	7.8	7.5	7.3	7.1	6.5	6.0
	0.4	10.0		10.0	10.0	10.0	10.0	9.9	9.7	9.5	9.2	8.9	8.7	8.4	8.1	7.8	7.1	6.5
	0.6	10.0					10.0	10.0	10.0	10.0	9.9	9.7	9.5	9.2	8.9	8.5	7.7	7.0
	0.8	10.0								10.0	10.0	10.0	10.0	9.9	9.6	9.3	8.3	7.4

2.2 ETa over Monthly Periods

For reconnaissance and preliminary planning purposes an estimate of mean monthly actual evapotranspiration (ETa) for a given crop can be obtained using the available soil water index (ASI). The ASI indicates the part of the month when available soil water is adequate for meeting full crop water requirements (ETa = ETm). A combination of ASI value, maximum evapotranspiration (ETm) and remaining available soil water [(1-p)Sa.D] provides an estimate of the mean monthly ETa.

$$ASI = \frac{In + Pe + Wb - [(1-p)Sa.D]}{\text{monthly } ETm}$$

where:

In	=	net monthly irrigation application, mm/month
Pe	=	effective rainfall, mm/month
Wb	=	actual depth of available soil water at beginning of the month, mm/root depth
(1-p)Sa.D	=	depth of remaining available soil water when ETa < ETm, mm / root depth
ETm	=	maximum evapotranspiration, mm/month

For the ASI it is assumed that In + Pe when equal or smaller than 30 ETm will fully contribute to the evapotranspiration and no deep percolation or runoff will occur; also mean monthly ETa is only affected by the total of In, Pe and Wb and not by their distribution over the month.

ASI can be greater than one, or smaller than zero, When ASI ≥1, then ETa = ETm; when ASI < 0 then ETa/ETm is so small that crop growth is hardly possible except when ETm is low and the remaining available soil water [(1-p)Sa.D] is high.

CALCULATION PROCEDURE

a. Available soil water index (ASI)
Determine: $ASI = \frac{In + Pe + Wb - [(1-p)Sa.D]}{\text{monthly } ETm}$

b. Actual evapotranspiration (ETa)
Select monthly mean ETa in mm/day from the calculated ASI, the remaining available soil water [(1-p)Sa.D] in mm/root depth when ETa < ETm, and maximum evapotranspiration (ETm) in mm/day (Table 22)

EXAMPLE

Given: Maize; July; ETm is 10.1 mm/day; soil is medium textured with Sa 140 mm/m; root depth (D) is 1.2 m.

net irrigation application (In)	= 145 mm/month
effective rainfall (Pe)	= 20 mm/month
actual depth of available water at beginning of month (Wb)	= 40 mm
In + Pe + Wb	= 205 mm/month

Calculation:

fraction p	Tables 19, 20	= 0.40
available soil water when ETa < ETm (1-p)Sa.D	calc	= 100 mm
ASI (205-100)/(31 x 10.0)	calc	= 0.33
ETa	Table 22	= 6.2 mm/day

Table 22 Monthly Mean Actual Evapotranspiration (ETa in mm/day) for ASI, Remaining Available Soil Water when ETa < ETm ([(1-p) Sa.D] in mm/root depth) and Maximum Evapotranspiration (ETm in mm/day)

	ASI = 0.83					ASI = 0.67					ASI = 0.5				
(1-p)Sa.D	ETm, mm/day					ETm, mm/day					ETm, mm/day				
mm/root depth	2	4	6	8	10	2	4	6	8	10	2	4	6	8	10
25	1.9	3.8	5.6	7.3	9.1	1.8	3.3	4.8	6.1	7.5	1.6	2.8	3.8	4.8	5.8
50	2.0	3.9	5.7	7.6	9.4	1.9	3.6	5.2	6.7	8.1	1.7	3.2	4.4	5.5	6.5
100	2.0	3.9	5.9	7.8	9.6	1.9	3.8	5.5	7.2	8.8	1.9	3.5	5.0	6.3	7.6
150	2.0	4.0	5.9	7.8	9.7	2.0	3.8	5.7	7.4	9.1	1.9	3.7	5.3	6.7	8.1
200	2.0	4.0	5.9	7.9	9.8	2.0	3.9	5.7	7.5	9.3	1.9	3.7	5.4	7.0	8.5

	ASI = 0.33					ASI = 0.17					ASI = 0				
(1-p)Sa.D	ETm, mm/day					ETm, mm/day					ETm, mm/day				
mm/root depth	2	4	6	8	10	2	4	6	8	10	2	4	6	8	10
25	1.3	2.1	2.8	3.5	4.2	1.1	1.5	1.8	2.2	2.5	0.8	0.8	0.8	0.8	0.8
50	1.6	2.7	3.5	4.3	5.0	1.4	2.1	2.8	3.0	3.3	1.2	1.5	1.6	1.7	1.7
100	1.8	3.2	4.3	5.3	6.2*	1.7	2.8	3.6	4.2	4.7	1.5	2.3	2.8	3.0	3.2
150	1.8	3.4	4.7	5.9	7.0	1.7	3.1	4.2	5.0	5.7	1.7	2.7	3.5	4.0	4.3
200	1.9	3.5	5.0	6.3	7.5	1.8	3.3	4.5	5.5	6.4	1.7	3.0	4.0	4.7	5.1

IV. ACTUAL YIELD (Ya)

When water supply does not meet crop water requirements, actual evapotranspiration (ETa) will fall below maximum evapotranspiration (ETm) or ETa < ETm. Under this condition, water stress will develop in the plant which will adversely affect crop growth and ultimately crop yield. The effect of water stress on growth and yield depends on the crop species and the variety on the one hand and the magnitude and the time of occurrence of water deficit on the other. The effect of the magnitude and the timing of water deficit on crop growth and yield is of major importance in scheduling available but limited water supply over growing periods of the crops and in determining the priority of water supply amongst crops during the growing season.

Crops vary in their growth and yield response to water deficit. When crop water requirements are fully met by available supply (ETa = ETm), the amount of total dry matter and yield produced per unit of water (kg/m^3) varies with crop. This can be expressed as the water utilization efficiency in kg/m^3 for total dry matter (Em) and harvested yield (Ey). Crops have different growth rates and crop water requirements; also the portion of the total dry matter that is harvested as yield varies with the crop (harvest index, Table 7). When ETa = ETm, these differences in growth and yield result in differences in Em and Ey. For example, Em for groundnut is about 1.6 and for maize about 2.5; with harvest index (cH) for groundnut (unshelled) equal to 0.35 and for maize 0.40 and taking into account the moisture percentage of the harvested part specific to the crop, the value of Ey for groundnut is about 0.65 and for maize about 1.15. However, as Ey also depends on the harvest index (cH) and the moisture percentage of the harvested part, a high Em does not always lead to a high Ey.

When water supply does not meet crop water requirements, or ETa < ETm, crops vary in their response to water deficits. In some crops there is an increase in water utilization efficiency (Ey) whereas for other crops Ey decreases with increase in water deficit. For example, with a water deficit spread equally over the total growing season, Ey will decrease for maize and increase somewhat for sorghum under similar climatic conditions. Although yield per unit area (kg/ha) for both crops will be lower when water supply is limited, the yield reduction will be greater in the case of maize.

When water deficit occurs during a particular part of the total growing period of a crop, the yield response to water deficit can vary greatly depending on how sensitive the crop is at that growth period. In general, crops are more sensitive to water deficit during emergence, flowering and early yield formation than they are during early (vegetative, after establishment) and late growth periods (ripening)(Table 23).

However, the yield response to water deficit can vary among varieties of the same crop. In general, high producing varieties are also the most sensitive in their response to water, fertilizer and other agronomic inputs. On the other hand, low producing varieties with little response to water may be more suitable for rainfed crop production in areas which are prone to drought. To attain high yields under irrigation, it is necessary to use high producing and most responsive varieties to water so that high water utilization efficiency for harvested yield (Ey) is obtained. For instance, many traditional maize varieties produce 2 to 3 ton/ha grain under erratic rainfall conditions and 4 to 5 ton/ha grain under full irrigation; this compares with yields of 8 to 10 ton/ha grain of high producing varieties under full irrigation but with drastically reduced yields under erratic rainfall or poor irrigation. Efforts directed toward increased yields by improved irrigation must be based on the use of high producing varieties obtained through local field evaluation and selection trials.

The response of yield to water cannot be considered in isolation from all the other agronomic factors, such as fertilizers, plant density and crop protection, because these factors also determine the extent to which actual yield (Ya) approaches maximum yield (Ym).

Table 23 — Sensitive Growth Periods for Water Deficit

Alfalfa	just after cutting (and for seed production at flowering)
Banana	throughout but particularly during first part of vegetative period, flowering and yield formation
Bean	flowering and pod filling; vegetative period not sensitive when followed by ample water supply
Cabbage	during head enlargement and ripening
Citrus	
grapefruit	flowering and fruit set > fruit enlargement
lemon	flowering and fruit set > fruit enlargement; heavy flowering may be induced by withholding irrigation just before flowering
orange	flowering and fruit set > fruit enlargement
Cotton	flowering and boll formation
Grape	vegetative period, particularly during shoot elongation and flowering > fruit filling
Groundnut	flowering and yield formation, particularly during pod setting
Maize	flowering > grain filling; flowering very sensitive if no prior water deficit
Olive	just prior flowering and yield formation, particularly during the period of stone hardening
Onion	bulb enlargement, particularly during rapid bulb growth > vegetative period (and for seed production at flowering)
Pea	flowering and yield formation > vegetative, ripening for dry peas
Pepper	throughout but particularly just prior and at start of flowering
Pineapple	during period of vegetative growth
Potato	period of stolonization and tuber initiation, yield formation > early vegetative period and ripening
Rice	during period of head development and flowering > vegetative period and ripening
Safflower	seed filling and flowering > vegetative
Sorghum	flowering yield formation > vegetative; vegetative period less sensitive when followed by ample water supply
Soybean	yield formation and flowering; particularly during pod development
Sugarbeet	particularly first month after emergence
Sugarcane	vegetative period, particularly during period of tillering and stem elongation > yield formation
Sunflower	flowering > yield formation > late vegetative, particularly period of bud development
Tobacco	period of rapid growth > yield formation and ripening
Tomato	flowering > yield formation > vegetative period, particularly during and just after transplanting
Water melon	flowering, fruit filling > vegetative period, particularly during vine development
Wheat	flowering > yield formation > vegetative period; winter wheat less sensitive than spring wheat

V. YIELD RESPONSE FACTOR (ky)

The response of yield to water supply is quantified through the yield response factor (ky) which relates relative yield decrease (1-Ya/Ym) to relative evapotranspiration deficit (1-ETa/ETm). Water deficit of a given magnitude, expressed in the ratio actual evapotranspiration (ETa) and maximum evapotranspiration (ETm), may either occur continuously over the total growing period of the crop or it may occur during any one of the individual growth periods (i.e. establishment (0), vegetative (1), flowering (2), yield formation (3), or ripening (4) period). The magnitude of water deficit refers in the former to the deficit in relation to crop water requirements over the total growing period of the crop and in the latter to the deficit in relation to the crop water requirements of the individual growth period (Table 24).

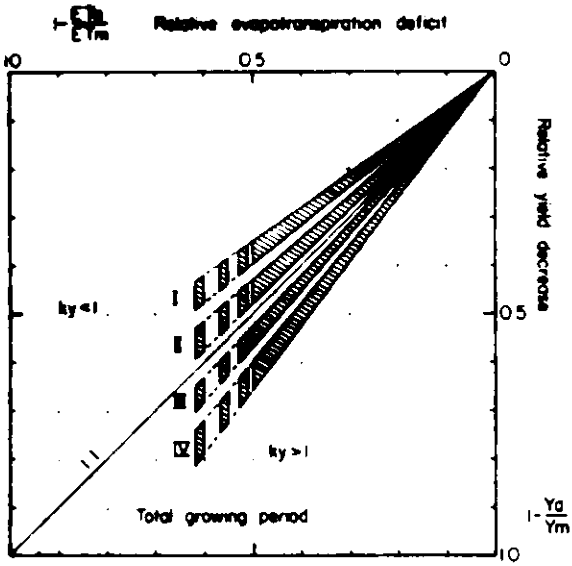
The generalized effect of water deficit on crop yield is schematically presented for both the total growing period and the individual growth periods (Figure 3). In general, for the total growing period, the decrease in yield is proportionally less with the increase in water deficit (ky < 1) for crops such as alfalfa, groundnut, safflower and sugarbeet (Group I) while it is proportionally greater (ky > 1) for crops such as banana, maize and sugarcane (Group IV). For the individual growth periods the decrease in yield due to water deficit during that growth period is relatively small for the vegetative (1) and ripening period (4) and relatively large for the flowering (2) and yield formation (3) period. Water deficit during a particular growth period can also be expressed as a water deficit over the total growing period when the relationship between the maximum evapotranspiration (ETm) of that growth period and ETm of the total growing period is known (see Figures in Part B).

The ky values for most crops are derived on the assumption that the relationship between relative yield (Ya/Ym) and relative evapotranspiration (ETa/ETm) is linear and is valid for water deficits of up to about 50 percent or 1 - ETa/ETm = 0.5. The values of ky are based on an analysis of experimental field data covering a wide range of growing conditions (see Bibliography). The experimental results used represent high-producing crop varieties, well-adapted to the growing environment and grown under a high level of crop management.

An evaluation of field experimental data indicates some scatter in ky values which is due to experimental inadequacies, and variations in climate, level of evapotranspiration and soil. Separation of ky according to the variation in these factors did not add to the accuracy obtainable. Since no standard reference values are available for comparison, the reliability of the presented ky values (Table 24) is assumed to be similar to that of the outcome of the analysis of the field experimental results; in most cases 80 to 85 percent of the yield variation due to different water treatments can be explained. In the final evaluation of the ky values, from the field experimental data, use is also made of known yield responses to soil salinity, the depth of the groundwater table and agronomic and irrigation practices.

The magnitude and duration of water deficit expressed as relative evapotranspiration deficits (1 - ETa/ETm) are made to correspond closely to the individual crop growth periods. Analysis of the available field experimental data in terms of the more precisely defined stress-day and drought indices proved difficult.

Application of the yield response factor (ky) for planning, design and operation of irrigation projects allows quantification of water supply and water use in terms of crop yield and total production for the project area. Under conditions of limited water distributed equally over the total growing season, involving crops with different ky values, the crop with the higher ky value will suffer a greater yield loss than the crop with a lower ky value. Both the likely losses in yield and the adjustments required in water supply to minimize such losses can be quantified. Similarly, such a quantification is



I	alfalfa groundnut safflower sugarbeet	
II	alfalfa cabbage citrus cotton grape	sorghum soybean sugarbeet sunflower tobacco wheat
III	bean citrus onion pea pepper	potato tomato water melon wheat
IV	banana maize sugarcane	

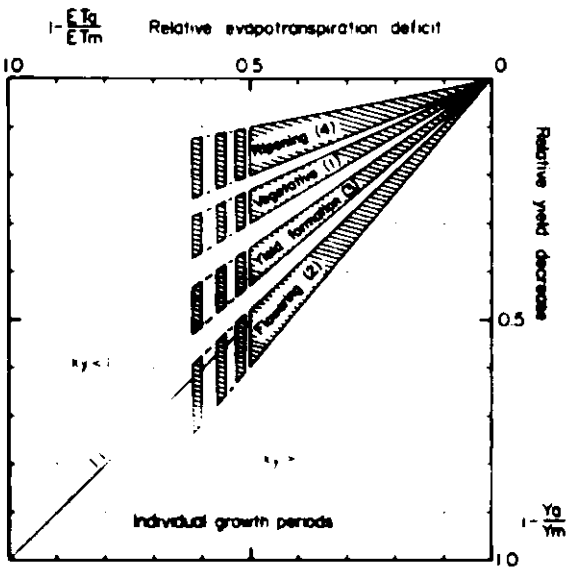


Fig. 3 Generalized relationship between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration (1 - ETa/ETm)

Table 24 Yield Response Factor (ky)

Crop	Vegetative period (1)			Flowering period (2)	Yield formation (3)	Ripening (4)	Total growing period
	early (1a)	late (1b)	total				
Alfalfa			0.7-1.1				0.7-1.1
Banana							1.2-1.35
Bean			0.2	1.1	0.75	0.2	1.15
Cabbage	0.2				0.45	0.6	0.95
Citrus							0.8-1.1
Cotton			0.2	0.5		0.25	0.85
Grape							0.85
Groundnut			0.2	0.8	0.6	0.2	0.7
Maize			0.4	1.5*	0.5	0.2	1.25*
Onion			0.45		0.8	0.3	1.1
Pea	0.2			0.9	0.7	0.2	1.15
Pepper							1.1
Potato	0.45	0.8			0.7	0.2	
Safflower		0.3		0.55	0.6		[illegible]
Sorghum			0.2	0.55	0.45	0.2	0.9
Soybean			0.2	0.8	1.0		0.85
Sugarbeet							
beet							0.6-1.0
sugar							0.7-1.1
Sugarcane			0.75		0.5	0.1	1.2
Sunflower	0.25	0.5		1.0	[illegible]		0.95
Tobacco	0.2	1.0			0.5		0.9
Tomato			0.4	1.1	0.8	[illegible]	1.05
Water melon	0.45	0.7		0.8	0.8	0.3	1.1
Wheat							
winter			0.2	0.6	0.5		
spring			0.2	0.65	0.55		1.15

possible when the likely yield losses arise from differences in the ky of individual growth periods.

The yield response to water deficit of different crops is of major importance in production planning. For example, under conditions of limited water supply and with water deficit equally spread over the total growing season, the yield decrease for maize (total growing period ky = 1.25) will be greater than for sorghum (ky = 0.9). Consequently, when such crops are grown within the same project area and maximum production per unit volume of water is being aimed at, maize would have the priority for water supply. Also when maximum total production for the project area is being aimed at, and land is not a restricting factor, the available water supply would be directed toward fully meeting the water requirements of maize over a restricted area; for sorghum, the overall production will increase by extending the area under irrigation without fully meeting water requirements provided water deficits do not exceed certain critical values.

Similarly, the yield response to water deficit in different individual growth periods is of major importance in the scheduling of available but limited supply in order to obtain highest yield. In general, crops are more sensitive to water deficit during emergence, flowering and early yield formation than they are during early (vegetative, after establishment) and late growth periods (ripening). This implies that timing of water supply is as crucial as the supply level over the total growing period. Planning of seasonal supply must therefore take into consideration the optimum allocation of water supply to the crop over the growing season. In terms of water management this would mean that water allocations of a controlled but limited supply would be directed toward meeting the full water requirements of the crop during the most sensitive growth periods for water deficit rather than spreading the available limited supply to the crop equally over the total growing period. For example, for maize, the supply would be directed particularly to the flowering and yield formation periods. It follows that where crops are grown under supplemental irrigation the water application must be programmed so that sufficient water is available in the soil during flowering and yield formation.

EXAMPLE:

Given: Maize with total growing period 1 May to 31 August (123 days)

	May	June	July	Aug	Total
growth period (day)	establ (25)	veg (30)	flow (30)	yield form (38)	(123)
	90	192	285	273	840

(i) Water supply is 10% (85 mm) less than total water requirements (840 mm) with deficit equally spread over the total growing period (123 days)

1 - ETa/ETm	1-755/840	calc	0.1	
1 - Ya/Ym	1.25 x 0.1	Table 24	0.125	Ya/Ym = 87.5%

(ii) Water supply during July is 30% (85 mm) less than water requirements of that month (flowering period 2, 285 mm)

1 - ETa/ETm	1-200/285	calc	0.3	
1 - Ya/Ym	1.5 x 0.3	Table 24	0.45	Ya/Ym = 55%

(iii) Water supply is 10% (85 mm) less than total water requirements (840 mm) with deficit occurring in the flowering period (July) only

1 - ETa/ETm	1-755/840	calc	0.1	
1 - Ya/Ym	at flowering	Fig. 20	0.45-0.65	Ya/Ym ≈ 55%

Calculation examples of yield response to alternative water supply schedules are also given in detail in Chapter VI.

VI. APPLICATION IN PLANNING, DESIGN AND OPERATION OF IRRIGATION PROJECTS

In the planning, design and operation of irrigation projects, the production objectives must be related to the physical resource base, particularly climate, soil and water supply, in order to ensure that production proposed and yields predicted can be achieved and maintained. Also, several technical, economic and organizational factors must be considered to arrive at a technically sound, managerially workable, economically and financially viable project which is at the same time in accordance with the development and production objectives.

An important element in the evaluation of crop production under irrigation is the available and required water supply over time and acreage. When available water supply is adequate and fully meets crop water requirements, the production is maximum and the required supply depends on the crop selected, the length of the growing season and the irrigated acreage. When available water supply is limited, production is determined by the extent to which full water requirements can be met by the available water supply over the total growing season.

The cropping patterns of the project (e.g. crops, crop rotation, crop intensity) and the efficiency with which production resources can be used are essential input considerations in the overall project planning. Selection of cropping patterns must carefully consider the climatic, soil and water requirements of crops. The length of the growing season and the climatic conditions within the growing season dictate the type of crops and the cropping pattern that can be considered. These must also match the available soil and water resources. The climatic and soil requirements and growing periods of crops are presented in Table 2.

For crops that are climatically suitable, their water requirements must be considered in relation to both water supply and the efficiency of water utilization in crop production (Ey). When water supply is adequate and full water requirements of the selected crops can be met, crop selection, total acreage and total production are primarily determined by factors other than water. When water supply is limited, crop selection, total acreage and total production are primarily determined by the extent to which the available water supply over the growing season can meet full water requirements of the crops, and the highest water utilization efficiency that can be obtained from the available water supply. Water utilization efficiency (Ey) of crops is presented in Table 2.

Decisions on the most suitable crop calendar must be made at an early stage of the project planning and design to attain the most efficient use of the available water supply and an adequate supply and distribution system. For project operation, the most suitable crop calendar must be clearly outlined well before the start of the growing season. Depending also on the available supply, an evaluation and first determination of the water supply schedules can be made. To achieve a high water use efficiency and a high production, the water supply schedules must be adjusted according to the changes in crop water requirements over the growing period. To cater particularly for periods of water shortage, continuous updating of the schedules is required.

Step by step calculation procedures are presented on crop selection, crop acreages, and water use and scheduling of available water supply in relation to crop production. Two main conditions are distinguished:

1. Adequate water supply condition when the available water meets full crop water requirements (i.e. ETa = ETm and Ya = Ym if other inputs do not limit yields). Here the role

of management is directed toward manipulating water and other inputs to attain maximum production per unit of land for the selected crops over the available acreage.

2. Limited water supply condition when available water either meets full crop water requirements over a restricted acreage (i.e. ETa = ETm and Ya = Ym) or partially meets crop water requirements over an extended acreage (i.e. ETa < ETm and Ya < Ym with other factors adequate). Here the role of management is directed toward manipulating water and other inputs to attain maximum production per unit of water for the selected crops and acreages.

These calculations constitute an essential input in the evaluation of crop production for a given irrigation project. In addition to water, other variables such as farmers' preference, availability of labour and farm machinery, market and profits, must be considered in determining optimum production. Presentation of optimization models that take such factors into account is outside the scope of this publication.

1. ADEQUATE WATER SUPPLY

When the available water supply fully meets crop water requirements, crop selection and crop acreage are primarily determined by factors other than water availability and water use, although the capacity and cost of the irrigation supply and distribution system do have an influence. To plan, design and operate the water supply and distribution system for the project in relation to water available and water requirements, the procedure must consider: (i) selection of crops and cropping pattern; (ii) monthly (or ten-day) and peak supply requirements; and (iii) schedule of irrigation water supply over the growing season.

1.1 Selection of Crops and Cropping Patterns

When water supply is adequate, crops and cropping patterns that can be considered suitable will be those whose climatic requirements are met by the prevailing climatic conditions and the length of the growing season (Table 2). When data on crop yields are not available for the given location, a first estimate can be made with the help of Table 1 or can be calculated by the yield prediction methods given in Chapter 1. Similarly, an estimate of yield per unit of water (Ey) for the climatically suitable crops can be obtained (Table 2) to indicate the crop water requirements per unit of produce.

CALCULATION PROCEDURE

a. **Determine climatically suitable crops**
Collect available climatic data; evaluate climatic conditions in relation to crop requirements; select crops that are most suitable for the given climate and soil.

b. **Determine cropping patterns**
Determine most likely length of growing periods of the selected crops in relation to the total growing season and time required for other farming operations.

c. **Select optimum cropping pattern in relation to yield**
Determine for alternative crops and cropping patterns the yield as determined by climate and select optimum cropping pattern and possible yields.

EXAMPLE:

Given:

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Tmean °C	14	15	17.5	21	25.5	27.5	28.5	28.5	26	24	20	15.5
RHmean %	65	65	63	50	45	50	55	57	60	64	68	68
n hour/day	7.4	8.0	8.9	9.7	10.8	11.4	11.5	11.1	10.4	9.6	8.6	7.5
Rs mm/day	4.9	6.4	8.5	9.8	10.8	11.3	11.3	10.4	9.1	7.1	5.4	4.5

no frost occurs during the total growing season

Calculation:

Climatically suitable selected crops (Table 2):

maize	24 - 28°C	120 days	May - August
cotton	25 - 30	180	April - October/November
sorghum	25 - 30	120	May - August
groundnut	26 - 30	120	May - October
wheat	18 - 22	150	November - April
bean	15 - 20	120	November - April
onion	15 - 20	120	November - April

Possible cropping patterns:

wheat/maize/bean/maize or sorghum
wheat/maize/bean/groundnut
wheat/cotton/bean/maize or sorghum

For selecting the optimum cropping pattern maximum harvested yield (Ym) and water utilization efficiency (Ey) should be taken into account in addition to other criteria:

		Ym ton/ha	Ey kg/m³	(Tables 1 and 2)
maize (grain)		7-9	0.8-1.6	
cotton (seed)		3-4.5	0.4-0.6	
sorghum (grain)		3.5-5.0	0.6-1.0	
groundnut (unshelled)		3.5-4.5	0.6-0.8	
wheat (grain)		4-6	0.8-1.0	
bean	dry	1.5-2.5	0.3-0.6	
	fresh	6-8	1.5-2.0	
onion	bulb	35-45	8-10	

1.2 Monthly (or ten-day) and Peak Supply Requirements

The main variables in determining the monthly (or ten-day) and peak supply requirements are: the water requirements of the crops, the crop acreages, the efficiency of the supply and distribution system, and the leaching requirements. To minimize the design capacity of the system, adjustments in the crop calendar and crop practices may be required. These may vary from making optimum use of seasonal rainfall and water stored in the soil from pre-season rainfall to reducing peak supply requirements by shifting sowing dates so that different crops do not reach peak water requirements at the same time.

CALCULATION PROCEDURE

a. Crop water requirements (ETm)
Calculate reference crop evapotranspiration (ETo) on a monthly or ten-day basis; select appropriate crop coefficient (kc); calculate crop water requirements (ETm = kc . ETo) in mm/period.

b. Net irrigation requirements (In)
Determine effective rainfall (Pe) and groundwater contribution (Ge) to crop water requirements in mm/period, and actual depth of available soil water over the root depth at start of the growing period (Wb) in mm; calculate In = ETm - (Pe + Ge + Wb) in mm/period.

c. Irrigation supply requirements (V)
Determine leaching requirements (LR) and conveyance (Ec), field canal (Eb) and field application efficiency (Ea) or project efficiency (Ep = Ec . Eb . Ea) as fraction; calculate for acreage (A):

$$V = \frac{10}{Ep} \cdot \frac{A \cdot In}{1 - LR} \quad \text{in } m^3\text{/period}$$

EXAMPLE

<u>Given</u>: Location 30°N; altitude 95 m; crop is grain maize, with growing period 1 May to 31 August; initial stage is 20 days; crop development stage is 35 days; mid-season stage is 40 days; and late season stage is 28 days.

	May	June	July	Aug	Total	
ETo, mm/day	8.9	9.4	8.8	7.6		ex.II.1.1
kc, fraction	0.4	0.75	1.15	0.85		ex.II.2
ETm, mm/day	3.6	7.1	10.1	6.5		ex.II.3
mm/month	110	212	314	201	840	
Pe, mm/month	20	-	-	-	20	
Ge, mm/month	-	-	-	-	-	
Wb, mm	-	-	-	-	-	

Leaching requirement (LR) is 0.44 of total supply requirements; project efficiency (Ep) is 0.4; field application efficiency (Ea) is 0.7.

<u>Calculation</u>:

Assume leaching to take place after growing season:

	May	June	July	Aug	Total
In, mm/month	90	212	314	201	820
V, m^3/ha/month					
at field inlet	1285	3030	4485	2870	11670
at headwork	2250	5300	7850	5025	20425
Vpeak, m^3/ha/month					7850
V including leaching, m^3/ha/total growing period					36500

1.3 <u>Schedule for Irrigation Water Supply over the Growing Season</u>

For high crop production, the design and operation of the supply and distribution system of the project must be geared toward delivering water to the fields at the pre-determined interval and depth of irrigation, which meets the changing water requirements of the crops over the growing season. The supply schedule within the supply and distribution system must be based on the supply requirements of the lowest irrigation unit or the individual field. The supply requirements at the field level are expressed in irrigation interval (i) in days and in net irrigation depth (d) in mm. The main variables in determining i and d when ETa = ETm are water requirements (ETm), root depth (D), water holding capacity of the soil (Sa) and level of available soil water depletion (p). To arrive at the supply schedule within the supply and distribution system of the project, expressed in flow rate (m^3/sec) and flow duration (hours), the supply requirements of the individual fields are weighted and subsequently determined for a block of fields and for areas served by main canals, taking into account the irrigation efficiency and leaching requirements.

CALCULATION PROCEDURE

a. Soil water balance (We)
Determine for monthly (or shorter) periods the soil water balance or actual depth of available soil water over the root depth at the end of a month (or period thereof) We = Pe + Ge + Wb - ETm in mm, and plot (see example line 1); note that We at the end of each month is equal to Wb at the beginning of the next month.

b. Total available soil water over root depth (Sa.D)
Determine total available soil water (Sa) in mm/m; determine for given crop root depth (D) in m for each month (or period thereof); calculate Sa.D in mm for each month (or period thereof), and plot (line 2).

c. Remaining available soil water over root depth when ETa < ETm [(1-p) Sa.D]
Determine for given crop and ETm the fraction (p) of the total available soil water when ETa = ETm (Table 20); calculate (1-p)Sa.D in mm for each month (or period thereof), and plot (line 3).

d. Interval and depth of irrigation application (i and d)
Apply graphical method; when soil water balance (line 1) meets maximum soil water depletion over which ETa = ETm, or (1-p)Sa.D (line 3), replenish soil water with water depth equal to p.Sa.D in mm, and plot (line 4); plot new soil water balance curve (line 5) parallel to the old one (line 1) until (1-p)Sa.D (line 3); repeat; read approximate date, interval (i) in days and net depth (d) in mm; note that to make maximum use of available soil water, step d can also be started at the time of harvest with depth of available soil water at time of harvest equal to (1-p)Sa.D.

e. Operation of supply and distribution system
Determine duration (hours) and interval (days) of field supply; quantify supply schedules for different crops and acreages over the growing season for selected method of delivery. (For details see FAO Irrigation and Drainage Paper No. 24, 1977, revised version, Part II, Chapter 2.)

In the following example, it is assumed that the irrigation supply is fully controlled and the interval and depth of irrigation application can be chosen to maintain ETa = ETm and Ya = Ym.

EXAMPLE

Given: Crop is maize; soil is medium textured with total available soil water (Sa) 140 mm/m; climatic and crop data are:

	May	June	July	Aug	Total	
ETm, mm/day	3.6	7.1	10.1	6.5		ex.II.3
ETm, mm/month	110	212	314	201	840	
Pe, mm/month	20	-	-	-		
Ge, mm/month	-	-	-	-		
Wb, mm	70 (pre-irrig.)					
D, m	0.5	1.0	1.2	1.2		

Water supply is adequate and can be fully controlled; application efficiency (Ea) is 0.7.

Calculation:

	May	June	July	Aug	
We = Pe + Ge + Wb - ETm mm/month	-20	-232	-546	-747	line (1)
Sa.D, mm	70	140	170	170	line (2)
p, fraction	0.75	0.5	0.4	0.55	Table 20
(1-p)Sa.D, mm	18	70	102	77	line (3)
apply plotting procedure					
number of irrigations	(pre)+2	4	4	1 (2)*	Fig. 4
approximate date	(1/5)	5/6	6/7	11/8	Fig. 4
	17/5	12/6	12/7	(27/8)*	
	28/5	20/6	19/7		
		28/6	28/7		
i, days	15	8	7	15	Fig. 4
d, mm	(70)+55	60	70	95	Fig. 4
irrigation depth (gross)	(100)+80	85	100	135	calc

* last irrigation falls shortly before harvest and can be omitted or scheduled earlier with a reduced depth.

Similar calculations can be made for different crops grown simultaneously in the project area. To arrive at an irrigation supply in terms of flow rate (m^3/sec) and flow duration (hours), the irrigation interval (i) and depth of irrigation (d) are weighted for different crops according to their respective field acreages, blocks of fields, acreages served by laterals and main canals, taking into account irrigation efficiency and leaching requirements.

However, to simplify the operation of the supply system, in many irrigation projects fixed irrigation intervals and/or fixed depth or irrigation application are used. Since crop water requirements change over the growing period, the use of fixed intervals and/or fixed depths of irrigation causes either over- or under-irrigation during the different parts of the growing period. This in turn leads to inefficient use of water or causes reduction in crop yields, as shown in the following example:

EXAMPLE

Given: Previous example on maize; a fixed irrigation interval (i) of 15 days is used.

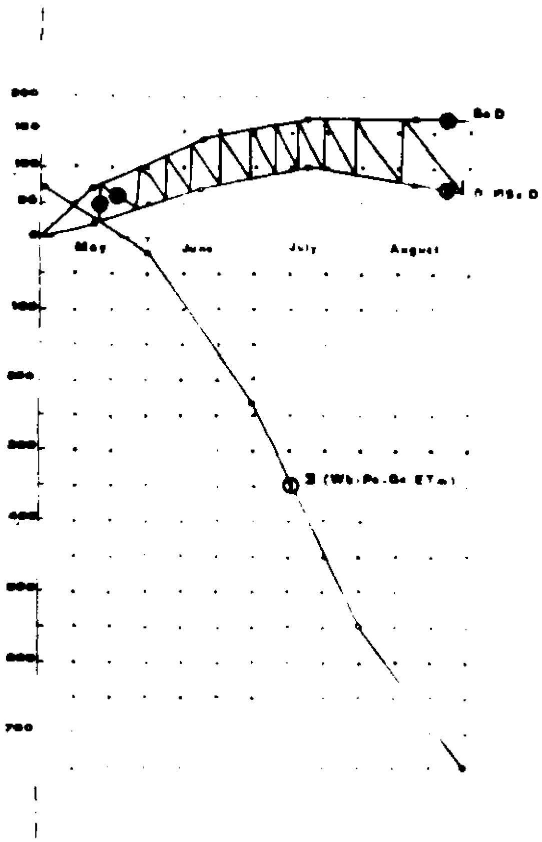


Fig. 4

Calculation: The 15 day interval is correct for May and August; during June and July the 15 day interval leads to crop water deficit. In July: ETm = 10.1 mm/day, Sa = 140 mm/m, D = 1.2 m, p = 0.4.

Sa.D, mm	140 x 1.2	calc	=	170 mm
p, fraction	at ETm = 10.1	Table 20	=	0.4
ETa, i = 15 days	(8.1 + 7.5 + 9.1 + 8.7)/4	Table 21	=	8.4 mm/day
1 - ETa/ETm	1 - 8.4/10.1	calc	=	0.17
ky maize	at flowering	Table 24	=	1.5
1 - Ya/Ym	1.5 x 0.17	calc	=	0.25
Yield decrease due to water deficit in July			=	25%

2. LIMITED WATER SUPPLY

When water supply is limited, considerations on crop selection and acreage irrigated should be based on crop yields as affected by the extent to which crop water requirements (ETm) are met by the available water supply over the growing season. A first evaluation can be made by considering the effect of limited seasonal supply on crop yields and total production. However, for a full evaluation of the effect of limited water supply on yield and production, consideration must be given to the effect of the limited water supply during the individual growth periods of the crops. Where crops under consideration are very sensitive to water supply deficits, scheduling of the supply is based on meeting full crop water requirements. Where crops under consideration are less sensitive to water deficit and can be grown with acceptable yields but without meeting full water requirements, scheduling of the supply is based on minimizing water deficits in the most sensitive growth periods. During periods of unpredictable water shortages, within season adjustments of water scheduling must be made in relation to the difference in the yield response to water deficits on the crops and their individual growth periods. This applies both to controlled and uncontrolled water supply at headworks.

To plan, design and operate the water supply and distribution system for the project in relation to production level and water requirements, the procedure must consider (i) selection of crop and cropping patterns; (ii) seasonal and monthly water supply requirements and crop production (yield per unit area and total project production); and (iii) schedule of irrigation water supply over the growing season.

2.1 Selection of Crops and Cropping Patterns

When water supply is limited, crops and cropping patterns that can be considered suitable will be those whose climatic requirements are met by the prevailing climatic conditions and the length of the growing season (Table 2). When data on crop yield under adequate water supply are not available for the given location, an estimate can be made with the help of Table 1, or can be calculated by the yield prediction methods given in Chapter 1. In addition, selection of crops and their acreages must consider the crops that are most efficient in water utilization (a high Ey) under adequate water supply, as well as those which are able to maintain an acceptable yield level under limited water supply (a low ky).

CALCULATION PROCEDURE

a. Determine climatically suitable crops
Collect available climatic data; evaluate climatic conditions in relation to crop requirements; select crops that are most suitable for the given climate and soil.

b. Determine crops and crop acreages in relation to water supply
Evaluate for the climatically suitable crops the available water supply in relation to water requirements, water utilization efficiency (Ey) and yield response factor (ky).

c. Select optimum cropping pattern
Determine for crops with high Ey and high ky values the crop rotation and crop acreages where full water requirements are met by available water supply.
Determine for crops with high Ey values and low ky values the crop rotation and crop acreages where water requirements are partially met by available water supply.

For the example, step (a) follows the analysis made under Chapter VI.3.1. Steps (b) and (c) are discussed jointly in relation to seasonal and periodic water supply and production level, Chapter VI.3.1 and 2.

2.2 Seasonal Supply

Under limited water supply, a first evaluation of actual crop yields (Ya) and total production (P) for the project area can be made by considering the yield response factor (ky) for the total growing period of the crops with high ky values in relation to the ratio available seasonal and required seasonal supply. Since ky is used together with the relative evapotranspiration deficit (1 - ETa/ETm), the available and required supplies need to be expressed in terms of ETa and ETm.

Actual yield (Ya)

The actual yield under limited water supply is obtained by expressing the available and required seasonal water supply in terms of ETa and ETm. Subsequent application of ky for the total growing period provides an estimate of the relative yield decrease (1 - Ya/Ym).

CALCULATION PROCEDURE

a. Available water supply
From hydrological data and irrigated acreage, determine, after correction for irrigation efficiency, the net water supply to the crop over the total growing period in m^3/ha and ETa in mm.

b. Relative evapotranspiration deficit (1 - ETa/ETm)
Determine crop water requirements (ETm) in mm for the total growing period and calculate (1 - ETa/ETm).

c. Relative yield (Ya/Ym)
Select appropriate yield response factor (ky) for the total growing period (Table 24), calculate (1 - Ya/Ym) = ky(1 - ETa/ETm) and obtain Ya/Ym.

EXAMPLE

Given: Crop is maize; total growing period 1 May to 31 August; crop water requirements (ETm) are 840 mm; effective rainfall is 20 mm; available water supply at headworks is 13 750 m /ha; project efficiency (Ep) = 0.4.

Calculation:

Available to crop, ETa	0.4 x 13 750/10 + 20	calc	=	570 mm
ETm		example	=	840 mm
1 - ETa/ETm	1 - 570/840	calc	=	0.32
ky		Table 24	=	1.25
1 - Ya/Ym	ky(1 - ETa/ETm)	calc	=	0.40
Ya/Ym		calc	=	60%

Total production for the project area (P)

To maximize total production under a limited water supply and a given cropping pattern of crops with high Ey values, a first evaluation of the total production (P) for the irrigated acreage can be obtained by considering the crop response factor (ky) for the total growing period. Total production (P) is defined as actual yield (Ya) over the total irrigated acreage (A) or P = A.Ya. Based on the ky values, two cases can be distinguished:

- when ky > 1; for maximum total production (P), the acreage (A) is based on available water supply meeting full crop water requirements or ETa = ETm; Ya = Ym over the acreage (Am) where Am is defined as the irrigated acreage with crop water requirements fully met.

- when ky < 1; for maximum total production (P), the acreage (A) is based on available water supply partially meeting the crop water requirements or ETa < ETm, and Ya < Ym but Aa > Am, where Aa is defined as the irrigated acreage with water supply less than the required supply to meet full crop water requirements.

The effect of limited water supply per unit area and the ky factor of the total growing period on total production (P) is shown in Table 25. Pm represents the total production from acreage Am with crop water requirements fully met by available supply (ETa = ETm, Ya = Ym and Pm = Am.Ym); Pa represents the total production from the acreage Aa with crop water requirements partially met by the available water supply and 'savings' in water supply are used to extend the irrigated acreage Am (ETa < ETm, Ya < Ym, but Aa > Am and Pa = Aa.Ya).

Table 25 Relative Total Production (Pa/Pm) for Different Values of ETa/ETm and ky factors for the Total Growing Period

ky	ETa/ETm				
	0.6	0.7	0.8	0.9	1.0
0.6	1.27	1.17	1.10	1.04	1.0
0.8	1.13	1.08	1.05	1.02	1.0
1.0	1.0	1.0	1.0	1.0	1.0
1.2	0.87*	0.91*	0.95*	0.98*	1.0*
1.4	0.73*	0.83*	0.90*	0.95*	1.0*

CALCULATION PROCEDURE

a. Available water supply
From hydrological data, and after correction for irrigation efficiency, determine for the total growing period the water supply available to the crop in m³; for different irrigated acreages determine water supply available to the crop in m³/ha.

b. Relative evapotranspiration (ETa/ETm)
Determine for the total growing period the crop water requirements (ETm) in mm and calculate ETa/ETm.

c. Relative total production (Pa/Pm)
Select yield response factor ky for the total growing period and determine for different values of ETa/ETm the relative total production (Pa/Pm) from Table 25.

EXAMPLE

Given: Crop is maize; growing period is 1 May to 31 August; water supply is 1 000 000 m ; project efficiency (Ep) is 0.4.

Calculation:

Available to crop	0.4 x 1 000 000					calc	= 400 000 m^3
ky						Table 24	= 1.25
ETm, mm						ex.II.3	= 840 mm
area, ha	40	47.6	50	60	70	assume	
average supply, m^3/ha	10 000	8 400	8 000	6 650	5 700	calc	
ETa, mm	840	840	800	665	570	calc	
ETa/ETm	(1.0)	1.0	0.95	0.8	0.68	calc	
ky	1.25	1.25	1.25	1.25	1.25	given	
Ya/Ym	(1)	1.0	0.94	0.75	0.6	calc	
Pa/Pm	(0.84)	1.0	0.98	0.94	0.89	Table 25	

2.3 Schedule of Water Supply

A full evaluation of crop yield response to limited water supply can only be made by considering the distribution of available water supply over the individual crop growth periods. Under conditions of limited water supply, the supply schedule should be directed towards minimizing water deficits during the most sensitive periods (or when ky for the individual growth period is high). This applies for most crops during the flowering and yield formation periods. In scheduling limited water supply two main conditions can be distinguished:

(i) available supply is fully controlled at headworks (viz. supply from a reservoir)

(ii) available supply at headworks is uncontrolled and varies with time (viz. available discharge of a river).

(i) Fully Controlled but Limited Supply

When water supply is fully controlled, the irrigated acreage is mainly determined by the total available water supply and the required supply to attain the expected level of crop yield. Supply scheduling is directed toward minimizing water deficits during the individual growth periods with high ky values.

CALCULATION PROCEDURE

a. Crop water requirements (ETm)
Determine for monthly (or ten-day) periods and for each crop growth period the maximum evapotranspiration (ETm) in mm.

b. Yield response to water supply (Ya/Ym and ETa)
Determine for the individual growth periods the respective ky value; select relative yield level (Ya/Ym) and determine corresponding actual evapotranspiration (ETa) in mm.

c. Irrigation schedule
Select for the individual growth periods the level of actual evapotranspiration (ETa) in mm/period, available soil water over root depth (Sa.D) in mm and fraction of soil water depletion (p) when ETa = ETm; calculate irrigation interval (i) in days and depth (d) in mm.

d. Irrigated acreage
From hydrological data determine for the individual growth periods total available water supply in m^3; calculate acreage in ha from available and required supply (V) in m^3/ha.

e. Operation of supply system
Determine duration (in hours) and interval (in days) of field supply, and quantify supply schedules for blocks of fields, and for acreages served by laterals and main canals.

EXAMPLE

Given: Crop is maize; growing period 1 May to 31 August with an establishment period of 25 days, a vegetative period of 30 days, a flowering period of 30 days and a yield formation period of 38 days. Monthly maximum evapotranspiration (ETm) is, for May 3.6, for June 7.1, for July 10.1 and for August 6.5 mm/day; soil is medium textured and total available soil water (Sa) is 140 mm/m; root depth during the establishment period is 0.5 m, during the vegetative period 1.0 m, during flowering and yield formation, 1.2 m. Available water supply is 1 000 000 m^3; project efficiency (Ep) is 0.4. Assume maximum irrigated acreage with yield per ha equal to 80% of the maximum.

Calculation

		(0) esta-blishm.	(1) vege-tative	(2) flow-ering	(3) yield form.	Total
ETm, mm/day	calc	3.6	6.4	9.5	7.2	
ETm, mm/period	calc	90	192	285	273	840
ky	Table 24	0.4	0.4	1.5	0.5	
water savings			X		X	
ky (period 1 & 3)[1]			X		X	0.8
(1 - Ya/Ym)	given					0.2
(1 - ETa/ETm)	calc	0	0.25		0.25	
ETa/ETm	calc	1	0.75		0.75	
ETa, mm/period	calc	90	144	285	205	724
ETa, mm/day	calc	3.6	4.8	9.5	5.4	
Sa.D, mm/rootzone	calc	70	140	170	170	
p, fraction	Table 20	0.75	0.5	0.4	0.55	
i, days	Table 21	15	26	7	28	
d, mm (i x ETa)	calc	(pre 70) 55 55	125	65 65 65 65 65	150*	630
Date	calc	(pre 1/5) 15/5 30/5	26/6	3/7 10/7 17/7 24/7 31/7	28/8*	

[1] Estimated value for the combined effect of water deficit in periods 1 & 3.

Irrigated acreage: 0.4 x 1000000/6 300 = 63 ha.

* Last irrigation falls shortly before harvest and can be omitted (or scheduled earlier with reduced depth).

When rainfall occurs, the irrigation interval can be extended with a number of days equal to Pe/ETa, where Pe is the effective rainfall in mm occurring during that irrigation interval.

(ii) Uncontrolled and Limited Supply

When water supply is uncontrolled, irrigated acreages are mainly determined by the available supply during the different growth periods, the effect of water deficits on yield during those periods and the selected yield level. Crop selection and crop calendar should, when possible, be adjusted so that periods with high ky values do not coincide with periods of limited water supply.

CALCULATION PROCEDURE

a. Crop water requirements (ETm)
Determine for monthly (or ten-day) periods and for the individual growth periods the maximum evapotranspiration (ETm) in mm.

b. Yield response to water supply (Ya/Ym and ETa)
Determine for the individual growth periods the effect of evapotranspiration deficit on crop yield (ky); select relative yield level (Ya/Ym); by comparing available water (ETa) with crop water requirements (ETm), determine the critical growth period for water deficit; determine acreage in ha from available and required supply for the critical growth period; check for other growth periods if water supply is adequate; if not, adjust acreage to attain selected yield level (Ya/Ym).

c. Irrigation schedule (i and d)
Select level of mean actual evapotranspiration (ETa) in mm/day, available soil water (Sa) in mm/m over root depth (D) in m, and level of soil water depletion (p) in fraction when ETa = ETm; calculate irrigation interval (i) in days and depth (d) in mm.

d. Operation of supply system
Determine duration in hours and interval in days of field supply, and quantify supply schedules for blocks of fields, and for acreages served by laterals and main canals.

EXAMPLE

Given: Crop is maize; growing period 1 May to 31 August, with an establishment period of 25 days, a vegetative period of 30 days, a flowering period of 30 days and a yield formation period of 38 days. Monthly maximum evapotranspiration (ETm) for May is 3.6 mm/day, for June 7.1, for July 10.1 and for August 6.5. Soil is medium texture and total available soil water (Sa) is 140 mm/m; root depth (D) during the establishment period is 0.5 m, during the vegetative period 1.0 m and during flowering and yield formation 1.2 m. Water supply is 161 000 m^3 in May, 261 000 m^3 in June, 269000 m^3 in July and 309000 m^3 in August. Assume maximum irrigated acreage with yield per ha equal to 70% of the maximum.

