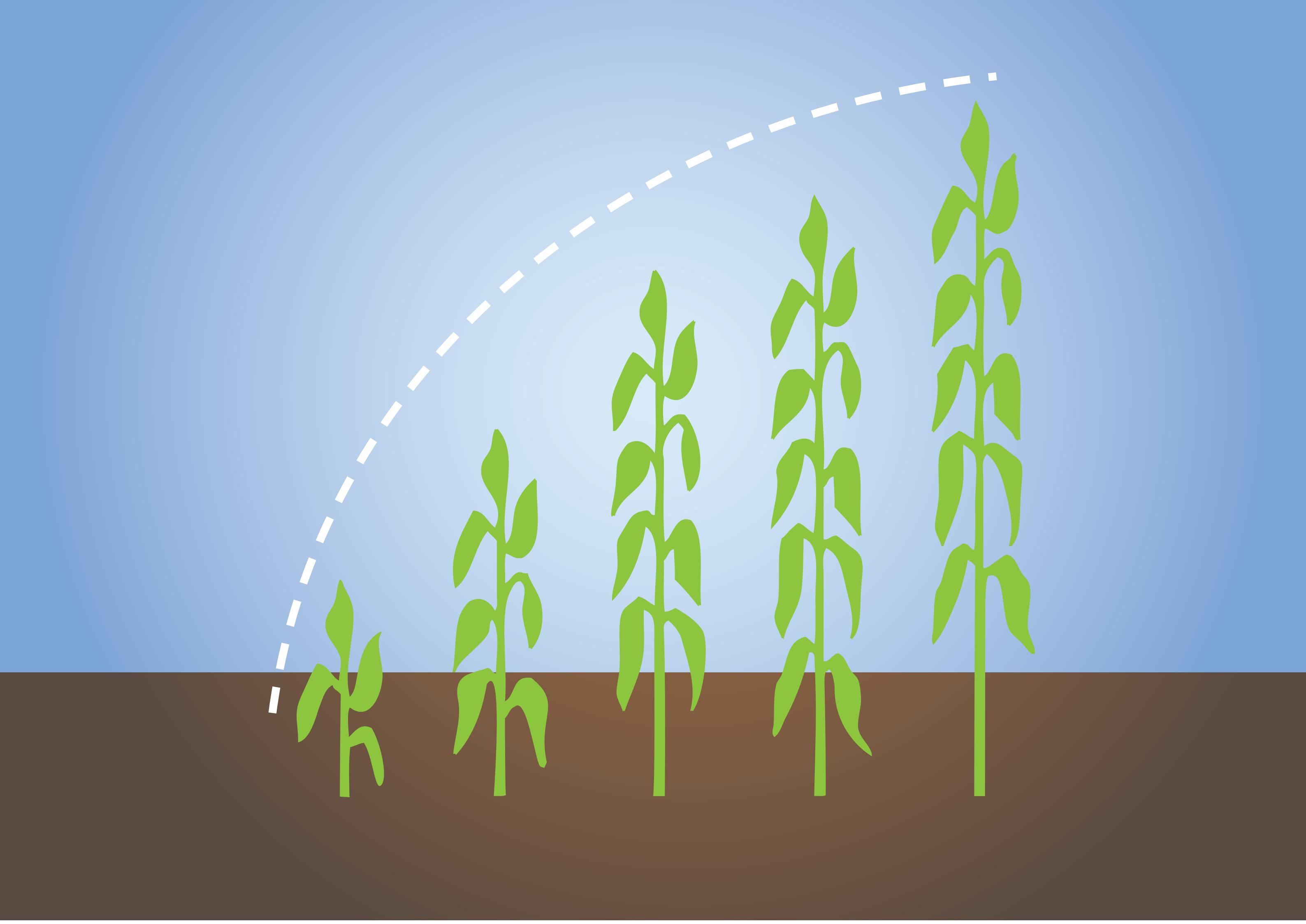

Yield response to water: the original FAO water production function

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GENERAL DESCRIPTION

FAO addressed the relationship between crop yield and water use in the late seventies proposing a simple equation where relative yield reduction is related to the corresponding relative reduction in evapotranspiration (ET). Specifically, the yield response to ET is expressed as:

