

I. MAXIMUM YIELD (Y_m)

The maximum yield level of a crop (Y_m) 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 (Y_m) 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 Y_m 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 Y_m 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 Y_m 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 (ET_m) for maximum yield (Y_m) is given in Chapter 11 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 (E_y) 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 (Y_m) 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 Agroecological Zone Project 1: 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 (Y_{me}) must be adjusted to the yield level obtainable under actual farming conditions. However, Y_{me} 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)

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

^{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./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; optPH = 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. 19 -20 °C	Ligh t 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, E _y , kg/m ³ (%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 (10-15.0%)	Alfalfa
sensitive	200-400;45-60:240-280	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	20-60 : 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	100-1.50: 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%.)	Watermelon
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 = 2.4kg P₂O₅
1 kg K = 1.2 kg K₂O

CALCULATION PROCEDURE

To calculate 'experimental' yield (Y_{me}) the steps needed are:
Calculate gross dry matter production of a standard crop (Y_o).
Apply correction for climate ($ET_m/(ea-ed)$).
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 (Y_o)

To calculate Y_o 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

$$Y_o = F * y_o + (1 - F)y_c$$

where:

- Y_o = gross dry matter production of a standard crop, kg/ha/day
- F = fraction of the daytime the sky is clouded, fraction; or $F = (R_{se} - 0.5R_s)/0.8R_{se}$ where R_{se} is the maximum active incoming shortwave radiation on clear days in cal/cm²/day (Table 3) and R_s is the actual measured incoming shortwave radiation in cal/cm²/day¹
- Y_o = gross dry matter production rate of a standard crop for a given location on a completely overcast day, kg/ha/day (Table 3)
- Y_c = gross dry matter production rate of a standard crop for a given location on a clear (cloudless) day, kg/ha/day (Table 3)

1 R_s is also expressed in mm/day equivalent evaporation; conversion is $59 \text{ cal/cm}^2 = 1 \text{ mm equivalent evaporation}$. When only sunshine duration data are available, R_s can also be calculated from $R_s = (0.25 + 0.50 n/N)R_a$, where R_a 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.

Table 3 Maximum Active Incoming Shortwave Radiation (Rse in cal/cm²/day 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 Sep	Apr Oct	May Nov	June Dec	July Jan	Aug Feb	Sept Mar	Oct Apr	Nov May	Dec June	
0°	Rse yc yo	343 413 219	360 424 226	369 429 230	364 426 228	349 417 221	337 410 216	343 413 218	357 422 225	368 429 230	365 427 228	349 418 222	337 410 216
10°	Rse yc yo	299 376 197	332 401 212	359 422 225	375 437 234	377 440 236	374 440 235	375 440 236	377 439 235	369 431 230	345 411 218	311 385 203	291 370 193
20°	Rse yc yo	249 334 170	293 371 193	337 407 215	375 439 235	394 460 246	400 468 250	399 465 249	386 451 242	357 425 226	313 387 203	264 348 178	238 325 164
30°	Rse yc yo	191 281 137	245 333 168	303 385 200	363 437 232	400* 471* 251*	417* 489* 261*	411* 483* 258*	384* 456* 243*	333 412 216	270 356 182	210 299 148	179 269 130
40°	Rse yc yo	131 219 99	190 283 137	260 353 178	339 427 223	396 480 253	422 506 268	413 497 263	369 455 239	298 390 200	220 314 155	151 241 112	118 204 91
* Values used in calculation example													

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).¹ Calculation of ETm is given in Chapter 11; for calculation of, mean saturation vapour pressure (ea) and mean actual vapour pressure (ed), both in mbar (Table 9), see Chapter 11, 1.1 Penman Method.