Calculation:

		(0) esta-blishm.	(1) vege-tative	(2) flow-ering	(3) yield form.	total
length of period (days)	given	25	30	30	38	123
ETm, mm/period	calc	90	192	285	273	840
ETm, mm/day	calc	3.6	6.4	9.5	7.2	
ky	Table 24	0.4	0.4	1.5	0.5	
ETa = 0.9 ETm mm/period	calc	81	173	257	246	
Ya/Ym for ETa/ETm = 0.9(%)	calc	96	96	85	95	
* ETa = 0.8 ETm mm/period	calc	72	154	228	218	
Ya/Ym for ETa/ETm = 0.8(%)	calc	92	92	70*	90	
ETa = 0.7 ETm mm/period	calc	63	134	200	191	
Ya/Ym for ETA/ETm = 0.7(%)	calc	88	88	55	85	
ETa = 0.6 ETm mm/period	calc	54	115	171	164	
Ya/Ym for ETA/ETM = 0.6(%)	calc	84	84	40	80	
available water supply in m^3/period	given	130000	240000	260000	370000	1000000
net average supply (Ep = 0.4)	calc	52000	96000	104000	148000	400000
Ya/Ym %	given					70
critical period				X		
* Irrigated acreage (104 000/2 280)				45.6		
net available water, m^3/ha	calc	1140	2105	2280	3245	

no supply restrictions in growth periods 0, 1 and 3

Irrigation schedule:

		(0)	(1)	(2)	(3)
ETa/ETm	calc	1.0	1.0	0.8	1.0
ETa, mm/day	calc	3.6	6.4	7.6	7.2
ETa, mm/period		90	192	228	273
D.Sa, mm/root depth	calc	70	140	170	170
p, fraction	Table20	0.75	0.5	0.4	0.55
i, days	Table 21	15	11	15	13
d, mm	calc	(pre 70) 55 55	70 70	115 115	95 95
approximate date	calc	(pre 30/4) 15/5 30/5	11/6 22/6	5/7 20/7	2/8 15/8

3. ADDITIONAL RELATED APPLICATIONS

3.1 Priority of Water Supply Amongst Crops During Periods of Water Shortages

In the operation of the supply and distribution system, decisions must be made on the best allocation of available water at the time of water shortage. During the individual growth periods, crops vary in their yield response to water deficits. To minimize yield reduction, the irrigation supply should be directed toward minimizing water deficits during the growth periods with high ky values.

When water supply is short, the ky values of the growth periods for crops grown simultaneously in the project area indicate the priority in water supply allocation. This priority can be expressed in terms of yield response to the level of water supply. Detailed calculations are given under VI.2.

EXAMPLE

Given: Start of the growing season is May; crops are maize, cotton and sunflower; water shortage occurs during July and August; attainment of maximum production per unit area is pursued.

Calculation:

From information for the different crops given in Part B:

	May	June	July	August	Sept.	Oct.
growth periods:						
maize	establ.	veg.	flow.	yield form.		
cotton	establ.	veg.	flow.	flowering	yield form.	ripening
sunflower	establ.	veg.	veg.	flowering	yield form.	
ky:						
maize	0.4	0.4	1.5	0.5		
cotton	0.2	0.2	0.5	0.5	0.5	0.25
sunflower	0.25	0.25	0.5	1.0	0.8	

Supply priority:

July: : 1 maize, 2 and 3 cotton and sunflower
August : 1 sunflower, 2 and 3 maize and cotton

3.2 Rehabilitation of Existing Projects through Improved Operation of Water Supply and Distribution Systems

For high yields, the operation of the water supply and distribution system must be directed toward meeting the crop water requirements over time and acreage. In some projects, supply schedules are based on a fixed interval and/or a fixed depth of water application, regardless of the changes in crop water requirements over the growing period. However, field data, reflecting yield losses due to excessive or inadequate water supply to the crop, are in many cases scarce or not available. In existing projects, the lack of this information often inhibits the required improvement programmes.

Improvement of existing projects calls for reliable data at the farm level on crop water requirements and irrigation supply scheduling in relation to crop yields. Based on these data, criteria for optimum water use at the farm level can be developed, w in turn can form the basis for determining the measures needed to improve the physical and managerial operations of the water supply system.

The likely benefits of improvement of the water supply system in existing projects can be obtained from an analysis of the present yield level compared to the maximum yield attainable under a high level of water management. To measure the effect of present water supply on present yields, an analysis is required on interval and depth of water application to the field over the growing season.

After first calculating maximum evapotranspiration (ETm) (Chapter II), the actual evapotranspiration (ETa) under the present water supply can be obtained (Chapter III). Subsequently, the relative evapotranspiration deficit (1 - ETa/ETm) for each crop growth period after first calculating maximum yield (Ym) (Chapter I) and, by applying the crop response factors (ky), the effect of water deficit on present relative yield can be obtained by $(1 - Ya/Ym) = ky(1 - ETa/ETm)$.

Calculations similar to those given in Chapter VI.2 can be applied to calculate, for the present available water supply, the yield level that can be obtained under improved irrigation supply scheduling. The present and improved yields are also subject to factors other than water. However, an indication of the expected yield increase due to improved water supply and management is obtained by following the presented methodology.

3.3 Reservoir Operation

In planning and design of water supply systems fed by reservoirs, the water release for irrigation is sometimes based on selected water duties or supply norms. The required supply for irrigation is then considered as an operational parameter, rather than an operational variable; the release then represents, for a given irrigated acreage, a fixed flow of water over a fixed, often calendar-based, time period. While the concepts of water duty and supply norms are helpful at the planning stage, considerations in relation to efficiency of water use and level of crop production greatly assist in the most effective operation of reservoir releases.

Reservoir operation over the growing season should be directed toward minimizing water shortages during these crop growth periods when crop yield response to water deficits is most sensitive. The calculations involved are (i) determination of available supply over the growing season; (ii) determination of crop water requirements (ETm) for the different crops for ten-day periods; (iii) selection of yield response factors (ky) for different crops and (iv) determination of the distribution of available supply over the growing season, based on minimizing crop yield losses due to water deficits. Since several crops may be involved, weighted averages need to be used. During periods of water shortages, the priority of supply amongst crops within the project area can subsequently be determined (Chapter VI.3.1).

3.4 Irrigation Efficiency

Irrigation efficiency is normally expressed in terms of the amount stored in the root zone as a percentage of the total water released at the project headworks. It is separated into three components: the conveyance efficiency (Ec), the field canal efficiency (Eb) and the field application efficiency (Ea) or project efficiency $Ep = Ec \cdot Eb \cdot Ea$. Main factors affecting irrigation efficiency are the size of the project, the number and the type of crops requiring adjustments in supply, the canal seepage, the size of the individual fields, the irrigation methods and practices, and managerial and technical facilities for water control. At the planning stage, irrigation efficiency is normally estimated on the basis of experience. The estimated values can be checked only 5 to 10 years after construction of the project, when operators and farmers have become familiar with the water distribution and application.

Irrigation efficiency (Ep) is expressed in terms of water loss (m^3/m^3). For practical purposes, it is normally considered as constant over the growing season. However, in most cases efficiencies will vary over the season. For instance, under conditions of limited water supply to the field and when under-irrigation is practised, most water applied to the fields is taken up by the crop and field application efficiency may be near 100 percent rather than the frequently assumed 50 to 70 percent. Also, when water is in short supply, more attention is given to water distribution and scheduling, and project efficiency is consequently higher. Furthermore, the effect of limited water supply on crop yields varies over the growing season, and consequently the impact of water loss on yield varies over the growing season.

Besides expressing it in terms of water losses (m^3/m^3), irrigation efficiency can also be expressed in terms of yield losses by applying the relationships between water supply and crop yield. Under conditions of adequate supply an increase in irrigation efficiency will save water. Thus an extension of the irrigated area is possible and the total yield is subsequently increased. Under conditions of limited supply, an increase in irrigation efficiency will also save water, making a reduction in water deficits to the crop occurring during different growing periods possible, and yield per unit area is subsequently increased.

Consideration of irrigation efficiency in relation to yield response to additional water supply assists in the evaluation of the need for improvement of irrigation efficiency, as, for instance, the decision on canal lining.

EXAMPLE

Given: Previous example (Chapter VI.2.3) where Ya/Ym is 0.7; Ep is 0.4. Assume 10% increase in Ep from 0.4 to 0.44; water supply shortage is experienced during the flowering period (July).

Calculation:

net average water supply during flowering (July), m^3	0.44 x 260 000	calc	114 400 m^3
net supply, m^3/ha	114 400/45.6	calc	2 500 m^3/ha
ETa/ETm	250/285	calc	0.88
ky, flowering	Table 24	given	1.5
(1 - Ya/Ym)	1.5(1 - 0.88)	calc	0.18
Ya/Ym		calc	0.82
Yield increase due to increasing efficiency	(0.82 - 0.7)/0.7	calc	17%

VII. ADAPTIVE RESEARCH

Crop production and optimum use of water are determined by the total environment, and consequently are location specific. The method presented for analysing the relationship between crop yield and water use allows an integration through a yield response factor (ky) of a large number of complex processes into a simple quantitative relationship between relative yield decrease (1 - Ya/Ym) and relative water deficit (1 - ETa/ETm). The method as such forms a basis of rational water management in relation to irrigated crop production.

In order that the method has a wide application, the relationship for the different crops is (i) derived from experimental data of high producing varieties obtained under conditions where production inputs other than water are adequate, and (ii) presented on a relative scale. However, production conditions during the growing period are location specific, e.g. water quality, fertilizer application, endemic plant diseases. Also, for many locations yield and water use data on which to base the analysis are often lacking. Thus, verification of the presented method and yield-water use relationship through adaptive research for a given production condition is very much warranted for use in planning, design and operation of existing and new irrigation projects.

The objectives of the experimental programme should include:

- establishment of crop growth and yield responses to different levels of water supply over the total growing period for specific crops
- the evaluation from the developed yield response functions of practical irrigation schedules which will guarantee optimal yields per unit of water and/or per unit or area.

The adaptive research programme must determine (i) the maximum yield (Ym) under conditions of full water requirements (ETm) with other growth factors not limiting yields and (ii) the effect of limited water (ETa) on yield (Ya) for the total and individual growth periods. This information will allow derivation of the relationships between yield and water use (ky).

It must be emphasized that detailed planning of the experimental programme, including the number of treatments and replications and the type and number of observations and measurements to be made, is most essential. In practice it has often shown that ambitiously devised programmes in the course of execution experienced great difficulties due to insufficient equipment, funds, labour and supervising personnel. The experimental programme should therefore, especially for the first year(s), be simple, with a limited number of variables involved, and be based on clear objectives and proper planning.

The experimental programme must be problem-solving oriented. Therefore, first of all, an analysis must be made of the present yields in relation to the agronomic and irrigation practices in farmers' fields in existing projects. This would include an analysis of crop and crop varieties, the present yield levels, the planting dates and growing periods, the crop husbandry practices such as plant population, cultivation methods, weed control, pest and disease control, and harvesting techniques as well as the frequency and depth of irrigation with special reference to irrigation methods and practices, irrigation efficiency, water quality, depth of groundwater table, and soil and fertility factors. Such an analysis is needed to determine possible limiting factors to high production and their adverse effects when improved water schedules based on experimentally determined relationships between yield and water use are applied in the field. Furthermore, the analysis of present field practices will indicate the variables, in addition to water supply, which may need to be included in the experimental design.

1. SITE SELECTION

The site selected should be fully representative for the climatic, soil and water conditions of the area where the results will be applied. Areas with steep slopes or low-lying areas subjected to flooding should be excluded. The soil should preferably be deep, without hard pans or dense layers with no physical or chemical limitations, and a high water table should be avoided except where such limitations form a part of the experimental treatment. A drainage system should be included whenever necessary.

The experimental area must be placed within an agricultural area surrounded by irrigated crops. The surrounding area must be large enough to avoid the so-called 'clothesline' effect (at least 100 x 100 m). A fully controlled and guaranteed water supply should be available.

2. IRRIGATION TREATMENTS

Experiments should be conducted with high-producing varieties well adapted to the prevailing climatic conditions, with an adequate plant population, soil fertility and crop protection. To obtain results that are statistically meaningful, each treatment should have sufficient replications.

Water supply schedules should be related to water requirements taking into account climatic and soil conditions, and crop development. Consequently, the interval and the depth of irrigation should vary accordingly over the growing period. Results have little meaning when fixed irrigation timing is used and only the depth of application is varied according to fractions of a reference level, e.g. 1.1, 0.9 and 0.7 times pan evaporation. Irrigation depth per application should preferably be sufficient to bring the soil water content to field capacity over the effective rooting depth, with additional water applied when leaching of salt is required.

In order to determine the frequency and depth of irrigation for each treatment, a preliminary supply schedule can be obtained by calculating:

- maximum evapotranspiration (ETm) and actual evapotranspiration (ETa) by the methods provided in Chapters II and III
- total available soil water over the root depth (Sa), using measured data on soil water content at field capacity (Sfc) and wilting point (Sw), and root depth (D)
- depletion level of total available soil water (p) for each treatment by information provided in Chapter III.

Supply schedules will need to be adjusted throughout the course of the experiment, also taking into account climatic conditions and rate of crop development. The supply schedule should be made possible by the irrigation method used, e.g. small depth of irrigation under surface irrigation methods.

The recommended irrigation treatments are:

(i) <u>One "wet treatment" or treatment with no water deficit over the total growing period</u> (ETa = ETm, Ya = Ym)

Experimental results obtained under this treatment will provide an indication of the accuracy of methods to predict crop water requirements (ETm) and the maximum yield (Ym) for the given crop variety and growing conditions.

Timing and depth of application is based on the calculated maximum evapotranspiration (ETm), the total available soil water (Sa), the root depth (D) and the water depletion level (p).
Soil water measurements to check the rate of water uptake from the soil as recorded in the soil water balance sheet are made frequently over the root depth. For a measure of soil water status tensiometers and gypsum blocks are needed.
Care must be taken that no excess water is lost un-measured through deep percolation or lateral movement.
Regular observation should be made on crop development (see check list).

(ii) <u>One "dry treatment" or treatment with considerable water deficit throughout the total growing period</u> (ETa ≪ ETm, Ya ≪ Ym)

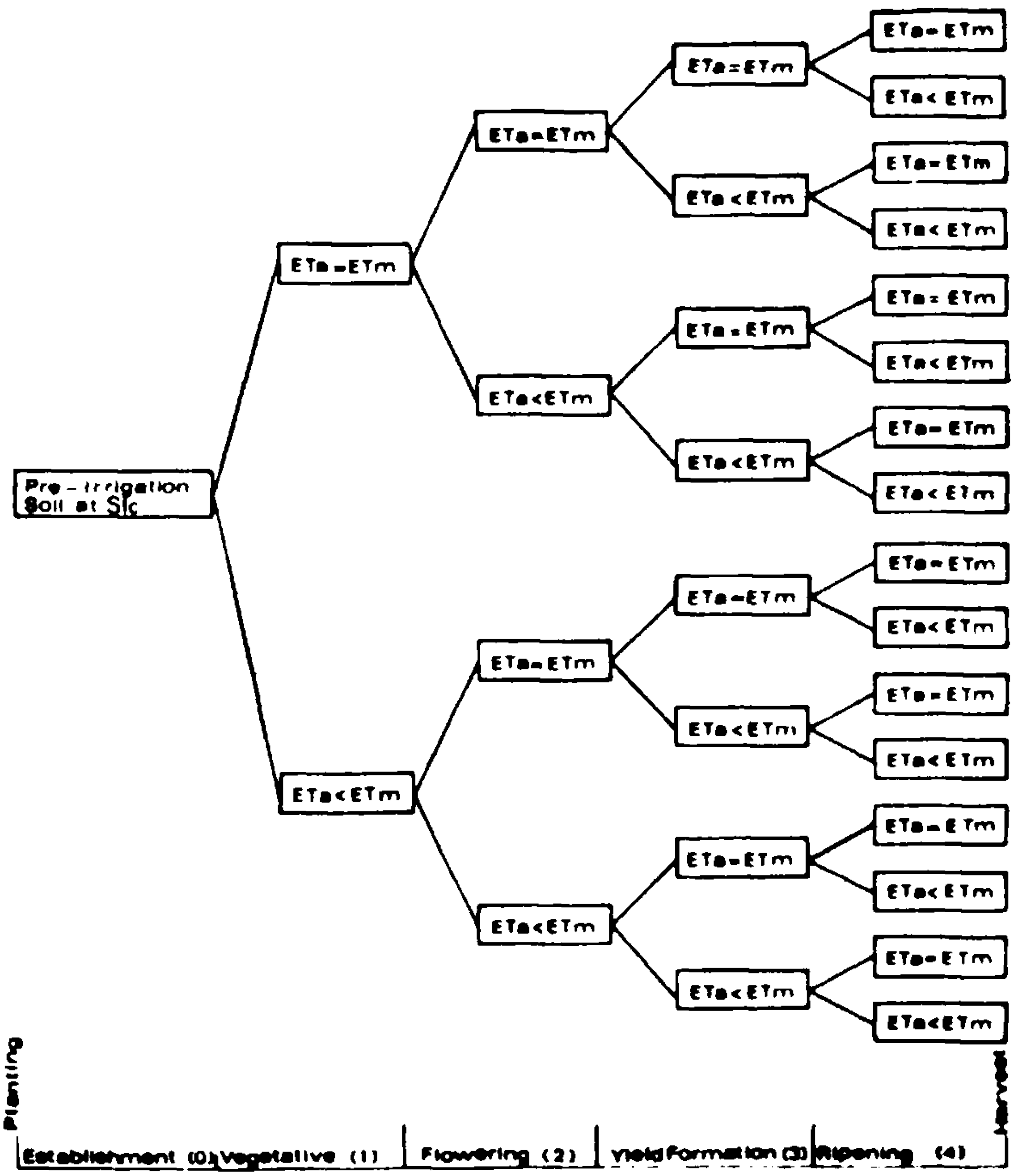
Experimental results obtained under this treatment will provide the actual yield (Ya) and actual evapotranspiration (ETa) under conditions of water deficit. These results allow a quantification of the crop response factor (ky) for the total growing period when ETa is compared to ETm and Ya is compared to Ym.

The water deficit and consequently the soil water depletion level at which irrigation is applied will depend on the crop, soil and level of ETm (Chapter III). Stunted growth and wilting will be observed but serious wilting for a long period must be avoided.
Timing and depth of irrigation should be based on a continuous measure of soil water status (soil sampling, gypsum blocks), combined with crop observations e.g. wilting, change of colour. The selection of the depletion level at which irrigation is applied should be based on literature references or Chapter III and actual evapotranspiration (ETa) should preferably be 40 to 50 percent below ETm.

(iii) <u>One or more "mixed treatments" with water deficit during selected individual growth periods only</u> (ETa ≤ ETm, Ya ≤ Ym)

Experimental results obtained under this treatment will provide the actual yield (Ya) and actual evapotranspiration (ETa) under conditions of periodic water deficits. These results allow a quantification of the crop response factor (ky) for the individual growth period (vegetation, flowering, yield formation, ripening) when for the individual growth periods ETa is compared to ETm and Ya is compared to Ym.

Depth and interval of irrigation are based on selected depletion levels of available soil water, e.g. for most grain crops selected levels are 60, 80 and 100 percent of the total available soil water (Sa). Treatment combinations are given in Figure 5. Literature references and Chapter III can be consulted for selecting the depletion levels for different crops and growth periods.
Soil water measurements should be made to record the rate of soil water uptake by the crops. Regular observations should be made on crop development (see check list). From water balance sheets, a measure of ETa can be obtained.
The level of soil water depletion (p) when ETa becomes smaller than ETm can also be determined by plotting ETa against time after irrigation. In order to make results applicable to other soils, the level of soil water depletion (p) should also preferably be expressed in soil water tension (bar) rather than in volume percentage alone.



Irrigation Treatment ETa/ETm

Veg.	Flow	Yield Form	Rip
1	1	1	1
1	1	1	<1
1	1	<1	1
1	1	<1	<1
1	<1	1	1
1	<1	1	<1
1	<1	[illegible]	[illegible]
1	<1	<1	<1
<1	1	1	1
<1	1	1	<1
<1	1	<1	1
<1	1	<1	<1
<1	<1	1	1
<1	<1	1	<1
[illegible]	[illegible]	[illegible]	[illegible]
<1	[illegible]	[illegible]	[illegible]

Fig. 5 Possible combination of irrigation treatments

3. EXPERIMENTAL DESIGN

The experimental design will depend on the number of irrigation treatments and the number of variables other than water to be considered. Statistical handbooks should be consulted on the most appropriate design, e.g. latin square, split-plot design. Number of replications for each treatment is normally four. During the first year a simple plot layout with latin square design with four water treatments and four replications can be used, e.g. for maize:

d_1	a_1	b_1	c_1
b_2	c_2	d_2	a_2
c_3	d_3	a_3	b_3
a_4	b_4	c_4	d_4

Latin square design

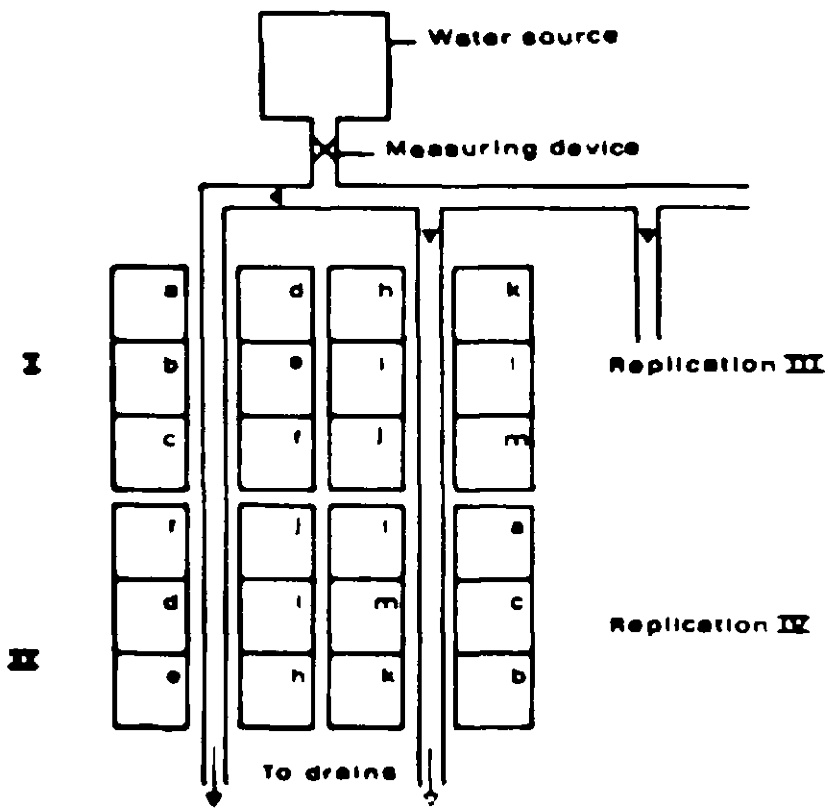
a. no water deficit over the total growing period

b. water depletion to 90% of the available soil water during the vegetative period (1)

c. water depletion to 90% of the available soil water during the yield formation (3) and ripening (4) periods

d. water depletion to 80% of the available soil water during the total growing period

The number of water treatments and/or other variables deemed necessary can be increased during the subsequent years. An example is given of an experimental layout with 12 treatments and 4 replications in a split-plot design.



Experimental layout, split-plot design

The size of the individual plots should be as large as possible with a minimum for most crops of 5 x 10 m. In determining the size of the plots, account must be taken in case of a row crop on exclusion of border rows (2), minimum number of rows required for yield records (5), minimum number of rows required for recording plant development for different growth periods (3), and crop samples for determining dry matter production during different crop growth periods (5). The experimental layout should include provision for irrigation ditches or pipes with measuring devices, drain ditches, access strips between plots and separating borders between plots and ditches to reduce lateral movements of water. Borders between plots should be as narrow as possible.

4. DATA COLLECTION

To allow a full evaluation of the relationship between yield and water use and for experimental data to be useful to other locations, a balanced data set on site, crop, climate, soil and water management must be collected. The data set to be collected depends on the purpose for which it will be used. Full use must be made of related data already available for the area of study. Collection and recording of data should follow a standardized form using an appropriate time scale depending on the event to be recorded.

There is no optimum data set, but there is a minimum data set related to the type of experiment and the purpose for which the data are to be analysed.

An indication of data requirements is given in the following checklist [1]. A subjective subdivision has been made in relation to type of experiment:

I. Field trials remote from research stations for crop performance and comparative analysis at different sites and seasons.

II. Site experiments for crop performance and water use studies for planning and design purposes.

III. Detailed experiments for testing water and crop production models requiring extensive instrumentation, frequent observations and samplings and a balanced set of all relevant data.

Coding includes:	a =	needed	0	once
	b =	desirable	00	before and after growing period
	c =	helpful	1	daily
			7	weekly
			14	fortnightly
			s	selected times
			c	continuous

The checklist is primarily oriented toward grain crops but can, with adjustment, also be applied to other crops.

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[1] Also based on the outcome of the FAO/CSIRO Conference on soil-weather-crop relations, Canberra, May 1976.

CHECKLIST FOR DATA ACQUISITION FROM EXPERIMENTS

LOCATION	:	I, II, III; location name; year/period; latitude; longitude; altitude; surroundings; exposure; slope and relief
CULTURAL OPERATIONS	:	I, II, III; land/plot history; land preparation; fertilizers; weed, pest and disease control; plot layout; irrigation method
CROP MATERIAL	:	I, II, III; crop species and cultivars; seed treatment; sowing rate, depth, and spacing and sowing method; III germination test
CROP HAZARDS	:	I, II, III; pest and disease occurrence; weeds; hail

CLIMATE:

An agrometeorological station should be established at or near the experimental field. The station should be surrounded by an irrigated field of at least 100 x 100 m, covered by a short crop. The station should be at least 10 x 10 m with short grass as ground cover. Minimum observations should include: (i) temperature, maximum and minimum; (ii) relative humidity (wet and dry bulb thermometers); (iii) precipitation (rain gauge); (iv) wind (wind totalizer); (v) sunshine duration (Campbell-Stokes recorder); and (vi) evaporation (class A pan). Radiation measurements at the station or nearby are recommended. Automatic recording instruments such as thermograph and hydrograph can be useful but should be placed within the Stevenson screen, preferably with a non-recording instrument. Where this is not possible, automatic recording instruments should be checked for reliability at frequent intervals. The station should be established in collaboration with the National Meteorological Service. For selection of instruments and observation practices, the national accepted standards are normally followed. (See FAO Irrigation and Drainage Paper No. 27, Agro-meteorological Field Stations, 1976.)

		I	II	III
1.	temperature	a_7	a_1	a_1
2.	humidity max/min	c_7	a_1	a_1
3.	precipitation	a_7	a_1	a_1
4.	wind	c_7	b_1	a_1
	sunshine		b_1	a_1
	radiation		b_1	a_1
	snow	b_s	a_s	a_s
	soil temperature		b_1	a_1

SOIL:

Detailed soil information is required which, in addition to general information (parent material, drainage, presence of stones or rock outcrops, evidence of erosion, micro-relief and slope) should include a description of the individual soil horizons (see Guidelines for Soil Description, FAO, MI 70805).

	I	II	III
soil type	a_o	a_o	a_o
soil texture	a_o	a_o	a_o
bulk density	c_o	a_o	a_o
fertility	c_{oo}	b_{oo}	a_{oo}
pH	c_{oo}	b_{oo}	a_{oo}
available water	b_o	a_o	a_o
retention curve	c_o	a_o	a_o
infiltration rate	b_o	a_o	a_o
hydraulic conductivity		b_o	a_o
ECe	b_o	a_{oo}	a_{oo}
SAR	c_o	b_o	a_o

WATER:

Measurements include soil water and in and outflow of water. Significant results of experiments depend almost exclusively on the accuracy with which the measurements are carried out.

Soil water measurements are carried out by: (i) soil water sampling for each treatment at different soil depth (soil layers); and (ii) tensiometers (range 10 to 70 cbar or up to about 40 percent depletion level) and gypsum blocks (range 30 to 90 percent soil water depletion) installed at different soil depths for each treatment with 2 to 3 replications per plot. Readings should be made daily and using averages for each plot and each treatment. Design with four treatments and four replications would require about 100 devices (4 treatments, 2 or 3 replications, 3 locations per plot at 3 depths). For determining the water balance the amount of irrigation water applied, drain outflow, and effective rainfall must be measured by flumes (open conducts), flow or venturi-meters (closed conducts) and rain gauges.

	I	II	III
soil water volume	b_{oo}	a_s	a_s
tension		a_s	a_s
groundwater			
depth	b_{oo}	a_{14}	a_{14}
quality	b_{oo}	a_{oo}	a_{14}
application			
depth	b_c	a_c	a_c
frequency	b_c	a_c	a_c
efficiency	b_o	a_s	a_s
water quality	b_o	a_{14}	a_{14}
temperature	b_o	a_{14}	a_{14}
in/out flow	a_c	a_c	a_c

CROP DEVELOPMENT:

Adequate records should be made on dates of crop development periods for each treatment requiring almost daily inspection together with crop observations, e.g. wilting, stunted growth.

	I	II	III
date of sowing	a_o	a_o	a_o
emergence	c_o	a_o	a_o
10% cover	c_o	a_o	a_o
full cover	b_o	a_o	a_o
flower initiation		b_o	a_o
50% flowering	c_o	a_o	a_o
ripening	a_o	a_o	a_o
harvest	a_o	a_o	a_o

CROP GROWTH AND YIELD:

For analysing yield response to water, crop observations and crop samples during the growing period are required since final yield alone frequently provides an insufficient indication on crop growth and yield of the effect of water deficit during different growth periods.

	I	II	III
plants /m²	b_o	a_o	a_o
tillers/plant	c_o	b_o	a_o
head bearing tillers	c_o	b_o	a_o
LAI		b_s	a_s
crop height	b_s	a_s	a_s
sample for dry matter at flower initiation		b_o	a_o
50% flowering		b_o	a_o
ripening		b_o	a_o
harvest	b_o	a_o	a_o
economic yield	a_o	a_o	a_o
1000 grain weight	c_o	b_o	a_o
grain quality	c_o	b_o	a_o
seed/head	c_o	b_o	a_o
seed/plant	c_o	b_o	a_o
root/plant		c_o	a_o
root development/depth	c_o	b_o	a_s

5. EVALUATION AND PRESENTATION OF RESULTS

All collected data should be examined individually for accuracy, reliability and consistency. Differences between treatments are to be analysed statistically. The relationships between yield and water deficit can be evaluated in a manner similar to that given in this publication. If the yield-water relationships show a wide variation within treatments, and if the yield response factors (ky) are markedly different from those presented, a further evaluation and interpretation of the results should be conducted in the light of limiting factors that may have been overlooked, e.g. an experiment conducted with unadpated varieties or with hidden adverse effects from poor soil or with conditions or excessively high evapotranspiration.

The presentation of the final evaluation of the results will depend on the nature of the user. The presentation to planners, engineers, agronomists, should include the appropriate supporting research information obtained during the course of the experiment, whereas presentation to farmers should adopt a more practical approach whereby the results are expressed in clear guidelines on depth and interval of irrigation water as related to expected yields. This may also take the form of actual demonstration on the farm.

PART B

CROP AND WATER

ALFALFA

Alfalfa (Medicago sativa) is believed to have originated in the Mediterranean region. It is grown as a forage crop, either for fresh produce or for hay. The crop is grown under a wide range of climates where average daily temperature during the growing period is above 5°C. The optimum temperature for growth is about 25°C and growth decreases sharply when temperatures are above 30°C and below 10°C. In warm climates the production is higher under dry as compared to humid conditions. Alfalfa can be used as an important break crop in the rotation and most crops can follow alfalfa with the exception of certain root crops such as sugarbeet, because of the high amount of root residue left in the soil.

Alfalfa is a perennial crop and produces its highest yields during the second year of growth. In climates with mild winters, alfalfa is grown for 3 to 4 years continuously, but in continental climates with cold winters it is grown for 6 to 9 years, with a dormant period in winter. The crop is also grown as a short season annual crop. Following seeding, the crop takes about 3 months to establish. Number of cuts varies with climate and ranges between 2 and 12 per growing season. Also, yield per cut for a given location varies over the year due to climatic differences.

Water use by the crop in relation to its production is high when compared to other forage crops such as forage maize, and when economic conditions permit alfalfa is replaced by maize as a forage crop.

Alfalfa is successfully grown on a wide variety of soils, with deep, medium textured and well-drained soils being preferred. Fertilizer requirements vary with production level and are 55 to 65 kg/ha P and 75 to 100 kg/ha K.[1] Alfalfa is capable of fixing atmospheric nitrogen which meets its requirements for high yields. However, a starter of approximately 40 kg N is beneficial for good, early growth.

The crop is moderately sensitive to soil salinity. Yield decrease related to electrical conductivity (ECe of extraction saturated paste in mmhos/cm) is: 0% at ECe 2.0 mmhos/cm, 10% at 3.4, 25% at 5.4, 50% at 8.8, and 100% at ECe 15.5 mmhos/cm.

WATER REQUIREMENTS

Crop water requirements (ETm) are between 800 and 1 600 mm/growing period depending on climate and length of growing period. The variation in water requirements in each cutting interval for alfalfa is similar to that during the total growing period from sowing to harvest for other crops. The kc value is about 0.4 just after cutting, increasing to 1.05 to 1.2 just priot to the next cutting with a mean value of 0.85 to 1.05. For seed production, the kc value is equal to 1.05 to 1.2 during full cover until the middle of flowering, after which the kc value is reduced sharply.

1/ Fertilizer requirements (kg nutrient/ha) of high-producing varieties under irrigation; accurate amounts are to be obtained from local research results or to be determined by experiments, soil testing and plant analysis and evaluation of economic conditions. Conversion: 1 kg P = 2.4 kg P_2O_5, 1 kg K = 1.2 kg K_2O.

WATER SUPPLY AND CROP YIELD

To stimulate root growth, the young stand should be irrigated frequently because root development is adversely affected by dryness. During each cutting interval the amount of total green matter produced increases to a maximum at the start of flowering when the quality for hay production is also at its best. To enhance growth, irrigation is normally applied just after cutting. When irrigation is applied just before cutting the top soil may still be wet at the time of cutting, hampering cutting and causing the cut material to mould more easily.

Excess irrigation may cause reduced soil aeration which is particularly harmful to the crop. During winter, when the crop is dormant or growing very slowly, the crop will tolerate short periods of flooding without causing much damage to the later growth of the crop.

The relationship between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration deficit (1 - ETa/ETm) is given in Figure 6. Within a certain range of relative evapotranspiration deficit (0 to 0.4), the yield response factor (ky) for both fresh and dry yield is smaller than one. This implies that water utilization efficiency (Ey) (kg of produce/m^3 of water) increases in this range of relative water deficit. Under conditions of limited water supply, overall production is increased by extending the area under irrigation rather than by meeting full crop water requirements over a limited area. Also, the effect of a reduced water supply on yield of alfalfa is less pronounced than that of many other crops that have ky values greater than one during the period of water shortage. Where cropping of several crops is involved, the irrigation supply to alfalfa may be reduced in favour of more sensitive crops.

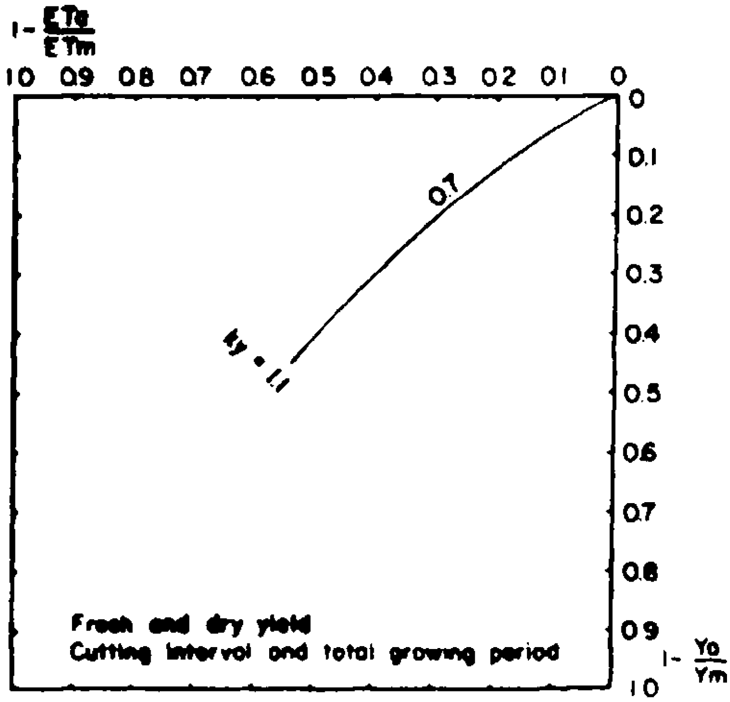


Fig. 6

Relationship between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration deficit (1 - ETa/ETm) for alfalfa

For calculation example see p. 40 and Chapter VI.

To reduce peak demands for water during the hot summer months, a dormancy period during these months is sometimes practised in North Africa. Water savings are utilized during spring and autumn when climatic conditions allow high yields with relatively lower water requirements. Where the crop is grown for seed, effective water savings may be made by timing the seed production during the period when normal water demands of a forage crop would be high.

The 'drought tolerance' of alfalfa, sometimes claimed during periods of low water requirements, appears to be due to its extensive rooting system which enables the crop to draw water from a large soil volume.

CUTTING INTERVAL

Cuts are normally taken at the start of flowering when the vegetative growth slows down. Temperature has a pronounced effect on cutting interval and cutting interval at different mean daily temperatures is:

Tmean, °C	10	15	20	25	30	[illegible]
Interval, days	(100)	50	35	25	20	18

When water and other growth factors are not limiting, a first indication of the time and number of cuts for a given location can be obtained from the summation of daily mean temperature (T) above 5°C and the time of cut is found when the sum $T - 5 = 500$ to 550 degree days (for example see Figure 7).

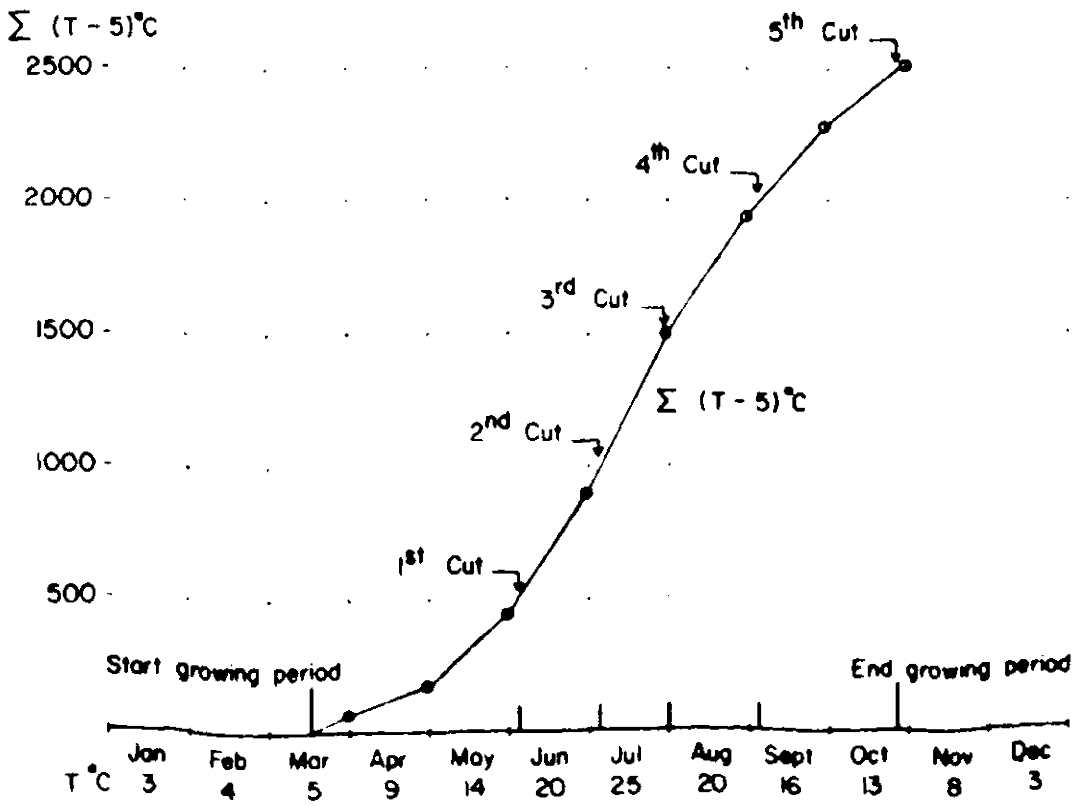


Fig. 7 Example of cutting interval over the growing period of alfalfa

WATER UPTAKE

Alfalfa has a deep rooting system extending up to 3 m in deep soils. The maximum root depth is reached after the first year. The crop can draw water from great soil depth and little response to irrigation has been shown with groundwater tables at 2 m or higher. Normally, when the crop is fully grown, 100 percent of the water is extracted from the first 1 to 2 m soil depth (D = 1-2 m). When maximum evapotranspiration (ETm) is 5 to 6 mm/day, about 50 percent of the total available soil water can be depleted before the uptake of water from the soil affects crop evapotranspiration (or p = 0.5). After cutting full cover is reached in 12 to 20 days depending on temperature, and peak ETm is reached soon after.

IRRIGATION SCHEDULING

To obtain maximum yields under conditions where water supply is not limited, an adequate supply to meet crop water requirements during the whole cutting interval is advisable. Irrigation practice for hay production varies with an application just after cutting to enhance rapid growth, or at the time when the crop is reaching full cover and water requirements are near maximum. Irrigation immediately following removal of the cut crop is often practised on land difficult to irrigate. Late application may result in soil remaining wet, thus delaying the drying of hay on the ground. For conditions free from water stress and depending on the level of maximum evapotranspiration (ETm), a soil water depletion level of about 50 percent of the total available soil water (p = 0.5) is permissible.

IRRIGATION METHODS

Surface irrigation is commonly used in alfalfa production. The most common method is border irrigation. Contour irrigation and wild flooding are sometimes practised. Where water is scarce or the soil permeability is high, water is supplied by overhead sprinkling.

YIELD

Crop yield varies with climate and length of total growing period. Good yields after the first year are in the range of 2 to 2.5 tons/ha per cut (hay with 10 to 15 percent moisture) of about 25 to 30 day cutting interval. For example, Hofuf, Saudi Arabia, 28 ton/ha of hay over 310 days involving 12 cuts; Davis, California, under experimental conditions, 22 ton/ha of hay over 200 day growing period involving 7 cuts. The water utilization efficiency for harvested yield (Ey) of hay with 10 to 15 percent moisture is 1.5 to 2.0 kg/m³ after the first year. The moisture content of fresh green matter is about 80 percent. From 18 to 20 percent of the dry weight is protein.

BANANA

Banana (Musa spp.) is one of the most important tropical fruits. Ripe banana fruits are sugary and eaten raw; unripe fruits, called plantains, are cooked and provide a starchy food with nutritional value similar to potato. Total world production of banana is about 39 million tons of fresh fruit.

The cultivated banana is believed to have originated in the lowland, humid tropics in Southeast Asia and is mostly grown between 30°N and S of the equator. A mean temperature of about 27°C is optimal for growth. Minimum temperature for adequate growth is about 16°C, below which growth is checked and shooting delayed. Temperatures below 8°C for long periods cause serious damage. Maximum temperature for adequate growth is about 38°C, depending on humidity and the radiation intensity. Bananas are day-neutral in their response to daylength.

A humidity of at least 60 percent or more is preferable. Strong winds, greater than 4 m/sec, are a major cause of crop loss due to the pseudostems being blown down. Under high wind conditions windbreaks are desirable.

Bananas can be grown on a wide range of soils provided they are fertile and well-drained. Stagnant water will cause diseases such as the Panama disease. The best soils are deep, well-drained loams with a high water holding capacity and humus content. Optimum pH is between 5 and 7. The demands for nitrogen and especially potash are high. Since the early stages of growth are critical for later development, nutrients must be ample at the time of planting and at the start of a ratoon crop. Short intervals between fertilizer applications, especially nitrogen, are recommended. Fertilizer requirements are 200 to 400 kg/ha N, 45 to 60 kg/ha P and 240 to 480 kg/ha K per year.

Banana is very sensitive to salinity and soils with an ECe of less than 1 mmho/cm are required for good growth.

Banana, 2 to 9 m tall, bears leaves on a pseudostem consisting of leaf stalks. The flowering stalk emerges (shooting) from the pseudostem and produces a hanging bunch of flowers. Fruits are formed on 'hands' with about 12 fingers; each bunch contains up to 150 fingers. After harvest the pseudostem is cut. The underground stem (corm or rhizome) bears several buds which, after sprouting, form new pseudostems, or so-called suckers. They are removed except for one or two which provide the ratoon crop.

Banana is normally multiplied vegetatively. Several types of suckers can be used. The development of the plant can be divided into three periods: vegetative, flowering and yield formation. The time from planting to shooting (vegetative) is about 7 to 9 months, but with lower temperatures at higher altitudes or in the subtropics, up to 18 months. The time from shooting to harvest (flowering and yield formation) is about 90 days. In tropical lowlands the time to harvest of the next ratoon crop is about 6 months. The number of ratoons varies. The average life of a commercial plantation can be from 3 to 20 years; with mechanical cultivation the economic life is often 4 to 6 years. Some varieties are replanted after each harvest.

Planting distances vary according to variety, climate, soil and management and are between 2 x 2 m and 5 x 5 m, corresponding to a density of 400 to 2 500 plants/ha. On steep slopes contour planting is practised. The crop is sometimes interplanted or is used as a nurse crop for crops such as cocoa.

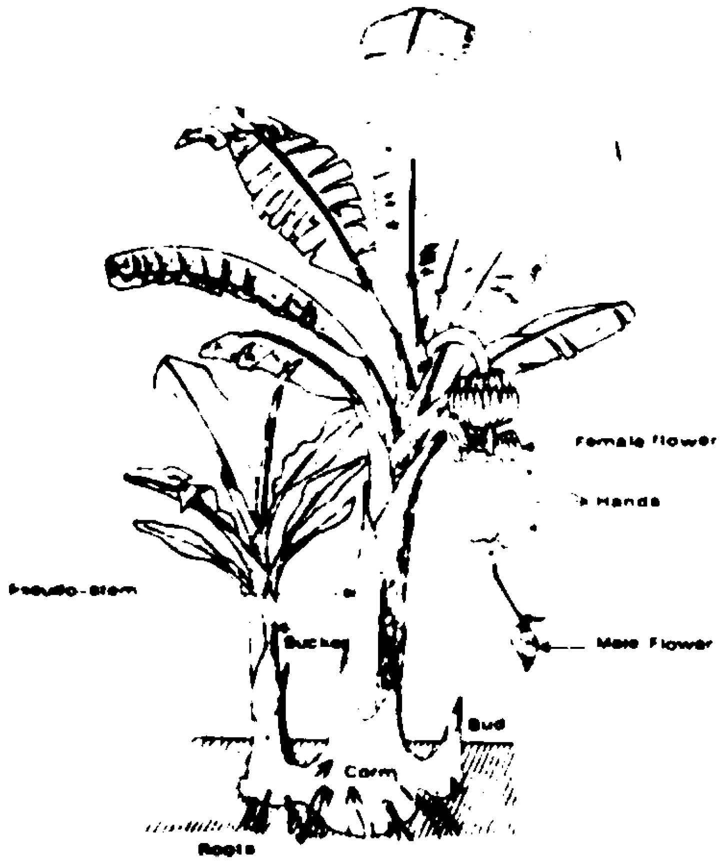


Fig. 8
Development of banana (Champion, 1963)

WATER REQUIREMENTS

Being a long duration crop, the total water requirements of banana are high. Water requirements per year vary between 1 200 mm in the humid tropics to 2 200 in the dry tropics. For rainfed production, average rainfall of 2 000 to 2 500 mm per year, well-distributed, is desirable, but banana often grows under less rainfall.

In relation to reference evapotranspiration (ETo) the maximum water requirements (ETm) can be determined with the crop coefficient (kc), or ETm = kc.ETo.

	kc											
	J	F	M	A	M	J	J	A	S	O	N	D
Subtropical climate												
First-year crop, March planting:												
Humid, light to mod. wind	-	-	.65	.6	[illegible]	[illegible]	.7	.85	.95	1.0	1.0	1.0
Dry, strong wind	-	-	.5	.45	.5	.65	.8	1.0	1.15	1.2	1.15	1.15
Second with ratoon starting in February:												
Humid, light to mod. wind	1.0	.8	.75			.75	.9	1.05	1.05	1.05	1.0	1.0
Dry, strong wind	1.15	.7	.75		[illegible]	.9	1.1	1.25	1.25	1.25	1.2	1.2

Tropical climate

Months following planting:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	.4	.4	.45	.5	.6	.7	.85	1.0	1.1	1.1	.9	.8	.8	.95	[illegible]
	suckering						shooting				harvesting				

WATER SUPPLY AND CROP YIELD

Banana requires an ample and frequent supply of water; water deficits adversely affect crop growth and yields. The establishment period and the early phase of the vegetative period (0-1) determine the potential for growth and fruiting and an adequate water and sufficient nutrient supply is essential during this period. Water deficits in the vegetative period (1) affect the rate of leaf development, which in turn can influence the number of flowers in addition to the number of hands and bunch production.

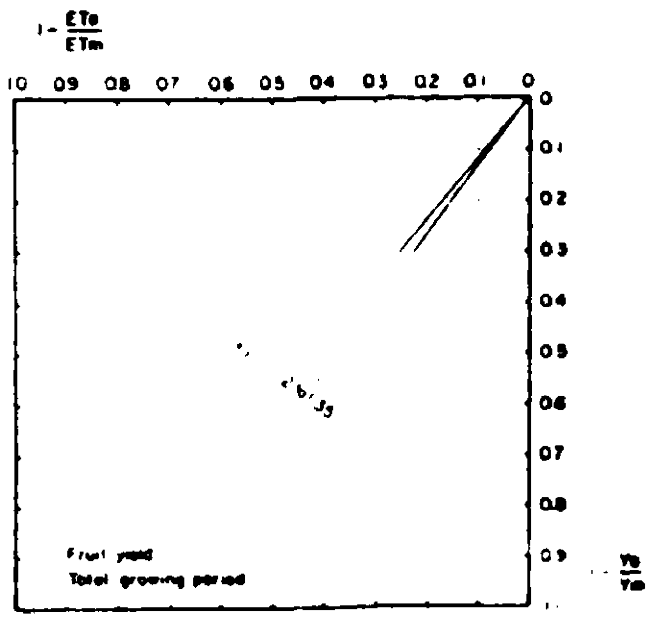
The flowering period (2) starts at flower differentiation, although vegetative development can still continue. Water deficits in this period limit leaf growth and number of fruits.