$$\left(1-\frac{Y_a}{Y_x}\right)=K_y\left(1-\frac{ET_a}{ET_x}\right) \quad (1)$$

where Y_x and Y_a are the maximum and actual yields, ET_x and ET_a are the maximum and actual evapotranspiration, and K_y is a yield response factor representing the effect of a reduction in evapotranspiration on yield losses. Equation 1 is a water production function and can be applied to all agricultural crops, i.e. herbaceous, trees and vines.

The yield response factor (K_y) captures the essence of the complex linkages between production and water use by a crop, where many biological, physical and chemical processes are involved. The relationship has shown a remarkable validity and allowed a workable procedure to quantify the effects of water deficits on yield.

This approach and the calculation procedures for estimating yield response to water were published in the *FAO Irrigation and Drainage Paper* No. 33 (Doorenbos and Kassam, 1979), which was considered one of FAO's milestone publications, and were used widely worldwide for a broad range of applications.

In this Chapter, the procedures used to quantify the yield response to water deficits using Equation 1 are briefly described. To get fully acquainted with the original procedures, the K_y use and related applications, the reader is referred to the original publication.

THE YIELD RESPONSE FACTOR (K_y)

The K_y values are crop specific and vary over the growing season according to growth stages with:

K_y >1: crop response is very sensitive to water deficit with proportional larger yield reductions when water use is reduced because of stress.

K_y <1: crop is more tolerant to water deficit, and recovers partially from stress, exhibiting less than proportional reductions in yield with reduced water use.

K_y =1: yield reduction is directly proportional to reduced water use.

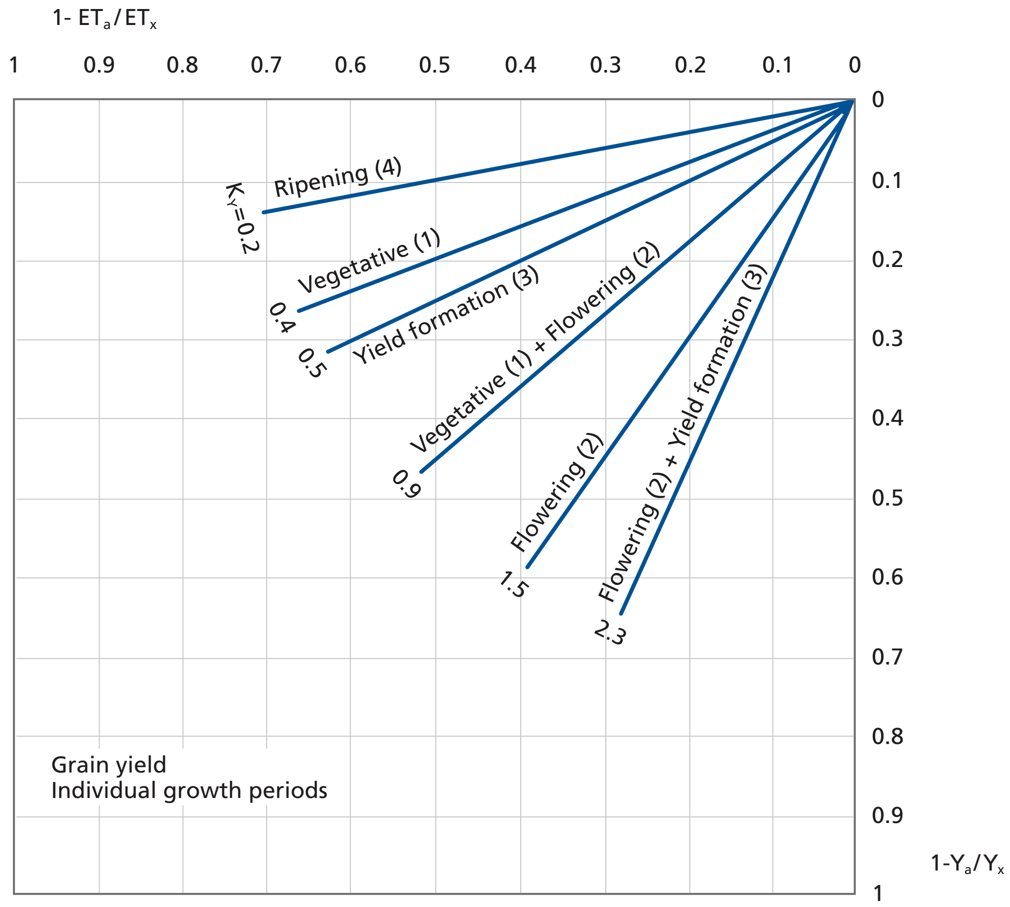
Based on the analysis of an extensive amount of the available literature on crop-yield and water relationships and deficit irrigation, K_y values were derived for several crops (Table 1).