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, $Ydm = K \cdot cT \cdot G \cdot Yo \cdot ETm/(ea-ed)$ 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:

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

	cH	
Alfalfa	0.4-0.5	First year
	0.8-0.9	Subsequent years
Maize	0.4-0.5	
Sorghum	0.35-0.45	
Wheat	0.3-0.4	

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

Alfalfa	$Y_{me} = 0.9 \cdot cH \cdot cT \cdot G \cdot Y_o \cdot ET_m / (ea - ed)$ kg/ha/period
Maize	$Y_{me} = 1.9 \cdot cH \cdot cT \cdot G \cdot Y_o \cdot ET_m / (ea - ed)$ kg/ha/period
Sorghum	$Y_{me} = 1.6 \cdot cH \cdot cT \cdot G \cdot Y_o \cdot ET_m / (ea - ed)$ kg/ha/period
Spring wheat	$Y_{me} = 1.17 \cdot cH \cdot cT \cdot G \cdot Y_o \cdot ET_m / (ea - ed)$ kg/ha/period
Winter wheat	$Y_{me} = 0.65 \cdot cH \cdot cT \cdot G \cdot Y_o \cdot ET_m / (ea - ed)$ kg/ha/period

EXAMPLE

Given: Maize, with optimum plant density; location 30°N; altitude 95m; total growing period 123 days from 1 May to 31 August; mean incoming shortwave radiation (R_s) over the total growing period 650 cal/cm²/day; mean temperature 27.5°C; mean relative humidity 55%; mean maximum evapotranspiration (ET_m) 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/ cm ² /day
F	mean	$(403 - 0.5 \times 650) / (0.8 \times 403)$	calc	0.24
Yo	mean	$(0.24 \times 253) + (1 - 0.24)475$	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	mean		calc	16.6 mbar
cT fraction	fraction	at 27.5°C	Table 4	0.6
Yme	total period	$1.9 \times 0.45 \times 0.6 \times 123 \times 422 \times 6.8 / 16.6$	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 (Y_{mp}).

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 (Y_{mp}) will give an indication of the efficiency in agricultural production.

CALCULATION PROCEDURE

To calculate potential yield (Y_{mp}) the steps needed are:

- a. Calculate gross dry matter production of a standard crop (Y_o).
 - 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 (Y_o)
- As in 1, Y_o in kg/ha/day is calculated for a given location applying the concept of De Wit (1965):

$$Y_o = F \cdot y_o + (1-F)y_c$$

where

- Y_o = gross dry matter production of a standard crop, kg/ha/day
- F = fraction of the daytime the sky is clouded, fraction; or ,
 $F = (R_{se} - 0.5R_s) / 0.8R_{se}$ where R_{se} is the maximum active incoming shortwave radiation on clear days in cal/cm²/day (Table 3) and R_s is the actual measured incoming shortwave radiation in cal/cm²/day. R_s can also be calculated from measured sunshine duration data (n) in hours/day
- Y_o = gross dry matter production rate of a standard crop for a given location on a completely overcast day, kg/ha/day (Table 3)
- y_c = 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 (y_m) can be larger or smaller than 20 kg/ha/hour as assumed for the standard crop. Production rates (y_m) in kg/ha/hour for groups of crops are given in Table 5.

Table 5 Production Rates (y_m 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 y_o and y_c can be adjusted for different crop groups:

- a. when $y_m > 20$ kg/ha/hour

$$Y_o = F(0.8 + 0.01 y_m)y_o + (1-F)(0.5 + 0.025 y_m)y_c \text{ kg/ha/day}$$
 b. when $y_m < 20$ kg/ha/hour

$$Y_o = F(0.5 + 0.025 y_m)y_o + (1-F)0.05y_m y_c \text{ kg/ha/day}$$

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/} 0.8-0.9 ^{1/}	Potato	tuber	0.55-0.65
			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

$$Ymp = cL \cdot cN \cdot cH \cdot G [F(0.8 + 0.01ym)yo + k1-F)(0.5 + 0.025ym)yc]$$

kg/ha/period

- b. when ym <20 kg/ha/hour

$$Ymp = cL \cdot cN \cdot cH \cdot G [F(0.8 + 0.025ym)yo + (1-F)(0.05ym)yc]$$

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/cm ² /day
F	Mean	$403 - 0.5 \times 650 / 0.8 \times 403$	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		$0.5 \times 0.5 \times 0.4 \times 123 [0.24(0.8 + 0.01 \times 65)253 + (1 - 0.24)(0.5 + 0.025 \times 65)475]$	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).