Water deficits in the yield formation period (3) affect both the fruit size and quality (poorly filled fingers). A reduced leaf area will reduce the rate of fruit filling; this leads, at harvest time, to bunches being older than they appear to be and consequently the fruits are liable to premature ripening during storage.

The ratio between relative yield decrease and relative evapotranspiration deficit (ky) is 1.2 to 1.35, with little difference between different growth periods (Fig. 9). For calculation examples see p. 40 and Chapter VI.

Fig. 9

Relationship between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration deficit (1 - ETa/ETm) for banana



Regular water supply under irrigation over the total growing season as compared to rainfed production with seasonal differences in water supply produces taller plants, with greater leaf area, and results in earlier shooting and higher yields. Interval between irrigation has a pronounced effect on yields, with higher yields being achieved when intervals are kept short. Under conditions of limited water supply, total production will be higher when full crop water requirements are met over a limited area than when crop water requirements are partially met over an extended area.

WATER UPTAKE

The banana plant has a sparse, shallow root system. Most feeding roots are spread laterally near the surface. Rooting depth will generally not exceed 0.75 m. In general 100 percent of the water is obtained from the first 0.5 to 0.8 m soil depth (D = 0.5-0.8 m) with 60 percent from the first 0.3 m. With maximum evapotranspiration (ETm) of 5 to 6 mm/day, a 35 percent depletion of the total available soil water should not be exceeded (p = 0.35).

IRRIGATION SCHEDULING

Since a depletion of total available soil water in excess of about 35 percent during the total growing period is harmful to growth and fruit production, frequent irrigation is important. The irrigation interval will depend on ETm and the soil water holding capacity in the rooting depth and may vary from 3 days under high evaporative conditions and light soils up to 15 days under low evaporative conditions and high water retaining soils. When rainfall and irrigation water is limited, it is advantageous to reduce the depth of each water application rather than to extend the irrigation interval.

IRRIGATION METHODS

Overhead sprinkler systems with small application at frequent intervals are commonly used in commercial banana plantations. Surface irrigation methods include the basin, furrow or trench irrigation systems. The trench system also serves as a drain during the rainy periods. Also drip irrigation is used; with drip irrigation under conditions of high evaporation, low rainfall and particularly when irrigation water contains even a small amount of salt, accumulation of salts at the boundary of wet and dry soil area will occur. Under such conditions leaching will often be needed since banana plants are highly salt-sensitive and damage to the crop can otherwise easily occur.

YIELD AND QUALITY

Yields can vary enormously. Under poor management yields are usually highest for the planted (first) crop and decline for the ratoon crops. Under intensive management with correct desuckering and control of pests and diseases, yields from the first ratoons are usually higher than for the plant crop. Good commercial yields of banana are in the range of 40 to 60 ton/ha. The water utilization efficiency for harvested yield (Ey) of fruits, containing about 70 percent moisture, is 2.5 to 4 kg/m³ for the plant crop and 3.5 to 6 kg/m³ for ratoon crops.

BEAN

Common bean (Phaseolus vulgaris) is known under different names (French bean, kidney bean, snap bean, runner bean, string bean). It can be grown as a vegetable crop for fresh pods or as a pulse crop for dry seed. World production of dry beans is about 18.7 million tons from about 30 million ha and green beans 2.2 million tons from 0.4 million ha.

Common bean grows well in areas with medium rainfall, but the crop is not suited to the humid, wet tropics. Excessive rain and hot weather cause flower and pod drop and increase the incidence of diseases. Optimum mean daily temperatures range between 15 and 20°C. The minimum mean daily temperature for growth is 10°C, the maximum 27°C. High temperatures increase the fibre content in the pod. Germination requires a soil temperature of 15°C or more, and at 18°C germination takes about 12 days, and at 25°C about 7 days. Most bean varieties are not affected by daylength. The length of the total growing period varies with the use of the product and is 60 to 90 days for green bean and 90 to 120 days for dry bean.

The crop does not have specific soil requirements but friable, deep soils with pH of 5.5 to 6.0 are preferred. Fertilizer requirements for high production are 20 to 40 kg/ha N, 40 to 60 kg/ha P and 50 to 120 kg/ha K. Bean is capable of fixing nitrogen which can meet its requirements for high yields. However, a starter dose of N is beneficial for good early growth. The crop is sensitive to soil-borne diseases and should be grown in a rotation; in the subtropics in the USA wheat, sorghum, onion and potato are common rotation crops, whereas in tropical Africa and Asia maize, sweet potato and cotton are common.

Normal sowing depth is about 5 to 7 cm. Spacing depends on variety. Bush types (erect) normally have a plant and row spacing of 5 to 10 x 50 to 75 cm, while pole-type (climbing) are 10 to 15 x 90 to 150 cm. Pole beans are also often grown on hills spaced 90 to 120 cm apart. Other spacings are possible, and these depend on the method of harvest.

Common bean is sensitive to soil salinity. The yield decrease at different levels of ECe is: 0% at ECe 1.0, 10% at 1.5, 25% at 2.3, 50% at 3.6 and 100% at ECe 6.5 mmhos/cm.

WATER REQUIREMENTS

Water requirements for maximum production of a 60 to 120-day crop vary between 300 and 500 mm depending on climate. The water requirements during the ripening period depend very much on whether the pod is harvested wet or dry. When grown for its fresh product, the total growing period of the crop is relatively short and during the ripening, which is about 10 days long, the crop evapotranspiration is relatively small because of the drying of the leaves. When the crop is grown for seed the ripening period is longer and the decrease in crop evapotranspiration is relatively greater. The growing period depends on the number of pickings, and when 3 or 4 pickings are taken the harvest period is 20 to 30 days. Crop coefficient (kc) relating reference evapotranspiration (ETo) to water requirements (ETm) for different development stages is, for common bean, green: during the initial stage 0.3-0.4 (15 to 20 days); the development stage 0.65-0.75 (15 to 20 days); the mid-season stage 0.95-1.05 (20 to 30 days); the late-season stage 0.9-0.95 (5 to 20 days) and at harvest 0.85-0.9. For common bean, dry, the kc value is: during the initial stage

0.3-0.4 (15 to 20 days); the development stage 0.7-0.8 (15 to 20 days); the mid-season stage 1.05-1.2 (35 to 45 days); the late-season stage 0.65-0.75 (20 to 25 days); and at harvest 0.25-0.3.

WATER SUPPLY AND CROP YIELD

Water supply needed for maximum yield for both fresh and dry produce is similar during much of the growing period but varies during the ripening period. For green beans supply is continued just prior to the last picking, but for dry bean it is discontinued about 20 to 25 days before crop harvest. With one picking only the harvest period is concentrated. This can be achieved to some extent by the timing of water supply so as to induce a slight water deficit to the crop during the ripening period and a soil water depletion to about 50 percent of the total available water may hasten the onset of maturity. Concentration of the harvest period is more easily achieved for bush than for pole types. The former normally have a more uniform ripening period.

The growth periods of a common bean crop are:

		green bean	dry bean
0	establishment	10-15 days	10-15 days
1	vegetative (up to first flower)	20-25	20-25
2	flowering (including pod setting)	15-25	15-25
3	yield formation (pod development and bean filling)	15-20	25-30
	ripening	0-5	20-25
		60-90	90-120 days

The relationships between relative yield decrease and relative evapotranspiration deficit are given in Figure 10. For calculation examples see p. 40 and Chapter VI.

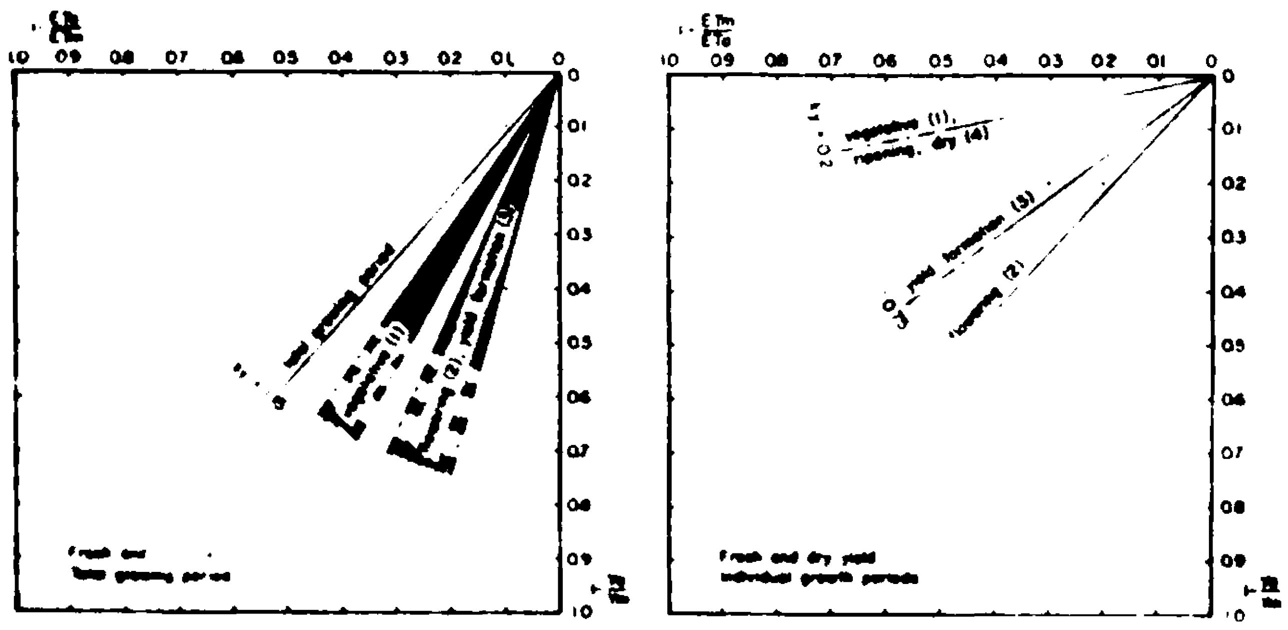


Fig. 10 Relationship between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration deficit (1 - ETa/ETm) for bean

However, a severe water deficit during the vegetative period (1) generally retards plant development and causes non-uniform growth.

During flowering (2) and yield formation (3) frequent irrigation results in the highest response to production, although excess water increases the incidence of diseases, particularly root rot. When nitrogen is supplied to the crop in the form of mineral fertilizer, irrigation should be accompanied by adequate application of nitrogen fertilizer in order to maximize yield.

When water supply is limited, some water savings could be made during the vegetative period (1) and, for dry bean, also during the ripening period without greatly affecting yield, provided water deficits are moderate. Total production is higher when full crop water requirements are met over a limited area than when the cultivated area is extended under limited supply conditions.

WATER UPTAKE

The tap root of the bean plant may reach a depth of 1 to 1.5 m. The lateral root system is extensive and is mainly concentrated in the first 0.3 m. At emergence, the rooting depth is about 0.07 m, at the start of flowering 0.3 to 0.4 m, and at maturity 1 to 1.5 m. Water uptake occurs mainly in the first 0.5 to 0.7 m depth (D = 0.5-0.7 m). Under conditions when ETm is 5 to 6 mm/day, 40 to 50 percent of the total available soil water can be depleted before water uptake is affected (p = 0.4-0.5).

IRRIGATION SCHEDULING

When the bean crop is grown with supplemental irrigation, water supply should be directed toward meeting water requirements during the establishment period (0) and the early part of the flowering period (2). When the crop is grown under full irrigation, the soil water depletion during the flowering (2) and yield formation (3) periods should not exceed 40 to 50 percent of the total available soil water (p = 0.4-0.5). When the crop is grown for dry seed the depletion level during the ripening period (4) should not exceed 60 to 70 percent. Water stress in the plant can be detected by eye because the leaves turn dark bluish-green in colour.

YIELD AND QUALITY

Water deficit during the yield formation period (3) gives rise to small, short discoloured pods with malformed beans. Also, the fibre content of the pods is higher and seeds lose their tenderness. Good commercial yield in favourable environments under irrigation is 6 to 8 ton/ha fresh and 1.5 to 2 ton/ha dry seed. The water utilization efficiency for harvested yield (Ey) for fresh bean containing 80 to 90 percent moisture is 1.5 to 2.0 kg/m^3 and for dry bean containing about 10 percent moisture, 0.3 to 0.6 kg/m^3.

CABBAGE

Cabbage (*Brassica oleracea* var. *capitata*) originates from the south and western coast of Europe. Annual world production is about 21 million tons of fresh heads from 1.1 million ha.

For high production the crop requires a cool, humid climate. The length of the total growing period varies between 90 (spring-sown) and 200 (autumn-sown) days, depending on climate, variety and planting date, but for good production the growing period is about 120 to 140 days. Most varieties can withstand a short period of frost of -6°C, some down to -10°C. Long periods (30 to 60 days) of -5°C are harmful. The plants with leaves smaller than 3 cm will survive long periods of low temperature but when the leaves are 5 to 7 cm, the plant will initiate a seed stalk and this leads to a poor quality yield. Optimum growth occurs at a mean daily temperature of about 17°C with daily mean maximum of 24°C and minimum of 10°C. Mean relative humidity should be in the range of 60 to 90 percent.

Generally, the heavier loam soils are more suited to cabbage production. Under high rainfall conditions, sandy or sandy loam soils are preferable because of improved drainage. The fertilizer requirements are high: 100 to 150 kg/ha N, 50 to 65 kg/ha P and 100 to 130 kg/ha K.

Cabbage is moderately sensitive to soil salinity. Yield decrease due to soil salinity at different levels of ECe is: 0% at ECe 1.8, 10% at 2.8, 25% at 4.4, 50% at 7.0 and 100% at ECe 12.0 mmhos/cm

Row spacing is dependent on the size of heads required for markets or between 0.3 and 0.5 m for heads of 1 to 1.5 kg each and 0.5 and 0.9 m for heads up to 3 kg each. An optimum production can be reached with a plant density in the range of 30 000 to 40 000 plants/ha. Planting can be by direct seeding with a seed rate of 3 kg/ha, or by transplanting from open field beds and from cold frames which are used to protect the crop from cold during germination and early plant development.

ull-grown cabbage

Cabbage is characterized by slow development during the first half of the growing period, which may be 50 days for early maturing and up to 100 for autumn-sown, late maturing varieties (establishment and vegetative periods, 0 and 1). During the following periods (yield formation and ripening periods, 3 and 4) the plant doubles its weight approximately every 9 days over a total period of 50 days. In the beginning of the yield formation period (3), head formation starts, followed by a sudden decrease in the rate of leaf-unfolding. Eventually, leaf unfolding ceases completely, whilst leaf initiation continues. This results in the formation of a restrictive skin by the oldest folded leaves within which younger leaves continue to grow until the firm, mature head is produced during the ripening period of 10 to 20 days (4). Depending on variety, the head can be pointed or round, green or red, smooth or crinkled. Crop rotation of at least 3 years is recommended to combat soil-borne diseases.

WATER REQUIREMENTS

Water requirements vary from 380 to 500 mm depending on climate and length of growing season. The crop transpiration increases during the crop growing period with a peak toward the end of the season. In relation to the reference evapotranspiration (ETo), the crop coefficient (kc) for cabbage is: during the initial stage 0.4-0.5 (20 to 30 days); the crop development stage 0.7-0.8 (30 to 35 days); the mid-season stage 0.95-1.1 (20 to 30 days), the late season stage 0.9-1.0 (10 to 20 days); and at harvest 0.8-0.95.

WATER SUPPLY AND CROP YIELD

The relationships between relative yield decrease and relative evapotranspiration deficit based on interpreted information are given in Figure 12. The response to water supply increases with development of the crop. During the slow development in the vegetative period (1), the crop yield is little affected by water deficit. Once rapid growth during yield formation period (3) is reached, the yield depressing effect of limited water supply becomes increasingly pronounced until the end of the growing period. Under conditions of limited water supply, a high total production is obtained by extending the area and partially meeting crop water requirements rather than by meeting full crop water requirements over a limited area.

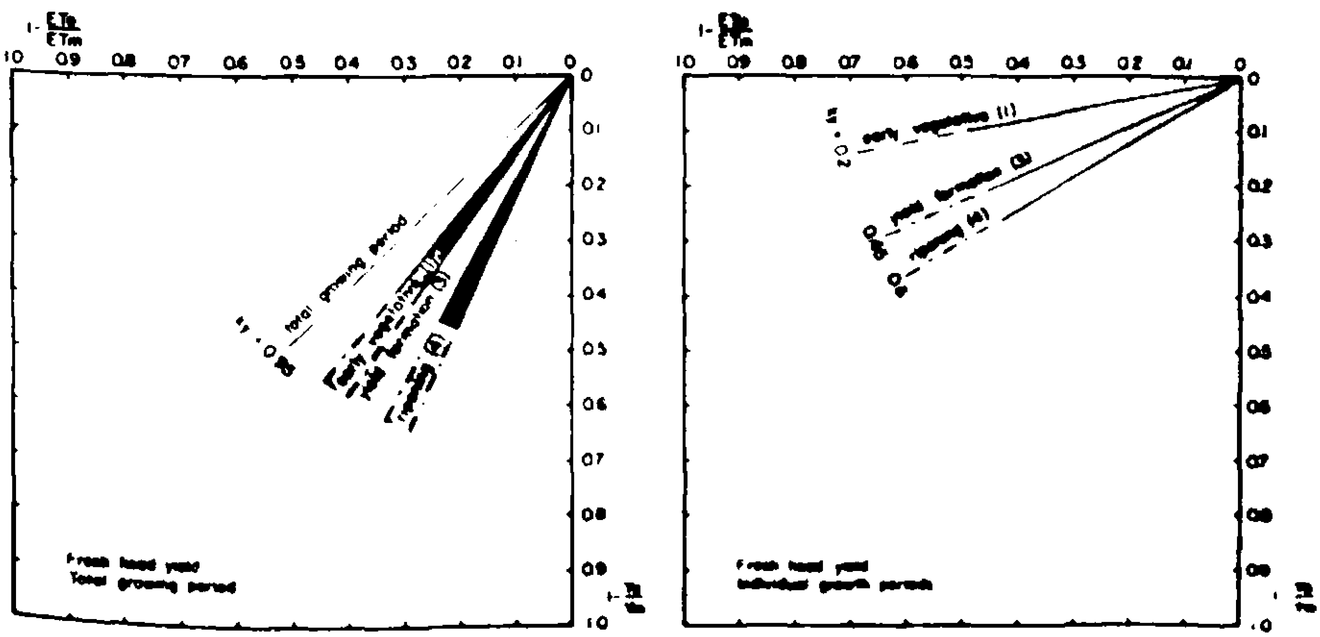


Fig. 12 Relationship between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration (1 - ETa/ETm) for cabbage

WATER UPTAKE

Cabbage has an extensive, shallow root system. The majority of the roots are found in the top 0.4 to 0.5 m of the soil with a rapid decrease in root density with depth. Normally 100 percent of the water is extracted from this layer (D = 0.4-0.5 m). Under conditions when ETm = 5 to 6 mm/day, the rate of water uptake by the crop starts to reduce when the available soil water has been depleted by about 35 percent (p = 0.35).

IRRIGATION SCHEDULING

Depending on climate, crop development and soil type, the frequency of irrigation varies between 3 and 12 days. If available water supply is limited, early irrigations should not be practised unless these can be continued until the end of the crop growing period. Water savings should preferably be made in the beginning of the crop growing period.

IRRIGATION METHODS

Furrow, sprinkler and trickle irrigation are used. However, the acreage under subsoil irrigation, which gives generally better results, is increasing. With subsoil irrigation, the depth of the water table is maintained between 0.3 and 0.7 m in fine, sandy loam and between 0.7 and 1.1 m in loam soils.

YIELD AND QUALITY

Under rainfed conditions, yields of 25 to 35 ton/ha fresh heads are normal, with a maximum of about 50 ton/ha when sprayed and well-fertilized. Under ideal climatic conditions and good irrigation and crop management, yields can be as high as 85 ton/ha. The utilization efficiency for harvested yield (Ey) for heads is about 12 to 20 kg/m^3.

The average water content of cabbage heads is about 90 percent, with a high vitamin B, C and calcium and phosphorous content. Smaller heads of poor quality are produced when the crop is grown under limited water supply, particularly during the later part of the growing period.

CITRUS

Citrus species are perennial in growth habit. The most commonly cultivated species are Citrus aurantifolia (lime), Citrus aurantium (sour or Seville orange), Citrus grandis (pummelo, shaddock), Citrus limon (lemon), Citrus medica (citron), Citrus paradisi (grapefruit), Citrus reticulata (mandarin, tangerine) and Citrus sinensis (sweet orange). Present world production of citrus is about 50 million tons of fresh fruit, of which 70 percent is orange, 14 percent mandarin and tangerine, 9 percent citron, lime and lemon and 7 percent grapefruit. The quantity of fresh fruit entering international trade is only exceeded by banana.

Citrus originates from the wet tropics in Southeast Asia, but large-scale commercial production is found in the subtropics under irrigation. In addition to fresh fruit and juice, citrus is grown for production of oil and citric acid.

Citrus trees normally start bearing fruit from the third year after planting, but economic yields are generally obtained from the fifth year onward. For flowering in spring a period of rest or reduced growth is needed. In the subtropics the low winter temperature induces this rest period, but in the absence of sufficient chilling, the rest period can be induced by water deficits.

Only a small percentage of the flowers produce mature fruits; during the flowering period fall of the weaker younger fruits occurs naturally and this is called 'June drop' in the northern or the 'December drop' in the southern hemisphere. Fruits take 7 to 14 months from flowering to maturity, corresponding to a harvest season from October/November to May/June in the northern hemisphere and from April/May to November/December in the southern hemisphere. Lemons, however, have a longer flowering period and are harvested throughout the year. For most cultivars, pollination is necessary for fruit development.

During ripening the amount of acid decreases while the sugar and aromatic substances increase. The fruit is of prime quality when sugar content is high. Picking takes place when the fruits are fully mature. Colour is not always an indication of fruit maturity. Degreening is conditioned by a period of cool weather. Green, mature fruits are obtained in the humid tropics, and with early or late season harvests in the subtropics. In the subtropics, fruits that have attained full colour, yellow or orange, in late autumn or early winter have been known to turn green again in spring, when not harvested. Fruits in the humid tropics tend to be large with thin, smooth rinds, a high juice content and lower total soluble solids and acid concentration.

Citrus is cultivated between 40°N and 40°S, up to 1800 m altitude in the tropics and up to 750 m altitude in the subtropics. For large-scale production geared toward export markets the crop is not suited to humid tropics because in addition to the difficulty of achieving the right fruit colour, humidity increases the incidence of pests and diseases. Only mandarins will tolerate humid conditions to a certain extent.

The optimum mean daily temperature for growth is 23 to 30°C. Growth is markedly reduced above 38°C and below 13°C. Active root growth occurs when soil temperatures are higher than 12°C. Most citrus species tolerate light frost for short periods only. Injury is caused by a temperature of -3°C occurring over several hours. Temperatures of -8°C cause branches to wither and -10°C generally kills the tree entirely. Flowers and young fruits are particularly sensitive to frost and are shed after very short periods of temperatures slightly below 0°C. Dormant trees are less susceptible to frost. Strong wind is harmful to citrus trees because flowers and young fruits fall easily; windbreaks are provided where necessary.

Citrus is grown on soils that are sufficiently aerated and deep to allow tap roots to penetrate to the desired depths (1-2 m). Light to medium textured soils, free from stagnant water and sticky impervious layers are preferred. Areas with a high water table should be avoided. Soil physical structure is of greater importance than the chemical properties, provided sufficient magnesium and minor elements such as zinc, copper and manganese are present in an available form. Soils with pH between 5 and 8 are preferred. The annual fertilizer requirements of citrus are 100 to 200 kg/ha N, 35 to 45 kg/ha P and 50 to 160 kg/ha K. Adequate fertility is important for both fruit quality and yield.

Citrus trees are sensitive to a high salt concentration in the soil. Yield decreases due to soil salinity are: 0% at ECe 1.7, 10% at 2.3, 25% at 3.3, 50% at 4.8, and 100% at ECe 8 mmhos/cm.

Propagation of citrus trees is done mostly by bud grafting, i.e. the insertion of buds of a desired variety on to a stock grown from seed of another variety. Normally citrus trees are transplanted. Planting distances vary according to soil conditions, the general topography, the variety and the type of tree to be planted, and are generally from 4 x 4 to 8 x 8. Planting may be square, rectangular, triangular or hexagonal. On steep slopes trees are planted in terraces or along contours. Tree density varies from 200 to 800 trees/ha. Young citrus orchards are often intercropped. In high rainfall areas permanent cover crops or broad-leaved weeds may be desirable, but in drier areas the soil is often kept bare. If an orchard is interplanted the companion crop should not strongly compete with the citrus trees for water and nutrients. A legume crop is often preferred.

WATER REQUIREMENTS

Citrus trees are evergreens and thus transpire throughout the year. Water requirements for high production vary with climate, ground cover, clean cultivation or no weed control, species and rootstock. The water requirements for grapefruit are somewhat higher than for the other citrus species. In general total water requirements vary between 900 and 1 200 mm per year.

The crop coefficients (kc) relating ETm citrus to the reference evapotranspiration (ETo) for the subtropics with winter rainfall are:

	J	F	M	A	M	J	J	A	S	O	N	D
Large, mature trees providing ≈ 70% tree ground cover, clean cultivated	.7		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.65	.65	.7	.7	.7
No weed control	.9		.85	.85	.85	.85	.85	.85	.85	.85	.85	.85

WATER SUPPLY AND CROP YIELD

As a perennial crop the response of citrus to water supply at a particular period of development will depend greatly on the level of water supply prior to that period during the same growing season and also the level of water supply during previous growing seasons.

In general, when water is insufficient, growth is retarded, leaves curl and drop, young fruits fall and fruits that mature are deficient in juice and inferior in quality. When the soil water depletion reaches permanent wilting point, tree growth is terminated and subsequently affects fruits and leaves, followed by twigs, branches and eventually the whole tree.

New vegetative growth in any year is influenced by residual effects of growth in previous seasons. The vegetative growth of young trees determines their final tree size and future fruit-bearing capacity. For mature trees, the growth vigour determines the replacement rate of fruit-bearing branches. Any effect of water deficit on root and leaf development may impair the number and size of fruits later in the season. Water deficits must be avoided when vegetative growth is most rapid. Prior to flowering and fruit set, however, too vigorous, luxurious growth may impair production of high quality fruit.

In citrus a rest period appears to be essential for flowering. The duration of the rest period determines the amount of flowers produced. The rest period, preferably of 2 months duration, can be induced either by low temperatures in winter (about 10°C) in the subtropics and in the tropics by a period of water deficit (monthly rainfall or irrigation <50 to 60 mm). The flower bud initiation occurs during this rest period when vegetative growth is minimum. Water deficits can have, however, some harmful effects for long-term crop production as compared to when dormancy is caused by a cold period. Once the rest period is ended, an adequate water supply is necessary because prolonged water deficits will not only delay flowering but also lead to overproduction of flowers. This can result in lower yields during the next season and possibly in subsequent seasons to a biennial fruit-bearing cycle. For lemons, water deficits in summer are commonly used to start off-season flowering for year-round production.

The flowering period is very sensitive to water deficits. Water deficits directly reduce fruit set; also during this period nutrition, especially nitrogen, is essential and adequate water is necessary to make the nutrients available to the crop. Moreover, water deficit during fruit set reduces yield by causing a heavy June or December fruit drop.

Water deficits during June or December (early yield formation) can increase fruit shedding and reduce the rate of fruit growth. After June or December drop, water deficits can affect the final fruit size. The increase in fruit size from June or December to maturity is highly dependent on water uptake, and the rate of enlargement of immature fruit is an indication of the need for irrigation. However, soil water depletions resulting in moderate water deficits after July or January (yield formation and ripening) can be desirable because the content of soluble solids and acids in the fruit is increased; also, tree growth is reduced which facilitates picking. In addition, a slight reduction in fruit size is often commercially desirable. When soils are fine textured, moderate water deficits after early yield formation provide better soil aeration, and diseases such as root-rot (Phytophtora spp.) may be prevented.

A more severe water deficit during summer followed by irrigation may induce out-of-season flowering which generally results in a worthless second fruit production and causes a possible reduction of yield in the following main crop. Only lemon can produce all year round without harmful effects on tree growth or yield. For other citrus species, the production of a second crop is a fairly reliable indication that the tree has been short of water at some stage.

Because of the carry-over effects of water deficits on tree growth and later yields, the relation between yield decrease and relative evapotranspiration deficit only applies when year to year water deficits are of similar magnitude (Fig. 13). Since data are largely obtained from subtropical climates with winter rainfall and where winter rainfall is sufficient to meet the crop water requirements in winter and early spring, the relationship in Figure 13 applies to water deficits only during the period just prior to flowering to early harvest. However, variation in yield per tree is always likely to be considerable.

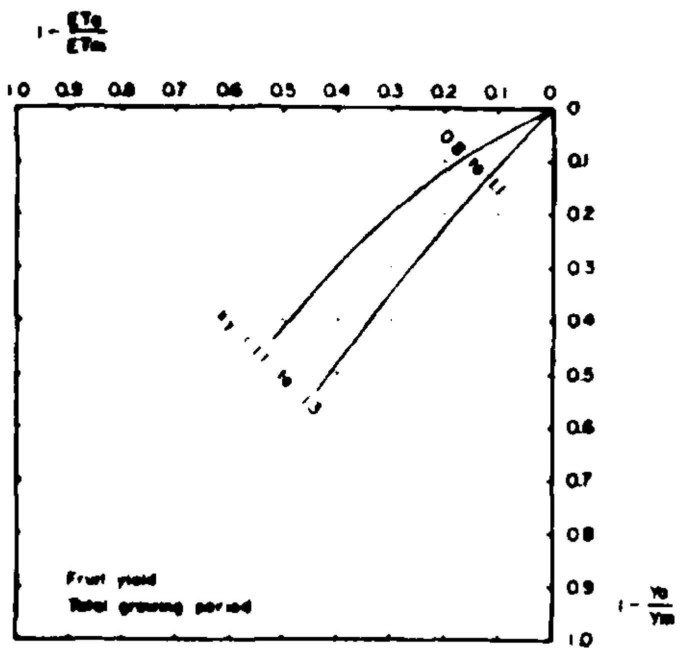


Fig. 13

Relationship between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration deficit (1 - ETa/ETm) for citrus

WATER UPTAKE

Most citrus species develop a single tap root. The lateral roots form a horizontal mat of feeding roots with weakly developed root hairs. Root development is largely dependent on the type of rootstock used and on the characteristics of the soil profile. Rooting depth varies between 1.20 and 2 m. In general, 60 percent of the roots are found in the first 0.5 m, 30 percent in the second 0.5 m, and 10 percent below 1 m. When water supply is adequate, normally 100 percent of the water is extracted from the first 1.2 to 1.6 m (D = 1.2-1.6 m) but under dry conditions the depth of water extracted below this depth increases. During prolonged periods of water deficit, soil water in a deep and well-drained soil may be utilized up to a soil depth of 2 or 3 m.

IRRIGATION SCHEDULING

Peak water requirements are reached between flowering and June or December drop. In this period frequent irrigation is necessary. When ETm is 5 to 6 mm/day, the fraction of available soil water (p) in this period equals about 0.4 but soil water depletion may be 60 to 70 percent from July or January to the end of autumn. During the latter period less frequent irrigation is advisable because during this period citrus is less sensitive to water deficits.

Irrigation scheduling requires great caution. Citrus trees demand good soil aeration and over-irrigation is highly detrimental, particularly to young trees. Too frequent and heavy irrigations may affect root development and yield and lead to leaching of nutrients. In climates where winters are too mild to induce a rest period, irrigation should be withheld for 2 to 3 months.

IRRIGATION METHODS

The most common surface irrigation methods are furrow irrigation (several furrows between the tree rows), check irrigation (basins containing one or more trees) or flood irrigation (where citrus trees are planted on beds or ridges). Because of uneven water distribution and the difficulty of applying small amounts of water the importance of surface irrigation for citrus is decreasing.

Sprinkler irrigation may provide a more uniform distribution of water and the possibility of applying the exact depth of required water. With the drip or micro-jet systems, water savings may be obtained because water is applied only to the root zone, leaving the remaining part of the soil dry. Sprinkler irrigation is also frequently used for frost protection.

YIELD LEVELS

Within an orchard yield varies greatly from tree to tree, while for a single tree yield varies from year to year. Sometimes a two-year fruit bearing cycle occurs.

Good yields of citrus are: orange - between 400 and 550 fruits per tree per year corresponding to 25 to 40 tons per ha per year; grapefruit - 300 to 400 fruits per tree per year and 40 to 60 tons per ha; lemons - 30 to 45 tons per ha per year; mandarin - 20 to 30 tons per ha per year. The water utilization efficiency for harvested yield (Ey) for citrus fruits is about 2 to 5 kg/m^3 with a moisture content of the fruits of about 85 percent, except for lime which contains about 70 percent moisture.

COTTON

Cotton (Gossypium hirsutum) is grown for fibre and seed. Present world production is about 12.7 million tons lint and 36.4 million tons seed cotton from about 31.4 million ha.

The origin of cotton is still uncertain. The development of the crop is sensitive to temperature. Cool nights and low daytime temperatures result in vegetative growth with few fruiting branches. The crop is very sensitive to frost and a minimum of 200 frost-free days is required. The length of the total growing period is about 150 to 180 days. Depending on temperature and variety, 50 to 85 days are required from planting to first bud formation, 25 to 30 days for flower formation and 50 to 60 days from flower opening to mature boll. No clear distinction can be made in crop growth periods since vegetative growth is continued during flowering and boll formation and flowering is continued during boll formation.

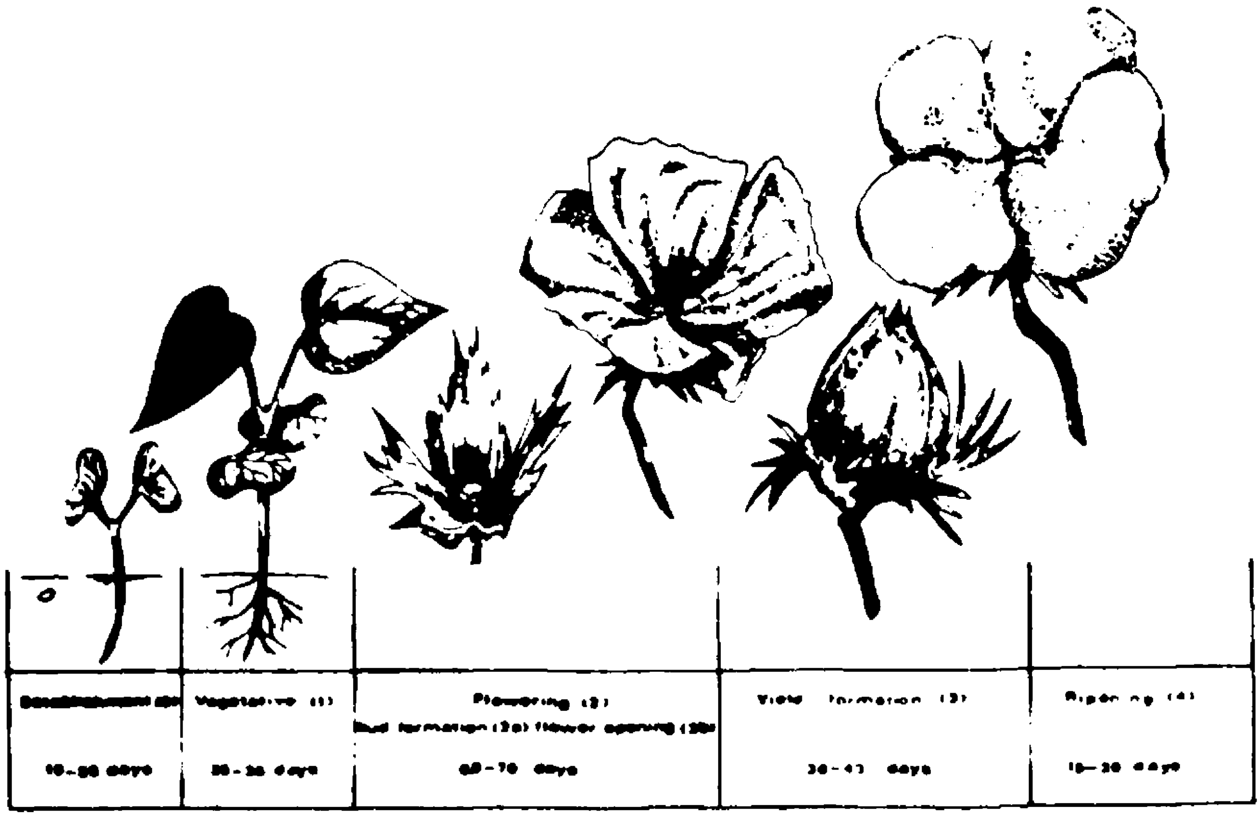


Fig. 14 Growth periods of cotton (after P.T. Walker)

Cotton is a short-day plant but day-neutral varieties exist. However, the effect of daylength on flowering is influenced by temperature. Germination is optimum at temperatures of 18 to 30°C, with minimum of 14°C and maximum of 40°C. Delayed germination exposes seeds to fungus infections in the soil. For early vegetative growth, temperature must exceed 20°C with 30°C as desirable. For proper bud formation and flowering, daytime temperature should be higher than 20°C and night temperature higher than 12°C, but should not exceed 40 and 27°C respectively. Temperatures between 27 and 32°C are optimum for boll development and maturation but above 38°C yields are reduced.

Strong and/or cold winds seriously affect the delicate young seedlings and at maturity will blow away fibre from opened bolls and cause soiling of the fibre with dust.

Cotton is extensively grown under rainfed conditions. Although the crop is relatively resistant to short periods of waterlogging, heavy rainfall, however, can cause lodging. Continuous rain during flowering and boll opening will impair pollination and reduce fibre quality. Heavy rainfall during flowering causes flower buds and young bolls to fall.

Cotton is grown on a wide range of soils but medium and heavy textured, deep soils with good water holding characteristics are preferred. Acid or dense subsoils limit root penetration. The pH range is 5.5 to 8 with 7 to 8 regarded as optimum. The fertilizer requirements of cotton under irrigation are 100 to 180 kg/ha N, 20 to 60 kg/ha P and 50 to 80 kg/ha K. Two-thirds of the nutrients are taken up during the first 60 days of the growing period. Nitrogen should be readily available at the start of the growing season; normally two applications are given with one after sowing and the other prior to flowering. Phosphate is applied before sowing. Plant spacing normally varies between 50/100 x 30/50 cm.

The crop is tolerant to soil salinity. Yield decreases at different ECe values are: 0% at ECe 7.7 mmhos/cm; 10% at 9.6, 25% at 13, 50% at 17 and 100% at ECe 27 mmhos/cm.

WATER REQUIREMENTS

Depending on climate and length of the total growing period, cotton needs some 700 to 1 300 mm to meet its water requirements (ETm). In the early vegetative period, crop water requirements are low, or some 10 percent of total. They are high during the flowering period when leaf area is at its maximum, or some 50 to 60 percent of total. Later in the growing period the requirements decline. In relation to reference evapotranspiration (ETo) the crop coefficient (kc) for the different development stages is: for the initial stage 0.4-0.5 (20 to 30 days), the development stage 0.7-0.8 (40 to 50 days), the mid-season stage 1.05-1.25 (50 to 60 days), the late-season stage 0.8-0.9 (40 to 55 days), and at harvest 0.65-0.7.

WATER SUPPLY AND CROP YIELD

The crop growth periods for cotton are shown in Figure 14. The relationships between relative yield decrease and relative evapotranspiration deficit are shown in Figure 15. For calculation examples see p. 40 and Chapter V.

Adequate water supply is needed for vigorous growth, good budding and fruiting and for the formation of healthy bolls. Excess water early in the growing period will restrict root and crop development. Cotton requires adequate water supply particularly just prior and during bud formation (2a). Continued water supply during flower opening (2b) and yield formation (3) periods results in prolonged and excessive growth and yield. Abrupt changes in water supply will adversely affect growth and cause flower and boll shedding. Severe water deficits during flowering may fully halt growth, but with subsequent water supply crop growth recovers and flower formation is resumed.

When the growing season is short such conditions lead to smaller yield. Water stress on cotton can be observed by discolouring of the stem and appearance of a bluish-green colour on the leaves.

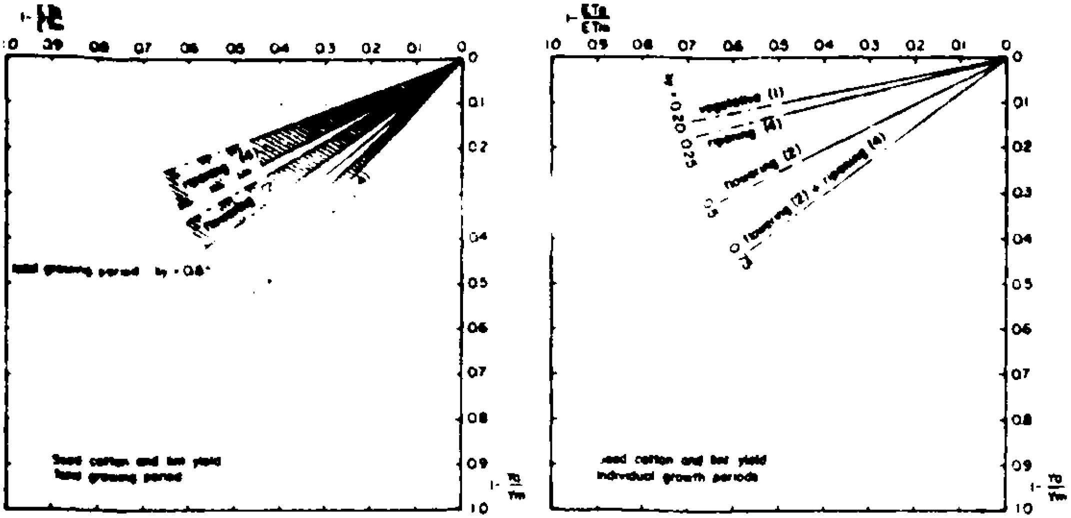


Fig. 15 Relationship between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration (1 - ETa/ETm) for cotton

Water supply for high production must be adjusted to the specific requirements of each growth period (see Scheduling). Optimum use of available water supply can be made by fully wetting the entire root zone up to 1.80 m at sowing and with subsequent wetting of the upper part (0.50 to 1 m) of the root zone only. Root activity may be increased and full utilization of the available soil water over the entire root zone is made with little or no soil water left at the end of the growing season. Other savings can be made by utilizing the available water in the entire root depth by timely discontinuing irrigation applications at the end of the total growing period. Also savings can be achieved by withholding supply during the flowering period (2) until some 70 percent of the total available soil water has been taken up by the crop. A combination of the above practices may save up to 20 percent water without greatly impairing yields.

At sowing, adequate soil water should be available for germination and establishment (0). During the vegetative period (1), soil water content over the root depth of some 0.75 m should not fall below 50 percent depletion; greater depletion of available soil water (up to 75 percent) will restrict vegetative growth but when followed by ample supply, vegetative growth will be somewhat excessive, which may cause late flowering, boll shedding and reduced yield when the growing season is short. At flowering (2), supply will need to be scheduled to control vegetative growth in relation to productive growth. Water deficits from onset of flowering to peak flowering may cause a more negative effect on yield as compared to when occurring after peak flowering. With severe water deficits during late flowering and early boll formation, boll shedding can be excessive. Moderate water deficit occurring during flowering (2) but high enough to restrict vegetative growth, will lead to good boll-set and higher yields, despite a reduction in number of flowers.

water supply should be available during the yield formation period (3). Depending on water holding capacity of the soil, development of the root system and evaporative demand, the water supply during the yield formation period (3) should be discontinued at a certain time before the ripening period (4). Excessive water supply during the yield formation period (3) may cause delay in boll opening and greater susceptibility to lodging and boll-rot. Under conditions of a long and warm growing season, an irrigation after the first harvest is sometimes practised to obtain a second yield.

When water supply is limited, a higher total production is obtained by extending the area and partially meeting crop water requirements rather than by meeting full crop water requirements over a limited area.

WATER UPTAKE

From emergence to early flowering, the tap root may extend in deep soils to a depth of 1.8 m. During the flowering period, additional root development occurs in the upper part of the root zone. Frequent, light irrigation application during early growth periods tends to cause shallow root systems. As a rule, some 70 to 80 percent of the total water uptake by the crop occurs over the first 0.9 m depth, where more than 90 percent of the total root weight is found. Normally when the crop is fully grown, 100 percent of the water is extracted from the first 1.0 to 1.7 m soil depth ($D = 1.0 - 1.7$ m). When water supply is terminated, water uptake will increasingly occur from lower soil depths but may not be sufficient during peak water requirement periods to maintain crop evapotranspiration and crop growth. Under conditions when ETm is 5 to 6 mm/day water uptake starts to be reduced when soil water depletion exceeds 65 percent ($p = 0.65$).

IRRIGATION SCHEDULING

To enhance root development, adequate water should be available in the soil at the time of sowing and pre-irrigation is required when stored soil water from pre-season rainfall is not available. In the vegetative period (1) irrigation may be scheduled when some 60 percent of the available soil water over the first 0.75 m has been taken up by the crop. During flowering (2) depletion of some 70 percent of available soil water will in general check vegetative growth without impairing yields; delayed irrigation during this period may cause considerable flower and bud shedding. During yield formation (boll filling) (3) and ripening (4), the soil water depletion may increase from 60 percent to higher values as the season progresses and depending on climate and depth of stored soil water, irrigation can be terminated 4 to 5 weeks before final picking.

When grown under conditions of high groundwater tables, even for short duration, and when soils are wet for long periods, the yield decrease may be up to 50 percent, not withstanding unrestricted water use. This may be due to inadequate soil aeration. The same phenomenum has been noticed under very frequent irrigation application.

IRRIGATION METHODS

Cotton is grown under a great variety of irrigation systems of which furrow irrigation is the most common surface system. In regions where the demand for water is great and water resources are small, sprinkler and drip irrigation methods become more and more accepted to economize on water applied and restrict return flow of low quality.

In the Near East region, cotton is also grown under controlled flood or spate irrigation, where with little or no rain a one-time pre-sowing irrigation of 0.5 to 1 m depth stores sufficient water in the root zone to allow the crop to reach maturity. Under such treatments soils must be deep and have a high water holding capacity. With growing season from August to March with ETm = 700 to 750 mm and ETa = about 450 mm, farmers' yields are about 800 kg/ha, with a maximum of about 1 700 kg/ha seed cotton.

YIELD AND QUALITY

A good yield of a 160 to 180 day cotton crop under irrigation is 4 to 5 ton/ha seed cotton of which 35 percent is lint. Water utilization efficiency for harvested yield (Ey) for seed cotton containing about 10 percent moisture is 0.4 to 0.6 kg/m³. Boll and fibre properties such as lint to seed ratio, and length, strength and fineness of lint, are primarily determined by the variety and to a lesser extent by irrigation and fertilizer practices. In general, the boll size, and the seed and lint index (weight per 100 seeds) increases under adequate water supply. However, the lint percentage (the ratio lint to seed) tends to decrease. Low soil water depletion levels during yield formation (3) tend to result in longer and finer fibre of decreased strength. The direct effect of water deficits on fibre properties, however, appears to be small because of the shedding of bolls which would have produced inferior fibre when allowed to mature.

Normally cotton seed contains 35 percent oil and 35 percent protein. Under irrigation there is an indication that severe water deficits substantially reduce the oil percentage in the seed, and more fibrous material with 20 percent lower oil and protein content is produced compared to an adequately irrigated crop.

GRAPE

Grape is believed to originate from the Caspian and Caucasian regions. Most cultivated vines belong to the European type (<u>Vitis vinefera</u>), the American bunch type (<u>V</u>. <u>labrusca</u> and its derivatives) or Muscadine type (<u>V</u>. <u>rotundifolia</u>). Of the total production, 10 percent is eaten as fresh fruit, 10 percent is used for raisin production (annual production about 1.1 million tons) and 80 percent for wine production (annual production about 31 million tons of wine).

Grape is grown between about 50°N and S, with suitable areas being small at these limits. The crop needs a long, warm to hot, dry summer and a cool winter. The subtropics with winter rain are most suited. Rain or cold and cloudy weather during flowering may adversely affect fruit setting whereas rain during ripening may lead to fruit rot. Where raisins are produced by sun-drying between the vine rows, at least one warm, sunny month without rain following harvest is essential.

In climates with a cool winter, the grape can survive temperatures down to -18°C, but once new growth begins, minor frost will kill the fruiting shoots. Rapid and succulent growth of shoots starts when mean daily temperatures reach 10°C. During flowering the rate of shoot growth declines and stops when the grapes are mature. The time from flowering to maturity can be expressed as the sum of mean daily temperature above 10°C or $\Sigma(T - 10°C)$, which is about 900 degree-days for early varieties and 2000 for late varieties. Under cool to moderate warm weather, fruits ripen slowly and produce dry table wines of good quality. In warmer climates, the heat before and during ripening favours a high sugar content, which makes fruits better suited for port and sherry production. During and after harvest no new shoot growth should take place but leaves should be retained. In the autumn shoots, then also called canes, become woody and lose their leaves.