TABLE 1 Seasonal K_y values from *FAO Irrigation and Drainage Paper No. 33*.

Crop	K_y	Crop	K_y
Alfalfa	1.1	Safflower	0.8
Banana	1.2-1.35	Sorghum	0.9
Beans	1.15	Soybean	0.85
Cabbage	0.95	Spring wheat	1.15
Cotton	0.85	Sugarbeet	1.0
Groundnuts	0.70	Sugarcane	1.2
Maize	1.25	Sunflower	0.95
Onion	1.1	Tomato	1.05
Peas	1,15	Watermelon	1.1
Pepper	1.1	Winter wheat	1.05
Potato	1.1		

The analysis of deficit irrigation studies also allowed, for a majority of crops, the development of crop response functions when water deficits occur at different crop stages. As illustrated for maize in Figure 1, yield response will differ largely depending on the stage the water stress occurs. Typically flowering and yield formation stages are sensitive to stress, while stress occurring during the ripening phases has a limited impact, as in the vegetative phase, provided the crop is able to recover from stress in subsequent stages.

FIGURE 1 Linear water production functions for maize subjected to water deficits occurring during the vegetative, flowering, yield formation and ripening periods. The steeper the slope (i.e. the higher the K_y value), the greater the reduction of yield for a given reduction in ET because of water deficits in the specific period.



CALCULATION PROCEDURES

The calculation procedure for Equation 1 to determine actual yield Y_a has four steps:

i. Estimate maximum yield (Y_x) of an adapted crop variety, as determined by its genetic makeup and climate, assuming agronomic factors (e.g. water, fertilizers, pest and diseases) are not limiting.
ii. Calculate maximum evapotranspiration (ET_x) according to established methodologies and considering that crop-water requirements are fully met.
iii. Determine actual crop evapotranspiration (ET_a) under the specific situation, as determined by the available water supply to the crop.
iv. Evaluate actual yield (Y_a) through the proper selection of the response factor (K_y) for the full growing season or over the different growing stages.

MAXIMUM YIELD (Y_x)

The *FAO I&D No. 33* recommended procedures for estimating maximum yield either from available local data for maximum crop yields or based on the calculation of maximum biomass and a corresponding harvest index, following two different procedures:

I. Wageningen procedure (De Wit, 1968; Slabbers, 1978)
II. Ecological zone approach (Kassam, 1977)

These procedures for yield estimation were developed in the late sixties and seventies. The considerable advances in agronomy and crop physiology, though, allow for the use of more precise methods to estimate maximum yields.

MAXIMUM CROP EVAPOTRANSPIRATION (ET_x)

Procedures for determining ET_x were based on FAO guidelines for crop-water requirements (ET_c), and the ET_x component of Equation 1, which is equal to ET_c, was determined through the product of the reference-crop evapotranspiration (ET_o) times the crop coefficient (K_c), i.e.

$$ET_x = K_c\, ET_o \tag{2}$$

Original procedures for determining ET_o are described in *FAO I&D No. 24* (Doorenbos and Pruitt, 1977), offering different equations for its calculation according to the available climate data. K_c values were provided for a large number of crops and procedures to determine ET_c over the growing season. Subsequently, revised procedures for calculating ET_o were introduced in *FAO I&D No. 56* (Allen et al., 1998), according to the FAO Penman-Monteith equation, which has now become the standard for estimating reference crop evapotranspiration.