In the tropics (with less than 1 percent of the world production), the vine is an evergreen and can produce fresh fruits throughout the year. In general, two harvests of relatively poor quality and low yields are obtained annually with harvest dates controlled by adjusting the time of pruning.

Grapes are adapted to a wide range of soils, except when poorly drained or when salt content is high. In general, light soils are preferred. High production can be obtained under rainfed conditions, but without summer rain a deep soil with a high water holding capacity is required. Under irrigation, grape can be grown successfully on shallow soils of 0.6 m depth or less.

On deep, fertile soil, the largest vines and high yields are produced. On soils of low fertility or limited depth, yields are usually lower, but fruit quality can be better. Fertilizer requirements are 100 to 160 kg/ha N, 40 to 60 kg/ha P and 160 to 230 kg/ha K. The greatest amount of nitrogen is needed during early spring growth and during the flowering period. During ripening, the nitrogen level must be low to prevent continuous vegetative growth.

Grape vines are moderately sensitive to soil salinity and yield decrease is 0% at ECe 1.5 mmhos/cm, 10% at 2.5, 25% at 4.1, 50% at 6.7 and 100% at 12 mmhos/cm.

Most grape varieties are propagated by cuttings, grown in a nursery for one year to produce roots. Where root louse is a problem, grape is grafted on resistant root-stocks. An important (and expensive) operation is the training, pruning and staking of the vines and thinning of clusters. In the tropics the time of pruning determines the time of fruiting. The plant spacing is also influenced by the pruning and training practices and can vary between 1.5 x 3.5 and 4.5 x 5.5 m.

WATER REQUIREMENTS

The crop coefficient (kc) will vary with cultural practices. The kc value, relating the maximum water requirements (ETm) to the reference evapotranspiration (ETo), for clean cultivated conditions, infrequent irrigation and a dry soil surface most of the time is:

Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Mature grapevines grown in areas with killing frost; initial leaves early May, harvest mid-September; ground cover 40-50% at mid-season											
-	-	-	-	.45-.5	.65-.75	.75-.9	.8-.95	.75-.9	.65-.75	-	-
Mature grapevines in areas with light frost; initial leaves early April, harvest late August to early September; ground cover 30-35% at mid-season											
-	-	-	.45-.5	.55-.65	.6-.75	.6-.75	.6-.75	.6-.75	.5-.65	.35-.4	-
Mature grapevines grown in hot, dry areas and mild winter; initial leaves late February - early March, harvest late July; ground cover 30-35% at mid-season											
-	-	.25	.45	.6-.65	.7-.75	.7-.75	.65-.7	.55	.45	.35	-

Total seasonal requirements vary between 500 and 1 200 mm, depending mainly on climate and length of growing period.

WATER SUPPLY AND CROP YIELD

Grape is a perennial crop and can adjust to a certain extent to limited water supply by developing a deep root system. When soil water even over great soil depth becomes limited and overnight recovery from wilting does not occur, growth will diminish and eventually stop. Subsequently leaf and shoot colour change to a dark greyish-green, the shoot tips become dry, the leaves curl, the tendrils abscise and eventually the leaves die and fall.

In the subtropics and temperate climates, flowerbud formation generally occurs during the late summer or autumn and the buds open during the next season. A slight deficiency of water, together with high sunshine and temperatures, is considered to be most favourable to flower bud formation. A dry summer and a relatively low yield appears to be more advantageous to flower bud formation than a wet summer and a heavy yield

For good fruit production in the same year and the following years, good vegetative growth during the first part of the growing period (vegetative period, 1) is important. Water deficit should not occur during this period of rapid lateral shoot growth. The soil water content should preferably be at field capacity at the end of the winter, by winter rain or by irrigation, to ensure adequate water supply during the first months of the growing period. Especially shoot elongation is very sensitive to water deficits. Adequately irrigated vines have significantly more prunings than those grown under water deficit conditions. If water stress occurs abruptly, the growth is checked and wilting and dieback occur; if water stress develops gradually the vine growth is adjusted by lessened shoot growth, smaller production and earlier ripening. However, vegetative growth should be low during fruit formation and should stop toward harvest to ensure good ripening of the fruit and maturing of the wood.

Prior and during flowering (2), adequate water supply is necessary for flower development. Water deficits at this time retard flower development while severe water deficit reduces fruit set. Also the nutrition requirements of the grapevine are high during this period and the subsequent fruit enlargement period. Leaching of nutrients must be avoided in this period.

Yield formation (fruit enlargement, 3) depends on a steady, continuous water supply, but in this period the crop is less sensitive to water deficits than during the period of shoot growth (1). Water deficits during fruit enlargement reduce fruit size. Later irrigation does not result in undersized fruits becoming normal size. Water deficits prior to or just after véraison (start of ripening, fruits soften and change colour) affect fruit size more than deficits just before harvest.

Severe water deficit causes shrivelling of the fruits at all stages of yield formation (3) and ripening (4) and is first observed in the immature fruits on any cluster. The shrivelling usually disappears after rewatering. Complete desiccation is confined to the smaller fruits (less than about 4 mm in diameter). When the crop is subjected to severe water deficits after véraison, maturity is delayed while the fruits may not even reach full maturity. A slight water deficit during the ripening period (4) may hasten maturity, while juice concentration is increased.

Water deficits throughout the growing season result in darker wine but may not affect the quality of the wine. Severe water deficit during yield formation (3) and ripening (4) results in the fruit having a dull colour. It also leads to sunburn but reduces the incidence of fruit rot. Severe deficits just after véraison reduce the content of total soluble solids.

After the fruit is mature and especially after harvest, the vines become adjusted to a limited water supply. Normally no further growth occurs, but leaves are retained and canes ripen even though soil water content is low. In hot, dry regions, water deficit after harvest will cause the leaves to fall; when weather becomes cool in autumn, new leaves can be formed without becoming mature. This will lead to poor production in the next year. Water supply after harvest must therefore be sufficient to maintain the healthy foliage and to prevent premature leaffall. However, too much water after harvest causes new shoot growth, which has the same detrimental effects as new leaf growth. The relation between relative yield decrease and relative evapotranspiration deficit is given for conditions when soil water stress occurs mainly in the second part of the total growing period, and water supply during early vegetative growth (1) and the flowering period (2) is adequate (Fig. 16). To maximize total production if water supply is limited the cultivated area may be extended and crop water requirements partially met, rather than meeting full crop water requirements on a limited area.

WATER UPTAKE

When root penetration is not obstructed, mature grapevines are deep rooted up to depths of 2 or 3 m, or more. In deep, coarse sand or gravelly soils, roots may be up to 4 to 8 m deep. The bulk of the roots are usually in the upper soil layer of 0.5 to 1.5 m. Normally 100 percent of the water is extracted from the first 1 to 2 m soil depth (D = 1-2 m). During vegetative growth (1), flowering (2) and the early part of yield formation (early 3) maximum evapotranspiration will be affected at a soil water depletion (p) of about 0.35 to 0.45, under conditions when ETm is 5 to 6 mm/day. Later in the growing period the soil water can be depleted to a higher level, while toward and after harvest time a high soil water depletion is required.

IRRIGATION SCHEDULING

When winter rainfall is ins[illegible] to fill the full root zone to field capacity, irrigation should be applied before [illegible] growth starts. Until the beginning of the

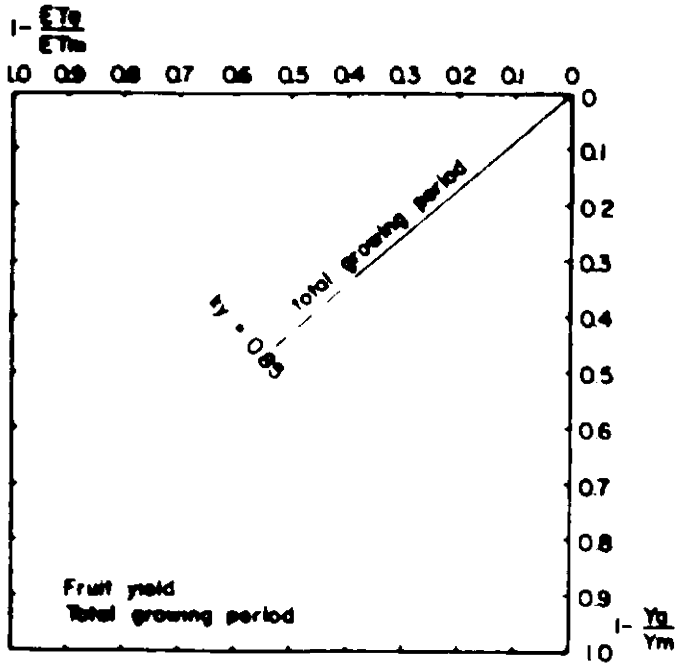


Fig. 16

Relationship between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration deficit (1 - ETa/ETm) for grape

véraison water must be applied when 35 to 45 percent of the total available soil water is depleted. Whether irrigation is necessary after véraison depends on the total available water over the root depth in relation to ETm. In shallow and light soils, irrigation will be necessary until harvest, but be applied at higher soil water depletion levels (soil water potential between 1 and 5 bars).

In deep, fine textured soils irrigation should be discontinued in time to achieve the desired soil water depletion level toward harvest time. In warm, dry climates or when the grapes are harvested early, a light irrigation may, however, be required to prevent the soil from becoming too dry (water potential not exceeding 5 to 10 bars).

When sprinkler irrigation is practised, after véraison irrigation should not take place during humid periods in order to assure rapid drying of the leaves (8 to 12 hours), and to reduce foliar burn and the hazard of fruit rot.

IRRIGATION METHODS

Furrow irrigation with 2 or 3 furrows between the rows is mostly used. Sprinkler irrigation becomes more common since it can also be used for spring frost protection where needed. Sprinkler is less advantageous when irrigation is also required during the ripening period because of the likely increase in bunch rot. In new vineyards and especially where irrigation water is scarce, drip irrigation is increasingly being introduced.

YIELD

Similarly to other perennial crops, yield per vine varies considerably from year to year and from plant to plant. The maximum yield level depends on the variety and growing environment. Good commercial yields in the subtropics are in the range of 15 to 20 kg grapes per vine or 15 to 30 (or more) tons/ha (80 to 85 percent moisture). Yields in the tropics are in the range of 5 to 10 ton/ha. The water utilization efficiency for harvested yield (Ey) for fresh fruits containing about 80 percent moisture is 2 to 4 kg/m^3 when grape is grown in the subtropics.

GROUNDNUT

Groundnut (Arachis hypogaea) originates from South America. Present annual world production of unshelled nuts is about 18.5 million tons from about 19.3 million ha.

The crop is grown between 40°N and S latitudes. Its growing period is 90 to 115 days for the sequential, branched varieties and 120 to 140 days for the alternately branched varieties. The mean daily temperature for optimum growth is 22 to 28°C; a reduction in yield occurs above 33°C and below 18°C. Germination is delayed at temperatures below 20°C. Groundnut is considered a day-neutral plant and daylength is not a critical factor influencing yield. For good yields, a rainfed crop requires about 500 to 700 mm of reliable rainfall over the total growing period.

The crop is best adapted to well-drained, loose, friable medium textured soils. Heavy textures cause problems in lifting the crop at harvest. Also, the top soil should be loose to allow the pegs (on which the fruits are formed) to enter the soil easily.

Being a legume, groundnut can fix nitrogen from the air. However, a pre-planting nitrogen application of 10 to 20 kg/ha is often recommended to assure good crop establishment. Phosphorous requirements are 15 to 40 kg/ha; potassium requirements 25 to 40 kg/ha. A too high application of potassium can cause a decrease in yield. For proper kernel formation and pod-filling, 300 to 600 kg/ha of calcium is required at the beginning of pod formation in the top soil where the fruits are formed. Limestone is used when soil acidity needs to be corrected and gypsum when only the Ca level needs to be increased. At pH lower than 6, liming may be necessary to avoid aluminium and manganese toxicity.

The crop is moderately sensitive to salinity and yield decrease for different soil salinity levels is: 0% at ECe 3.2 mmhos/cm, 10% at 3.5, 25% at 4.1, 50% at 4.9 and 100% at ECe 6.5 mmhos/cm.

The crop is planted at a row spacing of between 0.75 and 1.0 m corresponding to a plant density of about some 120 000 plants/ha for the small podded varieties and 70 000 plants/ha for large podded varieties. Seed rates are 30 to 50 kg/ha and 60 to 80 kg/ha for the two varieties respectively. When unshelled nuts are used for sowing, the pods are often pre-soaked to minimize damage to the seed. At sowing the soil water content should preferably not be below 60 percent available soil water.

Fig. 17 Groundnut during ripening

Crop rotation is recommended since groundnuts are able to abstract large amounts of nutrients from the soil and also to reduce infestation of root knot and lesion nematodes. Groundnut is generally preceeded by a crop requiring heavy fertilizer application such as maize. A 3 to 5 year rotation is preferred to a 2-year rotation.

WATER REQUIREMENTS

Depending on climate, the water requirements range from 500 to 700 mm for the total growing period. As related to development stages, the kc value for the initial stage is 0.4-0.5 (15 to 35 days), the development stage 0.7-0.8 (30 to 45 days), the mid-season stage 0.95-1.1 (30 to 50 days), the late-season stage 0.7-0.8 (20 to 30 days), and at harvest 0.55-0.6.

WATER SUPPLY AND CROP YIELD

Vegetative and reproductive growth show a definite response to water supply. However, excessive soil water is harmful because lack of oxygen in the soil limits the activity of the N-fixing bacteria; this is noted by an unhealthy growth pattern and yellowing of the leaves. Excessive soil water in heavy soils at harvest can cause the pods to be torn easily from the pegs with the pods remaining in the soil.

The relationship between relative yield decrease and relative evapotranspiration deficit, based on interpreted information, is given in Figure 18. For calculation examples see p. 40 and Chapter VI.

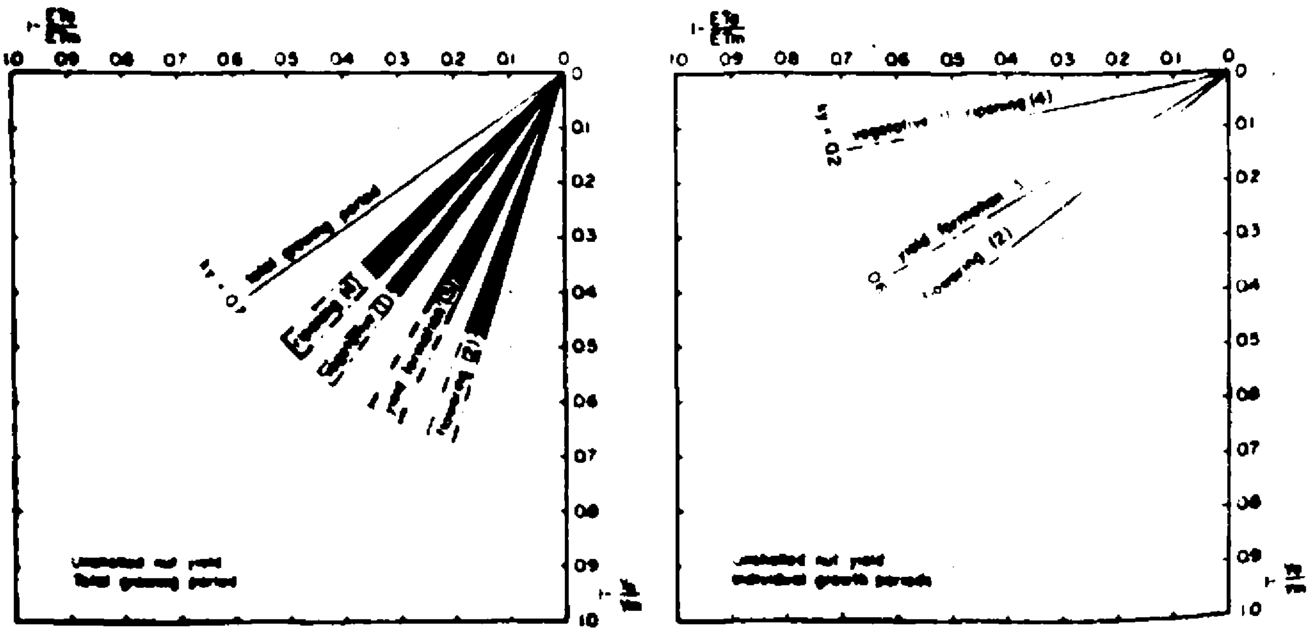


Fig. 18 Relationship between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration deficit (1 - ETa/ETm) for groundnut

The growth periods for groundnut are:

0	establishment	10 - 20 days
1	vegetative	25 - 35
2	flowering	30 - 40
3	yield formation (including pod setting and pod filling)	30 - 35
4	ripening	10 - 20

Flowering continues during part of the yield formation period but the pods from the late-formed flowers do not reach maturity.

The flowering period (2) is most sensitive to water deficit, followed by the yield formation period (3). In general, water deficits during the vegetative period (1) cause delayed flowering and harvest, and reduced growth and yield. Water deficits during flowering (2) cause flower drop or impaired pollination, whereas water deficits during the yield formation period (3) give a reduced pod weight. The early part of the yield formation period (pod setting) is particularly sensitive to water deficit. In the case of limited water supply, water savings should be made during the periods other than flowering (2) and early yield formation (3). A higher total production is obtained by increasing the cultivated area and partially meeting crop water requirements rather than by meeting full crop water requirements over a limited area.

WATER UPTAKE

The crop has a well-developed tap root with many laterals which may extend to a depth of 1.8 m. The major part of the root system is, however, found in the first 0.5 to 0.6 m soil layer. Full grown plants normally extract 100 percent of the water from the first 0.5 to 1.0 m of the soil (D = 0.5-1.0). Under an evapotranspiration rate of 5 to 6 mm/day, the rate of water uptake by the crop starts to reduce when some 50 percent of the total available soil water has been depleted (p = 0.5).

IRRIGATION SCHEDULING

Depending on the level of crop evapotranspiration and water holding capacity of the soil, intervals vary from 6 to 14 days up to 21 days for loam soils, with shorter intervals during flowering (2) when depletion of available soil water should not exceed 40 percent. In the case of supplemental irrigation, best results are obtained when water is applied during the flowering period (2).

IRRIGATION METHODS

On light-textured soils, sprinkler irrigation offers advantages by light and frequent water application, sufficient to wet the first 0.6 m of the soil. Furrow irrigation is frequently used on medium textured soils.

YIELD AND QUALITY

Under rainfed conditions good average yields vary from 2 to 3 ton/ha unshelled nuts under a high level of management. Under irrigation and a high level of management, yields can be 3.5 to 4.5 ton/ha unshelled nuts. The water utilization efficiency for the harvested yield (Ey) for unshelled, dried nuts with a moisture content of about 15 percent is 0.6 to 0.8 kg/m^3. Groundnuts contain about 30 percent protein and are rich in vitamins B and C. The oil content for the Virginia bunch type (alternately branched), is between 38 and 47 percent; for the small seeded Spanish types (sequentially branched), 47 to 50 percent. Oil content is reduced considerably when water deficits occur during the yield formation period (3).

MAIZE

Maize (Zea Mays) originates in the Andean region of Central America. It is one of the most important cereals both for human and animal consumption and is grown for grain and forage. Present world production is about 335 million tons grain from about 118 million ha.

The crop is grown in climates ranging from temperate to tropic during the period when mean daily temperatures are above 15°C and frost-free. Adaptability of varieties in different climates varies widely. Successful cultivation markedly depends on the right choice of varieties so that the length of growing period of the crop matches the length of the growing season and the purpose for which the crop is to be grown. Variety selection trials to identify the best suitable varieties for given areas are frequently necessary.

When mean daily temperatures during the growing season are greater than 20°C, early grain varieties take 80 to 110 days and medium varieties 110 to 140 days to mature. When grown as a vegetable, these varieties are 15 to 20 days shorter. When mean daily temperatures are below 20°C, there is an extension in days to maturity of 10 to 20 days for each 0.5°C decrease depending on variety, and at 15°C the maize grain crop takes 200 to 300 days to mature. With mean daily temperature of 10 to 15°C maize is mostly grown as a forage crop because of the problem of seed set and grain maturity under cool conditions. For germination the lowest mean daily temperature is about 10°C, with 18 to 20°C being optimum. The crop is very sensitive to frost, particularly in the seedling stage but it tolerates hot and dry atmospheric conditions so long as sufficient water is available to the plant and temperatures are below 45°C. Temperature requirements, expressed as sum of mean daily temperatures, for medium varieties are 2 500 to 3 000 degree days, while early varieties require about 1 800 and late varieties 3 700 or more degree days.

In respect of daylength, maize is considered to be either a day-neutral or a short-day plant. The growth of maize is very responsive to radiation. However, five or six leaves near and above the cob are the source of assimilation for grain filling and light must penetrate to these leaves. For optimum light interception, for grain production, the density index (number of plants per ha/row spacing) varies but on average it is about 150 for the large late varieties and about 500 for the small early varieties. Sowing methods and spacing vary, and fertility and water are decisive factors in choosing the optimum density in relation to light interception and highest yields. Plant population varies from 20 to 30 000 plants per ha for the large late varieties to 50 to 80 000 for small early varieties. Spacing between rows varies between 0.6 and 1 m. Sowing depth is 5 to 7 cm with one or more seeds per sowing point. When grown for forage, plant population is 50 percent higher.

The plant does well on most soils but less so on very heavy dense clay and very sandy soils. The soil should preferably be well-aerated and well-drained as the crop is susceptible to waterlogging. The fertility demands for grain maize are relatively high and amount, for high-producing varieties, up to about 200 kg/ha N, 50 to 80 kg/ha P and 60 to 100 kg/ha K. In general the crop can be grown continuously as long as soil fertility is maintained.

Maize is moderately sensitive to salinity. Yield decrease under increasing soil salinity is: 0% at ECe 1.7 mmhos/cm, 10% at 2.5, 25% at 3.8, 50% at 5.9 and 100% at ECe 10 mmhos/cm.

WATER REQUIREMENTS

Maize is an efficient user of water in terms of total dry matter production and among cereals it is potentially the highest yielding grain crop. For maximum production a medium maturity grain crop requires between 500 and 800 mm of water depending on climate. To this, water losses during conveyance and application must be added. The crop factor (kc) relating water requirements (ETm) to reference evapotranspiration (ETo) for different crop growth stages of grain maize is for the initial stage 0.3-0.5 (15 to 30 days), the development stage 0.7-0.85 (30 to 45 days) the mid-season stage 1.05-1.2 (30 to 45 days), during the late season stage 0.8-0.9 (10 to 30 days), and at harvest 0.55-0.6.

WATER SUPPLY AND CROP YIELD

The growth periods of maize are shown in Figure 19. The relationships between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration deficit are shown in Figure 20. For calculation examples see p. 40 and Chapter VI.

Frequency and depth of irrigation and rain has a pronounced effect on grain yield. Maize appears relatively tolerant to water deficits during the vegetative (1) and ripening (4) periods. Greatest decrease in grain yields is caused by water deficits during the flowering period (2) including tasselling and silking and pollination, due mainly to a reduction in grain number per cob. This effect is less pronounced when in the preceeding vegetative period (1) the plant has suffered water deficits. Severe water deficits during the flowering period (2), particularly at the time of silking and pollination, may result in little or no grain yield due to silk drying. Water deficits during the yield formation period (3) may lead to reduced yield due to a reduction in grain size. Water deficit during the ripening period (4) has little effect on grain yield.

The effect of limited water on maize grain yield is considerable and careful control of frequency and depth of irrigation is required to optimize yields under conditions of water shortage. Where water supply is limited it may therefore be advantageous to meet, as far as possible, full water requirements (ETm) so as to achieve near maximum yield from a limited acreage rather than to spread the limited water over a larger acreage.

Maize flourishes on well-drained soils and waterlogging should be avoided, particularly during the flowering (2) and yield formation (3) periods. Waterlogging during flowering (2) can reduce grain yields by 50 percent or more.

WATER UPTAKE

When evaporative conditions correspond to ETm of 5 to 6 mm/day, soil water depletion up to about 55 percent of available soil water (Sa) has a small effect on yield (p = 0.55). To enhance rapid and deep root growth a somewhat greater depletion during early growth periods can be advantageous. Depletion of 80 percent or more may be allowed during the ripening period.

Although in deep soils the roots may reach a depth of 2 m, the highly branched system is located in the upper 0.8 to 1 m and about 80 percent of the soil water uptake occurs from this depth. Normally 100 percent of the water is taken up from the first 1 to 1.7 m soil depth (D = 1 to 1.7 m). Depth and rate of root growth is, however,

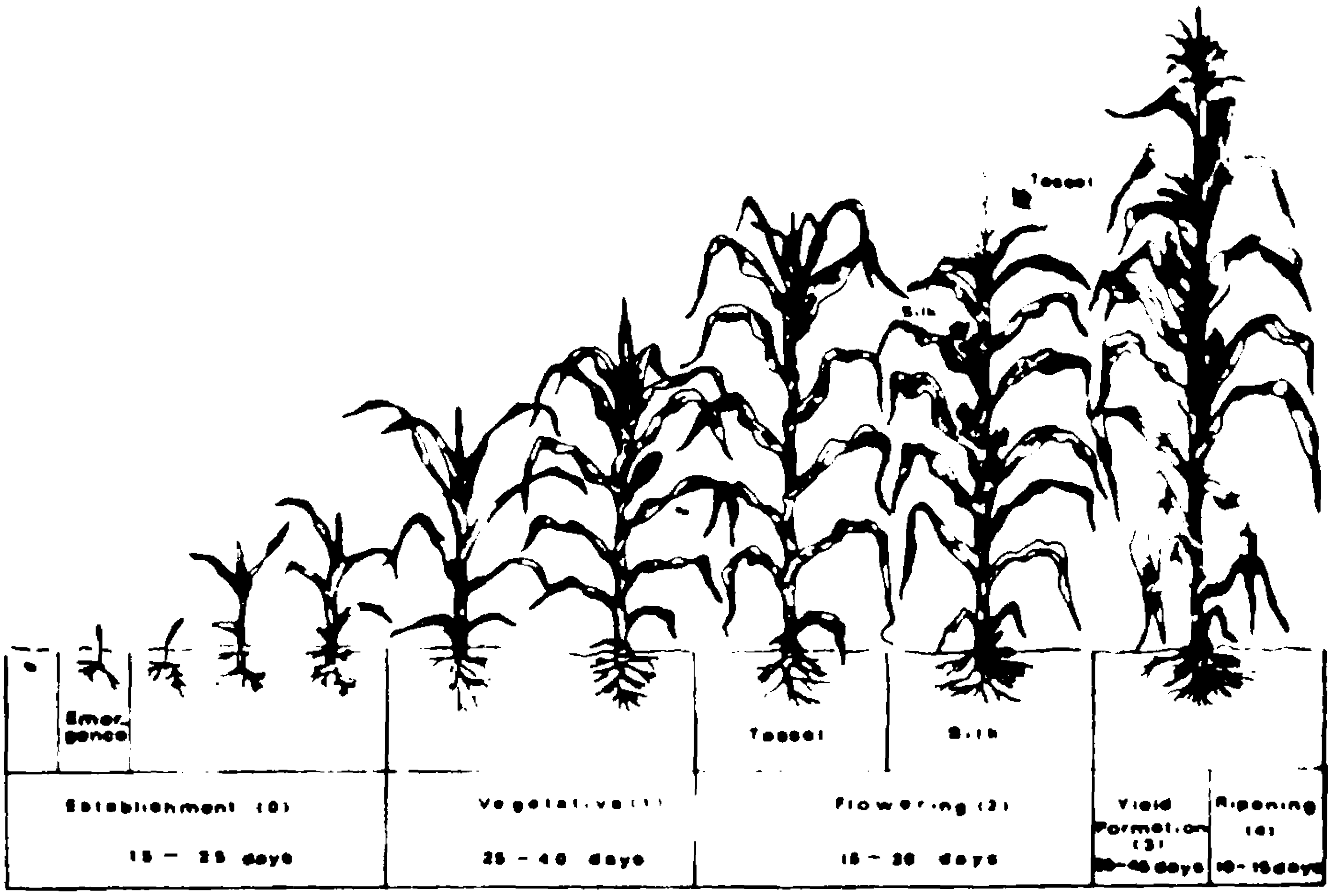


Fig. 19 Growing periods of maize (after Hanway, 1966)

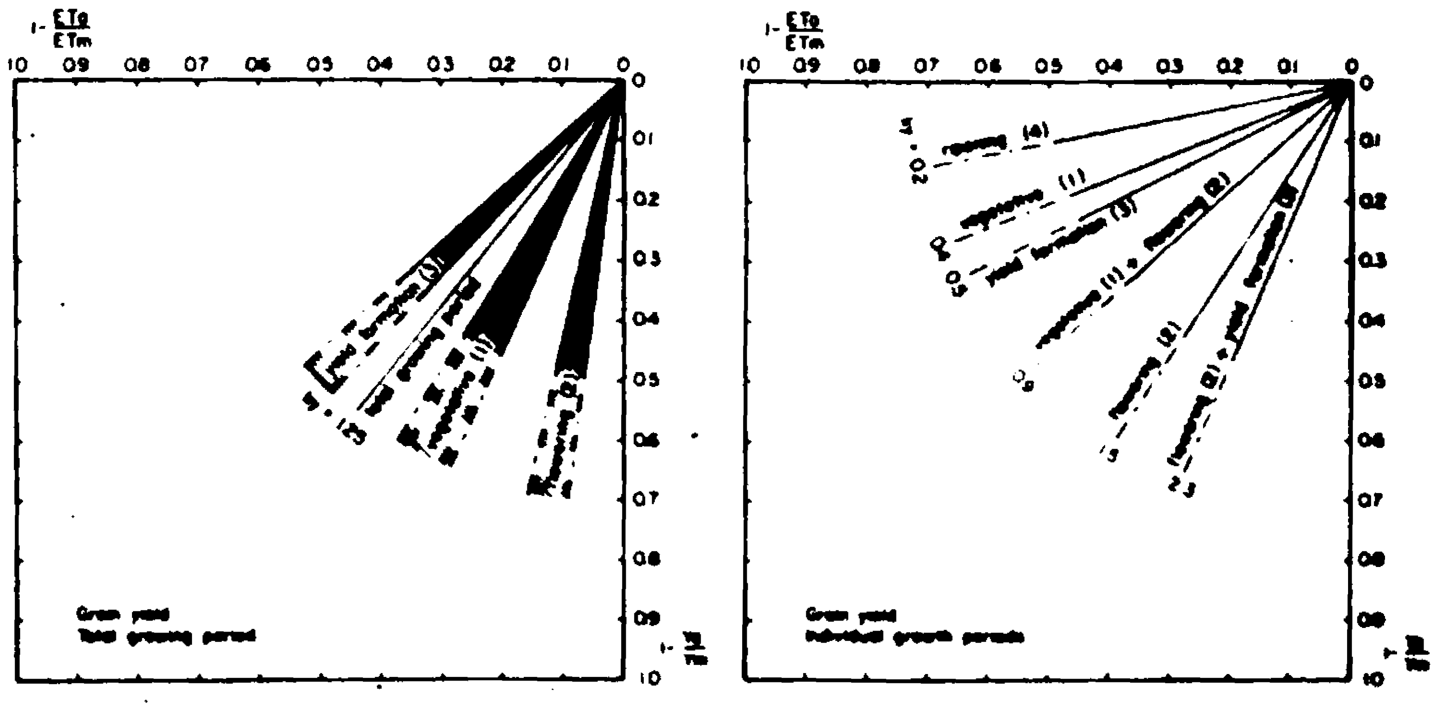


Fig. 20 Relationship between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration deficit (1 - ETa/ETm) for maize

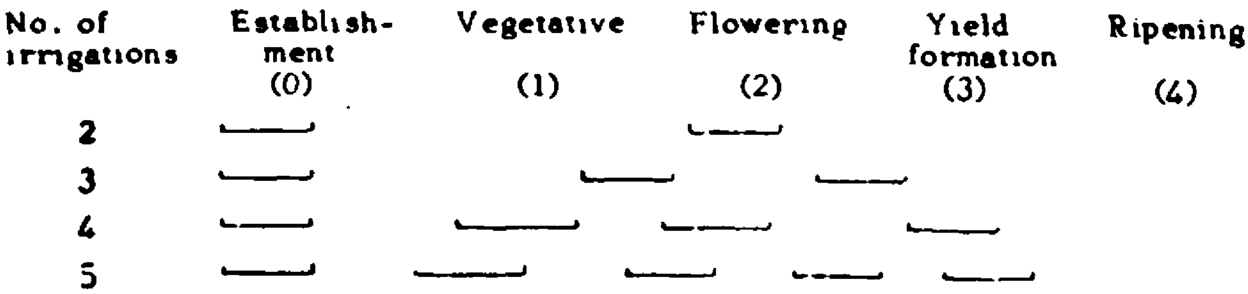
greatly affected by rainfall pattern and irrigation practices adopted. In addition to soil water and nutrient status, root development is strongly influenced by textural and structural stratification, salts and water table.

IRRIGATION SCHEDULING

To obtain a good stand and rapid root development, the root zone should, where feasible, be wetted at or soon after sowing. Taking into account the level of ETm, to meet full water requirements, the water depletion level is about 40 percent in the establishment period (0), between 55 and 65 percent during periods 1, 2 and 3, and up to 80 percent during the ripening period (4).

Where rainfall is low and irrigation water supply is restricted, irrigation scheduling should be based on avoiding water deficits during the flowering period (2) followed by yield formation period (3). When a severe water deficit during the flowering period (2) is unavoidable, water may be saved by reducing supply during the vegetative period (1) as well as during the yield formation period (3) without incurring additional yield losses.

Under conditions of marginal rainfall and limited irrigation water supply, the number of possible irrigation applications may vary between 2 and 5. A suggested timing of these irrigation applications is given below. To obtain a good stand and proper root development, the potential root zone should be wet either from rainfall or irrigation prior or soon after sowing.



YIELD

Under irrigation a good commercial grain yield is 6 to 9 ton/ha (10 to 13 percent moisture). The water utilization efficiency for harvested yield (Ey) for grain varies then between 0.8 and 1.6 kg/m^3.

OLIVE

Olive (Olea europacal) probably originated from the Eastern Mediterranean region of the Middle East. Present production is about 8.5 million tons green and black table olives and 1.6 million tons oil. Of the total production, 95 percent is produced in the Mediterranean region with Spain and Italy being the main producing countries.

The crop is indigenous to the Mediterranean region with a mild, rainy winter and a hot, dry summer. A dormancy period of about two months with average temperatures lower than 10°C is condusive to flower bud differentiation. Some cultivars are adapted to areas with higher winter temperatures but reduced flowering is noted under these conditions. During the dormancy period, the tree tolerates short periods of frost of -6°C, but during the bearing period frost causes damage to the fruits which are then only suitable for oil production. High temperatures and dry winds cause poor fruit setting and excessive drop of young fruits with remaining fruits shrivelling on the tree. A long, sunny, warm summer results in a high oil content of the fruit. High humidity at flowering causes flower drop and infestation of sooty mould.

The crop produces acceptable yields on poor soil as long as it is deep, well-aerated and free from waterlogging. Under waterlogged conditions damage through lack of oxygen and fungal diseases increases sharply. The fertilizer requirements are 200 to 250 kg/ha N, 55 to 70 kg/ha P and 160 to 210 kg/ha K. Nitrogen is applied prior to or during the flowering and fruit formation period.

The olive tree is moderately tolerant to soil salinity provided ECe does not exceed 8 mmhos/cm, but ECe of 4.5 mmhos/cm or less is preferred.

Raised for two years in the nursery, the tree is transplanted early in the season with 15 to 20 trees/ha under poor rainfed conditions and up to 300 trees/ha under irrigated conditions. Tree density is also dependent on the method of pruning. Early pruning is not essential but is often practised to obtain strong stems. However, for older trees, pruning during winter is necessary for high yields. Intercropping with grain forage and vegetable crops is sometimes practised in young orchards but is discontinued after 15 to 20 years under rainfed and after 6 years under irrigation.

More fruits are set than can be supported by sufficient nutrient supply, and this tendency increases as the trees get older. Consequently, a small number of flowers produce fruits. Early flower drop can be attributed to inadequate pollination, nutrient deficiencies or water shortage. Late flower and fruit drop is caused mainly by olive moth and olive fly attacks and water shortage. On the other hand, abundant fruiting adversely affects growth of annual shoots and the next year crop and eventually leads to alternate fruit bearing. This tendency is greater in older trees but alternate bearing is less pronounced with good soil and climate, and adequate management practices. The economic life of a tree is 50 years under rainfed conditions but under favourable growing conditions it can be much longer. A profitable harvest is obtained after 6 years but under more extreme conditions, after 15 to 20 years.

WATER REQUIREMENTS

Olive trees are commonly grown without irrigation in areas with an annual rainfall of 400 to 600 mm but are even found in areas with about 200 mm rainfall. For high yields, 600 to 800 mm are required. The crop coefficient (kc) relating maximum evapotranspiration (ETm) to reference evapotranspiration (ETo) is between 0.4 and 0.6.

WATER SUPPLY AND CROP YIELD

The annual growth cycle of the olive tree in the subtropics with winter rain, together with the timing of cultivation practices, is shown in Figure 21.

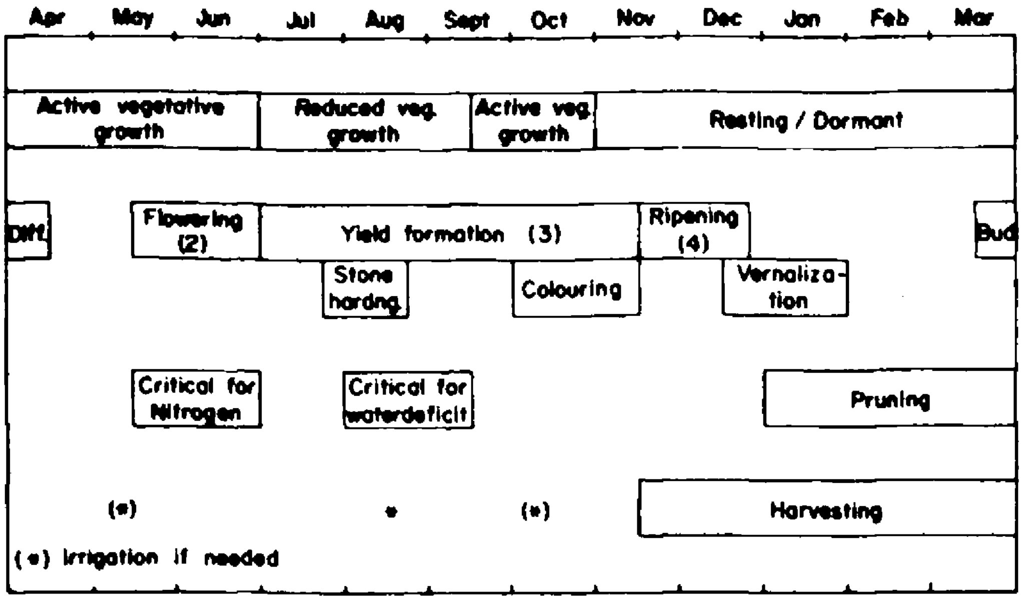


Fig. 21 Annual growth cycle for olive in the subtropics in the northern hemisphere with winter rain (after Pansoit and Rebour, 1961)

In the subtropics with winter rain, adequate soil water is generally available until the later part of the summer. For high yields, adequate water is required from the start of the stone hardening onward until the end of yield formation (3). During the yield formation period (3) adequate water supply increases fruit size and the flesh/pit ratio but the ripening period (4) is prolonged and the colouring of the fruit is delayed. Table olives, with a high flesh/pit ratio, require more water during the yield formation period (3) than olives produced for oil. In subtropical climates with little winter rain, water supply is also needed prior to flowering (2). Water deficits during the flowering period (2) may result in increased flower and fruit drop. Where needed, irrigation prior to the start of flowering is recommended because irrigation during the flowering period (2) may lead to leaching of the essential supply of soil nitrogen.

Yields are strongly affected by twig growth during spring and early summer (from April to June in the northern hemisphere) and adequate water should be available during this time. This applies also to the winter period because water deficits in winter cause reduced twig growth and defoliation. Further, this also causes a large percentage of imperfect flowers during spring while retarding flowering.

Adequate water supply during the active growth periods tends to reduce alternate bearing cycles. Water deficits in the spring adversely affect leaf development and active growth, causing a reduction in yield during the same year and possibly also the next. When the crop is grown fully under irrigation, application of water could be discontinued only during the period between start of flowering and the beginning of stone hardening.

Excess water results in short twigs, dense foliage with short and narrow leaves and reduced yields.

Under conditions of limited water supply, overall production is increased by extending the area and partially meeting crop water requirements, rather than by meeting full crop water requirements over a limited area.

WATER UPTAKE

After 3 to 4 years the tree forms a fascilar root system which continues to grow with age. In heavy textured and poorly aerated soils, roots are concentrated near the soil surface but are found at a greater depth in light textured soils. Lateral roots can be up to 12 m long. The tree thus explores a large volume of soil for nutrients and water. Generally, water uptake occurs over the first 1.2 to 1.7 m of soil depth (D = 1.2 to 1.7 m). Under conditions when maximum evapotranspiration (ETm) is 5 to 6 mm/day, the rate of soil water uptake by the crop starts to reduce when some 60 to 70 percent of the total available soil water has been depleted.

IRRIGATION SCHEDULING

With winter rain of about 500 mm, irrigation is applied during and after stone hardening. Under conditions of little winter rain, irrigation is applied during bud differentiation (early spring), prior to flowering (early summer) and during yield formation and particularly during stone hardening. Irrigation is also applied at (a) two to three weeks before flowering; (b) when the fruit reaches one third its full size; and (c) when the fruit reaches almost full size.

For oil production, irrigation supply must be discontinued early enough to give a dry period during ripening. This will have little effect on the oil content but will reduce the water content of the fruit.

Irrigation is applied by different surface methods, but when limited water is available, localized irrigation is preferred.

YIELD AND QUALITY

The fruits of irrigated trees reach a high oil content later in the season than those of rainfed trees. Also, for irrigated trees the change of fruit colour from green to black is more gradual. Oil content as percentage of fresh fruit weight tends to be higher for rainfed than for irrigated trees but little difference is noted with oil content expressed as percentage of dry matter.

Time of picking depends on the use of the harvested product. Varieties with fruits of a high flesh/pit ratio and uniform shape are used for table olive production. In the northern hemisphere, green table olives are harvested from mid-September onward with end of harvest being determined when the fruit colour changes to green-yellow. Black table olives are harvested in December. Olives for oil are harvested from mid-December until March with oil content independent of the time of harvest.

Maximum oil content and weight are reached six to eight months after flowering. Olive fruits can be harvested long before they fall naturally.

Yields vary from year to year and from tree to tree. Good commercial yields under irrigation are 50 to 65 kg/tree of fruit with a possible maximum of 100 kg/tree of fruit. Oil content of the fresh fruit ranges from 20 to 25 percent. The water utilization efficiency for harvested yield (Ey) for fresh olives containing about 30 percent moisture is 1.5 to 2.0 kg/m^3.

ONION

Onion (Allium cepa) is believed to have originated in the Near East. The crop can be grown under a wide range of climates from temperate to tropical. Present world production is about 16 million tons of bulbs from 1.5 million ha.

Under normal conditions onion forms a bulb in the first season of growth and flowers in the second season. The production of the bulb is controlled by daylength and the critical daylength varies from 11 to 16 hours depending on variety. The crop flourishes in mild climates without extremes in temperature and without excessive rainfall. For the initial growth period, cool weather and adequate water is advantageous for proper crop establishment, whereas during ripening, warm, dry weather is beneficial for high yield of good quality. The optimum mean daily temperature varies between 15 and 20°C. Proper crop variety selection is essential, particularly in relation to the daylength requirements; for example, a long day temperate variety in tropical zones with short days will produce vegetative growth only without forming the bulb. The length of the growing period varies with climate but in general 130 to 175 days are required from sowing to harvest.

The crop is usually sown in the nursery and transplanted after 30 to 35 days. Direct seeding in the field is also practised. The crop is usually planted in rows or on raised beds, with two or more rows in a bed, with spacing of 0.3 to 0.5 x 0.05 to 0.1 m. Optimum soil temperature for germination is 15 to 25°C. For bulb production the plant should not flower since flowering adversely affects yields. Bulbs are harvested when the tops fall: For initiation of flowering, low temperatures (lower than 14 to 16°C) and low humidity are required. Flowering is, however, little affected by daylength.

Onion can be grown on many soils but medium textured soils are preferred. Optimum pH is in the range of 6 to 7. Fertilizer requirements are normally 60 to 100 kg/ha N, 25 to 45 kg/ha P and 45 to 80 kg/ha K.

The crop is sensitive to soil salinity and yield decrease at varying levels of ECe is: 0% at ECe 1.2 mmhos/cm, 10% at 1.8, 25% at 2.8, 50% at 4.3 and 100% at ECe 7.5 mmhos/cm.

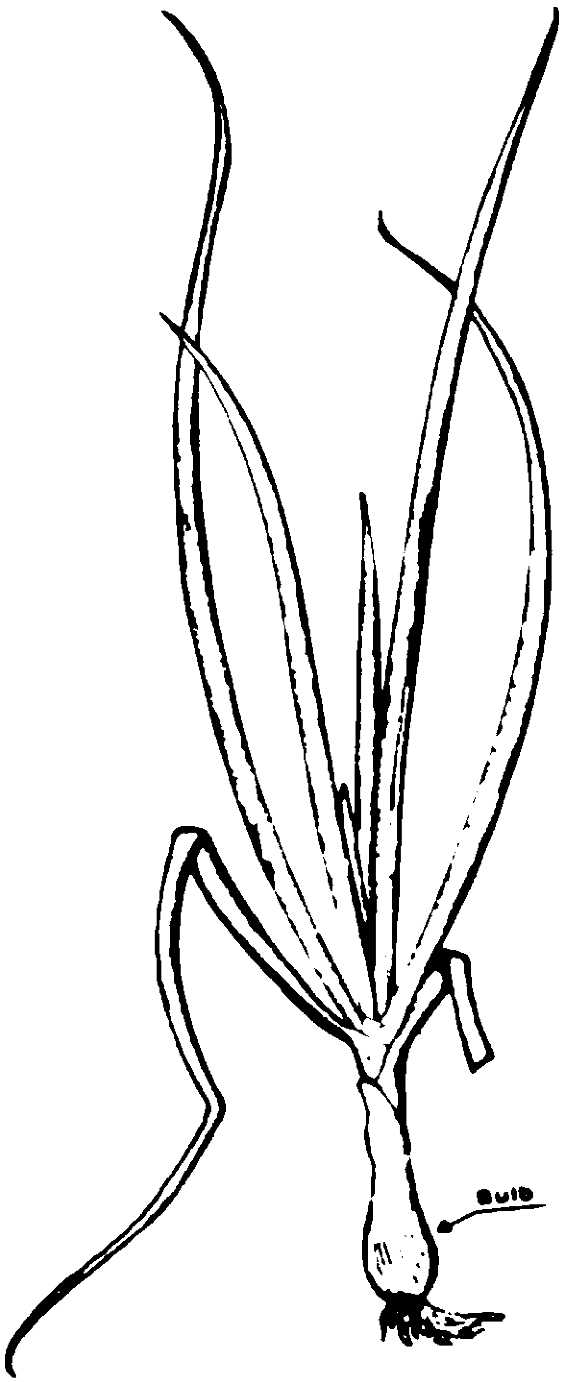


Fig. 22 Onion during yield formation period (3)

WATER REQUIREMENTS

For optimum yield, onion requires 350 to 550 mm water. The crop coefficient (kc) relating reference evapotranspiration (ETo) to water requirements (ETm) for different development stages after transplanting is, for the initial stage 0.4-0.6 (15 to 20 days), the crop development stage 0.7-0.8 (25 to 35 days), the mid-season stage 0.95-1.1 (25 to 45 days), the late-season stage 0.85-0.9 (35 to 45 days), and at harvest 0.75-0.85.

WATER SUPPLY AND CROP YIELD

Onion, in common with most vegetable crops, is sensitive to water deficit. For high yield, soil water depletion should not exceed 25 percent of available soil water. When the soil is kept relatively wet, root growth is reduced and this favours bulb enlargement. Irrigation should be discontinued as the crop approaches maturity to allow the tops to desiccate, and also to prevent a second flush of root growth.

The growth periods of an onion crop with a growing period of 100 to 140 days in the field are: establishment period (from sowing to transplanting, 0) 30 to 35 days; vegetative period (1) 25 to 30 days; yield formation (bulb enlargement, 3) 50 to 80 days and ripening period (4) 25 to 30 days.

The relationships between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration deficit (1 - ETa/ETm) are shown in Figure 23. For examples see p. 40 and Chapter VI.

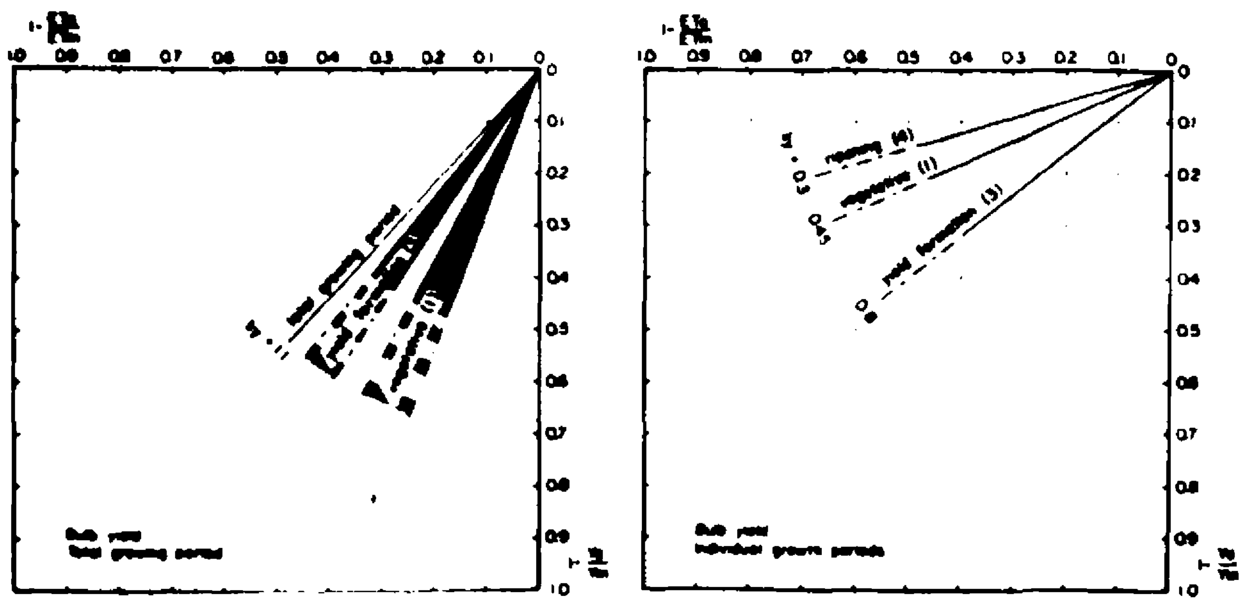


Fig. 23 Relationship between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration deficit (1 - ETa/ETm) for onion

The crop is most sensitive to water deficit during the yield formation period (3), particularly during the period of rapid bulb growth which occurs about 60 days after transplanting. The crop is equally sensitive during transplantation. For a seed crop, the flowering period is very sensitive to water deficit. During the vegetative growth period (1) the crop appears to be relatively less sensitive to water deficits.

For high yield of good quality the crop needs a controlled and frequent supply of water throughout the total growing period; however, over-irrigation leads to reduced growth.

To achieve large bulb size and high bulb weight, water deficits, especially during the yield formation period (bulb enlargement, 3), should be avoided. Under limited water supply small water savings can be made during the vegetative period (1) and the ripening period (4). However, under such conditions water supply should preferably be directed toward maximizing production per hectare rather than extending the cultivated area with limited water supply.

WATER UPTAKE

The crop has a shallow root system with roots concentrated in the upper 0.3 m soil depth. In general 100 percent of the water uptake occurs in the first 0.3 to 0.5 m soil depth (D = 0.3-0.5 m). To meet full crop water requirements (ETm) the soil should be kept relatively moist; under an evapotranspiration rate of 5 to 6 mm/day, the rate of water uptake starts to reduce when about 25 percent of the total available soil water has been depleted (p = 0.25).

IRRIGATION SCHEDULING

The crop requires frequent, light irrigations which are timed when about 25 percent of available water in the first 0.3 m soil depth has been depleted by the crop. Irrigation application every 2 to 4 days is commonly practised. Over-irrigation sometimes causes spreading of diseases such as mildew and white rot. Irrigation can be discontinued 15 to 25 days before harvest. Most common irrigation methods are furrow and basin.

YIELD AND QUALITY

Frequent irrigation is required to prevent cracking of the bulb and forming of 'doubles'. Also adequate water supply is essential for a high quality crop. A good bulb yield under irrigation is 35 to 45 ton/ha. The water utilization efficiency for harvested yield (Ey) for bulbs containing 85 to 90 percent moisture is 8 to 10 kg/m^3.

PEA

Pea (*Pisum sativum*) is grown as a vegetable crop for both fresh and dried seed. Present world production is about 13.5 million tons dry pea and 4.8 million tons fresh pea.

The varieties range from tall climbing to small bunch types with the latter having a shorter growing period. Pea is a cool climate crop and optimum mean daily temperature is 17°C with a minimum of 10°C and a maximum of 23°C. Germination is affected by soil temperature; at 5°C germination takes 30 days or more, at 10°C about 14 days and at 20 to 30°C about 6 days. Young plants can tolerate light frost but flowers and green pods are injured by light frost. In the tropics near the equator, peas are grown at about 1 500 m altitude, or as a winter crop in areas away from the equator. The normal growing period is 65 to 100 days for fresh pea with an additional 20 days for dry peas. The growing period is extended under cool conditions.

The crop does well on most soils with good drainage and pH of 5.5 to 6.5. Fertilizer requirements are about 20 to 40 kg/ha N, 40 to 60 kg/ha P and 80 to 160 kg/ha K. Pea is capable of fixing atmospheric nitrogen, which meets its requirements for high yields. However, a starter dose of 20 to 40 kg/ha N is beneficial for good early growth.

Pea is sensitive to soil salinity with yield decrease at different levels of ECe similar to that of bean, or 0% at ECe 1.0, 10% at 1.5, 25% at 2.3, 50% at 3.6, and 100% at ECe 6.5 mmhos/cm.

Plant spacing depends on variety and type and whether bunch or climbing, and is between 0.6 to 0.9 x 0.05 to 0.1 m with a wider spacing when grown along with stakes. Depth of sowing is 2 to 5 cm. Prevention against root rot requires good drainage and rotation. Common rotation crops are alfalfa, potatoes and sugarbeet.

WATER REQUIREMENTS

Water requirements (ETm) of pea are similar to bean (350 to 500 mm). The crop coefficient (kc) relating maximum evapotranspiration (ETm) to reference evapotranspiration (ETo) is: during the initial stage 0.4 (10 to 25 days), the development stage 0.7-0.8 (25 to 30 days), the mid-season stage 1.05-1.2 (25 to 30 days), the late-season stage 1.0-1.15 (5 to 10 days) (fresh) and 0.65-0.75 (20 to 30 days) (dried), and at harvest 0.95-1.1 (fresh) and 0.25-0.3 (dried).

WATER SUPPLY AND CROP YIELD

The growing periods of pea are:

		fresh	dried	
0	establishment	10-25	10-25	days
1	vegetative	25-30	25-30	
2	flowering (including pod set)	15-20	15-20	
3	yield formation (pod development and pod filling)	15-20	20-25	
4	ripening	0-5	15-20	
		65-100	85-120	days

The relationships between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration deficit (1 - ETa/ETm) are shown in Figure 24. For calculation examples see p. 40 and Chapter VI.

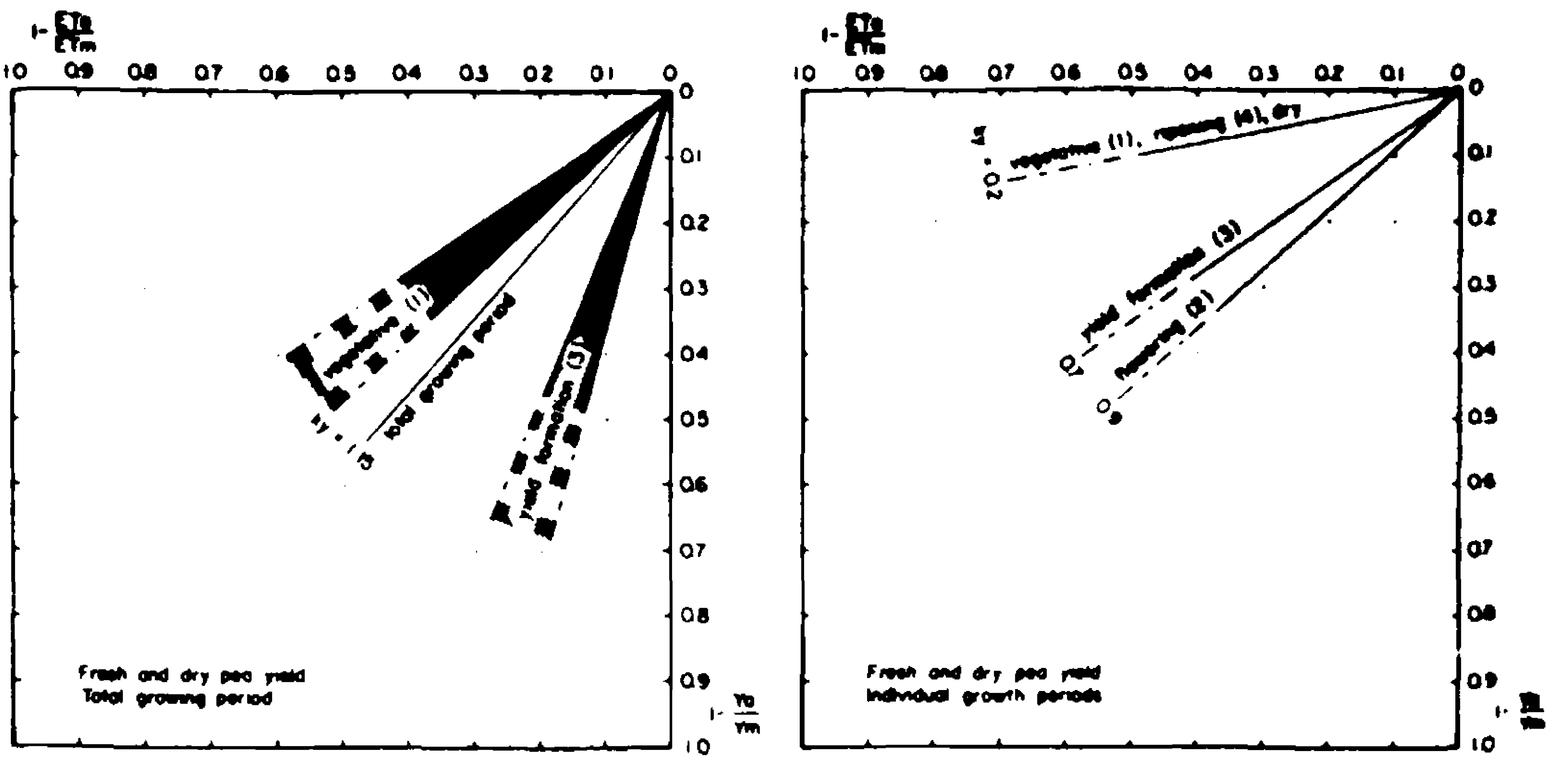


Fig. 24 Relationship between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration deficit (1 - ETa/ETm) for pea

The sensitive periods for water deficits are flowering (2) and yield formation (3). Unlimited water supply during the vegetative period (1) increases vegetative growth but may not necessarily affect the pea yield; water deficit in this period has a relatively small effect on yield. Similarly, water deficit during the ripening period for dry peas has a small effect on yield.

When rainfall is insufficient, irrigation during the flowering period (2) increases the number of marketable pods and number of seeds per pod, and during the yield formation period (3) increases the weight of both pod and seed. The crop tends to wilt more readily during periods of water shortage when adequate water was available in the preceeding periods.

For high yields the soil water depletion should not exceed 60 percent of the total available soil water during the vegetative period (1), and 40 percent during flowering (2) and yield formation (3) periods. Too frequent and light irrigation application results in uneven ripening. With harvest consisting of one picking it is sometimes recommended to withhold water supply during the latter part of the yield formation period (3) to advance ripening of the most developed pods. This applies particularly to varieties with a long and non-uniform ripening period.

Under conditions of limited water supply a high total production is obtained by meeting full crop water requirements on a limited area rather than by extending the area and partially meeting crop water requirements.

WATER UPTAKE

The crop has a tap root with many thin laterals. Rooting depth in deep soils can extend to 1 to 1.5 m but the effective depth of water uptake is generally restricted to the first 0.6 to 1.0 m (D = 0.6-1.0 m). The uptake pattern over soil depth, however, depends greatly on the irrigation practices. The uptake of water in relation to ETm is little affected up to soil water depletion of about 40 percent of total available soil water (p = 0.4).

IRRIGATION SCHEDULING

For optimum yield levels the soil water depletion in most climates should not exceed 40 percent of the total available soil water and irrigation frequencies of 7 to 10 days are common. When water supply is short, irrigation should be adequate during the flowering (2) and yield formation (3) periods with possible savings during the vegetative (1) and ripening (4) periods. When frequent irrigation is not possible, water supply should be scheduled as pre-irrigation, at flowering (2) and at the yield formation period (3) respectively, or with one irrigation only at least about 40 to 60 days after the pre-irrigation.

YIELD AND QUALITY

When irrigation is irregular, pods and seeds are less uniform in size, more variable in colour and also the date of maturity will vary. A high water deficit during late yield formation results in tough seeds of poor quality. In general, increase in seed size is accompanied by a decrease in the sugar content and the tenderness of the seed, and an increase in the starch and protein contents. Correct timing of the harvest remains an essential requirement for a good quality product. In suitable climates, good yields under irrigation are between 2 and 3 ton/ha shelled fresh pea (70 to 80 percent moisture) and 0.6 and 0.8 ton/ha dry pea (12 percent moisture). The water utilization efficiency for harvested yield (Ey) for fresh pea is about 0.5 to 0.7 kg/m^3 and for fresh pea about 0.15 to 0.20 kg/m^3.

PEPPER

Pepper (Capsicum annum and Capsicum frutescens) is thought to originate from tropical America. Most of the peppers grown belong to C. annum but the small, pungent peppers belong to C. frutescens. Present world production is about 5.5 million tons fresh fruit from 0.7 million ha.

Pepper thrives in climates with growing season temperatures in the range of 18 to 27°C during the day and 15 to 18°C during the night. Lower night temperatures result in greater branching and more flowers; warmer night temperatures induce earlier flowering and this effect is more pronounced as light intensity increases.

The crop is grown extensively under rainfed conditions and high yields are obtained with rainfall of 600 to 1 250 mm, well-distributed over the growing season. Heavy rainfall during the flowering period causes flower shedding and poor fruit setting, and during the ripening period rotting of fruits.

Light-textured soils with adequate water holding capacity and drainage are preferred. Optimum pH is 5.5 to 7.0 and acid soils require liming. Waterlogging, even for short periods, causes leaf shedding. Fertilizer requirements are 100 to 170 kg/ha N, 25 to 50 kg/ha P and 50 to 100 kg/ha K.

The crop is moderately sensitive to soil salinity, except in the seedling stage when it is more sensitive. Yield decrease at different levels of ECe is: 0% at ECe 1.5 mmhos/cm, 10% at 2.2, 25% at 3.3, 50% at 5.1 and 100% at ECe 8.5 mmhos/cm.

Seeds are sown in nursery beds which in the cooler climates are sometimes enclosed and heated since soil temperatures in the range of 20 to 24°C are considered optimum for germination. Seedlings of 10 to 20 cm height are transplanted in the field after 25 to 35 days. The length of the total growing period varies with climate and variety but in general it takes 120 to 150 days from sowing to the latest harvest. Prior to transplanting, the seedlings raised in enclosed and heated nurseries are hardened by increased ventilation. The plants are sometimes topped 10 days before transplanting to encourage branching. Plant spacing is 0.4 to 0.6 m x 0.9 m. For production of fruits for canning, closer spacings are sometimes used. Flowering starts 1 to 2 months after transplanting with first picking of green peppers 1 month later. Thereafter, ripe, red peppers are picked at 1 to 2 week intervals for up to 3 months. Ripe chillies are semi-dried for 3 to 15 days, with the final weight being about 25 percent of the fresh fruit weight.

WATER REQUIREMENTS

Total water requirements (ETm) are 600 to 900 mm and up to 1 250 mm for long growing periods and several pickings. The crop coefficient (kc) relating reference evapotranspiration (ETo) to maximum evapotranspiration (ETm) is 0.4 following transplanting, 0.95 to 1.1 during full cover and for fresh peppers 0.8 to 0.9 at time of harvest.

WATER SUPPLY AND CROP YIELD

The relationship between relative yield decrease and relative evapotranspiration deficit is given for the total growing period in Figure 27.

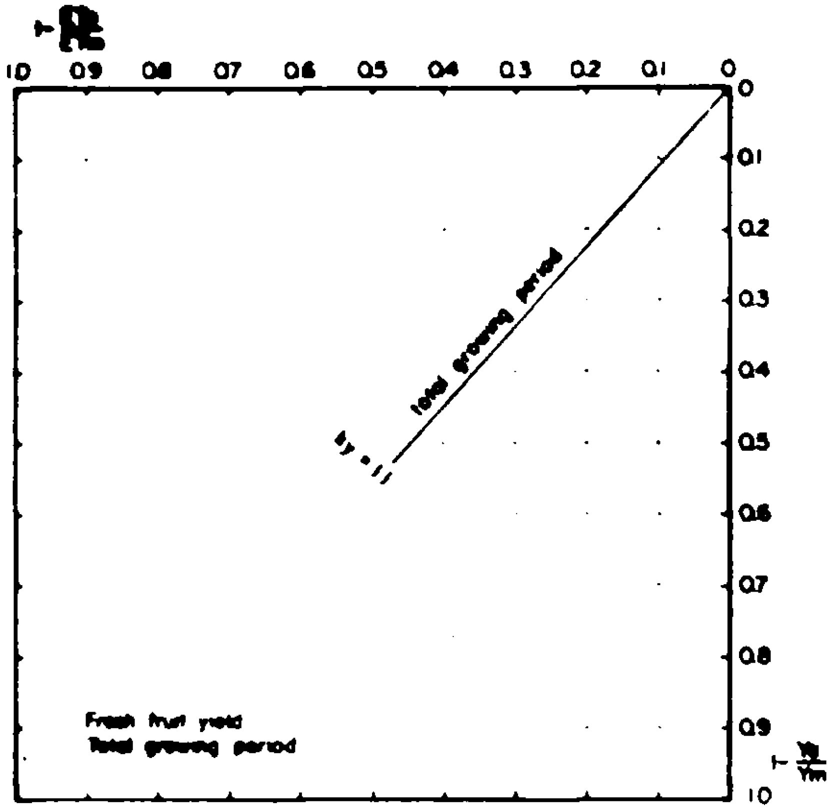


Fig. 25

Relationship between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration deficit (1 - ETa/ETm) for pepper

For high yields, an adequate water supply and relatively moist soils are required during the total growing period. Reduction in water supply during the growing period in general has an adverse effect on yield and the greatest reduction in yield occurs when there is a continuous water shortage until the time of first picking. The period at the beginning of the flowering period is most sensitive to water shortage and soil water depletion in the root zone during this period should not exceed 25 percent. Water shortage just prior and during early flowering reduces the number of fruits. The effect of water deficit on yield during this period is greater under conditions of high temperature and low humidity. Controlled irrigation is essential for high yields because the crop is sensitive to both over and under irrigation (Figure 26).

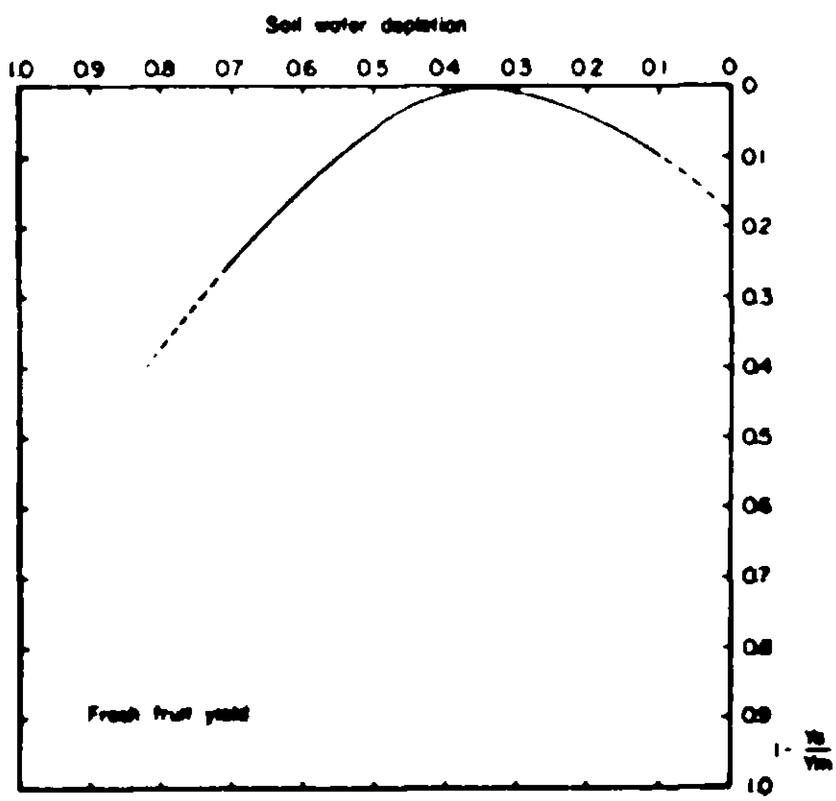


Fig. 26

Relationship between relative yield decrease (1 - Ya/Ym) and soil water depletion for pepper

With poor quality (saline) water the yield of first pickings is reduced but the effect is less pronounced on later pickings. Sprinkling with poor quality (saline) water causes leaf burn and 'nose rot' of the fruits. Water deficits during yield formation period lead to shrivelled and malformed fruits. The pungent quality of the fruit (hotness) can to a certain degree be influenced by water supply.

Under conditions of limited water supply, total production is increased by meeting full crop water requirements over a limited area, rather than by extending the area and partially meeting the crop water requirements.

WATER UPTAKE

Pepper has a tap root which is broken at the time of transplanting and a profusely branched lateral root system subsequently develops. Root depth can extend up to 1 m but under irrigation roots are concentrated mainly in the upper 0.3 m soil depth. Normally 100 percent of the water uptake occurs in the first 0.5 to 1.0 m soil depth (D = 0.5-1.0 m). Under conditions when maximum evapotranspiration is 5 to 6 mm/day, 25 to 30 percent of the total available soil water can be depleted until soil water uptake will be reduced (p = 0.25 to 0.30).

IRRIGATION SCHEDULING

For optimum yield levels the soil water depletion in most climates should not exceed 30 to 40 percent of the total available soil water. Due to the low depletion level light irrigation applications are required. Irrigation frequencies of 4 to 7 days are common. When water supply is short, irrigation should preferably be adequate up to the first picking and savings may be made thereafter.

IRRIGATION METHODS

Peppers are grown under surface, sprinkler and drip irrigation. With sprinkler irrigation, yields tend to be higher under light applications as compared to heavy intensity sprinkling. However, with poor quality water, heavy intensity and large amounts are generally preferred with sprinkler irrigation because of reduced leaf burning and improved leaching of salts. The crop is particularly suitable for drip irrigation where very high yields can be obtained.

YIELD AND QUALITY

Yields vary greatly with climate and length of growing period, e.g. number of pickings. Under irrigation commercial yields are in the range of 10 to 15 ton/ha fresh fruit and 20 to 25 ton/ha are obtained under favourable climatic conditions. However, the marketable yield percentage may vary. Number of pickings is 1 for machine harvesting and up to 6 for hand picking, depending on the length of the harvesting period. The water utilization efficiency for harvested yield (Ey) for fresh pepper containing about 90 percent moisture varies between 1.5 and 3.0 kg/m

PINEAPPLE

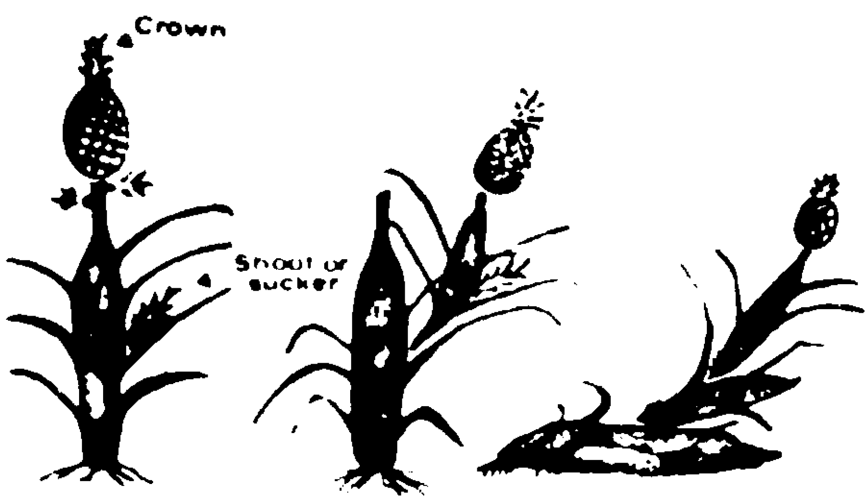
Pineapple (<u>Ananas comosus</u>) is a perennial crop grown for its fruits and used as a fresh and processed product. World production is about 5.5 million tons fresh fruit.

The origin of the pineapple is still uncertain but the Parana-Paraguay Basin has been considered as a possible area. For good growth pineapple requires mean daily temperatures of 22 to 26°C with an optimum of 23 to 24°C. Mean daily maximum and minimum temperatures of 30 and 20°C respectively for the whole growing period are considered optimum. Temperatures below or above this range affect fruit quality or the acid and sugar content.

The crop is grown between 31°N and 34°S, primarily in regions with high relative humidity. A combination of optimum temperature and high humidity results in soft, large leaves and juicy fruits, low in acid content. Fruits ripening in periods with cool temperatures and low radiation levels, e.g. in winter or at high altitudes, are of inferior quality because of poor shape for canning. Requirements for canning are: a cylindrical shape, fruit eyes of a relatively shallow surface and a small fruit core in relation to the fruit.

Pineapple can grow on a wide range of soils but a sandy loam texture is preferred. Optimum soil pH is 4.5 to 6.5. The soil should have a low lime content. The crop is sensitive to waterlogging and therefore requires a well-drained soil with good aeration. For high production the fertilizer needs are 230 to 300 kg/ha N, 45 to 65 kg/ha P and 110 to 220 kg/ha K.

Pineapple is usually grown in double rows on raised beds. With a spacing of 0.6 x 0.3 m in beds 0.75 to 0.90 m apart, plant population is about 50 000 per ha. Shading is sometimes used where temperatures are high and radiation intense to protect the crop from scorching. The crop is multiplied using slips, crowns and shoots or suckers, but in comparison with using suckers as planting material, the period from planting to harvest is about 20 percent longer when slips are used, and about 35 percent longer when crowns are used. Use of different planting material allows a manipulation of the crop growing period and particularly in selection of the time of harvest when climatic conditions are favourable for high quality fruits. Normally the plant crop is followed by one ratoon crop, but when climatic conditions are favourable, the crop will continue to bear fruits but quality rapidly declines after the first ratoon. However, in warm tropical climates, e.g. at low altitudes near the equator, no ratoon crop is possible because suckers do not develop. The period from planting to harvest of the plant crop is 1 to 2 years and of the ratoon crop 9 months to 1.5 years depending on planting material and climate.



...nt crop, first ratoon and second ratoon (Collins, 1960)

Flower initiation in pineapple is induced by low temperature, water deficit or hormone sprays; the latter results in a uniform fruiting and harvest period.

WATER REQUIREMENTS

Crop water requirements (ETm) for high production are very different from those of most other crops. Because there is a suspension of transpiration during the day, maximum evapotranspiration is low and varies between 700 and 1 000 mm per year The crop coefficient (kc) relating reference evapotranspiration (ETo) to ETm is about 0.4 to 0.5 for the total growing period.

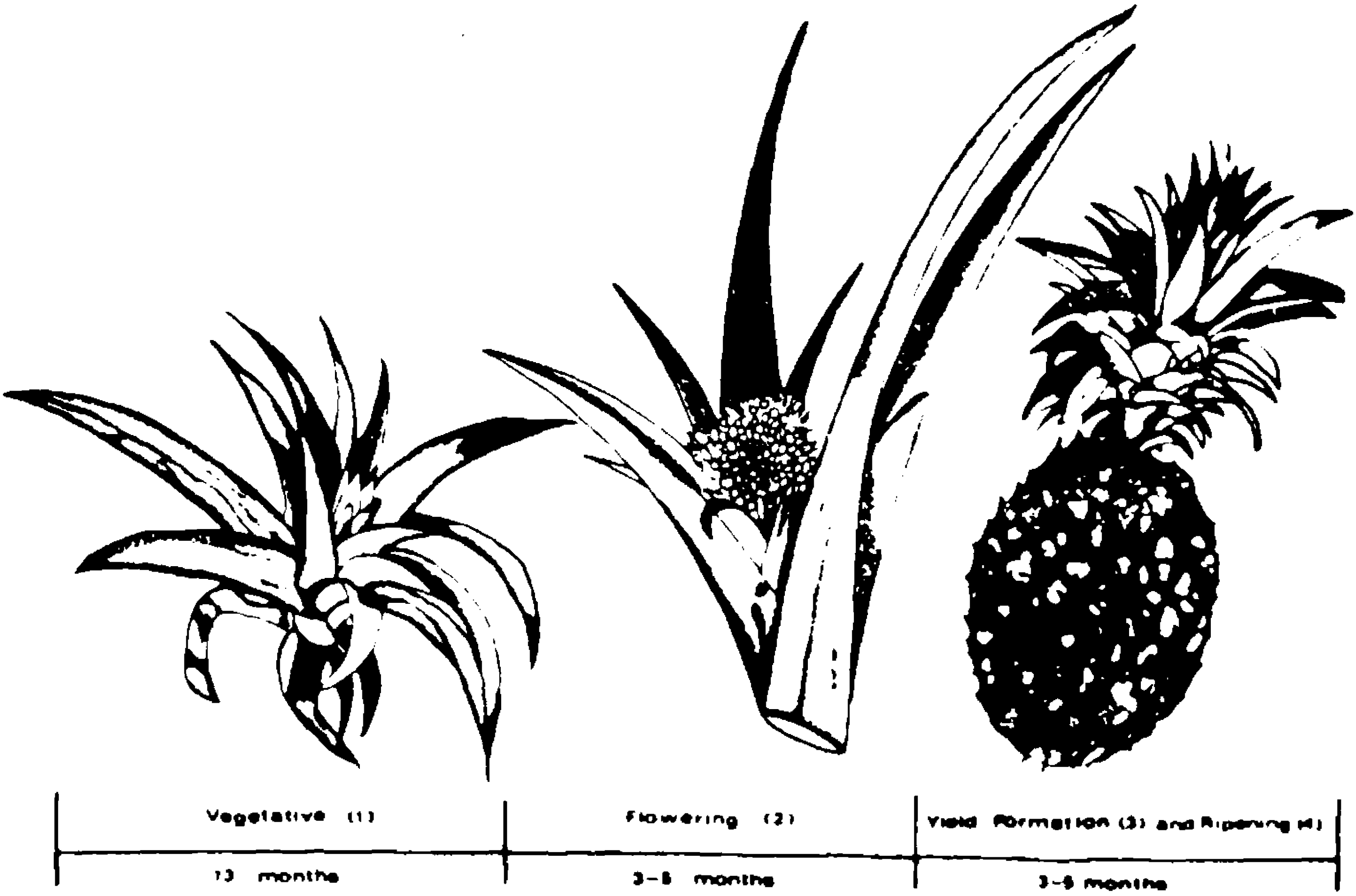


Fig. 28 Growth periods of a 20-month pineapple (after E.A.C., 1977)

WATER SUPPLY AND CROP YIELD

Pineapple can survive long dry periods through its ability to retain water in the leaves which is used during these periods. Also due to its low water use, the plant can survive on a small depth of stored soil water. However, the crop is sensitive to water deficit, especially during the vegetative growth period, when the size and fruiting characteristics are determined. Water deficits retard growth, flowering and fruiting. Water supply during this period should meet full water requirements of the crop. Water deficit at flowering has a less serious effect and may even hasten fruiting and result in uniform ripening. An ample water supply at flowering will lead to vigorous stem growth and a large core which is disadvantageous when the fruit is used for canning.

Frequent irrigation or rain at the time of harvest may cause deterioration of the quality of the fruit and make the crop susceptible to the fungus causing heart rot. In addition, waterlogging affects fruit quality.

Where water supply is limited, mulching is practised to reduce soil evaporation and soil temperature. Dew has been found to contribute to meeting the water requirements of the crop.

WATER UPTAKE

The rooting system of pineapple is shallow and sparse. In deep soils, maximum root depth may extend up to 1 m but roots are generally concentrated in the first 0.3 to 0.6 m, from which normally 100 percent of the water is extracted (D = 0.3-0.6 m). Under conditions when maximum evapotranspiration is 5 to 6 mm/day, water uptake starts to be reduced when about 50 percent of the available soil water has been depleted (p = 0.5).

IRRIGATION SCHEDULING

Adequate water supply is essential particularly during the vegetative period. The interval of application can be based on the prevailing rate of maximum evapotranspiration (ETm) and the fraction (p) of the total available soil water. Where rainfall is small and irrigation water supply is restricted, irrigation scheduling should be based on avoiding water deficits during the period of vegetative growth (1). Supply of water can be restricted during the period of ripening (4) whereas some water savings can be made by allowing higher depletion levels up to 75 percent during flowering (2). During the month prior to harvest irrigation is discontinued. The method of irrigation is mostly by sprinkler.

YIELD AND QUALITY

The fruit contains about 80 to 85 percent water and 10 to 14 percent sugar. Irrigation has an effect on the sugar/acid ratio, particularly in the period prior to harvest when frequent high irrigation decreases the sugar content. The infestation by soil-borne fungus diseases is increased.

Under commercial production, weight per fruit is about 1.5 to 1.8 kg, and total yield between 75 and 90 ton/ha fresh fruit. The water utilization efficiency for harvested yield (Ey) for fresh fruit is about 5 to 10 kg/m³ for the plant crop and 8 to 12 kg/m³ for the first ratoon crop.

POTATO

Potato (Solanum tuberosum) originates in the Andes from the tropical areas of high altitude. The crop is grown throughout the world but is of particular importance in the temperate climates. Present world production is some 290 million tons fresh tubers from 21 million ha.

Yields are affected by temperature and optimum mean daily temperatures are 18 to 20°C. In general a night temperature of below 15°C is required for tuber initiation. Optimum soil temperature for normal tuber growth is 15 to 18°C. Tuber growth is sharply inhibited when below 10°C and above 30°C. Potato varieties can be grouped into early (90 to 120 days), medium (120 to 150 days) and late varieties (150 to 180 days). Cool conditions at planting lead to slow emergence which may extend the growing period. Early varieties bred for temperate climates require a daylength of 15 to 17 hours, while the late varieties produce good yields under both long or short day conditions. For tropical climates, varieties which tolerate short days are required for local adaptation.

Potato is grown in a 3 or more year rotation with other crops such as maize, beans and alfalfa, to maintain soil productivity, to check weeds and to reduce crop loss from insect damage and diseases, particularly soil-borne disease. Potato requires a well-drained, well-aerated, porous soil with pH of 5 to 6. Fertilizer requirements are relatively high and for an irrigated crop they are 80 to 120 kg/ha N, 50 to 80 kg/ha P and 125 to 160 kg/ha K. The crop is grown on ridges or on flat soil. For rainfed production in dry conditions, flat planting tends to give higher yields due to soil water conservation. Under irrigation the crop is mainly grown on ridges. The sowing depth is generally 5 to 10 cm, while plant spacing is 0.75 x 0.3 m under irrigation and 1 x 0.5 m under rainfed conditions. Cultivation during the growing period must avoid damage to roots and tubers, and in temperate climates ridges are earthed up to avoid greening of tubers.

The crop is moderately sensitive to soil salinity with yield decrease at different levels of ECe: 0% at 1.7, 10% at 2.5, 25% at 3.8, 50% at 5.9 and 100% at ECe 10 mmhos/cm.

WATER REQUIREMENTS

For high yields, the crop water requirements (ETm) for a 120 to 150 day crop are 500 to 700 mm, depending on climate. The relationship between maximum evapotranspiration (ETm) and reference evapotranspiration (ETo) is given by the crop coefficient (kc) which is: during the initial stage 0.4-0.5 (20 to 30 days), the development stage 0.7-0.8 (30 to 40 days), the mid-season stage 1.05-1.2 (30 to 60 days), the late-season stage 0.85-0.95 (20 to 35 days), and at maturity 0.7-0.75.

WATER SUPPLY AND CROP YIELD

The growth periods of potato are given in Figure 29. The relationship between relative yield decrease and relative evapotranspiration deficit is given in Figure 30. For calculation examples see p. 40 and Chapter VI.

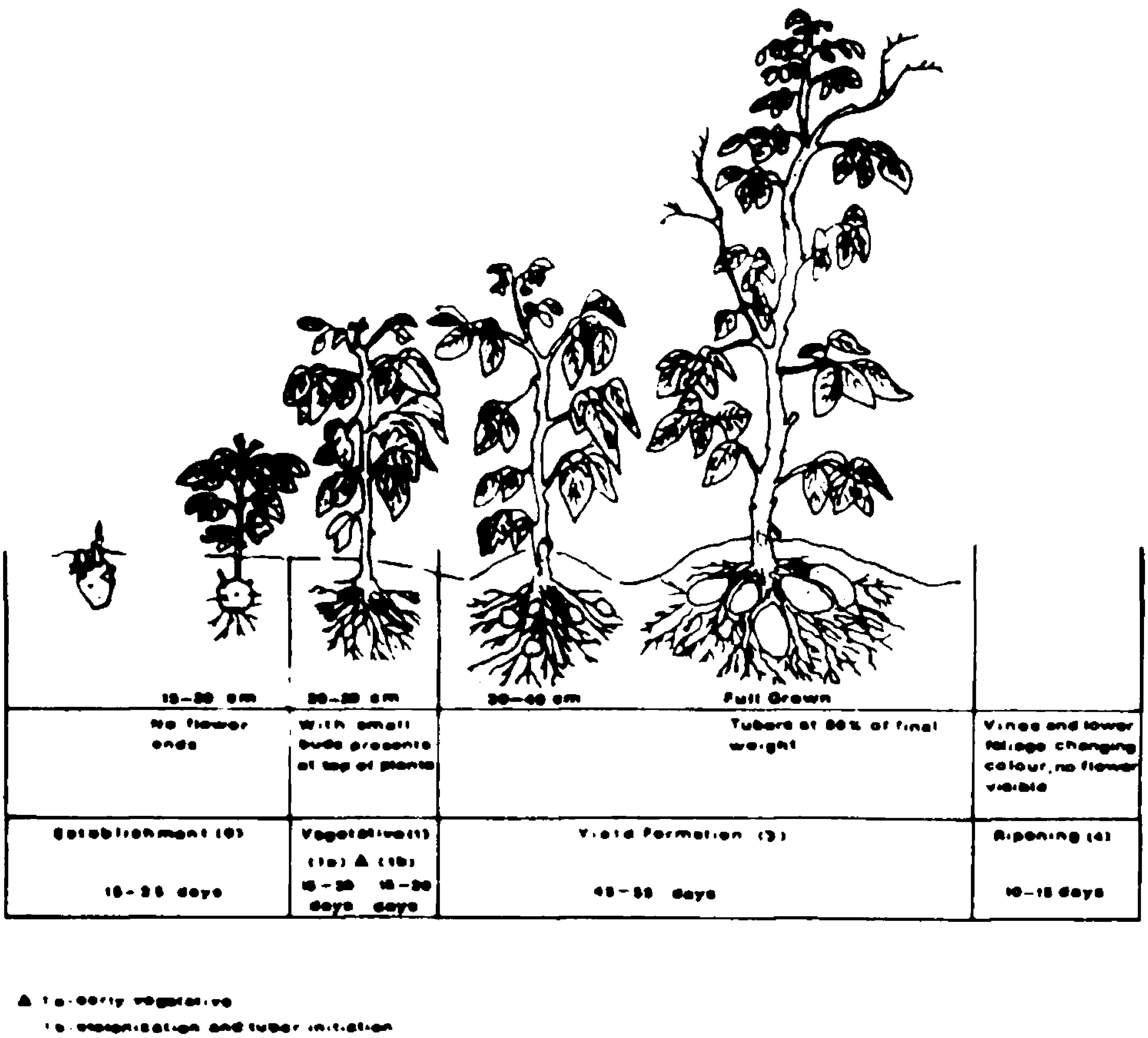


Fig. 29 Growth periods of potatoes (after W.C. Sparks, 1972)

Potato is relatively sensitive to soil water deficits. To optimize yields the total available soil water should not be depleted by more than 30 to 50 percent. Depletion of the total available soil water during the growing period of more than 50 percent results in lower yields. Water deficit during the period of stolonization and tuber initiation (1b) and yield formation (3) have the greatest adverse effect on yield, whereas ripening (4) and the early vegetative (1a) periods are less sensitive. In general, water deficits in the middle to late part of the growing period thus tend to reduce yield more than in the early part. However, varieties vary in their sensitivity to water deficit. Some varieties respond better to irrigation in the earlier part of the yield formation period (3) while others show a better response in the latter part of that period. Yields of varieties with few tubers may be somewhat less sensitive to water deficit than those with many tubers.

To maximize yield, the soil should be maintained at a relatively high moisture content. This, however, can have an adverse effect when frequent irrigation with relatively cold water may decrease the soil temperature below the optimum value of 15 to 18°C for tuber formation. Also, soil aeration problems can sometimes occur in wet, heavy soils.

Since the potato is a relatively sensitive crop in terms of both yield and quality, under conditions of limited water supply the available supply should preferably be directed towards maximizing yield per ha rather than spreading the limited water over a larger area. Savings in water can be made mainly through improved timing and depth of irrigation application.

WATER UPTAKE

Under evaporative conditions with ETm of 5 to 6 mm, the effect of soil water depletion up to 25 percent on yield is small (p = 0.25). Since potato has a shallow root system, normally 70 percent of the total water uptake occurs from the upper 0.3 m and 100 percent from the upper 0.4 to 0.6 m soil depth (D = 0.4-0.6 m). The uptake pattern will, however, also depend on the soil texture and structure.

IRRIGATION SCHEDULING

Where rainfall is small and irrigation water supply is restricted, irrigation scheduling should be based on avoiding water deficit during the period of stolonization and tuber initiation (1b) and yield formation (3). Supply of water can be restricted during the early vegetative (1a) and ripening (4) periods. Savings can also be attained by allowing higher soil water depletion toward the ripening period (4) so that all available stored water in the root zone is used by the crop. This practice may also hasten maturity. Correct timing of irrigation may save 1 to 3 irrigation applications including the last irrigation prior to harvest.

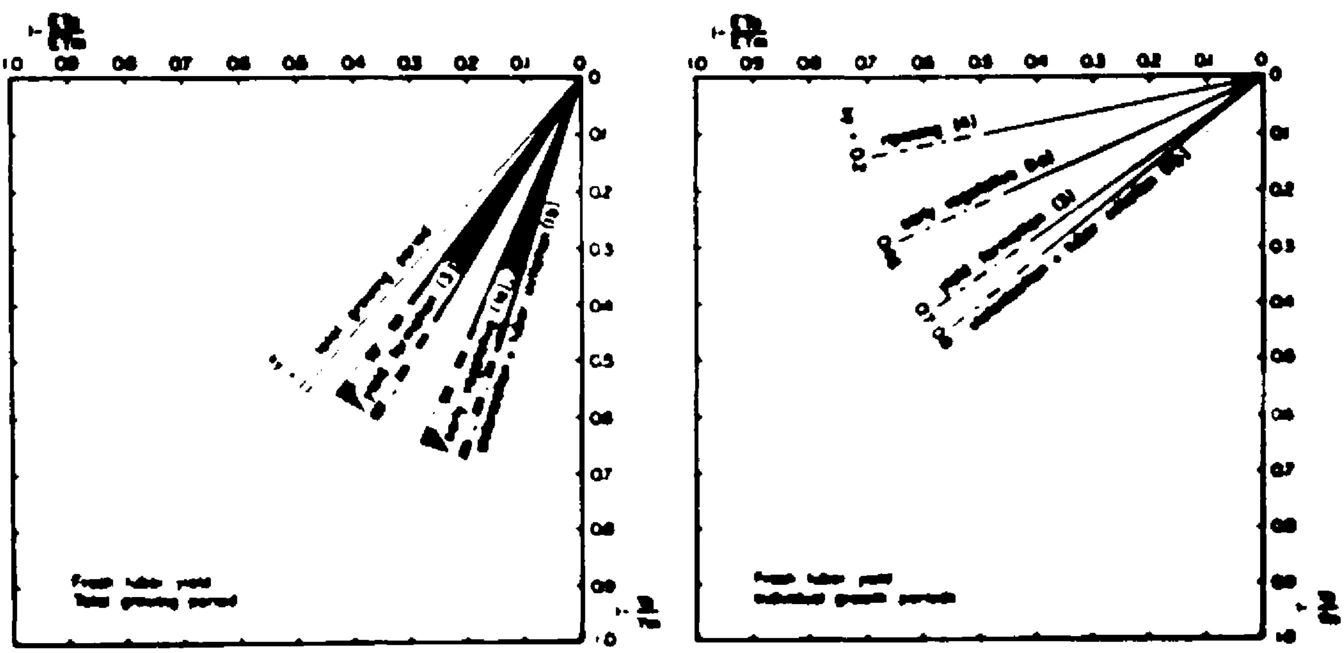


Fig. 30 Relationship between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration (1 - ETa/ETm) for potato

IRRIGATION METHODS

Most common irrigation methods for potato are furrow and sprinkler. Yield response to frequent irrigation is considerable because the crop has a shallow root system and requires a low soil water depletion. For example, very high yields are obtained with the mechanized sprinkler systems where evapotranspiration losses are replenished each or every two days.

YIELD AND QUALITY

Water supply and scheduling are important in terms of quality. Water deficit in the early part of the yield formation period (3) increases the occurrence of spindled tubers, which is more noticeable in cylindrical than in round tubered varieties. Water deficit during this period followed by irrigation may result in tuber cracking or tubers with black hearts. Dry matter content may increase slightly with limited water supply during the ripening period (4). Frequent irrigation does reduce occurrence of tuber malformation.

Good yields under irrigation of a crop of about 120 days in the temperate and subtropical climates are 25 to 35 ton/ha fresh tubers and in tropical climates yields are 15 to 25 ton/ha. The water utilization efficiency for harvested yield (Ey) for tubers containing 70 to 75 percent moisture is 4 to 7 kg/m^3.

RICE
(paddy)

Rice (*Oryza sativa*) is believed to originate from southeast Asia. The present world production is about 345 million tons from about 142 million ha.

In general, Indica rice is grown in the humid tropics and Japonica rice is best suited to temperate and subtropical climates. The total growing period normally varies between 90 and 150 days depending on variety, temperature and sensitivity to daylength. The early maturing varieties are day-neutral and the late maturing varieties are short-day plants. The response of rice to temperature differs with variety. In general, below 12°C germination does not occur. Rice seedlings from the nursery bed can be transplanted to the field when the mean daily temperature is about 13 to 15°C. Temperatures between 22 and 30°C are required for good growth at all stages but during flowering and yield formation small differences between day and night temperatures are required for good yield. Optimum daytime air and water temperatures for the growth of rice are in the range of 28 to 35°C. The decrease of temperature of water during the night under hot conditions helps to maintain favourable water temperatures during daytime but should not decrease below 18°C.

Rice is normally transplanted at random with an optimum spacing varying between 0.15 x 0.15 and 0.30 x 0.30 m.

A wide range of soils are suitable for rice cultivation but heavier soils are preferred due to low percolation losses. The crop has a high tolerance to acidity with optimum pH between 5.5 and 6. For high production, fertilizer requirements are 100 to 150 kg/ha N, 20 to 40 kg/ha P and 80 to 120 kg/ha K. Split applications before transplanting, at tillering and heading have the greatest effect on yield. Nitrogen fertilizer application may be lower where there is a considerable biological N-fixation by blue-green algae and bacteria.

Rice is moderately tolerant to salinity. Yield decreases for different salinity levels are: 0% at ECe 3.0 mmhos/cm, 10% at 3.8, 25% at 5.1, 50% at 7.2 and 100% at ECe 11.5 mmhos/cm.

WATER REQUIREMENTS

Water requirements of paddy rice for evapotranspiration are between [illegible] and 700 mm, depending on climate and length of the total growing period. Evaporation losses tend to become somewhat smaller at shallow submersion or when the topsoil partially dries out. Evapotranspiration increases with vegetative growth and is highest just before flowering to early yield formation, after which it declines somewhat. For paddy rice, the maximum evapotranspiration (ETm) in relation to reference evapotranspiration (ETo) is given by the crop coefficient (kc) for the different months or during the first month and the second month 1.1 to 1.15, mid-season 1.1 to 1.3 and the last month 0.95 to 1.05.

WATER SUPPLY AND CROP YIELD

The growth periods of rice are shown in Figure 31 and the relationship between relative yield decrease (1 - Ye/Ym) and relative evapotranspiration deficit (1 - ETa/ETm) for the total growing period are shown in Figure 32.