ACTUAL CROP EVAPOTRANSPIRATION (ET_a)

It is very difficult to estimate the actual crop evapotranspiration with precision. *FAO I&D No. 33* provided tables from which ET_a could be estimated from data on evapotranspiration rate, available soil water and wetting intervals. The tables however proved cumbersome and later were replaced by more accurate ET_a calculations based on daily water balance calculations and digital computation methods.

Water balance calculations allow the level of available soil water in the root zone to be determined on a daily basis. As long as soil water is readily available for the crop, then $ET_a = ET_x$. When a critical soil moisture level is reached, defined as a fraction of the total available soil water content (p), transpiration is reduced because the stomata close and thus $ET_a < ET_x$, until the level of soil water in the root zone reaches the permanent wilting point, when ET_a is assumed to be zero. This critical soil-water content is estimated from soil, crop and rooting characteristics and from the ET_o rate. Depletion of soil-water content between p and the permanent wilting point will result in a proportional reduction of ET_a.

FAO I&D No. 56 provides detailed procedures to assess the impact of stress on reduced evapotranspiration based on the water balance calculations with parameters on critical soil-water content values and rooting depth.

ACTUAL CROP YIELD (Y_a) AND YIELD REDUCTION

Based on the estimated Y_x and the calculated ET_x and ET_a, actual yield (Y_a) may be determined using Equation (1).

However, in many planning and management studies requiring the estimation of yield in relation to the water availability, the yield reduction is expressed in relative terms, e.g. as a fraction or percentage $\left(1-\frac{Y_a}{Y_x}\right)$ rather than absolute (Y_a).

As a matter of fact, the errors in estimating actual yields with water production functions are quite important, given the empirical nature of the relationships and the uncertainty of estimating the parameters discussed above.

COMPUTERIZED CALCULATION PROCEDURES (CROPWAT)

The use of the water production functions, Equation (1), is facilitated using the CROPWAT model (Smith, 1992) that provides computation procedures to determine yield reductions based on the FAO *I&D* No. 33 approach using daily water balance calculations. CROPWAT has been widely used as a practical management tool for irrigation scheduling and to estimate yield reductions under water deficit condition. Standard values for crop parameters (K_c, p, rooting depth, etc.) and K_y values are included in the model and can be modified to adjust to local conditions.

CROPWAT includes various modules to calculate reference evapotranspiration from daily, decade or monthly climatic data, crop-water requirements and irrigation water requirements from climatic and crop data, as well as scheme water supply for varying cropping patterns. CROPWAT was designed as a practical tool to carry out standard calculations for design and management of irrigation schemes, and for improving irrigation practices. It may also be used for irrigation scheduling under full or deficit irrigation conditions and for this, it uses the yield response factors derived from the crop-water production functions synthesized in FAO *I&D* No. 33. In order to allow the calculation from a wide-range of countries a climatic database CLIMWAT (Smith, 1993) has been included in the CROPWAT software, based on agro-meteorological data compiled by the FAO agro-meteorological service with over 3 200 stations from 144 countries and spanning the years from 1961 to 1990.

LIMITATIONS AND APPLICATIONS OF FAO I&D NO. 33

Procedures for estimating yield response to water developed in FAO *I&D* No. 33 have been very popular among economists and engineers, and have been used in several practical applications at field, scheme, regional and national level. For many years, this water production function approach has been the standard for planning and was an input to many economic models dealing with water allocation. It is still useful when a quick, first approximation of yield reduction related to water limitations is needed, especially when both herbaceous crops, trees and vines have to be considered simultaneously. Recent examples of applications can be found at basin scale (e.g. Xiaojuan *et al.*, 2011), at field scale (e.g. Yacoubi *et al.*, 2010) and in decision support systems (e.g. Gastélum *et al.*, 2008).