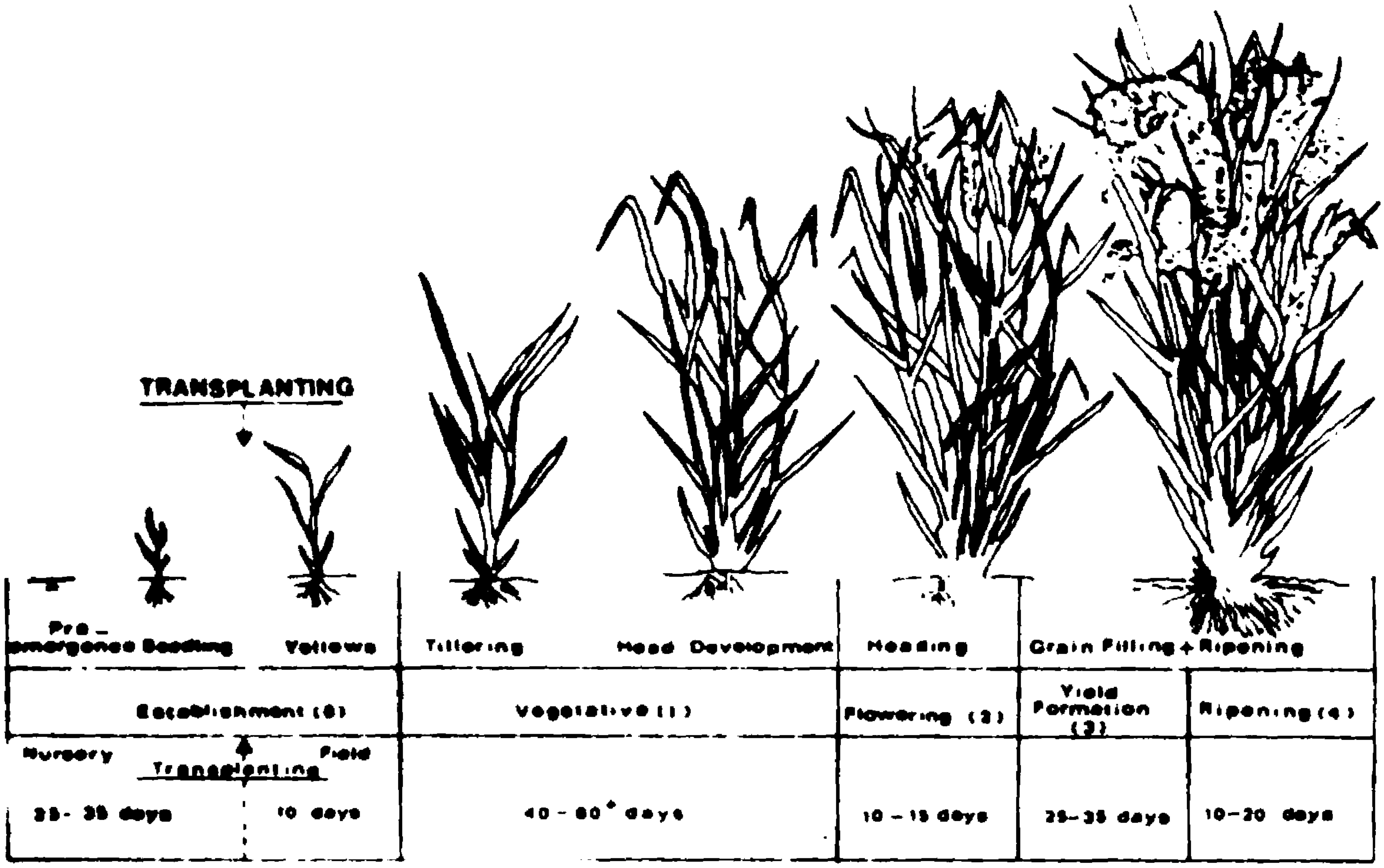


Fig. 31 Growth periods of rice

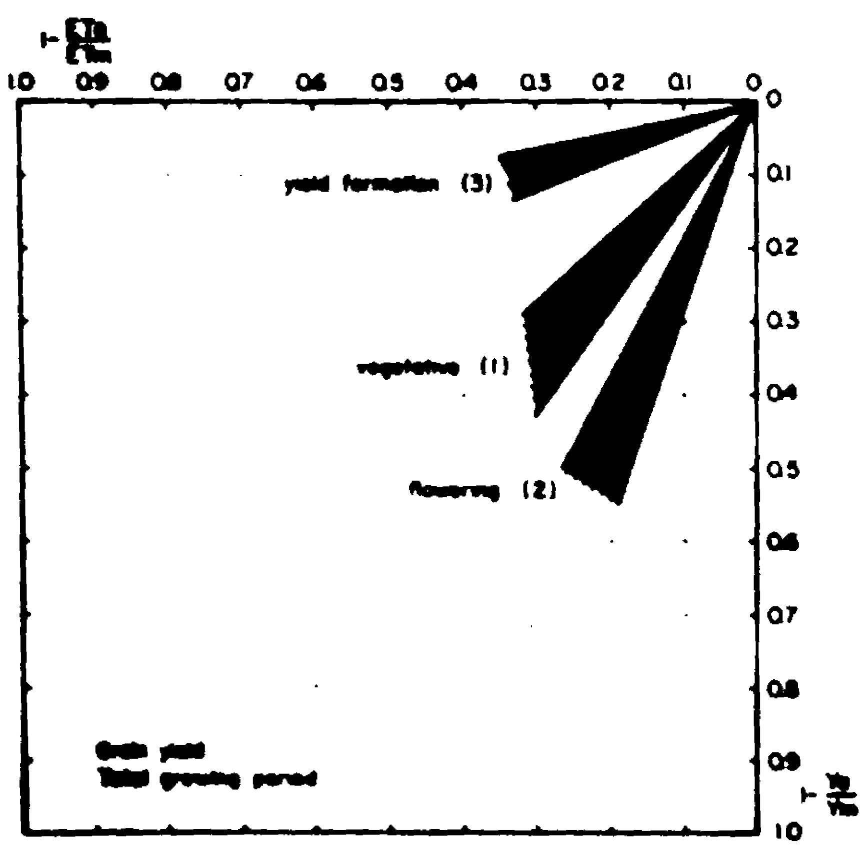


Fig. 32

Relationship between relative yield (1 - Ya/Ym) and relative evapotranspiration (1 - ETa/ETm) for rice

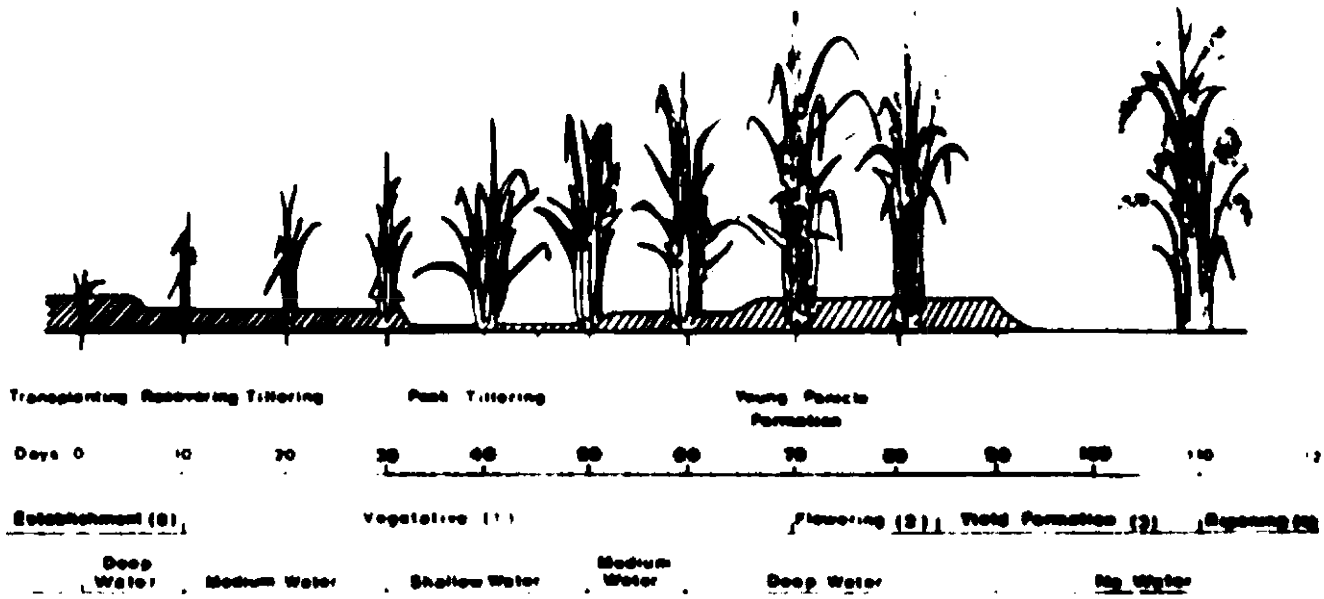


Fig. 33 Controlled water depth in paddy field (Kung, 1971)

Adequate water during the total growing period is needed for vigorous growth and high yield. Because plants have to recover from transplanting and for formation of the roots, adequate water supply just following transplanting is important. For high yields, the water depth in the paddy field required at different growth stages is shown in Figure 33.

The most sensitive periods to water deficit are flowering (2) and the second half of the vegetative period (head development). When moisture content of the soil decreases to 70 to 80 percent of the saturation value, rice yields begin to decline. At a soil water content of 50 percent of saturation, yield decrease is 50 to 70 percent. At a soil water content of 30 percent, no yield can be expected and plants die when soil water content is below 20 percent (Figure 34).

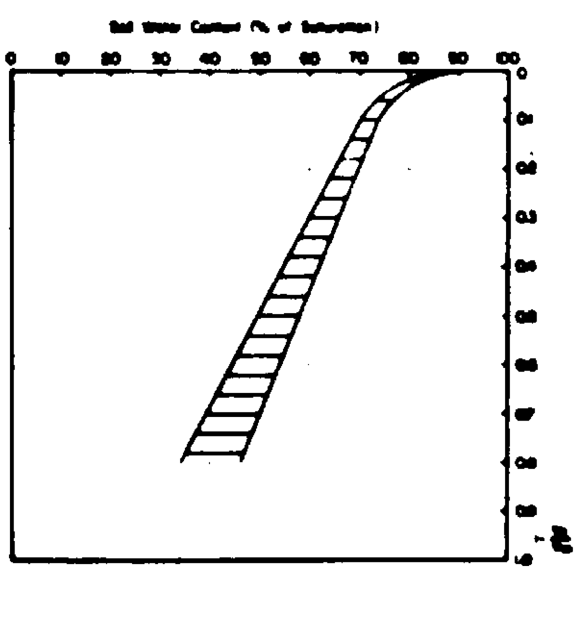


Fig. 34 Relationship between relative yield decrease (1 - Ya/Ym) and moisture content of the soil for rice

WATER UPTAKE

The root system of rice increases gradually from transplanting, reaching a maximum at the time of heading, and decreases after flowering while at maturity most of the roots are dead. Root growth continues under low oxygen concentrations in the soil. At the time of head initiation, root growth is horizontal and upward, producing a dense surface mat. Maximum rooting depth is about 1 m in the absence of a dense subsoil layer.

IRRIGATION SCHEDULING

Several irrigation scheduling practices have been developed. Because paddy rice is mostly grown under conditions of near soil saturation and submersion, loss through percolation should be minimal. A dense subsoil layer is obtained by puddling the wet soil which requires 100 to 200 mm of water, and sometimes up to 300 mm, including the pre-planting irrigation.

- 'Continuous submergence' with intermittent drainage is the most promising method (Figure 33). During and immediately after transplanting the water is kept at 10 cm for about a week after transplanting to secure healthy growth of the seedlings. In the following tillering period, submergence is shallow (maximum 3 cm) to maintain high soil temperatures. Drainage and drying of the top soil is practised during this period since rice can tolerate a water shortage and root development is enhanced. Drainage must be completed 30 days prior to heading. From this time onward, adequate water supply during head development through flowering is essential. Because root activity at this time is at its maximum, water temperature should preferably be high but below 35°C. Continuous flow irrigation or drainage and renewal of water once or twice during this period is sometimes practised. During the ripening period fields should gradually be drained to facilitate harvest operations. Usually fields are completely drained 30 to 45 days after heading, with the shorter period for early rice varieties and the longer for late varieties. Untimely drainage adversely affects yields.

- With the 'intermittent irrigation method', soil water during the non-submersion period must be adequate. When the soil water content falls slightly below saturation, water is added until a shallow submergence is attained. Intermittent irrigation saves water by reducing surface runoff and percolation losses, and also increases the amount of rainfall that is used effectively.

- With the 'heading stage submergence method', the soil is kept at saturation or is lightly submerged during almost the whole growing period, except for a period of 25 days prior to about 10 days after heading when rice fields are submerged to a depth of 10 cm.

- When 'water saving' is essential, the field after puddling and transplanting is supplied with water to keep soil water content in the root depth at not less than 75 percent of full saturation throughout the total growing period. Moderate submergence is only practised during a period of 30 days starting at head initiation till the end of flowering. Especially on soils with high percolation rates, substantial water savings up to 50 percent can be made.

Compared to continuous submersion, water savings are estimated:

	water applied	yield
continuous submersion	100%	100%
intermittent irrigation	80%	50%
heading stage submersion	60%	75%
water saving irrigation (controlled)	75%	110%

Although rice is an aquatic plant and grows well under submerged conditions, deep and prolonged submersion of paddy rice adversely affects plant growth. High yielding varieties are more susceptible to flood damage than most traditional varieties. The most susceptible stages for whole plant submergence are head development and flowering. Relatively little damage is done when the head and upper leaves remain above the flood water surface (Figure 35).

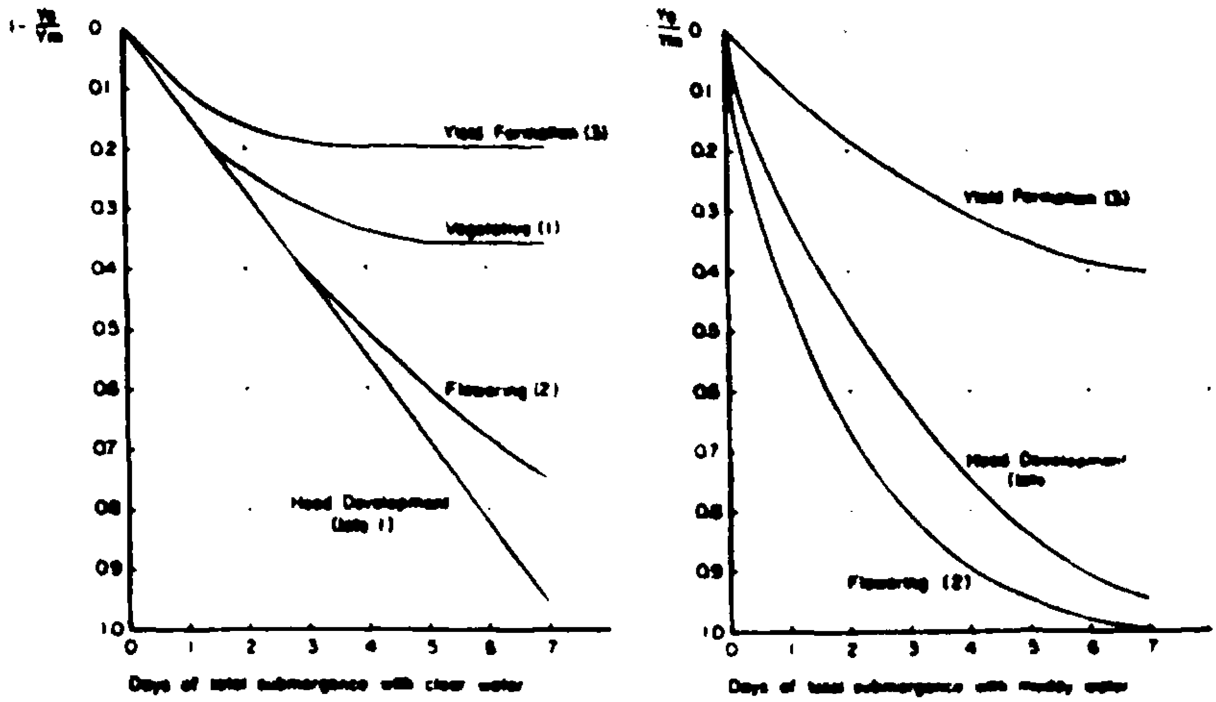


Fig. 35 Relationship between relative yield decrease (1 - Ya/Ym) and number of days of total submergence with clear and muddy water for rice

Ways to decrease surface runoff and percolation include controlled submersion with high water depths practised only during a few selected stages of growth. Also, accurate land levelling and good puddling and impervious levees will reduce water losses. To reduce excessive percolation on soil compaction or application of heavy soil is practised. Artificial sealings, like polyethylene membranes, asphalt barriers or concrete barriers have been tried experimentally.

IRRIGATION METHODS

Basin irrigation is used for rice production. Fields should be level and both water supply and drainage should be fully controllable. Size of the fields can vary greatly depending on topography, land ownership and level of water supply.

YIELD AND QUALITY

Alternate wetting and drying during the yield formation and ripening periods may cause grain to crack. The crop should be harvested before the grain is completely dry since cracks are more readily formed when the grain is quite hard. Slow drying gives a higher percentage of whole grains while the moisture content of 20 percent is sometimes used as a guide to determine ripeness of the grain in the field. A moisture content of 15 percent is critical for crack formation, while internal cracks occur at greater dryness of the seed.

Good yields under fully controlled irrigation with high inputs are 6 to 8 ton/ha paddy (unmilled rice). Under controlled flood irrigation good yields are 3 to 4 ton/ha. The water utilization efficiency for harvested yield (Ey) for paddy containing about 15 to 20 percent of moisture, is 0.7 to 1.1 kg/m^3. Milling percentage of rice is about 65 percent.

FISH PRODUCTION

Rice and fish production can take place at the same time. The fish is either stocked (bred species) or is introduced with the irrigation water into the rice field (wild species). Standing water in the fields should be 5 to 25 cm, depending on fish size. During periods of field drainage the fish should be able to take refuge in supply and drainage ditches or in specially constructed depressions. Fish production in cropped paddy fields can amount to 400 kg/ha/year. However, under conditions of high crop and water management for rice production, the value of fish yield generally does not balance the reduction in rice yield. Problems are also experienced with use of herbicides and pesticides being toxic to fish.

Rice and fish production can be alternated when field layout and water control structures are adapted to suit both rice and fish production. High rice yields and high fish production can be obtained. For fish production the fields should be adequately fertilized, and additional feeding is normally required. With a proper combination of fish species, good production is 5 to 10 ton/ha/year. Species commonly used in combination with rice cultivation are common carp (Cyprimus carpio), Tilapia spp. sepat siam (Trichogaster pectoralis) and kissing gurami (Helostoma temmincki).

See also H. Tsutsui, Water management in paddy fields. FAO Irrigation and Drainage Paper. In press.

SAFFLOWER

Safflower (*Carthamus tinctorius*) is only known in its cultivated form with centres of origin probably in the Near East. The estimated world production is about 0.7 million tons of seed per year from about 1 million ha. The flowers from the spiny cultivars are grown for oil, while some spineless cultivars are used for dye production.

Safflower is not suited to lowland, humid tropics. Large scale commercial cropping is practised in USA and USSR between 30° and 45°N and in Australia between 15° and 35°S. Emerging plants need cool temperatures for root growth and rosette development (mean daily temperature 15 to 20°C) and higher temperatures during stem growth, flowering and yield formation periods (20 to 30°C). There is no germination below 2°C. At 5°C germination takes 16 days and at 16°C, 4 days. The seedling is frost-resistant up to -7°C but after this stage frost below -2°C kills the plant. The crop seems to be sensitive to daylength but the effect is difficult to quantify. The length of the growing period for an autumn-planted crop varies from 200 to 230 days; when planted in spring, 120 to 160 days.

Safflower requires a fertile, fairly deep and well-drained soil. [illegible] irrigated production a medium-textured soil is preferable. Shallow soils seldom produce high yields. On suitable soils roots go down to 3.5 m; dense subsoils retard root growth. The crop is well adapted to the presence of a water table at a depth of up to 1 m. Under irrigation, the fertilizer requirements are 60 to 110 kg/ha N, 15 to 30 kg/ha P and 25 to 40 kg/ha K. Though there is a rather wide tolerance to pH, high yields are obtained on soils with a neutral reaction; when pH is lower than 6 liming may be advisable.

Fig. 36
Safflower, spiny cultivar during flowering period (Weiss, [illegible]

The crop is moderately tolerant to salinity, ranking just below cotton. Yield decrease due to soil salinity is: 0% at ECe 5.3, 10% at 6.2, 25% at 7.6, 50% at 9.9 and 100% at ECe 14.5 mmhos/cm. During germination the seedlings are about half as tolerant, which is relatively high compared to other crops.

Row spacing varies from 0.5 to 0.8 m, with 35 plants per metre of row. Seed rate for broadcast sowing of the irrigated crop is 40 to 50 kg/ha; for row crops, seed rate is 20 to 25 kg/ha.

WATER REQ[illegible]

The reputation of safflower as a drought resistant crop is mainly based on its ability to withdraw water from a depth of up to 3.5 m. It has proved, however, to have well-defined water requirements. For optimum crop yields, the total water requirements vary between 600 and 1 200 mm depending on climate and length of total growing period. The crop water requirements (ETm) as related to reference evapotranspiration are given by the crop coefficients (kc): initial stage 0.3-0.4 (20 to 35 days); crop development stage 0.7-0.8 (35 to 75 days); mid-season stage 1.05-1.2 (45 to 65 days); late season stage 0.65-0.7 (25 to 40 days) and at harvest 0.21-0.25.

WATER SUPPLY AND CROP YIELD

Safflower is particularly susceptible to excess water because of its reaction to diseases under wet conditions. Excessive humidity, especially fog, induces head rot; excessive soil water causes root rot; excessive rain at flowering (period 2) adversely affects pollination and prevents complete seed filling which may not be noticeable in the field; excessive rainfall after the crop reaches maturity leads to seed germination in the head.

The relationships between relative yield reduction and relative evapotranspiration deficit based on interpreted information are shown in Figure 37. Water deficits during the early vegetative period (1a) and the late vegetative period (1b) cause a reduction in growth and prolong the total growing period. Safflower tolerates periods of water deficit but for maximum production flowering and yield formation (3) are the most sensitive periods to water deficit. Under conditions of limited water supply, overall production is increased by extending the area and partially meeting the crop water requirements rather than by meeting the full crop water requirements over a limited area.

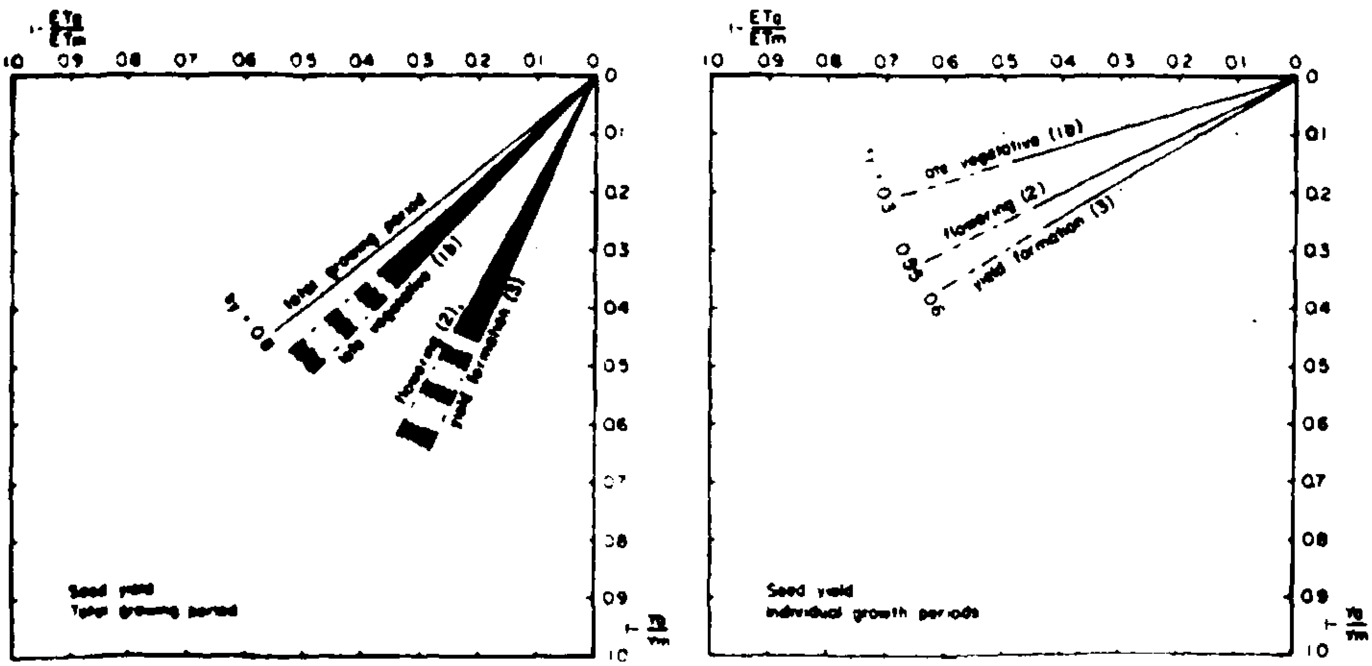


Fig. 37 Relationships between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration deficit (1 - ETa/ETm) for safflower

For a 155-day total growing period the length of the different growth periods

0	establishment	4-10 days
1a	early vegetative (rosette development)	25
1b	late vegetative (elongation and branching)	60
2	flowering	30
	yield formation (seed filling)	25
	ripening	10
		150 - 160 days

WATER UPTAKE

The rooting system of safflower is extensive and in deep soils roots may extend to 3.5 m, but normally 100 percent of the water uptake of a full grown crop takes place from the first 1 to 2 m (D = 1.0-2.0 m). Under conditions when maximum evapotranspiration is 5 to 6 mm/day, water uptake starts to be reduced when 60 percent of the total available soil water has been depleted.

IRRIGATION SCHEDULING

Irrigation scheduling should be aimed at minimizing excess soil water, particularly in relation to the sensitivity of the crop to root rot. A deep pre-planting irrigation is therefore very effective, followed by infrequent but heavy applications of water. Due to the deep rooting already during the early vegetative period (1 a), the soil depth must be considered when deciding on the desirability of heavy watering.

In deep soils with high water holding capacity, usually two irrigation applications are sufficient, i.e. one before planting and one during flowering. However, a frequent mistake is a too early second application. On soils of lighter texture or when evapotranspiration demands are high, three or more applications may be necessary.

IRRIGATION METHODS

The crop is most commonly grown under surface irrigation, by the border method, allowing heavy irrigation applications. Also subirrigation is used and gives high yields.

YIELD AND QUALITY

Under rainfed conditions yields depend on initial soil water storage and on the rainfall during the growing season. Good rainfed yields are in the range of 1 to 2.5 ton/ha; under irrigation in the range of 2 to 4 ton/ha. The water utilization efficiency for harvested yield (E_y) for seed containing 8 to 10 percent moisture varies between 0.2 and 0.5 kg/m³.

The oil content varies from 20 to 40 percent depending on the variety and some recently developed Indian varieties may yield up to 50 percent oil. These new varieties are early maturing, more cold resistant and spineless, but are more susceptible to root rot and rust.

SORGHUM

Sorghum (Sorghum bicolor) appears to have been domesticated in Ethiopia about 5000 years ago. Present world production is about 52 million tons grain from 44 million ha.

Sorghum has a number of features which make it a drought-resistant crop. It is extensively grown under rainfed conditions for grain and forage production. In dry areas with low and/or erratic rainfall the crop can respond very favourably to supplemental irrigation. However, considerable differences exist amongst varieties in their response to irrigation and those that are considered very drought-resistant respond slightly while others produce high yields under irrigation but are poor yielding when water is limiting. Temperature is an important factor in variety selection. Optimum temperatures for high producing varieties are over 25°C but some varieties are adapted to lower temperatures and produce acceptable yields. When mean daily temperatures during the growing season are greater than 20°C, early grain varieties take 90 to 110 days and medium varieties 110 to 140 days to mature. When mean daily temperatures are below 20°C, there is an extension of about 10 to 20 days in the growing period for each 0.5°C decrease in temperature, depending on variety, and at 15°C a sorghum grain crop would take 250 to 300 days to mature. With mean daily temperatures in the range of 10 to 15°C, the sorghum crop can only be grown as a forage crop because of the problems with seed set and grain maturity under cool conditions. Low temperatures (<15°C) during flowering and yield formation, and high temperatures (>35°C) lead to poor seed set, problems with ripening and reduced yields.

For optimum light interception the density index (plants per ha ; row spacing) is about 3000 when adequate water and fertilizers are available (100 000 to 150 000 plants per ha). In areas where water (rainfall + irrigation) is in short supply, the greater the shortage, the greater is the advantage of wider spacing. Sorghum is a short-day plant but day-neutral varieties exist.

The crop does well on most soils but better so in light to medium textured soils. The soil should preferably be well-aerated and well-drained. Sorghum is relatively tolerant to short periods of waterlogging. The fertilizer requirements are up to 180 kg/ha N, 20 to 45 kg/ha P and 35 to 80 kg/ha K.

Sorghum is moderately tolerant to soil salinity. Yield decrease due to soil salinity under irrigation is: 0% at ECe 4 mmhos/cm, 10% at 5.1, 25% at 7.2, 50% at 11 and 100% at ECe 18 mmhos/cm.

WATER REQUIREMENTS

For high production crop water requirements (ETm) of 110 to 130 day sorghum are between 450 and 650 mm depending on the climate; to this the losses during conveyance and application must be added. The crop coefficient (kc) relating maximum evapotranspiration (ETm) to reference evapotranspiration (ETo) is: during the initial stage 0.4 (20 to 25 days), the development stage 0.7-0.75 (30 to 40 days), the mid-season stage 1.0-1.15 (40 to 45 days), the late season stage 0.75-0.8 (30 days) and at harvest 0.5-0.55.

WATER SUPPLY AND CROP YIELD

The growth periods of sorghum are:

0	establishment, from sowing to head initiation	15-20 days
1	vegetative, from head initiation to head emergence	20-30
2	flowering, from emergence to seed set	15-20
3	yield formation, from seed set to physiological maturity	35-40
4	ripening, from physiological maturity to harvest	10-15
		95-125 days

The relationships between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration deficit (1 - ETa/ETm) are shown in Figure 38. For calculation examples see p. 40 and Chapter VI.

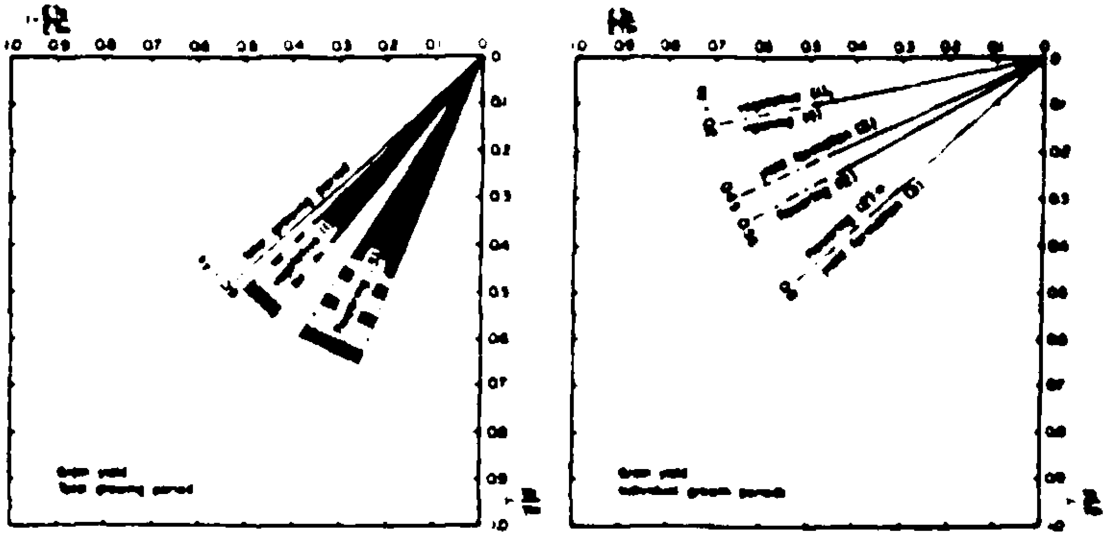


Fig. 38 Relationship between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration deficit (1 - ETa/ETm) for sorghum

Sorghum is relatively more drought-resistant than many other crops, e.g. maize. This is due to an extensive root system, effective control of evapotranspiration and stomata with an ability to recover rapidly after periods of water stress, and an ability to withstand desiccation. Further, where the growing season is long, the tillering varieties are able to recover to a certain extent from water deficits in the earlier growth periods by forming additional head-bearing tillers. Severe water deficits during the flowering period (2) cause pollination failure or headblast. The resulting yield reduction can be partly offset by additional head-bearing tillers.

Sorghum shows a high degree of flexibility toward depth and frequency of water supply because of its drought resistance characteristics. When water supply is limited it may be advantageous to spread available water over a larger area. While yield per unit area will be reduced, water utilization efficiency for yield will be greater resulting in higher overall production in relation to volume of water supplied. The timing of supply should aim at reducing water deficits to a minimum during the establishment (0), flowering, (2) and early yield formation (early 3) periods.

WATER UPTAKE

The primary root system, with little branching, grows rapidly in deep soils to 1 to 1.5 m. The secondary system starts several weeks after emergence and extends rapidly up to 2 m, depending on depth of soil wetting. The maximum depth is generally reached at the time of heading. In deep soils the extensive root system allows additional flexibility in irrigation scheduling. Depending on depth and frequency of irrigation, 60 percent (less frequent) to 90 percent (frequent) of the water uptake occurs from the first metre of soil depth. Normally, when sorghum is full grown, 100 percent of the water is extracted from the first 1 to 2 m (D = 1-2 m). Under conditions when ETm is 5 to 6 mm/day, about 55 percent of the total available soil water can be depleted without reducing water uptake (p = 0.55). During ripening (4) 80 percent can be depleted.

IRRIGATION SCHEDULING

Where rainfall is not sufficient and irrigation water supply is restricted, irrigation to attain optimum production should be based on avoiding water deficits during the periods of peak water use from flowering (2) to early yield formation period (3). Where water supply will be limited during the flowering period, water savings can be made without causing additional heavy yield losses by reducing water supply during the vegetative (1), late yield formation (late 3) and ripening period (4).

The number of irrigations normally varies between one and four, depending on climatic conditions, and soil texture. The greatest water utilization efficiency will be obtained when these irrigations are well-timed in relation to the sensitivity of the crop to water deficits.

Irrigation is mostly by surface (border, basin or corrugation) method.

YIELD

A good yield under irrigation is 3.5 to 5 ton/ha (12 to 15 percent moisture). The water utilization efficiency for harvested yield (Ey) for grain is between 0.6 and 1.0 kg/m^3.

Grain yield under spate irrigation with little or no rainfall, a total growing period of 90 days with ETm = 425 to 450 mm and net depth applied of about 300 mm, is about 800 kg/ha with a maximum of 1 300 kg/ha.

SOYBEAN

Soybean (*Glycine max*) is one of the most important world crops and is grown for oil and protein. Present world production is about 6.2 million tons of seed over 45 million ha. The crop is mainly grown under rainfed conditions but irrigation, specifically supplemental irrigation, is increasingly used.

The crop is grown under warm conditions in the tropics, subtropics and temperate climates. Soybean is relatively resistant to low and very high temperatures but growth rates decrease above 35°C and below 18°C. In some varieties, flowering may be delayed at temperatures below 24°C. Minimum temperatures for growth are about 10°C and for crop production about 15°C. Only 25 to 30 percent of the flowers produce set pods, the final number depending on the plant vigour during the flowering period. Year to year temperature variations can lead to differences in flowering.

Soybean is basically a short-day plant, but response to daylength varies with variety and temperature and developed varieties are adapted only to rather narrow latitude differences. Daylength has an influence on the rate of development of the crop; in short-day types, increased daylength may result in the delay of flowering and taller plants with more nodes. Short days hasten flowering, particularly for late-maturing varieties. Vegetative growth normally ceases during yield formation. The length of the total growing period is 100 to 130 days or more. Soybean is often grown as a rotation crop in combination with cotton, maize and sorghum. Row spacing varies from 0.4 to 0.6 m with 30 to 40 seeds per metre of row.

The crop can be grown on a wide range of soils except those which are very sandy. Optimum soil pH is 6 to 6.5. The fertilizer requirements are 15 to 30 kg/ha P and 25 to 60 kg/ha K. Soybean is capable of fixing atmospheric nitrogen which meets its requirements for high yields. However, a starter dose [illegible] beneficial for good early growth.

A shallow water table, particularly during the early growth period can adversely affect yields. The plant is sensitive to waterlogging, but moderately tolerant to soil salinity. Yield decrease due to soil salinity is: 0% at ECe 5 mmhos/cm, 10% at 5.5, 25% at 6.2, 50% at 7.5 and 100% at ECe 10 mmhos/cm.

WATER REQUIREMENTS

Water requirements (ETm) for maximum production vary between 450 and 700 mm/season depending on climate and length of growing period. The water requirements are given by the crop coefficient (kc) in relation to reference evapotranspiration (ETo) and kc is: during the initial stage 0.3-0.4 (20 to 25 days), the development stage [illegible] 0.8 (25 to 35 days), the mid-season stage 1.0-1.15 (45 to 65 days), the late-season stage 0.7-0.8 (20 to 30 days) and at harvest 0.4-0.5.

WATER SUPPLY AND CROP YIELD

The growth periods of soybean are shown in Figure 39. The relationships based on interpreted information on relative yield decrease (1 - Ya/Ym) and rel[illegible]

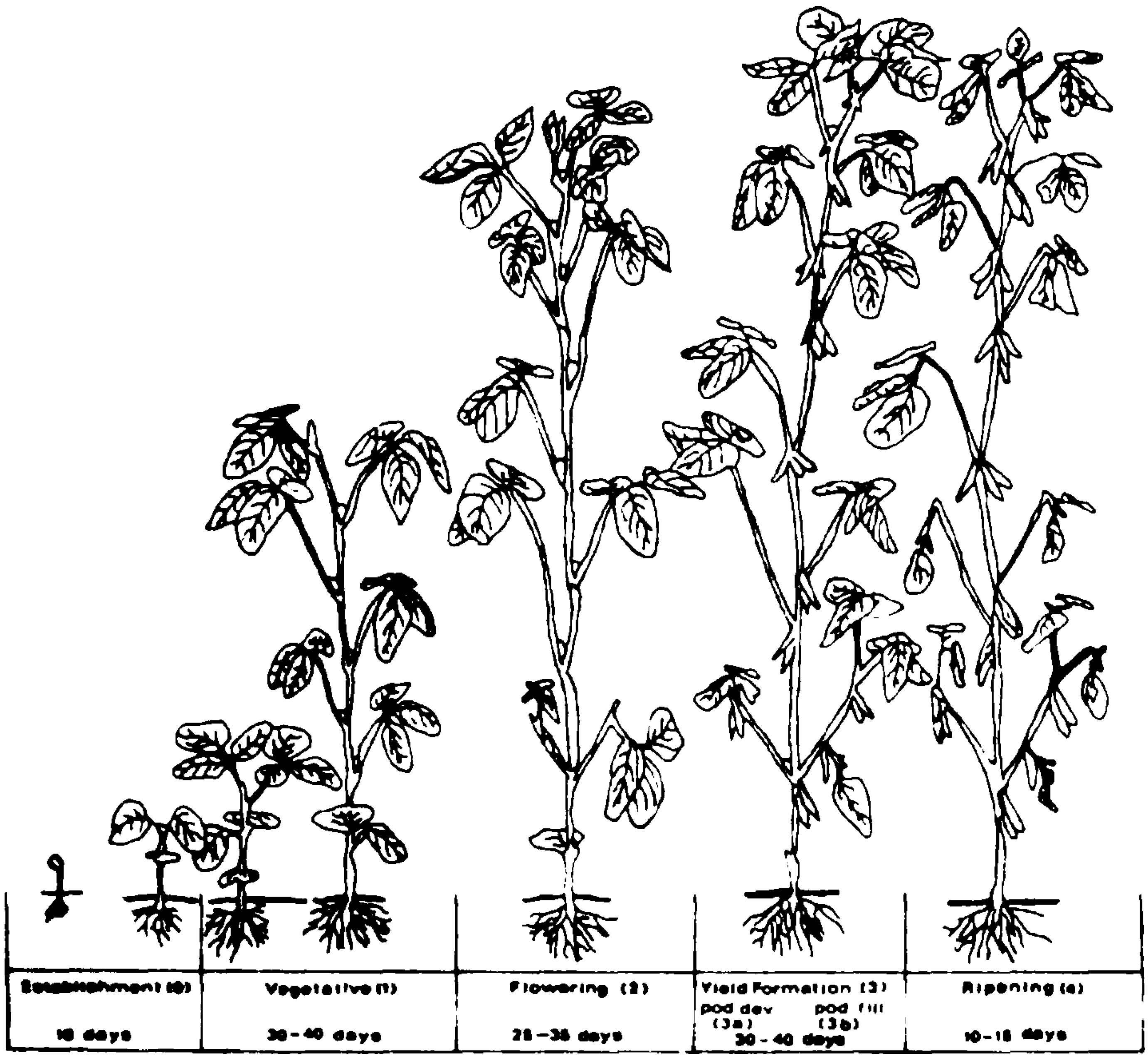


Fig. 39 Growth periods of soybean (after Chiang)

evapotranspiration deficit (1 - ETa/ETm) are given in Figure 40 for total growing period and the individual growth periods. (For examples see p. 40 and Chapter VI.)

Adequate water (between 15 and 50 percent soil water depletion) must be available for germination. Water deficiency or excess water during the vegetative period (1) will retard growth. Growth periods most sensitive to water deficits are the flowering (2) and yield formation periods (3), particularly the later part of the flowering period (end 2) and early part of the yield formation (pod development, 3a) period when water deficits may cause heavy flower and pod dropping. Irrigation after severe water deficits during period 2 may cause similar symptoms. The seeming drought-resistance of the crop during flowering (2) and early yield formation (pod development, 3a) is the result of the flowering period extending over one month; light water deficits during a part of this period can be compensated for by better retention of later-formed flowers and pod setting. For normal pod filling and high yield the soil water during the yield formation period (pod filling, 3b) should not exceed the 50 percent depletion level.

When water supply is limited, savings in water can be made by reducing the supply during the vegetative period (1) and particularly near crop maturity (late 4). When required, a pre-irrigation should be given to allow proper crop establishment. Water savings should be minimal during the late flowering period (late 2) and early yield formation period (pod developme[illegible]

For maximum production, water supply may be directed toward enlarging the area under irrigation rather than toward meeting maximum crop water requirements over a restricted acreage. However, crop water demands should be met durin[illegible] [illegible] (3a).

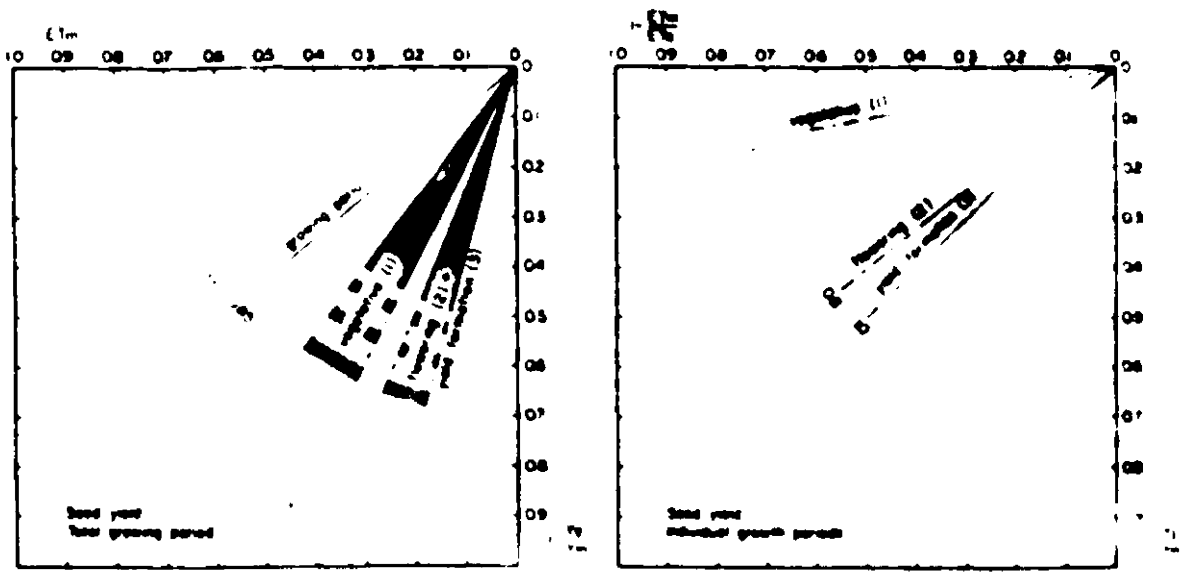


Fig. 20 Relationship between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration deficit (1 - ETa/ETm) for soybean

[illegible]

Depending on soil water availability, early root development in deep soils is relatively rapid and vigorous. Most rapid root growth is often noted after the start of flowering. The tap root may extend to over 1.5 m. The crop can effectively draw all available soil water up to 1.8 m. If soil depth is restricted, the tap root is less pronounced and lateral roots are more developed. While the crop can grow on heavy soils, the roots tend not to penetrate even moderately compacted layers. Although the roots are generally concentrated in the first 0.6 m or even sometimes the first 0.3 m, considerable soil water, particularly during the later growth periods, can be extracted from the lower parts of the root zone. However, under normal conditions 100 perce[illegible] of the water uptake [illegible] (D = 0.6-1.3 m).

At germination, the soil water content should not exceed 85 percent or fall below 50 percent of available soil water. After establishment (0), the crop can withstand short periods of drought. For irrigation scheduling under medium evaporative conditions (ETm 5 to 6 mm/day), an allowable depletion level of 55 percent may be assumed (p = 0.55).

IRRIGATION SCHEDULING

Soybean is usually not grown under full irrigation. In many climatic conditions, however, one or more supplemental irrigations during critical growth periods will substantially increase yields. If one application can be given, the most likely timing will be in the late flowering period (2), when small pods are beginning to appear. If two applications can be given, it is usually wise to give the first application at pre-emergence to assure a rapid establishment of the plant. A third application, where possible, will give the best results if given at the beginning of pod filling (3b).

IRRIGATION METHODS

In areas where soybean is irrigated, the costs of sprinkler irrigation only can be borne if it is grown in rotation with high value crops. Furrow irrigation is most common.

YIELD AND QUALITY

Yield can vary widely with water availability, fertilization and row spacing. Under rainfed conditions, good soybean yields vary between 1.5 and 2.5 ton/ha seed. High yields of improved varieties are between 2.5 and 3.5 ton/ha seed under irrigation. The water utilization efficiency for harvested yield (Ey) for seed containing 6 to 10 percent moisture is 0.4 to 0.7 kg/m^3. The effect of irrigation on oil and protein content of the grain is rather insignificant. However, under adequate irrigation there is a tendency toward a slight increase in protein content and a slight decrease in oil content.

SUGARBEET

Sugarbeet (Beta vulgaris) provides about 40 percent of the world's sugar production. Present world production is about 295 million tons of beets from about 9.5 million ha.

The crop is believed to originate from Asia. Sugarbeet is a biennial crop but for sugar production beets are harvested in the first year. Flowering occurs during the second year. The crop is grown under rainfed conditions but also widely under irrigation in the subtropics where the crop is known for its high tolerance to saline and alkali soils.

The crop needs a relatively long growing period, normally from 140 to 160 up to 200 days. Large amounts of sugar are formed in the leaves. The greater part is used for growth processes during the vegetative period, while in the late grow[illegible] period when vegetative growth slows down a large part is stored in the roots. [illegible] ever, sugar yield is determined by both root size and sugar concentration. W[illegible] rapid growth of the storage root the sugar concentration reaches a steady value w[illegible] is principally determined by climate, water supply and nitrogen level in the soil and is influenced to some extent by variety and plant spacing. Sugar percentage in the root is often greater than 15 percent of the fresh root weight. The crop is harvested toward the end of the first season's growth, when the roots contain maximum amount of sugar.

The crop is grown in different climates. Seed germination is possible at 5°C but the effective minimum is considered to be 7 to 10°C. Higher temperatures during vegetative growth are preferred, but high sugar yields are obtained when night temperatures are between 15 and 20°C and day temperatures between 20 and 25°C during the latter part of the growing period. During this period temperatures greater than 30°C greatly decrease sugar yields. For high sugar yields and low vegetative growth in the latter part of the growing period, progressively cooler nights should be accompanied by an exhaustion of available soil nitrogen and soil water.

When the crop is grown for seed, several weeks at low temperatures, near 4°C, are required to induce flowering, which tends to be accelerated by long days.

The crop can be grown on a wide range of soils with medium to slightly heavy textured, well-drained soils preferred. Restricted deep root growth in the early part of the growing period due to soil compaction may result in formation of forked and sprangled roots with reduced yields. Soil pH smaller than 5.5 is unfavourable to growth. Crust forming at the soil surface at the time of germination can lead to poor crop stand.

Adequate nitrogen is required to ensure early maximum vegetative growth. Nitrogen is often given in split applications, a small amount at planting and the rest after thinning. Nitrogen either in an excessive amount or when applied late during the growing season reduces sugar content. Fertilizer applications may be up to 150 kg/ha N, 50 to 70 kg/ha P at planting and 100 to 160 kg/ha K.

A deep, well-prepared seed bed is advantageous. Seeds are planted 1 to 2 cm deep in single or double rows, with width between single rows 0.5 to 0.7 m and double rows about 1 m. When the plant has 4 to 8 leaves, thinning, by hand or by machine, is frequently needed to space 3 to 6 beets per metre row. Seed rates vary between 12 and 30 kg/ha. Plant densities under commercial production vary from 40 000 up to 100 000 plants/ha.

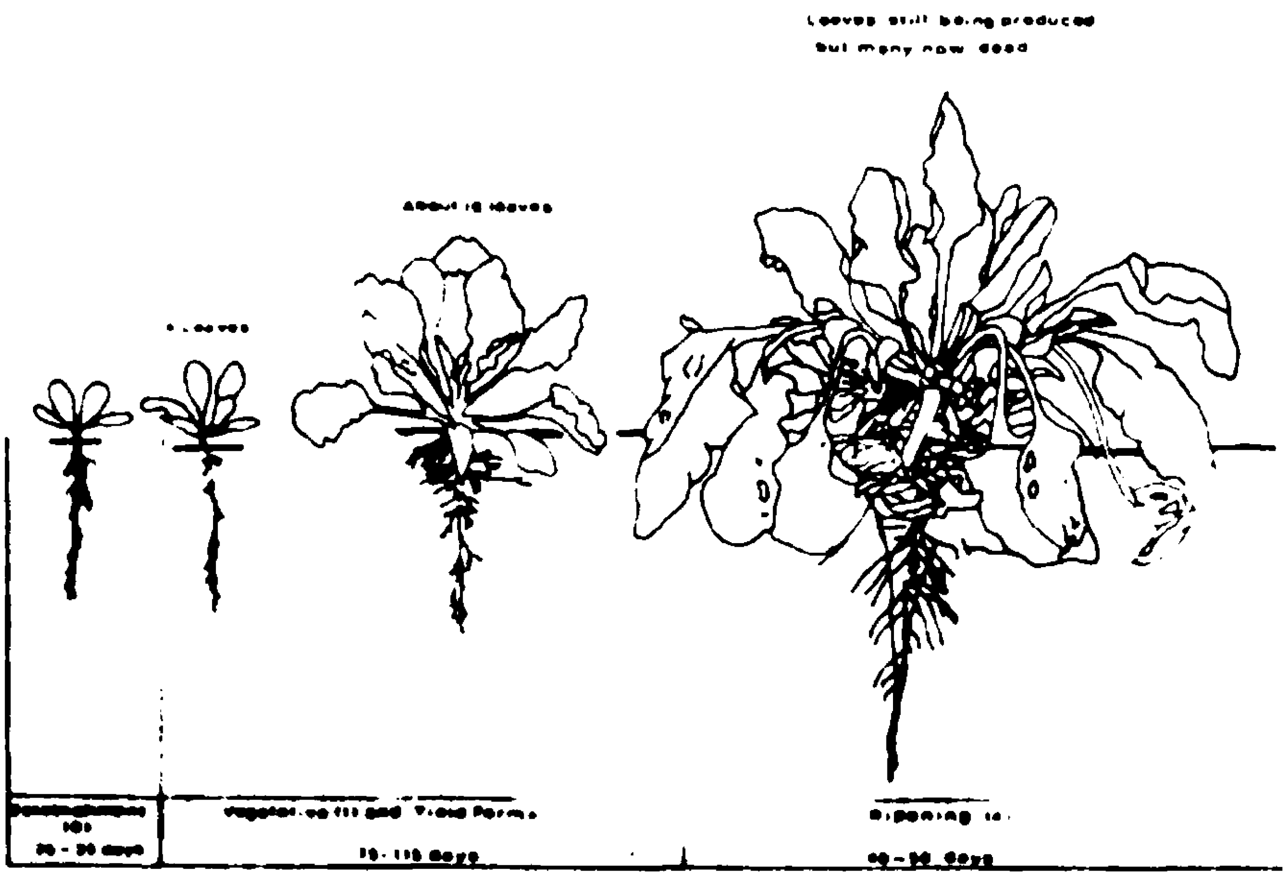
Except during the early stages, after crop establishment, the crop is tolerant to salinity. Yield decrease is 0% at ECe 7, 10% at 8.7, 25% at 11, 50% at 15 and 100% at ECe 24 mmhos/cm. During early growth ECe should not exceed 3 mmhos/cm.

WATER REQUIREMENTS

For maximum production, water requirements of the crop are related to reference crop evapotranspiration (ETo). The crop coefficient (kc) is 0.4-0.5 during the initial stage (25 to 30 days), 0.75-0.85 during the crop development stage (35 to 60 days), 1.05-1.2 during mid-season stage (50 to 70 days), 0.9-1.0 during the late-season stage (30 to 50 days) and 0.6-0.7 at time of harvest. Total water requirements are in the range of 550 to 750 mm/growing period, but vary with climate and length of the total growing period. Time of sowing affects the rate of crop development, particularly from emergence to when the crop has reached its maximum height, which for an autumn-sown crop may be 140 days, for a spring-sown crop about 90 days and for a late spring/early summer-sown crop about 60 days.

WATER SUPPLY AND CROP YIELD

The duration of the different growth periods of the sugarbeet crop with 140 to 200 day growing period is shown in Figure 41. The relationship between relative yield decrease and relative evapotranspiration deficit for sugar and beet production is shown for the total growing season in Figure 42.



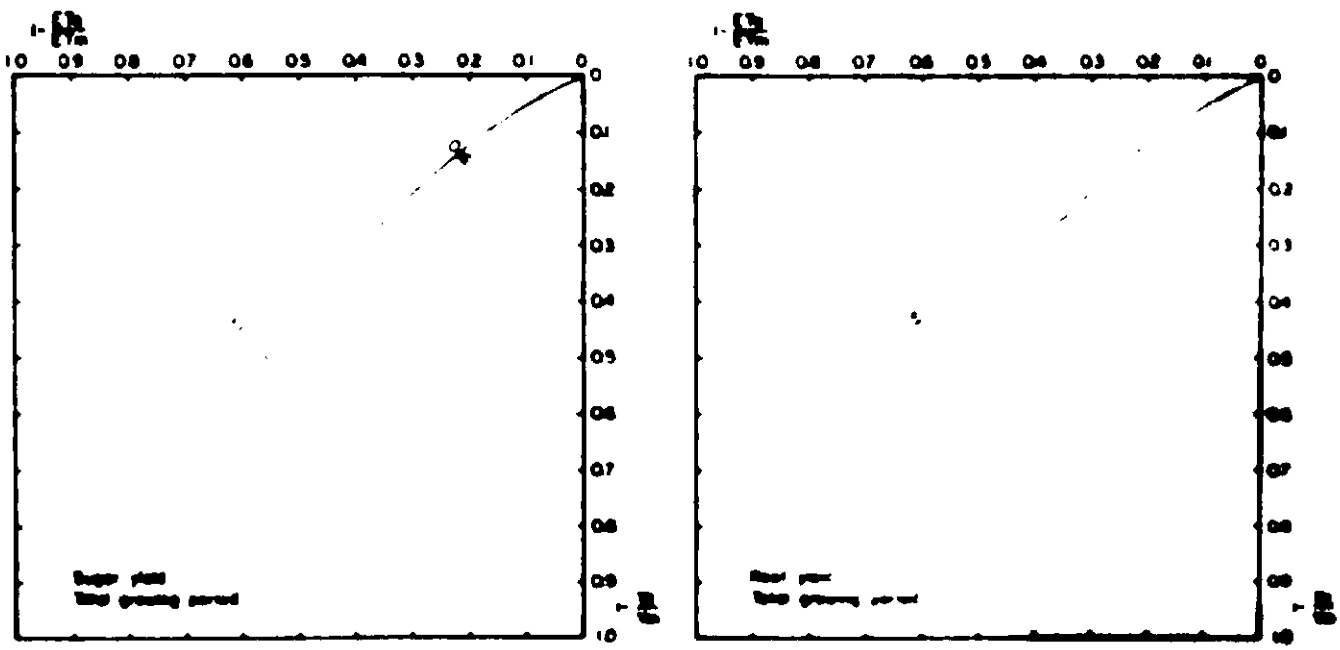
Growth periods of sugarbeet (after G.B. Heathcote)

When grown for sugar, flowering and seed production is avoided. Sugarbeet is particularly sensitive to water deficits at the time of crop emergence and a period of about a month after emergence (0). Frequent, light irrigations are preferred during this period, and irrigation may also be needed to reduce crust formation on the soil and to reduce salinity of the top soil. Early over-watering may retard leaf development and can encourage flowering during the first year (bolting).

Water deficits in the middle part of the growing period (vegetative and yield formation periods, 1 and 3) tend to affect sugar yields more strongly when occurring during later periods. Ample supply in the later part of the growing period (ripening period, 4) has an adverse effect on sugar concentration although it may increase the root size, with the final effect on yield being small. Water deficits together with a nitrogen deficiency toward the end of the growing period lead to a reduction in root growth but an increase in sugar concentration. In general, top growth toward the end of the growing period tends to be negatively correlated with sugar production. Irrigation supply must be discontinued at least 2 to 4 weeks prior to harvest.

Thus, except during emergence and early growth periods, it appears that the crop is less sensitive to moderate water deficits. The effect of reduced water supply over the total growing period is often masked by the overriding influence of temperature, nitrogen availability and reduced water needs during a period just prior to harvest.

When available water resources are limited and when maximum overall production is aimed at, water supply should be directed toward expanding the area under irrigation rather than concentrating the supply over a limited area to meet maximum water requirements (ETm) over the total growing period. This is because there is an increase in the efficiency of water utilization (Ey) for both roots and sugar yield when water supply is reduced so that yields decrease less than proportionally with the reduction of water supply (ky < 1) provided the growing environment during the later part of the growing period is favourable to sugar storage (Figure 42).



... relationship between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration deficit (1 - ETa/ETm) for sugarbeet

WATER UPTAKE

In deep soils the crop can develop a deep tap root system but normally 100 percent of the water is extracted from the first 0.7 to 1.2 m soil depth (D = 0.7-1.2 m). Under conditions when ETm is 5 to 6 mm/day, 50 to 60 percent of the total available soil water can be depleted without reducing water uptake (p = 0.5-0.6), with higher depletion levels just before harvest. When the plant is under water stress the leaves become dark green in colour and when the water stress is severe the leaves fail to recover from midday wilting in the evening.

IRRIGATION SCHEDULING

Frequent, light irrigations during the establishment period (0) are advantageous and sufficient soil water must be available at emergence. An irrigation is frequently applied after thinning. Irrigation intervals can be selected using Table 21. The irrigation is discontinued at least 2 to 4 weeks before harvest to increase sugar concentration in the beets. The soil should, however, not be too dry to hamper lifting of the beets at harvest.

IRRIGATION METHODS

The most common method is furrow irrigation. Border irrigation is sometimes practised but it is not common. Sprinkler irrigation offers advantages particularly during the germination and emergence period when frequent but light applications may be adequate. However, young plants will be damaged when sprinkling with poor quality (saline) water.

YIELD LEVEL

A good commercial yield of 160 to 200 day sugarbeet is 40 to 60 ton/ha of fresh beet at 15 percent sugar. Under certain conditions yields of up to 70 to 80 ton/ha are obtained. The water utilization efficiency for harvested yield (Ey) for beets containing 80 to 85 percent moisture is 6 to 9 kg/m^3 and for sucrose containing no moisture 0.9 to 1.4 kg/m^3.

A few comparative studies have been made between sugarbeet and sugarcane performance. For a given location, climate is the most important factor in dictating which crop is likely to be more suitable from the point of view of production.

SUGARCANE

The present area of sugarcane (*Saccarum officinarum*) is about 13 million ha with a total commercial world production of about 700 million ton/year cane or 55 million ton/year sucrose.

Sugarcane originated in Asia, probably in New Guinea. Most of the rainfed and irrigated commercial sugarcane is grown between 35°N and S of the equator. The crop flourishes under a long, warm growing season with a high incidence of radiation and adequate moisture, followed by a dry, sunny and fairly cool but frost-free ripening and harvesting period.

Optimum temperature for sprouting (germination) of stem cuttings is 32 to 38°C. Optimum growth is achieved with mean daily temperatures between 22 and 30°C. Minimum temperature for active growth is approximately 20°C. For ripening, however, relatively lower temperatures in the range of 20 to 10°C are desirable, since this has a noticeable influence on the reduction of vegetative growth rate and the enrichment of sucrose in the cane.

A long growing season is essential for high yields. The normal length of the total growing period varies between 9 months with harvest before winter frost to 24 months in Hawaii, but it is generally 15 to 16 months. Plant (first) crop is normally followed by 2 to 4 ratoon crops, and in certain cases up to a maximum of 8 crops are taken, each taking about 1 year to mature. Growth of the stool is slow at first, gradually increasing until the maximum growth rate is reached after which growth slows down as the cane begins to ripen and mature. The flowering of sugarcane is controlled by daylength, but it is also influenced by water and nitrogen supply. Flowering has a progressive deleterious effect on sucrose content. Normally, therefore, flowering is prevented or non-flowering varieties are used.

Sugarcane does not require a special type of soil. Best soils are those that are more than 1 m deep but deep rooting to a depth of up to 5 m is possible. The soil should preferably be well-aerated (after heavy rain the pore space filled with air > 10 to 12 percent) and have a total available water content of 15 percent or more. When there is a groundwater table it should be more than 1.5 to 2.0 m below the surface. The optimum soil pH is about 6.5 but sugarcane will grow in soils with pH in the range of 5 to 8.5.

Sugarcane has high nitrogen and potassium needs and relatively low phosphate requirements, or 100 to 200 kg/ha N, 20 to 90 kg/ha P and 125 to 160 kg/ha K for a yield of 100 ton/ha cane, but application rates are sometimes higher. At maturity, the nitrogen content of the soil must be as low as possible for a good sugar recovery, particularly where the ripening period is moist and warm.

Row spacing varies usually between 1.1 and 1.4 m; number of sets per ha depends on the number of buds per set and may vary between 21000 and 35000.

Sugarcane is moderately sensitive to salinity and decrease in crop yield due to increasing salinity is: 0% at ECe 1.7 mmhos/cm, 10% at 3.3, 25% at 6.0, 50% at 10.4 and 100% at ECe 18.6 mmhos/cm.

WATER REQUIREMENTS

Adequate available moisture throughout the growing period is important for obtaining maximum yields because vegetative growth including cane growth is directly proportional to the water transpired. Depending on climate, water requirements (ETm) of sugarcane are 1 500 to 2 500 mm evenly distributed over the growing season. The crop coefficient (kc) values, relating ETm to reference evapotranspiration (ETo) for the different growth stages are:

Development stages	days	kc coefficients *
planting to 0.25 full canopy	30-60	0.40-0.60
0.25 to 0.50 full canopy	30-40	0.75-0.85
0.50 to 0.75 full canopy	15-25	0.90-1.00
0.75 to full canopy	45-55	1.00-1.20
peak use	180-330	1.05-1.30
early senescence	30-150	0.80-1.05
ripening	30-60	0.60-0.75

* kc values depend on minimum relative humidity and wind velocity (see Irrigation and Drainage Paper No. 24)

WATER SUPPLY AND CROP YIELD

Growth periods of sugarcane are shown in Figure 43. Because yield is formed when the crop is in the vegetative form, the yield formation period also involves vegetative growth.

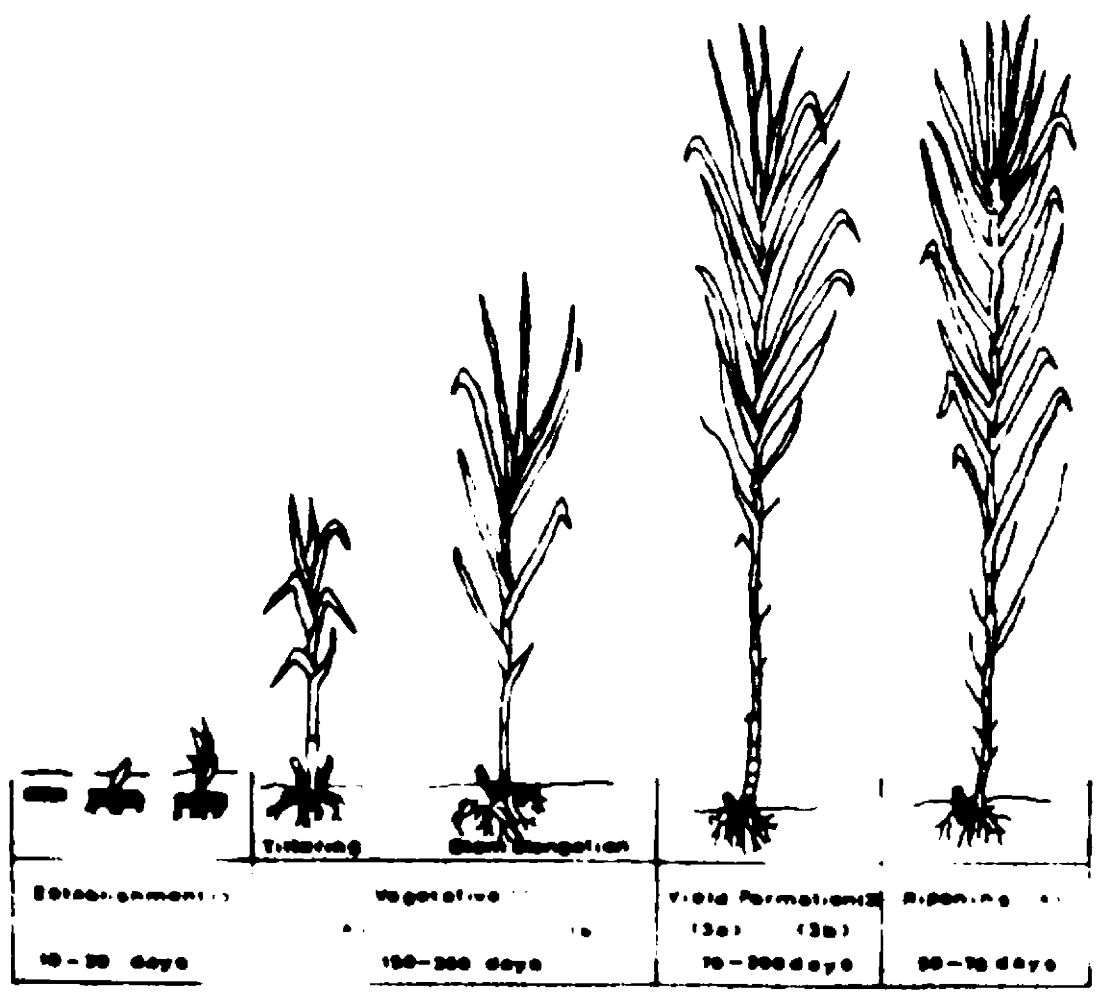


Figure 43 Growth periods of sugarcane (after Kuyper, 19[illegible])

Frequency and depth of irrigation should vary with growth periods of the cane. During the establishment period (0), including emergence and establishment of young seedlings, light, frequent irrigation applications are preferred. During the early vegetative period (1) the tillering is in direct proportion to the frequency of irrigation. An early flush of tillers is ideal because this furnishes shoots of approximately the same age. During stem elongation (1b) and early yield formation (3a), irrigation interval can be extended but depth of water should be increased. There is a close relationship between stalk elongation during these periods and water use, and adequate water supply is important during this period of active growth when the longest internodes are formed. With adequate supply this period is reached early and also total cane height is greater. The response of sugarcane to irrigation is greater during the vegetative and early yield formation periods (1 and 3a) than during the later part of the yield formation period (3b), when active leaf area is declining and the crop is less able to respond to sunshine. During the ripening period (4), irrigation intervals are extended or irrigation is stopped when it is necessary to bring the crop to maturity by reducing the rate of vegetative growth, dehydrating the cane and forcing the conversion of total sugars to recoverable sucrose. With the check of vegetative growth, the ratio between dry matter stored as sucrose and that used for new growth also increases. During the yield formation period (3) frequent irrigation has an accelerating effect on flowering, which leads to a reduction of sugar production.

The relationships between relative yield decrease and relative water deficit for the total growing period and for the individual growth periods are shown in Figure 44. Water deficit during the establishment period (0) and early vegetative period (tillering, 1a) has an adverse effect on yield as compared to water deficit in later growth periods. Water deficit slows down germination and tillering and the number of tillers is smaller. Water deficit during the vegetative period (stem elongation, 1b) and early yield formation (3a) causes a lower rate of stalk elongation. Severe water deficit during the later part of yield formation (3b) forces the crop to ripen. During the ripening period (4), a low soil moisture content is necessary. However, when the plant is too seriously deprived of water, loss in sugar conten[illegible] be greater than sugar formation.

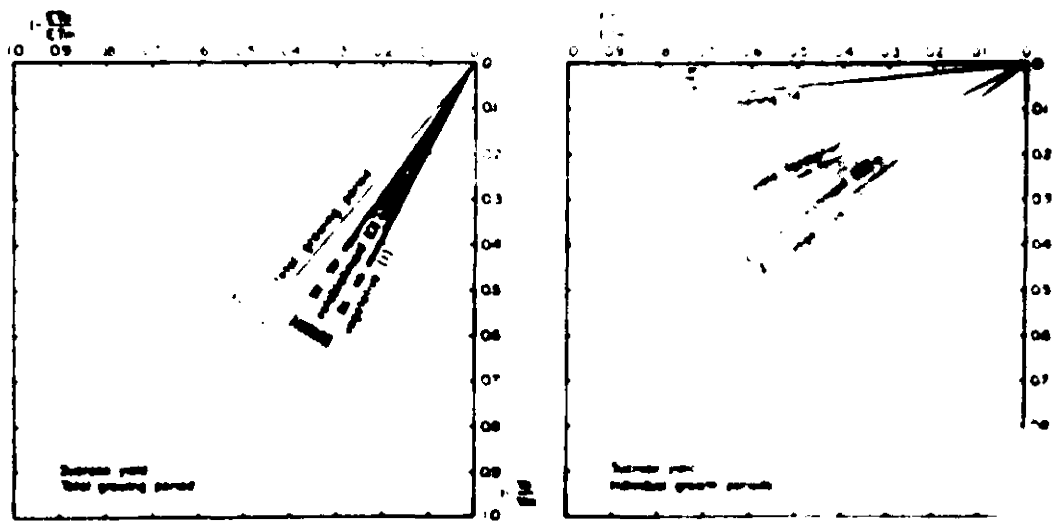


Fig. 44 Relationships between relative yield d[illegible] and relative evapotranspiration deficit [illegible] m) for sugarcane

When water supply is limited, and apart from other considerations, the acreage can be enlarged using water saved during the yield formation period (3); this will result in a slightly lower yield per hectare but overall production will be higher.

WATER UPTAKE

Rooting depth varies with soil type and irrigation regime; infrequent, heavy irrigations normally result in a more extensive root system. Rooting depth can be up to 5 m but active root zone for water uptake is generally limited to the uppermost layers. When these layers are depleted the uptake from greater depth increases rapidly but normally 100 percent of the water is extracted from the first 1.2 to 2.0 m (D = 1.2-2.0 m). With evapotranspiration during the growing season of 5 to 6 mm/day, the depletion level during the vegetative (1) and yield formation period (3) can be 65 percent of the total available water without having any serious effects on yields (p = 0.65).

IRRIGATION SCHEDULING

When irrigation water is not scarce, Table 21 can be used to determine frequency and depth of irrigation required for a high yield. Under minimum crop water stress conditions and taking into account the level of ETm, the depletion level of the total available soil water for the establishment period (0) is about 30 percent. Because of the low depletion level and a poorly formed root system, frequent irrigation is required during this period. This applies also to a ratoon crop because a new root system has to be developed.

During the vegetative (1) and yield formation (3) periods, the depletion level (p), depending on ETm, is about 0.65 and frequency and depth of irrigation is very dependent on the water holding capacity of the soil and the root depth. A lower frequency of irrigation with a higher application in depth may cause the development of a deeper root system provided rooting is not restricted by layers which are difficult to penetrate. During the ripening period (4), a low soil water level is required. Irrigation water is applied only in an extremely dry situation but depth of application is reduced.

Where irrigation water is limited and rainfall is scarce, irrigation scheduling should be based on avoiding water stress during the establishment period (0), followed by the vegetative period (1). However, when irrigation water is scarce during period (1), the reduction in the height of canes can be partly regained in the yield formation period (3).

IRRIGATION METHODS

Furrow irrigation is most commonly used and is particularly effective for early plant crop. In later crop growth periods and during ratoon crops, the water distribution may become increasingly problematic because of deterioration of the furrows. Reduced furrow length is sometimes used to allow better distribution of water over the field in a later stage.

A recent trend is in the direction of sprinkler and drip irrigation. For sprinkler irrigation, increasing use is made of spray guns, hand and automatically moved, replacing the cumbersome boom and labour-intensive hand-moved sprinkler laterals. Prevailing winds of more than 4 or 5 m/sec will limit their usefulness. An optimum combination of distance between field roads for harvesting and for moving guns with different spray length must be analysed. Drip irrigation using double wall drip lines has been successfully employed particularly in Hawaii; replacement of burned drip lines after harvest is compensated for by the [illegible] high labour cost.

YIELD LEVEL AND QUALITY

Sugar yield depends on cane tonnage, sugar content of the cane and on the cane quality. It is important that the cane is harvested at the most suitable moment when the economic optimum of recoverable sugar per area is reached. Cane tonnage at harvest can vary between 50 and 150 ton/ha or more, which depends particularly on the length of the total growing period and whether it is a plant or a ratoon crop. Cane yields produced under rainfed conditions can vary greatly. Good yields in the humid tropics of a totally rainfed crop can be in the range of 70 to 100 ton/ha cane, and in the dry tropics and subtropics with irrigation, 110 to 150 ton/ha cane. The water utilization efficiency for harvested yield (Ey) for cane containing about 80 percent moisture is 5 to 8 kg/m^3 and for sucrose containing no moisture 0.6 to 1.0 kg/m^3, both with the highest values for good ratoon crops in the subtropics.

Toward maturity, vegetative growth is reduced and sugar content of the cane increases greatly. Sugar content at harvest is usually between 10 and 12 percent of the cane fresh weight, but under experimental conditions 18 percent or more has been observed. Sugar content seems to decrease slightly with increased cane yields. Luxurious growth should be avoided during cane ripening which can be achieved by low temperature, low nitrogen level and restricted water supply. With respect to juice purity, this is positively affected by low minimum temperatures several weeks before harvest.

SUNFLOWER

Sunflower (*Helianthus annuus*) originates from central and north America. Lately its importance as an oil crop has grown and at present it is the second most important oil crop next to soybean. Total annual world production is some 10 million tons of seed from some 9.5 million ha.

Sunflower thrives in climates ranging from arid under irrigation to temperate under rainfed conditions, but is susceptible to frost. Mean daily temperatures for good growth are between 18 and 25°C. The total growing period varies from 70 days in parts of Russia where the season is short to 200 days at higher altitudes in Mexico. In the subtropics under irrigation the total growing period is about 130 days. For temperate climates the optimum planting date for early as well as late maturing varieties is between late spring and early summer. Delay in planting results in shortening of the vegetative period and early maturity, causing a decrease in head diameter and seed weight. Sunflower is a short-day plant with a variable response to daylength, but day-neutral varieties exist.

The crop is mainly grown under rainfed conditions on a wide range of soils. Under erratic and low rainfall, a rather deep soil with good water holding capacity is required. Due to its deep root system (2 to 3 m) soil water can be explored at great depths. Optimum soil pH is in the range of 6.0 to 7.5, but at lower values liming may be necessary. Fertilizer application is in general 50 to 100 kg/ha N, 20 to 45 kg/ha P and 60 to 125 kg/ha K. The crop is particularly sensitive to boron deficiency.

Optimum plant density is about 60 000 plants/ha with row spacing of about 0.9 m; seed rate is between 4 and 10 kg/ha. Both transplantation and direct seeding are practised.

In the major sunflower growing areas salinity problems are minor; an indication of tolerance to salinity during crop establishment is shown by the emergence percentage of seedlings which is 80 to 100% at ECe 0, 70 to 75% at 4.5, 30 to 60% at 9.5, 15 to 55% at 10 and 0 to 25% at ECe 13 mmhos/cm. However, in later growth periods sunflower is moderately tolerant to salinity.

WATER REQUIREMENTS

The water requirements of sunflower vary from 600 to 1000 mm, depending on climate and length of total growing period. Evapotranspiration increases from establishment to flowering, and can be as high as 12 to 15 mm/day. High evapotranspiration rates are maintained during seed setting and early ripening period. Percentage of total crop water use over the different growth periods is about 20 percent during vegetative period, 55 percent during the flowering period and the remaining 25 percent during the yield formation and ripening periods. The crop coefficient (kc) is 0.3-0.4 during the initial stage (20 to 25 days), 0.7-0.8 during the crop establishment stage (35 to 40 days), 1.05-1.2 during the mid-season stage (40 to 50 days), 0.7-0.8 during the late-season stage (25 to 30 days) and 0.4 at maturity or harvest.

WATER SUPPLY AND CROP YIELD

In respect of total yield produced, water requirements of sunflower are relatively high compared to most crops. Despite its high water use, the crop has an ability to withstand short periods of severe soil water deficit of up to 15 atmosphere tension. Long periods of severe soil water deficit at any growth period cause leaf-drying with subsequent reduction in seed yield. With heavy rain or irrigation following an extremely dry period, only a partial recovery occurs.

The duration of the different growth periods of a 140-day crop is shown in Figure 45. The relationships between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration deficit (1 - ETa/ETm) are shown in Figure 46. For calculation examples see p. 30 and Chap

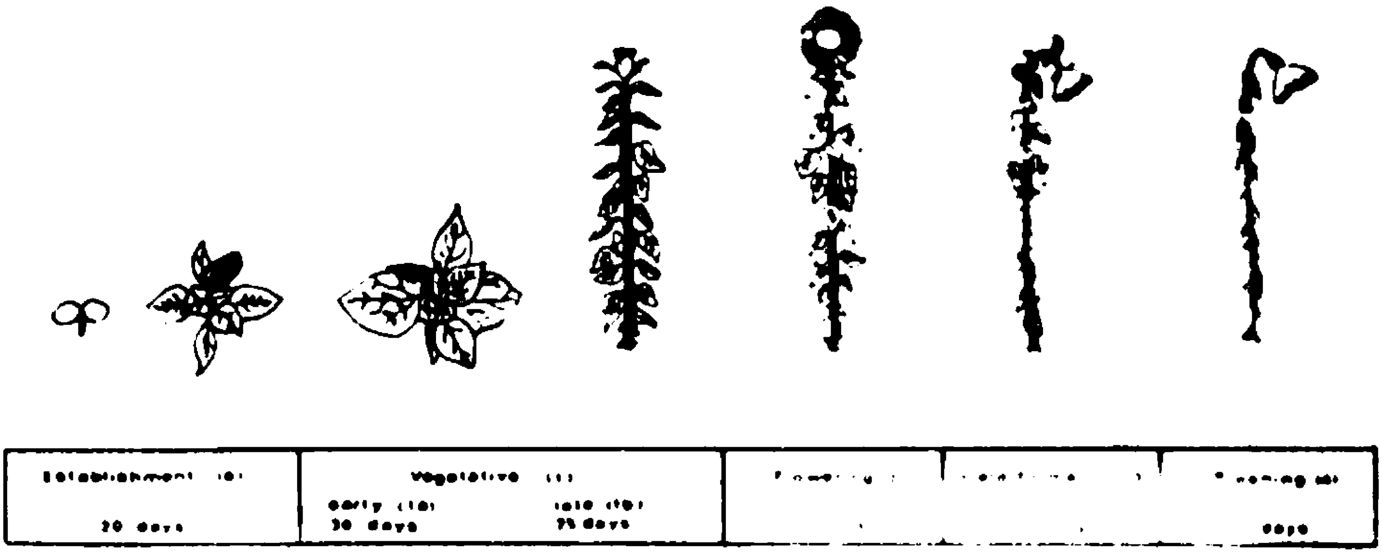


Fig. 45 Growth periods of sunflower

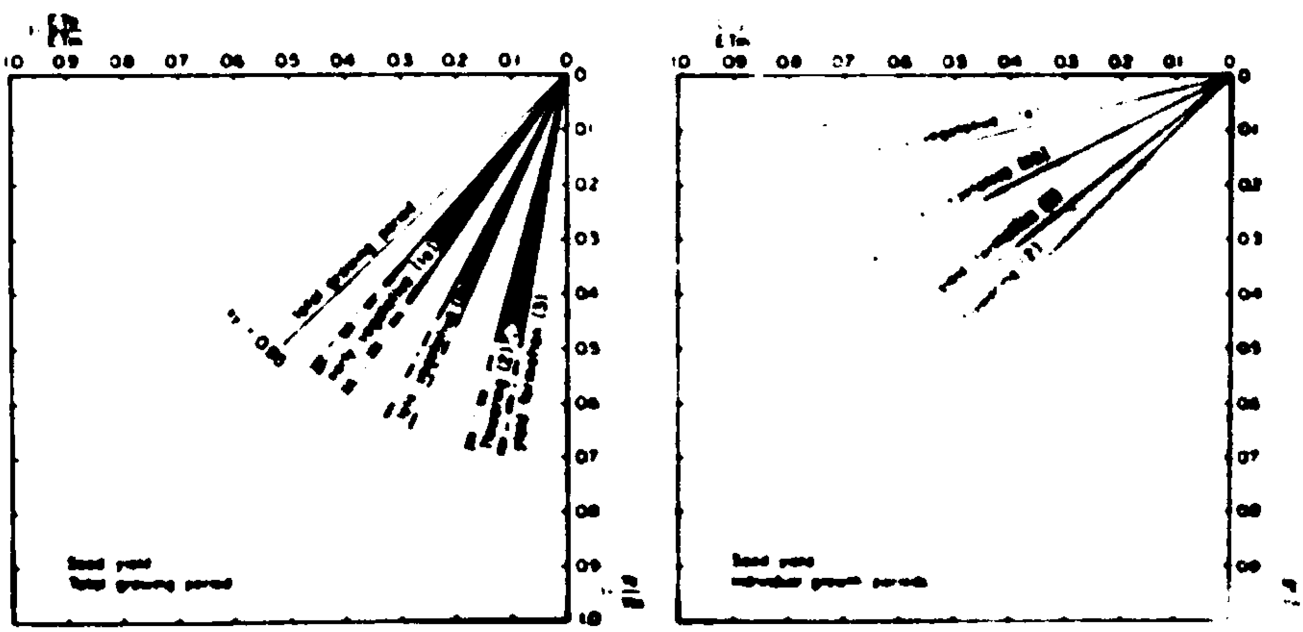


Fig. 46 Relationship between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration deficit (1 - ETa/ETm) for sunflower

Severe water deficits during the early vegetative period (1a) result in reduced plant height but may increase root depth. Adequate water during the late vegetative period is required for proper bud development (1b). The flowering period (2) is the most sensitive to water deficits which cause considerable yield decrease since fewer flowers come to full development. Yield formation (3) is the next most sensitive period to water deficit, causing severe reduction in both yield and oil content.

WATER UPTAKE

In deep soils the root system of sunflower may extend up to 2 to 3 m but normally, when the crop is full grown, 100 percent of the water is extracted from the first 0.8 to 1.5 m (D = 0.8-1.5 m). Under conditions when maximum evapotranspiration is 5 to 6 mm/day, the water uptake is affected when about 45 percent of the total available soil water is depleted (p = 0.45).

IRRIGATION SCHEDULING

For high production, soil water depletion should not exceed 45 percent of the available soil water, particularly during the late vegetative, flowering and yield formation periods. Due to the deep root system, 2 to 4 heavy irrigation applications are usually sufficient when the crop is grown on deep, medium textured soils. In addition a pre-irrigation is given when required. Application should be scheduled during the late vegetative (1b) and the flowering (2) periods. When water supply is limited, water savings can be made during the ripening period (4).

IRRIGATION METHODS

The crop is most suited to surface irrigation, particularly by furrow irrigation, allowing infrequent and heavy application.

YIELD AND QUALITY

The giant varieties, grown for poultry feeding and human consumption because of their low oil content, produce seed yields in the range of 0.8 to 1.5 ton/ha under rainfed conditions. The seeds of dwarf and semi-dwarf varieties contain 25 to 35 percent oil and give a total yield similar to the giant varieties. New Russian varieties with seeds of low hull content have an oil content of up to 50 percent. Under irrigation seed yields of 2.5 to 3.5 ton/ha are commonly obtained. The water utilization efficiency for harvested yield (Ey) for seeds containing 6 to 10 percent moisture is 0.3 to 0.5 kg/m^3.

TOBACCO

Tobacco (Nicotiana tabacum) is believed to have originated from [illegible] America. Present world production is about 5.7 million tons of leaves from 4.5 million ha.

The crop can be broadly divided according to the method of curing the leaves: flue, fire, air or sun-cured. In general, the dark-coloured air and fire-cured tobacco is used for pipe and cigar tobacco, whereas the light-coloured flue and sun-cured is used for cigarette tobacco.

Tobacco is grown under a wide range of climates but requires a frost-free period of 90 to 120 days from transplanting to last harvest of leaves. Optimum mean daily temperature for growth is between 20 and 30°C. A dry period is required for ripening and harvest of the leaves. Excess rainfall results in thin, lightweight leaves. Sun-cured or oriental tobacco requires a relatively dry climate to develop its full aroma. Except for some short-day varieties, cultivated tobacco is day-neutral in its response to flowering.

A light, sandy soil is required for flue-cured, light tobacco. Air-cured, dark tobacco is grown on silty loam to clay loam soils, while fire-cured and air-cured, light tobacco is mostly grown on medium textured soils. The crop is sensitive to waterlogging and demands well-aerated and drained soils. The optimum pH ranges from 5 to 6.5. Quality of the leaves is affected by soil salinity. Depending on the type of tobacco, fertilizer requirements vary and in general are 40 to 80 kg/ha N, 30 to 90 kg/ha P and 50 to 110 kg/ha K.

Tobacco is sown on seed beds and is transplanted 40 to 60 days after sowing when the plants are about 15 cm tall. During the first weeks the seed beds are often covered to protect the young seedlings against unfavourable weather. Spacing after transplantation varies with variety and is generally between 1.2 to 0.9 x 0.9 to 0.6 m. Crop rotation after one or two seasons is recommended with crops such as grass, sorghum, millet and maize that are not susceptible to root eelworm.

To produce high value leaves, topping (removal of flower buds) and desuckering (removal of side shoots) is often practised. Time and height of topping depends on the type of tobacco but is usually done when [illegible]0 percent of the plants have their buds in flower.

WATER REQUIREMENTS

The water requirements (ETm) for maximum yield vary with climate and length of growing period from 400 to 600 mm. During the first weeks after emergence in the seed bed the seedlings require 3 to 5 litres/m² daily. After 30 to 40 days the seedlings receive less water so as to obtain a more robust plant. After 40 to 60 days, the seedlings are transplanted and the crop is harvested 90 to 120 days after transplanting. The period of maximum water requirements occurs 50 to 70 days after transplanting and is followed by a decrease in water requirements.

The crop coefficient (kc) relating crop water requirements (ETm) to reference evapotranspiration (ETo) for the different development stages after transplanting are: during the initial stage 0.3-0.4 (10 days), the development stage [illegible] the mid-season stage 1.0-1.2 (30 to 35 days), during the late-season stage 0.9-1.0 (30 to 40 days) and at harvest 0.75-0.85.

WATER SUPPLY AND CROP YIELD

The growth periods of tobacco are shown in Figure 47. The relationships between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration (1 - ETa/ETm) are given in Figure 48. For calculation examples see p. 40 and Chapter VI.

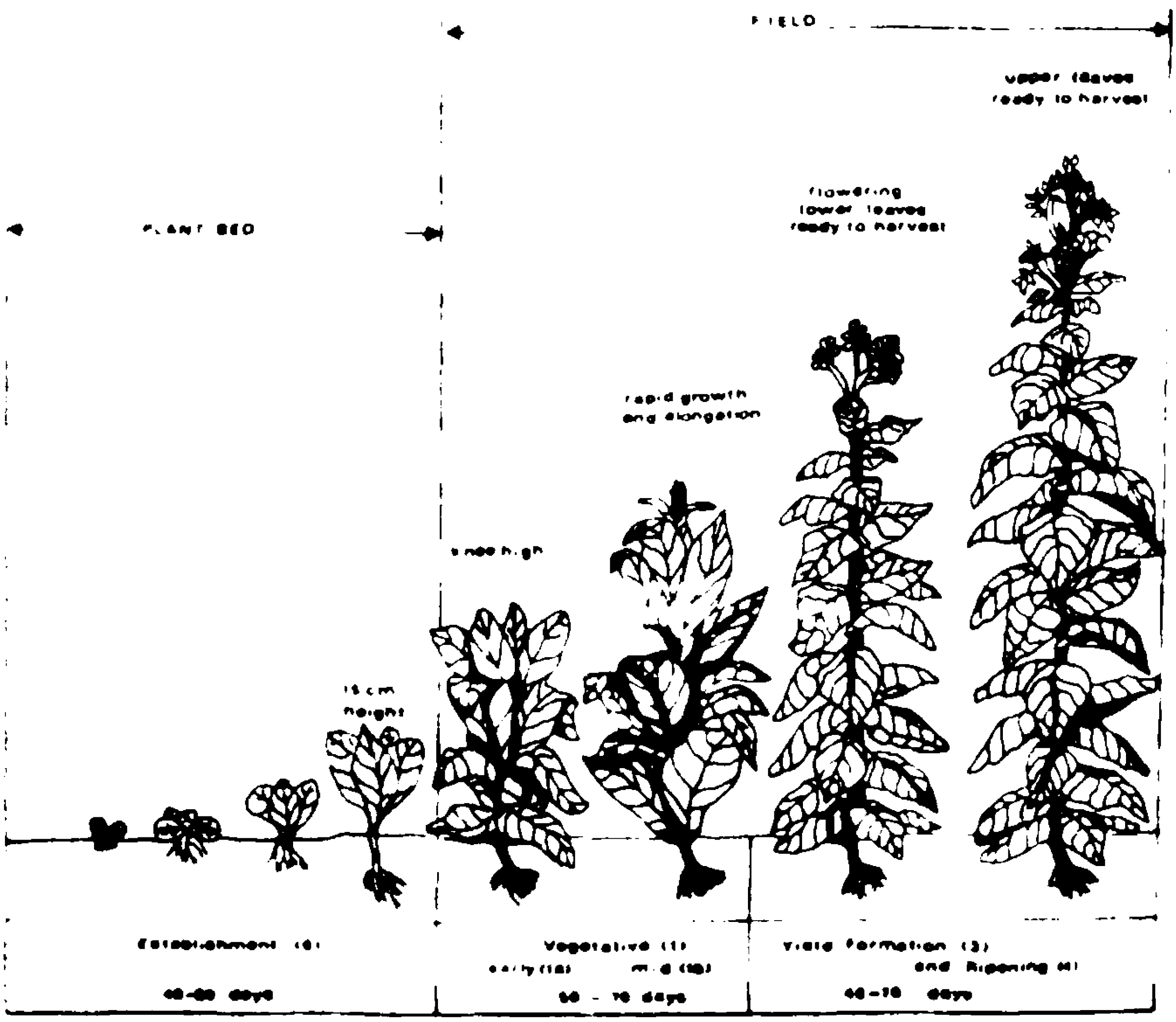


Fig. 47 Growth periods in tobacco (Lucas)

The water regimes from which a full crop of tobacco can be obtained vary from stored soil water, rainfall, supplemental irrigation or full irrigation. Careful water scheduling is required because too frequent irrigation damages the crop. Water deficits in certain periods may increase yields and it is recommended practice to subject seedlings during the establishment period (0) prior to transplanting to a period of moderate water deficit to increase their drought resistance. Also, moderate water deficits during the early vegetative period (1a) may enhance root development.

Moderate water deficits during the first 20 to 30 days after transplanting have little effect on final yield but cause temporary retarded growth; however, the crop recovers rapidly with subsequent irrigations. In most cases, final yields may be larger compared to a crop receiving full irrigation throughout this growth period (1a).

Water deficits during the mid-vegetative period (rapid growth, 1b) result in reduced growth and smaller leaves. Severe water deficits during the yield formation and ripening periods (3 and 4) affect leaf weight and chemical composition which in turn affects the fire-holding capacity. However, a mild water deficit during ripening (4) is desirable to restrict growth of new young leaves.

Excess water results in leaves of low quality. Heavy rain or irrigation may cause 'wilting', 'wet feet' or 'drowning'. Waterlogging for two or more days generally severely damages the crop and may kill the plants.

To obtain maximum total production under limited water supply, management should be directed towards increasing the area and partially meeting the crop water requirements rather than meeting full crop water requirements over a limited area.

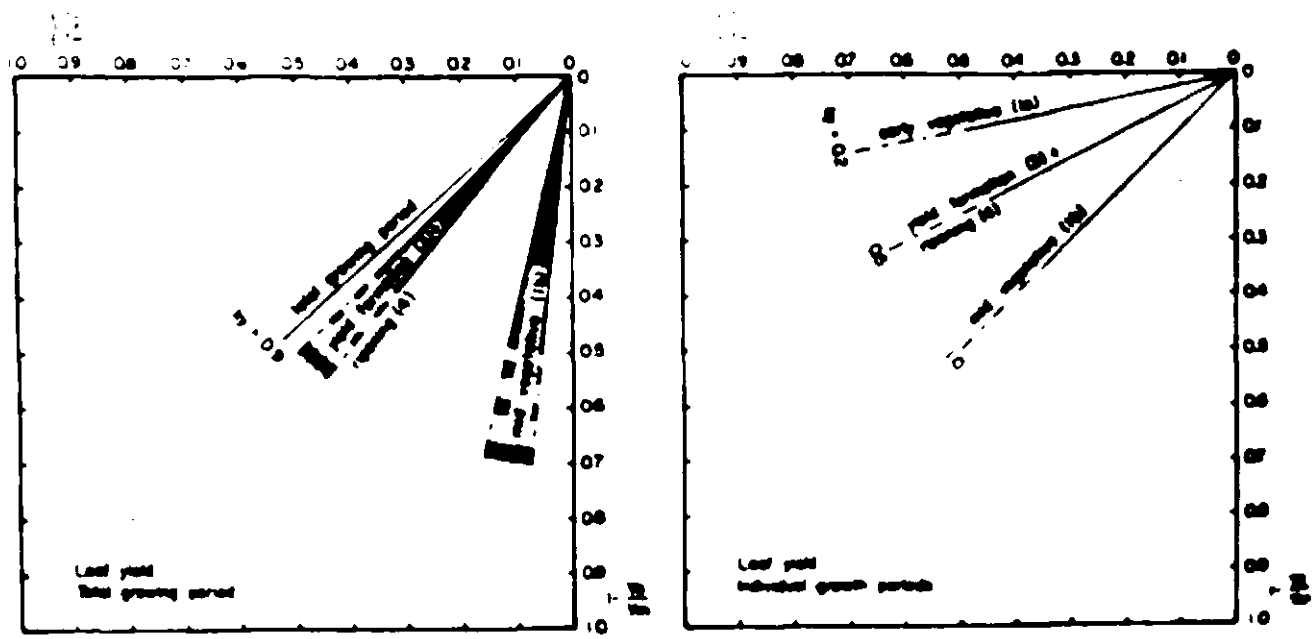


Fig. 48 Relationship between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration deficit (1 - ETa/ETm) for tobacco

WATER UPTAKE

Tobacco has a well-developed tap root with extensive horizontal lateral roots. Normally 75 percent of the water uptake occurs over the first 0.3m and 100 percent over the first 0.5 to 1.0 m (D = 0.5-1.0 m). Root development is enhanced by withholding water supply during early vegetative period (1a). Also topping and desuckering will favour root development. Full rooting depth is reached some 40 to 50 days after transplanting. Under conditions when ETm is 5 to 6 mm/day, water uptake will be affected when 50 to 60 percent of the total available soil water has been depleted (p = 0.6).

IRRIGATION SCHEDULING

Water must be supplied daily to the young seedlings in the seed bed (0) even when evapotranspiration is moderate. At the end of the seed bed period (0) water is withheld for a few days. Immediately before and during transplanting water is supplied to the plants individually to help them through the first weeks after transplanting. During the rapid growth period (1b), water should be supplied frequently. During the early yield formation period (3), at flowering, few deep irrigations may be sufficient to obtain optimum yields of high quality. When water is limited, water should be applied at transplanting, during the period of rapid growth (1b), and during the early yield formation period (3).

IRRIGATION METHODS

Surface and sprinkler irrigation are mostly practised. The quality of the water is important in selecting the most suitable irrigation method, e.g. sprinkler irrigation should be avoided when only low quality water is available.

YIELD AND QUALITY

Normally 18 to 22 leaves are harvested with 2 to 3 leaves per week for 30 to 50 days. Occasionally, when half the leaves have been harvested and if the remaining leaves show a uniform ripening, the whole plant is harvested, thus saving labour. Good yields under commercial production with adequate water supply are in the range of 2 to 2.5 ton/ha of leaves. The water utilization efficiency for harvested yield (Ey) for cured leaves containing about 10 percent moisture is 0.4 to 0.6 kg/m^3.

Irrigation practices together with cultivation practices, e.g. topping, and soil fertility affect leaf quality. Nicotine content of the leaf is generally 1.5 to 2.5 percent of dry leaf matter for the flue-cured tobacco and 3 to 4 percent for the air-cured tobacco. Tobacco grown under dry conditions frequently has a dark, small leaf which is dull in colour and lacks elasticity. However, it has a high nicotine content. Under adequate water supply the leaves are thinner and more elastic, and also the colour is improved, while the nicotine content is optimal. Over-irrigation, particularly during the latter part of the total growing period results in inferior leaf quality.

TOMATO

Tomato (Lycopersicon esculentum) is the second most important vegetable crop next to potato. Present world production is about 41 million tons fresh fruit from 2 million ha.

Tomato is a rapidly growing crop with a growing period of 90 to 150 days. It is a daylength neutral plant. Optimum mean daily temperature for growth is 18 to 25°C with night temperatures between 10 and 20°C. Larger differences between day and night temperatures, however, adversely affect yield. The crop is very sensitive to frost. Temperatures above 25°C, when accompanied by high humidity and strong wind, result in reduced yield. Night temperatures above 20°C accompanied by high humidity and low sunshine lead to excessive vegetative growth and poor fruit production. High humidity leads to a greater incidence of pests and diseases and fruit rotting. Dry climates are therefore preferred for tomato production.

Tomato can be grown on a wide range of soils but a well-drained, light loam soil with pH of 5 to 7 is preferred. Waterlogging increases the incidence of diseases such as bacterial wilt. The fertilizer requirements amount, for high producing varieties, to 100 to 150 kg/ha N, 65 to 110 kg/ha P and 160 to 240 kg/ha K.

The seed is generally sown in nursery plots and emergence is within 10 days. Seedlings are transplanted in the field after 25 to 35 days. In the nursery the row distance is about 10 cm. In the field spacing ranges from 0.3/0.6 x 0.6/1 m with a population of about 40000 plants per ha. The crop should be grown in a rotation with crops such as maize, cabbage, cowpea, to reduce pests and disease infestations.