While the *FAO I&D No. 3*3 approach is solidly based on crop-water use principles, the simplification introduced by using one empirical yield response factor (K_y) to integrate the complex linkages between production and water use for crop production, limits its applicability for making accurate estimates of yield responses to water. Moreover, factors other than water such as nutrients, different cultivars, etc. also affect the response to water. In fact, adjustments for site-specific conditions would be needed if greater accuracy is sought. Determination of K_y values after adaptive research has been carried out in numerous studies for various crops and under different environments. Results showed a wide range of variations of K_y values and suggest that the within-crop variation in K_y may be as large as that between crops (Stanhill *et al., 1985*).

As an example of the differences in K_y values from different studies, it is instructive to compare the results under a cooperative research programme carried out by the International Atomic Energy Agency (IAEA) against the original K_y values of the *FAO I&D No. 33*. Table 2 summarizes the comparison of K_y values as published in the *FAO Water Report No. 22*, *Deficit Irrigation*, 2002.

Despite the robustness of the production function approach, the differences in K_y values between the two publications are important, and no specific trend can be extracted from the deviations in the K_y values under different conditions. It can be concluded that application of the water production function approach has proved useful for general planning, design and operation of irrigation projects and for the rapid assessment of yield reductions under limited water supply. It has found applications from water supply allocation among crops during periods of water shortage to various studies at national or regional scales, where generalized crop conditions prevail.

For improved strategies and practices related to on-farm water management aiming to increasing efficiency and productivity of water use, Equation 1 is of limited use and more accurate predictions are required for yield response under actual field conditions. *AquaCrop* (Chapter 3), provides a valid alternative for herbaceous crops, as the incorporation of advanced knowledge of crop-water relationships allows a more accurate modelling of actual crop growth and yield formation processes under various soil water availability, climate and soil fertility conditions.

TABLE 2 Comparison of K_y values between *FAO Irrigation and Drainage Paper No. 33* and IAEA investigations (FAO, 2002) at different stages of crop development. Tr-0000=water deficit occurring during the whole season; Tr-0111=water deficit occurring during initial crop stage; Tr-1011=water deficit occurring during crop development; Tr-1101=water deficit occurring during midseason; Tr-1110=water deficit occurring during late season. Where different values of K_y are reported by IAEA for the same crop, they refer either to experimental results of different countries or to experimental results of different locations within the same country.

Crop	Tr-0000			Tr-0111			Tr-1011			Tr-1101			Tr-1110		
	FAO	IAEA	(%)	FAO	IAEA	(%)	FAO	IAEA	(%)	FAO	IAEA	(%)	FAO	IAEA	(%)
Beans	1.15	0.59	-49	0.20	0.38	90	1.10	1.75	59	0.75	1.44	92	0.20	0.06	-70
	1.15	1.43	24	0.20	0.56	180	1.10	1.35	23	0.75	0.87	16	0.20	0.17	-15
Cotton	0.85	1.02	20	0.20	0.75	275	0.50	0.48	-4				0.25		
	0.85	0.71	-16	0.20	0.80	300	0.50	0.60	20		0.05				
	0.85	0.99	16				0.50	0.76	52						
Groundnut	0.70			0.20			0.80	0.74	-8	0.60			0.20		
Maize	1.25	1.33	6	0.40			1.50			0.50			0.20		
Potato	1.10			0.60	0.40	-33		0.33		0.70	0.46	-34	0.20		
Soybean	0.85			0.20	0.56	180	0.80	1.13	41	1.00	1.76	76			
Sugarcane	1.20			0.75	0.20	-73		1.20		0.50	1.20	140	0.10		
	1.20			0.75	0.40	-47		1.20		0.50	1.20	140			
Sunflower	0.95	0.91	-4	0.40	1.19	198	1.00	0.94	-6	0.80	1.14	43			
Spring wheat	1.15	1.32	15	0.20	0.55	175	0.65	0.90	38	0.55	0.44	-20		0.25	
Winter wheat	1.00	0.87	-13	0.20	2.54	1170	0.60	0.81	35	0.50	0.48	-4		0.62	

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