The crop is moderately sensitive to soil salinity. Yield decrease at various ECe values is: 0% at ECe 2.5 mmhos/cm, 10% at 3.5, 25% at 5.0, 50% at 7.6 and 100% at ECe 12.5 mmhos/cm. The most sensitive period to salinity is during germination and early plant development, and necessary leaching of salts is therefore frequently practised during pre-irrigation or by over-watering during the initial irrigation application.

WATER REQUIREMENTS

Total water requirements (ETm) after transplanting, of a tomato crop grown in the field for 90 to 120 days, are 400 to 600 mm, depending on the climate. Water requirements related to reference evapotranspiration (ETo) in mm/period are given by the crop factor (kc) for different crop development stages, or: during the initial stage 0.4-0.5 (10 to 15 days), the development stage 0.7-0.8 (20 to 30 days), the mid-season stage 1.05-1.25 (30 to 40 days), the late-season stage 0.8-0.9 (30 to 40 days) and at harvest 0.6-0.65.

WATER SUPPLY AND CROP YIELD

The plant produces flowers from bottom to top during the active development of the stem. Fruits can be harvested while the plant is still flowering at the top. Sometimes three flowering periods related to three harvests can be distinguished. However, for mechanical harvesting where the fruits are used for tomato paste, only one picking is made. Water supply needs to be adjusted according to the use of the product, e.g. for salad or paste.

Highest yields of salad tomatoes are obtained by frequent, light irrigation. Where mechanical harvesting is used, heavy, infrequent irrigation is more appropriate with the last irrigation applied long before harvest.

The growth periods of tomato for the first harvest are:

0	establishment (in nursery)	25-35	days
1	vegetative	20-25	
2	flowering	20-30	
3	yield formation	20-30	
4	ripening	15-20	
		100-140	

For subsequent harvest periods, 2, 3 and 4 will overlap and an additional 20 to 30 days are required for each harvest.

The relationship between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration deficit (1 - ETa/ETm) is given in Figure 49. The crop is most sensitive to water deficit during and immediately after transplanting and during flowering (2) and yield formation (3). Water deficit during the flowering period (2) causes flower drop. Moderate water deficit during the vegetative period (1) enhances root growth.

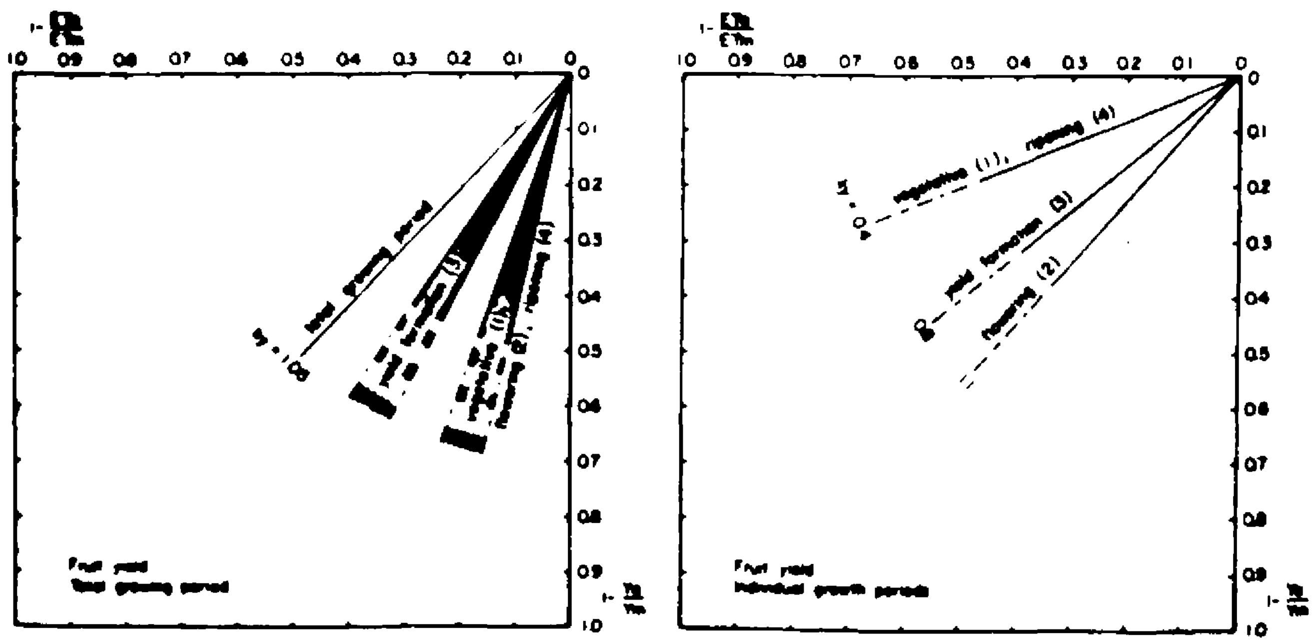


Fig. 49 Relationship between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration deficit (1 - ETa/ETm) for tomato

For high yield and good quality, the crop needs a controlled supply of water throughout the growing period. Whereas under water limiting conditions some water savings may be made during the vegetative (1) and ripening (4) periods, water supply should preferably be directed toward maximizing production per ha rather than extending the cultivated area under limited water supply.

WATER UPTAKE

The crop has a fairly deep root system and in deep soils roots penetrate up to some 1.5 m. The maximum rooting depth is reached about 60 days after transplanting. Over 80 percent of the total water uptake occurs in the first 0.5 to 0.7 m and 100 percent of the water uptake of a full grown crop occurs from the first 0.7 to 1.5 m (D = 0.7-1.5 m). Under conditions when maximum evapotranspiration (ETm) is 5 to 6 mm/day, water uptake to meet full crop water requirements is affected when more than 40 percent of the total available soil water has been depleted (p = 0.4).

IRRIGATION SCHEDULING

The crop performance is sensitive to the irrigation practices. In general a prolonged severe water deficit limits growth and reduces yields which cannot be corrected by heavy watering later on. Highest demand for water is during flowering. However, withholding irrigation during this period is sometimes recommended to force less mature plants into flowering in order to obtain uniform flowering and ripening. Care should be exercised in this to avoid damage to the mature plants.

Excessive watering during the flowering period (2) has been shown to increase flower drop and reduce fruit set. Also this may cause excessive vegetative growth and a delay in ripening. Water supply during and after fruit set must be limited to a rate which will prevent stimulation of new growth at the expense of fruit development. Heavy, irregular irrigations or dry periods alternating with wet periods should be avoided. For production of salad tomato with more than one harvest, the crop flourishes best under light, frequent irrigation, well-distributed over the growing period with the soil depletion level during the different growth periods remaining below 40 percent ($p < 0.4$). This promotes optimum growth during the total growing period and results in high yield of good quality. With one harvest uniform ripening is required and the depletion level during this period may increase to 60 to 70 percent.

When water supply is limited, application for a salad crop can be concentrated during periods of transplanting, flowering (2) and yield formation (3). For a crop grown for paste production, a more extensive irrigation may be applied with last heavy irrigation applied prior to flowering.

IRRIGATION METHODS

Surface irrigation by furrow is commonly practised. Under sprinkler irrigation the occurrence of fungal diseases and possibly bacterial canker may become a major problem. Further, under sprinkler, fruit set may be reduced with an increase in fruit rotting. In the case of poor quality water, leaf burn will occur with sprinkler irrigation; this may be reduced by sprinkling at night and shifting of sprinkler lines with the direction of the prevailing wind. Due to the crops specific demands for a high soil water content achieved without leaf wetting, trickle or drip irrigation has been successfully applied.

YIELD AND QUALITY

Frequent light irrigations improve the size, shape, juiciness and colour of the fruit, but total solids (dry matter content) and acid content will be reduced. However, the decrease in solids will lower the fruit quality for processing. In selecting the irrigation practices consideration must therefore be given to the type of end product required. Prolonged water deficits during the yield formation period (3) interrupted by heavy irrigation leads to fruit cracking. Where fruit rot is a problem, frequent sprinkler irrigation should be avoided during the period of yield formation.

A good commercial yield under irrigation is 45 to 65 ton/ha fresh fruit, of which 80 to 90 percent is moisture, depending on the use of the product. The water utilization efficiency for harvested yield (Ey) for fresh tomatoes is 10 to 12 kg/m^3.

WATERMELON

Watermelon (*Citrullus vulgaris*) is native to the dry areas of tropical and subtropical Africa south of the equator. The crop can survive the desert climate when groundwater is available and the fruit sometimes serves as a source of water for human consumption. World production is about 23 million tons fruit from 1.8 million ha.

The crop prefers a hot, dry climate with mean daily temperatures of 22 to 30°C. Maximum and minimum temperatures for growth are about 35 and 18°C respectively. The optimum soil temperature for root growth is in the range of 20 to 35°C. Fruits grown under hot, dry conditions have a high sugar content of 11 percent in comparison to 8 percent under cool, humid conditions. The crop is very sensitive to frost. The length of the total growing period ranges from 80 to 110 days, depending on climate.

The crop prefers a sandy loam soil texture with pH of 5.8 to 7.2. Cultivation in heavy textured soils results in a slower crop development and cracked fruits. For high production fertilizer requirements are 80 to 100 kg/ha N, 25 to 60 kg/ha P and 35 to 80 kg/ha K.

The crop is moderately sensitive to salinity. Yield decrease due to salinity appears to be similar to that of cucumber, or: 0% at ECe 2.5 mmhos/cm, 10% at 3.3, 25% at 4.4, 50% at 6.3 and 100% at ECe 10 mmhos/cm.

Watermelon is normally seeded directly in the fields. Thinning is practised 15 to 25 days after sowing. Spacing between plants and rows varies from 0.6 x 0.9 to 1.8 x 2.4 m. Seeds are sometimes placed on hills spaced 1.8 x 2.4 m. In areas prone to frost, sowing time is dictated often by the occurrence of frost; sometimes black plastic mulch is used for frost protection.

WATER REQUIREMENTS

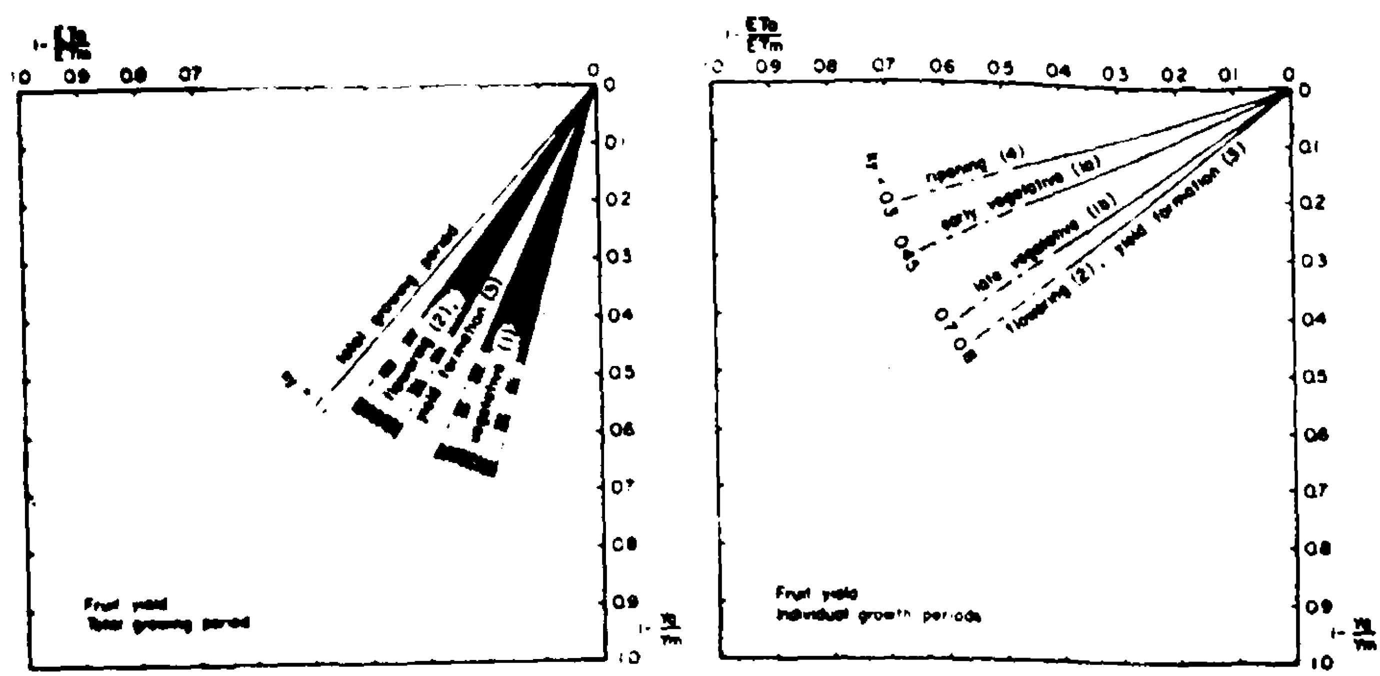
Under conditions of high evaporation, irrigation intervals may be as short as 6 to 8 days. For maximum production the crop coefficients (kc) relating water requirements (ETm) to reference evapotranspiration (ETo) are: during the 10 to 20 day initial stage, 0.4-0.5, during the 15 to 20 days development stage, 0.7-0.8; the 35 to 50 day mid-season stage 0.95-1.05; and the 10 to 15 day late-season stage, 0.8-0.9. After 70 to 105 days, at harvest, kc is 0.65-0.75. Water requirements for the total growing period for a 100-day crop range from 400 to 600 mm.

WATER SUPPLY AND CROP YIELD

The crop can deplete soil water to a soil water tension of over 2 atmospheres without the yield being affected. Irrigation should take place when, depending on the level of evaporation, the soil water has been depleted some 50 to 70 percent of available soil water. In dry climates with moderate evaporation and little rain the watermelon produces an acceptable yield (15 ton/ha) with one heavy irrigation in the beginning of the growing period when soil water over the full root depth is brought to field capacity.

The growth periods of a 80 to 110 day watermelon are: the establishment period (0) of 10 to 15 days; the vegetative period (1) of 20 to 25 days, including early (1a) and late vegetative growth (vine development, 1b); the flowering period of 15 to 20 days; yield formation (fruit filling, 3) of 20 to 30 days and ripening (4) 15 to 20 days. The crop usually has 4 fruits per plant, which is controlled by pruning practices,and harvest date depends on the number of fruits per plant and on uniformity of ripening.

The relationship between relative yield decrease and relative evapotranspiration deficit is given in Figure 50. Water deficit during the establishment period (0) delays growth and produces a less vigorous plant. When water deficit occurs during the early vegetative period (1a), less leaf area is produced which causes yield reduction. The late vegetative period (vine development, 1b), the flowering period (2) and the yield formation period (fruit filling, 3) are the most sensitive periods to water deficit. During the ripening period (4) a reduced water supply improves fruit quality. Yields are little affected by water deficits immediately prior to harvest.



Relationship between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration deficit (1 - ETa/ETm) for watermelon

Whereas under limiting conditions some water savings may be made during vegetative (1) and ripening (4) periods, water supply should be directed toward maximizing production per ha by meeting full crop water requirements rather than extending the cultivated area under limited supply.

WATER UPTAKE

Water uptake varies with soil type and irrigation practices. The root system can be deep and extensive up to a depth of 1.5 to 2 m. The active root zone where most of the water is abstracted under adequate water supply is limited to the first 1.0 to 1.5 (D = 1.0-1.5 m). Under moderate evapotranspiration (ETm is 5 to 6 mm/day), the crop can deplete the available soil water up to 40 or 50 percent before ETm is affected (p = 0.4-0.5).

IRRIGATION SCHEDULING

Where evaporation is high and rainfall is low, frequent irrigation with an interval from 7 to 10 days may be necessary. Irrigation under dry conditions must be scheduled at the start of the growing period (pre-irrigation), during the late vegetative period (vine development, 1b), the flowering period (2) and the yield formation period (3). In these periods soil water depletion must not exceed 50 percent. During the ripening period (4) relatively dry soils are preferred to increase sugar content and to avoid the flesh becoming more fibrous and less juicy.

Under moderate evaporation and deep soil with some rain during the growing season, one heavy irrigation may be sufficient to bring the crop to maturity.

IRRIGATION METHODS

The most common method is by furrow. Under conditions where crop water requirements are high and the soils are light textured, drip irrigation has been successfully applied with a reduction in overall water demands. The crop has been grown successfully under spate or flood irrigation on basins with one application of 250 to 350 mm and little or no rainfall and with farmers' yields of about 12 ton/ha with a maximum of 20 ton/ha.

YIELD AND QUALITY

Within certain water deficit limits, irrigation practices do not greatly affect the number of fruits per plant but affect the fruit size, shape, weight and quality. Ample water supply during the ripening period (4) reduces the sugar content and adversely affects the flavour. Severe water deficit in the ripening period on the other hand causes cracked and irregularly-shaped fruits.

A good commercial yield under irrigation is 25 to 35 ton/ha. The water utilization efficiency for harvested yield (Ey) for fresh fruits containing about 90 percent moisture varies between 5 and 8 kg/m^3.

WHEAT

Bread and durum wheat (Triticum aestivum and T. turgidum) were domesticated in the Near and Middle East. Present world production is about 420 million tons from 325 million ha.

The crop is grown as a rainfed crop in the temperate climates, in the subtropics with winter rainfall, in the tropics near the equator, in the highlands with altitudes of more than 1 500 m and in the tropics away from the equator where the rainy season is long and where the crop is grown as a winter crop.

Wheat is grown under irrigation in the tropics either in the highlands near the equator and in the lowlands away from the equator. In the subtropics with summer rainfall the crop is grown under irrigation in the winter months. In the subtropics with winter rainfall it is grown under supplemental irrigation.

The length of the total growing period of spring wheat ranges from 100 to 130 days while winter wheat needs about 180 to 250 days to mature. Daylength and temperature requirements are key factors in variety selection. Varieties can be grouped as winter or spring types according to chilling requirements, winter hardiness and daylength sensitivity. Winter wheat requires a cold period or chilling (vernalization) during early growth for normal heading under long days. Winter wheat in its early stages of development exhibits a strong resistance to frost, down to - 20°C. The resistance is lost in the active growth period in spring and during head development and flowering periods frost may lead to head sterility. Because of this sometimes more damage is done to the winter crop by spring frost than by winter frost.

In areas of severe winters, cold winds and little snow, spring wheat varieties are grown. Spring wheat does not require chilling for heading and it is day-neutral. However, it is also sensitive to frost. For winter and spring wheat minimum daily temperature for measurable growth is about 5°C. Mean daily temperature for optimum growth and tillering is between 15 and 20°C. Occurrence of (spring) frost is an important factor in selection of sowing date. A dry, warm ripening period of 18°C or more is preferred. Mean daily temperatures of less than 10 to 12°C during the growing season make wheat a hazardous crop. Knowledge of genetic characteristics and particularly the growth and development pattern of wheat varieties is essential for meeting the combination of various climatic requirements for growth development and yield formation.

The crop can be grown on a wide range of soils but medium textures are preferred. Peaty soils containing high sodium, magnesium or iron should be avoided. The optimum pH ranges from 6 to 8. For good yields the fertilizer requirements are up to 150 kg/ha N, 35 to 45 kg/ha P and 25 to 50 kg/ha K.

Wheat is relatively tolerant to a high groundwater table; for sandy loam to silt loam a depth of groundwater of 0.6 to 0.8 m can usually be tolerated, and for clay 0.8 to 1 m. For short periods the crop can withstand without visible harm a minimum depth of 0.25 m. With a rise of groundwater table to 0.5 m for long periods the yield decrease is 20 to 40 percent.

The crop is moderately tolerant to soil salinity but the ECe should not exceed 4 mmhos/cm in the upper soil layer during germination. Yield decrease due to salinity is 0% at ECe 6.0, 10% at 7.4, 25% at 9.5, 50% at 13 and 100% at ECe 20 mmhos/cm.

With pre-irrigation or sufficient rain to wet the upper soil layer, seeds are drilled 2 to 4 cm deep as against 5 to 8 cm in dry soils, so that light showers will not cause the seeds to germinate. Under favourable water supply including irrigation and adequate fertilization row spacing is 0.12 to 0.15 m (450 to 700000 plants/ha) but increases to 0.25 m or more under poor rainfall conditions (less than 200000 plants/ha). Sowing rates under irrigation are 100 to 120 kg/ha (drilled) to 110 to 140 kg/ha (broadcast). Wheat is often grown in rotation and legumes, sunflower and maize are considered as suitable rotation crops.

WATER REQUIREMENTS

For high yields water requirements (ETm) are 450 to 650 mm depending on climate and length of growing period. The crop coefficient (kc) relating maximum evapotranspiration (ETm) to reference evapotranspiration (ETo) is: during the initial stage 0.3-0.4 (15 to 20 days), the development stage 0.7-0.8 (25 to 30 days), the mid-season stage 1.05-1.2 (50 to 65 days), the late-season stage 0.65-0.7 (30 to 40 days) and at harvest 0.2-0.25.

WATER SUPPLY AND YIELD

Growth periods of winter and spring wheat are shown

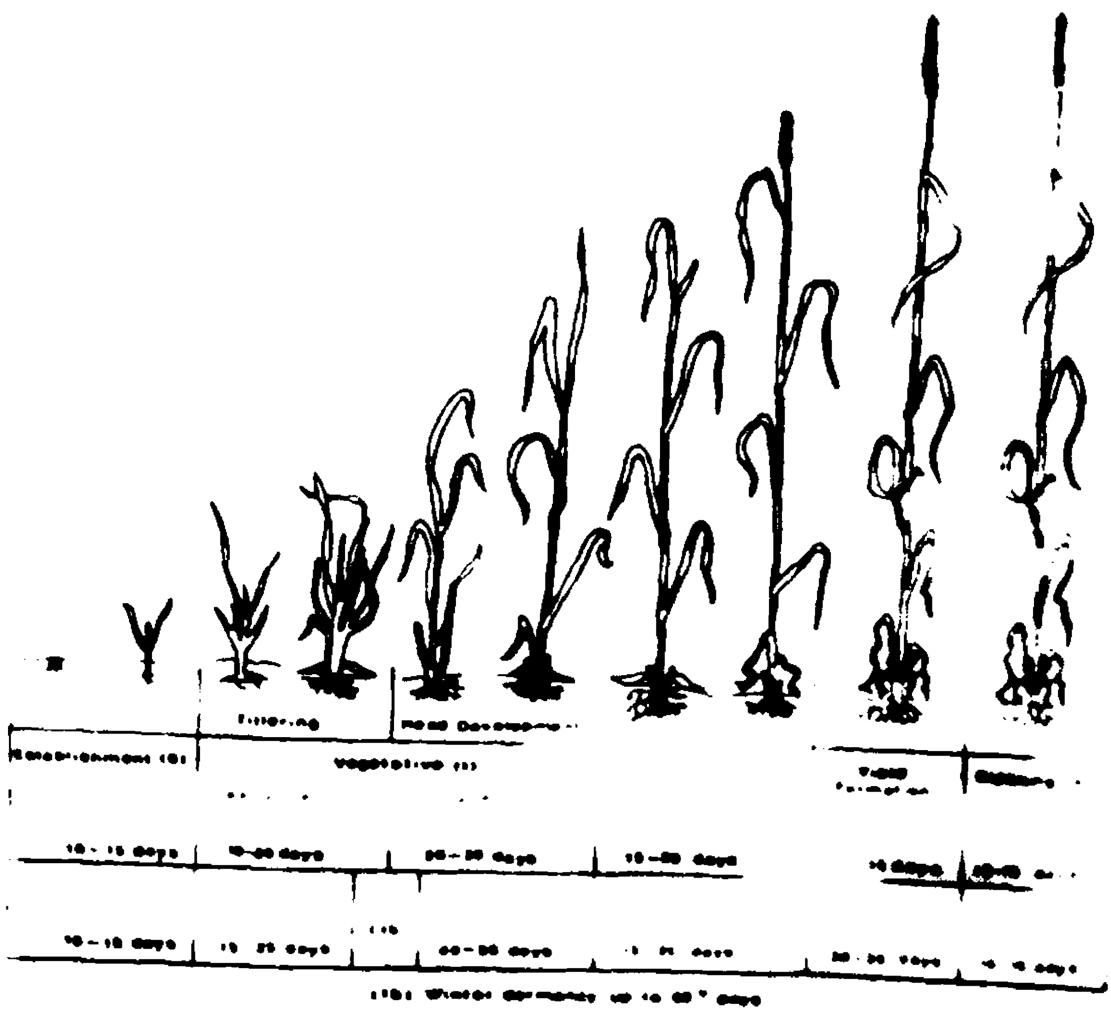


Fig. 51 Growth periods of winter and spring wheat (Large, 1954)

Grain yield and grain straw ratio are related to the duration and intensity of water deficit but the relations vary depending on the growth period during which the deficits occur. There is, however, some variation in variety as to the magnitude of the resulting yield decrease. The relationships between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration deficit (1 - ETa/ETm) for winter and spring wheat are shown in Figures 52 and 53. For calculation examples see p. 40 and Chapter VI.

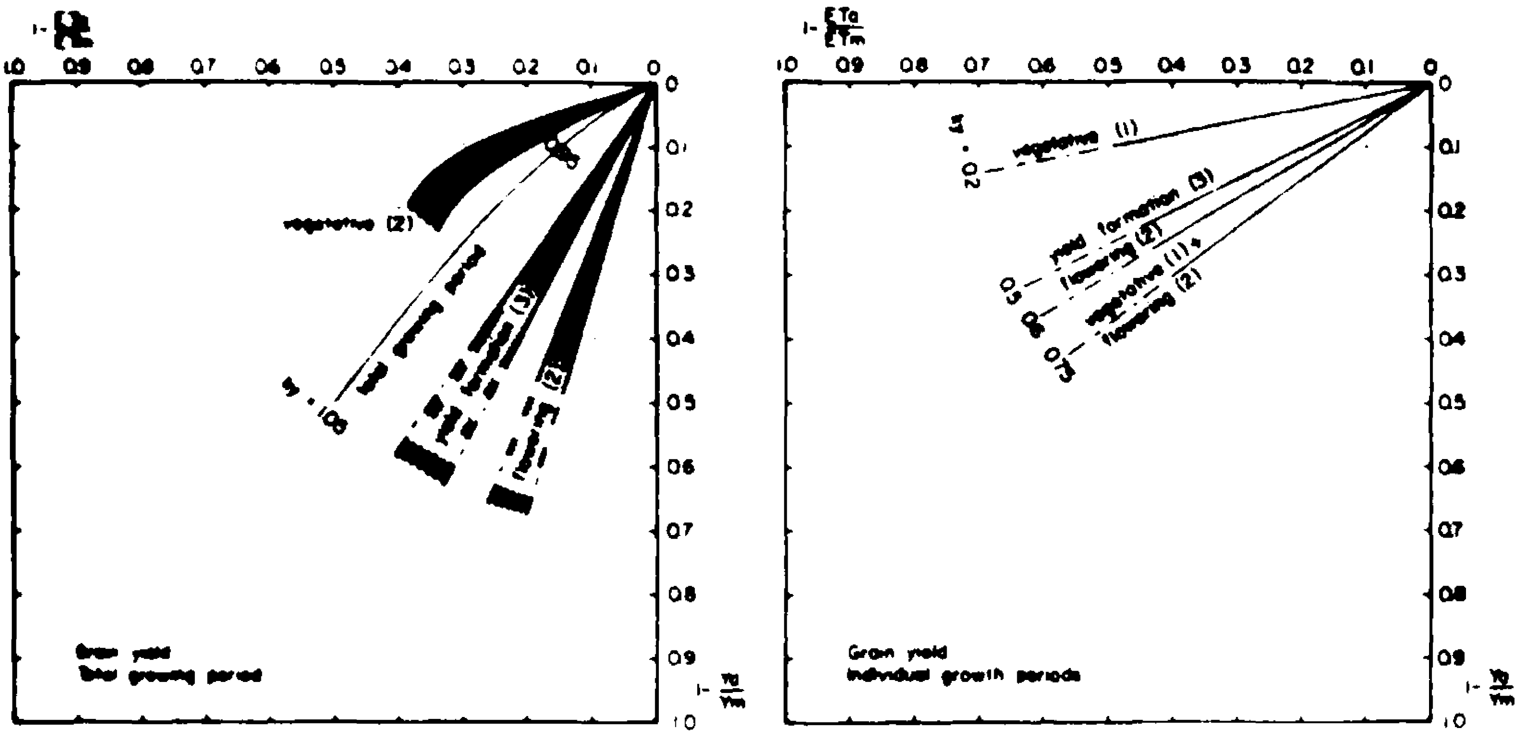


Fig. 52 Relationship between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration deficit (1 - ETa/ETm) for winter wheat

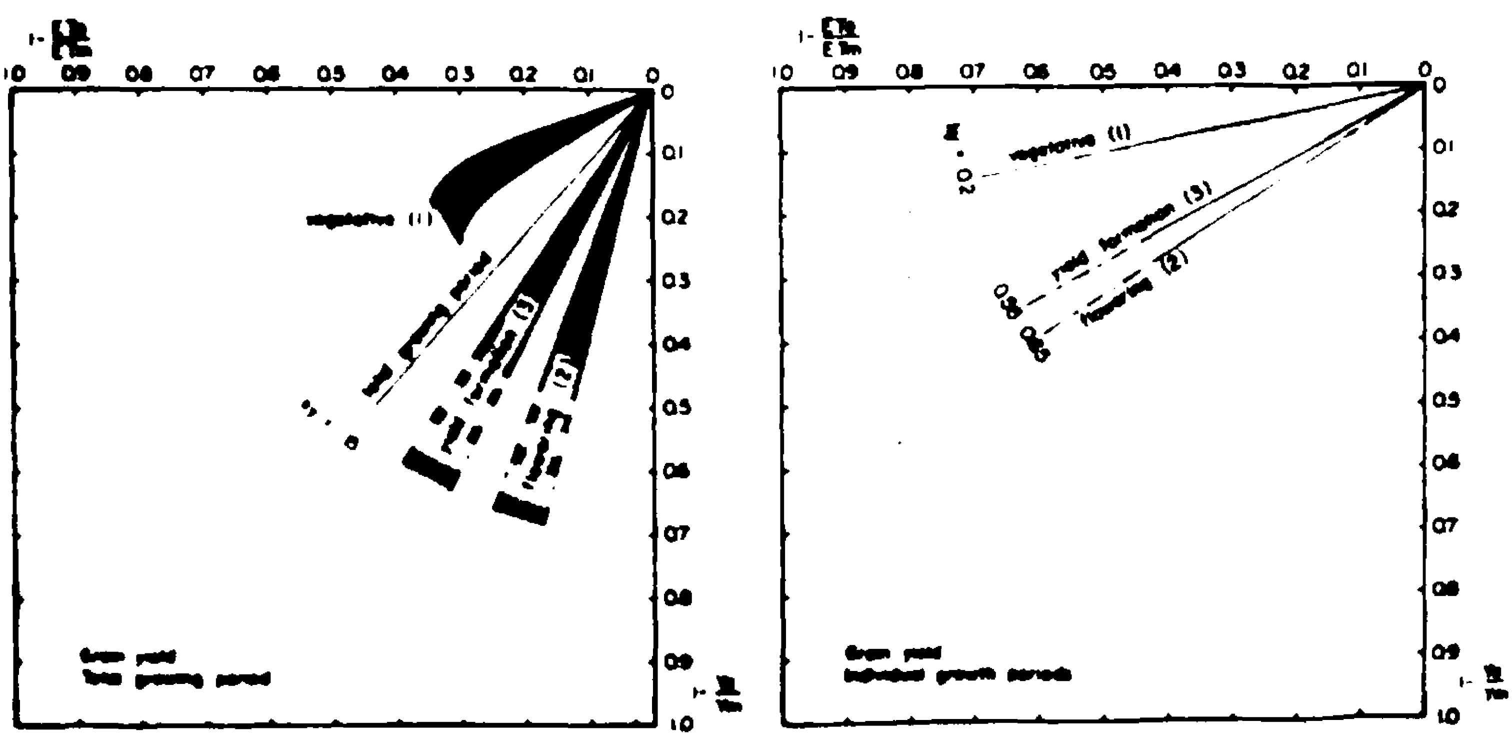


Fig. 53 Relationship between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration deficit (1 - ETa/ETm) for spring wheat

The relationships indicate that sensitivity to water deficit is somewhat higher in spring that in winter wheat, and this difference is thought to be the result of 'conditioning' of winter wheat which enables it to adjust its growth pattern in relation to water deficit.

[illegible] varieties are particularly [illegible] the [illegible] varieties, early irrigation or heavy pre-and early season rain can produce good yields particularly when soils are deep and have a good water holding capacity and with an adequate amount of stored soil water, significant water deficits may occur only in the yield formation period (3). Only with irrigation or rain in the early growth periods (0 and 1a) plant and head number per m^2 are considered higher compared to no rain or irrigation. In the latter situation the time to heading is also usually shortened.

Slight water deficits in the vegetative period (1) may have little effect on crop development or may even somewhat hasten maturation. The flowering period (2) is most sensitive to water deficit. Pollen formation and fertilization can be seriously affected under heavy water stress and during the time of head development and flowering water shortage will reduce the number of heads per plant, head length and number of grains per head. At the time of flowering root growth may be very much reduced and may even cease and considerable damage can be caused in this period. The loss in yield due to water deficits during the flowering period (2) cannot be recovered by providing adequate water supply during the later growth periods.

Water deficit during the yield formation period (3) results in reduced grain weight and hot, dry and strong wind in combination with a water deficit during this period causes shrivelling of grain. During the ripening period (4) a drying-off period is often induced by discontinuing irrigation [illegible] during this period only has a slight effect on yield.

In summary, provided there is adequate water during the esta[illegible] period (0) the critical periods for water defi[illegible]

- when the plants are some 15 cm tall, just completing tillering and just starting elongation; at this time the total number of heads and number of potential seeds per head is being determ[illegible]

- at the end of head development to heading or the time that the flowering period (2) begins; water deficit will greatly reduce the number of seeds per head;

- at early yield formation period (early 3) when water deficits combined with hot, dry winds would re[illegible] an incomplete [illegible] a reduced yield of poor qual[illegible] [illegible]elled grains.

Wheat has the ability to form additional tillers when heavy water stress during the late vegetative period (1c) is followed by heavy water application. Yields may be improved through the formation of additional heads but harvest is delayed and losses from other causes such as lodging and non-uniform ripening are often increased.

WATER UPTAKE

Wheat has a prima[illegible] [illegible]m and later it develops a fibrous root system. The latter roots are formed from the nodes which are at or near the ground surface. Depth and density of rooting are affected by water, nutrients and oxygen in the soil. In deep soils, the active rooting depth for spring wheat is 0.9 m with a maximum of 1.2 to 1.5 m and a spread of 0.15 to 0.25 m in all directions. For winter wheat, active rooting depth is up to 1.2 m with maximum of 1.5 to over 2 m and a similar spread. The top root ratio increases with crop development and is about 2 during the vegetative period.

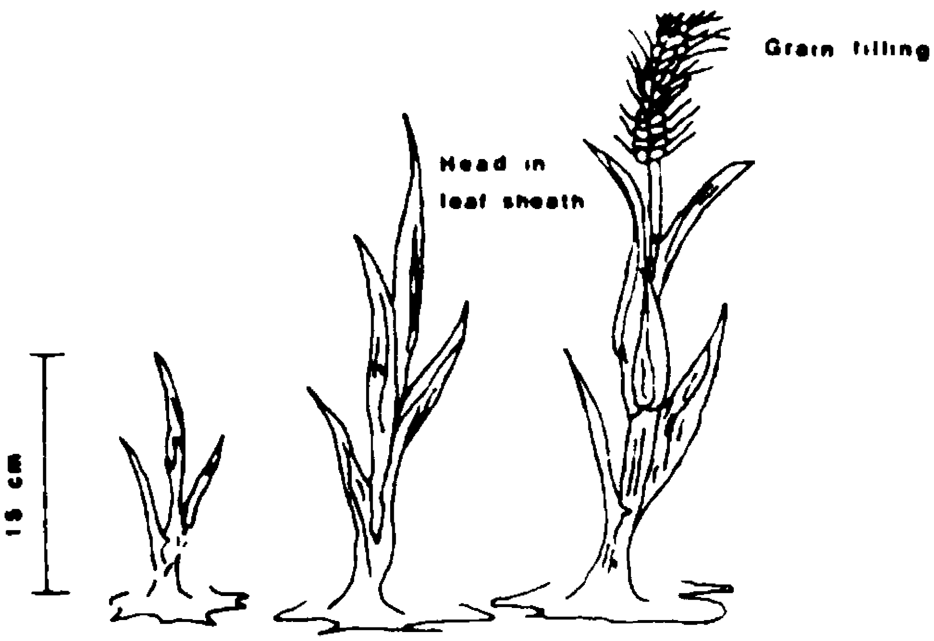


Fig. 54 Critical periods for water deficit of wheat

about 4 before heading, and about 10 to 11 during the yield formation (3) and ripening (4) period. In winter wheat the primary root system is developed in the autumn and full rooting depth in the spring is reached earlier than in spring wheat which requires 50 to 75 days after emergence to reach full depth.

Water uptake and extraction patterns are related to root density. In general 50 to 60 percent of the total water uptake occurs from the first 0.3 m, 20 to 25 percent from the second 0.3 m, 10 to 15 percent from the third 0.3 m and less than 10 percent from the fourth 0.3 m soil depth. Normally 100 percent of the water uptake occurs over the first 1.0 to 1.5 m (D = 1.0-1.5 m).

Under conditions when maximum evapotranspiration is about 5 to 6 mm/day water uptake of the crop is little affected at soil water depletion of less than 50 percent of the total available soil water (p = 0.5). Moderate water stress to the crop occurs at depletion levels of 70 to 80 percent and severe stress occurs at levels exceeding 80 percent.

IRRIGATION SCHEDULING

Taking into account ETm, for non-stress conditions about 50 to 60 percent of available soil water can be utilized by the crop before the next irrigation, with somewhat higher depletion levels during the ripening period (4). There is a distinct advantage for both winter and spring wheat in having the entire root zone filled to field capacity prior to or soon after sowing to attain optimum root development. Overwatering during the vegetative period (1) produces luxurious growth that can cause lodging, which may also occur after a too heavy irrigation in the late yield formation period (late 3), particularly with sprinkler irrigation.

Where rainfall is low and irrigation water supply is limited, in addition to pre-irrigation, applications should be scheduled to avoid water deficits during the flowering period (2) and at about 50 to 90 days after sowing of spring wheat. Irrigation and rainfall during the late yield formation period (late 3) show little effect on yields when sufficient soil water in the root zone is carried over from the previous period to see the crop into the ripening period.

[illegible]sas, USA - Winter Wheat

To irrigate a large area most efficiently with limited water supply: one heavy autumn irrigation to wet the full root zone during September-November, one spring irrigation and one irrigation in the flowering period (2).

Texas, USA - Winter Wheat

(i) high production level: preplanting irrigation to wet soil profile to [illegible] m, one irrigation when about 120 mm of soil water has been depleted which with normal rainfall is about March, with next two irrigations at the end of April and late May. When rainfall is below normal during spring, irrigation may be required starting early March.

(ii) medium production level: preplanting irrigation [illegible] when some 130 mm has been depleted at the beginning of April, the second at beginning of May. In dry areas three spring irrigations may be required.

(iii) low production level: preplanting irrigation or during germination, with one spring irrigation early May to ensure sufficient soil water available during peak water requirement period.

USSR - Winter Wheat

High yield with one full irrigation and one to four spring irrigations with soil water depletion in the first 1 m soil depth not exceeding 70 percent of the total available water.

Canada - Winter Wheat

One irrigation during the establishment period (0) but still beneficial when applied as late as the flowering period (2). With two irrigations, highest yields when applied during early vegetative (1a) and flowering periods. With three irrigations the additional application is given at the late vegetative period (1c) but the effect on yield between two and three spring irrigations may be small.

Israel (approximately 250 mm winter rain) - Winter Wheat

Sowing in dry soil with application of 150 mm after sowing; in the case of substantial rain, irrigation should bring the upper 0.6 m to field capacity. The second irrigation is applied when water depletion in the upper 1 m has reached 100 to 120 mm. In average years no further irrigation is required until heading. If at flowering (heading) soil water depletion is less than 30 mm, irrigation can be delayed until early yield formation period (early 3) when the first 0.6 m is brought to field capacity. If at heading soil water depletion is greater than 50 mm irrigation should be applied at that time with no further irrigation afterwards.

Israel - Spring Wheat

During early growth adequate water should be available in the soil profile and one application of 150 mm is recommended. Winter rains of 250 mm are usually adequate to bring the crop to maturity. At flowering 150 mm of available soil water should be stored in the root zone; when smaller, an additional irrigation is required.

Northern India - Spring Wheat

In addition to pre-irrigation, one irrigation during early vegetative period (1a), irrigations - one during early vegetative period (1a) and one just prior to head emergence through flowering period (2); three irrigations - during early vegetative period (1a), just prior to head development through flowering period (2) and early yield formation period (early 3); four irrigations - during early vegetative (1a), late vegetative (1b), flowering (2) and early yield formation (early 3) periods.

IRRIGATION METHODS

Normally wheat is irrigated by surface methods of which furrow, border and basin are most common. Sprinkler irrigation is also practised, especially when water supply is limited or the topography or the soil are less suited to surface irrigation.

YIELD AND QUALITY

When yields are low under limited water supply, the protein percentage of the grain increases, particularly under high nitrogen application. The effect of nitrogen on protein percentage is much reduced under medium to optimum water supply, although both grain and protein yield are higher. Water deficits during the yield formation period result in shrivelled grains which reduce flour yield.

A good yield of wheat under irrigation is 4 to 6 ton/ha (12 to 15 percent moisture). The water utilization efficiency for harvested yield (Ey) for grain is about 0.8 to 1.0 kg/m^3.

It is assumed that when (In + Pe + Wb) < (30 . ETm) on a monthly basis, the net irrigation application (In) and the effective rainfall (Pe) will fully contribute to evapotranspiration and no deep percolation and runoff will occur. Also, mean monthly ETa is not affected by the distribution of In and Pe over the month (Table 22, Part A.III).

APPENDIX II

GLOSSARY

A	irrigated crop acreage - ha
Aa	irrigated crop acreage when crop water requirements (ETm) are partially met - ha
Am	irrigated crop acreage when crop water requirements (ETm) are fully met - ha
ASI	available soil water index or the fraction of the month when the available soil water supply from irrigation, rain and stored soil water is adequate to meet full crop water requirements (ETm) - fraction
c	adjustment factor for calculated reference evapotranspiration (ETo) in the Penman and Radiation methods - fraction
cH	correction for harvested part on net total dry matter of a crop, also called harvest index - fraction
cL	correction for crop development over time and leaf area on total dry matter of a crop - fraction
cN	correction for net dry matter (respiration) on gross dry matter of a crop - fraction
cT	correction for temperature on gross dry matter (photosynthesis) of a crop - fraction
D	root depth or soil depth from which the crop extracts most of the soil water needed for evapotranspiration or effective root depth - m
d	net depth of irrigation water application - mm
Ea	field application efficiency or ratio between the amount of water stored in the root zone and the amount of water supplied at the field inlet - fraction
ea	saturation vapour pressure or upper limit of pressure exerted by water vapour in the air when saturated at a given air temperature - mbar
Eb	field canal efficiency or ratio between the amount of water supplied to the field inlet and the amount of water supplied to a block of fields - fraction
Ec	conveyance efficiency or ratio between the amount of water supplied to a block of fields and the amount of water diverted at headworks - fraction
ECe	electrical conductivity or measure of salt content in the extracted soil water when the soil is saturated with water - mmhos/cm
ed	actual vapour pressure exerted by water vapour contained in the air - mbar
Em	water utilization efficiency for total dry matter produced by the crop per unit of water evapotranspired - kg/m^3
Ep	project efficiency of ratio between the amount of water stored in the root zone and the amount of water released at project headworks (Ep = Ea . Eb . Ec) - fraction
Epan	pan evaporation or rate of water loss from an unscreened class A pan - mm/day
ETa	actual crop evapotranspiration rate ($ETa \leqslant ETm$) - mm/day or mm/period
ETm	maximum evapotranspiration rate of the crop when soil water is not limited; also called crop water requirements - mm/day or mm/period

ETo	reference evapotranspiration rate for a given climate when soil water is not limited - mm/day or mm/period
Ey	water utilization efficiency for harvested yield or the amount of harvested yield produced by the crop per unit of water evapotranspired (harvested part includes moisture percentage specific to the crop product) - kg/m^3
F	fraction of the daytime the sky is clouded - fraction
f( )	function of ( )
G	length of total growing period of a crop - days
Ge	effective contribution of groundwater to evapotranspiration - mm/period
i	irrigation interval between successive irrigation applications - days
In	net irrigation requirements or sum of crop water requirements (ETm) minus effective rainfall (Pe), groundwater contribution (Ge) and stored soil water (Wb); (In = ETm - Pe - Ge - Wb) - mm/period
K	correction for crop species on gross dry matter of a standard crop - fraction
kc	crop coefficient relating reference evapotranspiration rate (ETo) to the maximum evapotranspiration rate (ETm), or ETm = kc . ETo - fraction
kpan	pan coefficient relating the pan evaporation rate (Epan) to the reference evapotranspiration rate (ETo), or ETo = kpan . Epan - fraction
ky	yield response factor or ratio between relative yield decrease (1 - Ya/Ym) and relative evapotranspiration deficit (1 - ETa/ETm) for high producing varieties adapted to the growing environment - fraction
LAI	leaf area index of a crop or ratio between the green leaf area and the ground surface - m^2/m^2
LR	leaching requirement or the depth of water required to drain through the root zone to control soil salinity in relation to net irrigation requirements (In) - fraction
N	maximum possible sunshine duration - hour /day
n	actual sunshine duration - hour /day
P	total production of a crop per unit area (Ya) for the project area (A); (P = Ya . A) - kg or ton/season
p	portion of the total available soil water which can be depleted without affecting maximum evapotranspiration rate; (ETa = ETm) - fraction
Pa	total crop production from acreage Aa, partially meeting crop water requirements; (ETa < ETm, Ya < Ym) and (Pa = Aa . Ya) - kg or ton/season
Pe	effective rainfall or the part of the precipitation that contributes to crop water requirements - mm/period
Pm	total crop production from acreage Am, meeting full crop water requirements; (ETa = ETm, Ya = Ym) and (Pm = Am . Ym) - kg or ton/season
Ra	extraterrestrial radiation received at the top of the atmosphere - $cal/cm^2/day$ or mm equivalent evaporation/day
RH	relative humidity or actual amount of water vapour (ed) at a given temperature in relation to the maximum amount the air can hold at that temperature (ea) - percent
RHmax	maximum relative humidity during a day or mean of daily maxima for a period - percent
RHmean	mean relative humidity during a day or for a period - percent

Rn	total net radiation or the difference between incoming and outgoing shortwave and longwave radiation - cal/cm^2/day or mm equivalent evaporation/day
Rnl	net longwave radiation or difference between outgoing and incoming longwave radiation - cal/cm^2/day or mm equivalent evaporation/day
Rs	incoming shortwave radiation - cal/cm^2/day or mm equivalent evaporation/day
Rse	maximum active incoming shortwave radiation on clear days or that part of the maximum incoming shortwave radiation on clear days that is effective in photosynthesis - cal/cm^2/day
Sa	total available soil water which is between field capacity (Sfc) and wilting point (Sw) - mm/m
Sfc	soil water content at field capacity or depth of soil water held in the soil after ample irrigation or heavy rain when, after 1 to 3 days, the rate of downward movement has substantially decreased or when soil water tension is 0.1 to 0.3 atmosphere - mm/m
St	actual depth of available soil water at a given point in time - mm/m
Sw	soil water content at wilting point or depth of soil water held in the soil at soil water tension of 15 atmosphere when plants are considered for practical purposes to be no longer able to extract water from the soil - mm/m
T	temperature of the air - ^oC
t	number of days after irrigation - days
t'	number of days after irrigation during which ETa = ETm - days
Tmean	mean daily temperature of the air - ^oC
U	total windrun at 2 m height - km/day
Uday	total windrun or average windspeed during daytime at 2 m height - km/day or m/sec
Umean	mean total daily windrun or average daily windspeed at 2 m height - km/day or m/sec
Unight	total windrun or average windspeed during night at 2 m height - km/day or m/sec
V	irrigation supply requirements or the total volume of water delivered over a given period to a field, a block of fields or project area - m^3/period
W	weighting factor in the Penman and Radiation methods, dependent on temperature and altitude - fraction
Wb	actual depth of available soil water over the root depth at the beginning of a period - mm
We	actual depth of available soil water over the root depth at the end of a period - mm
Ya	actual harvested yield of a high producing variety, adapted to the given environment with growth factors other than water not limited ($Ya \leqslant Ym$, $ETa \leqslant ETm$) - kg or ton/ha
yc	gross dry matter production rate of a standard crop for a given location on a clear (cloudless) day - kg/ha/day
Ydm	maximum net total dry matter of a crop - kg or ton/ha
Ym	maximum harvested yield for a high producing variety adapted to the given environment with growth factors not limited - kg or ton/ha
ym	maximum leaf gross dry matter production rate of a crop for a given climate - kg/ha/hour

Yme calculated maximum harvested yield in dry weight for a high yielding variety adapted to the given environment with growth factors not limited (method calibrated with experimental results) - kg/ha or ton/ha

Ymp calculated maximum yield potential in dry weight for a high producing variety adapted to the given environment with growth factors not limited - kg/ha or ton/ha

Yo gross dry matter production rate of a standard crop for a given location - kg/ha/day

yo gross dry matter production rate of a standard crop for a given location on a completely overcast (clouded) day - kg/ha/day

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APPENDIX IV

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