PPK300

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Soil water balance, evaporation, transpiration

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Sentral terms and symbols.

Potential evapotranspiration for an area is the sum of evaporation from the soil surface and the transpiration of the plant stand, when the soil moisture status is so that water transport to soil surface and plants is unlimited. The mathematical term or symbol (in equations, etc.) may be:

ET_o (e.g. in Loomis & Connor, below referred to as LC)

EP (e. g. in the plant modelling activities at our department, IMP)

Values for potential evapotranspiration, measured or calculated, refers to an area with a dense plant stand completely covering the surface, and optimally supplied with water. Usually the plant stand is grass, but in the US lucern in a dense stand, 8-10 cm in height, and with a complete cover of leaves (LAI=> 3), may be the standard.

Potential evapotranspiration can be measured directly in a weighable lysimeter, where the different entries in the water budget can be measured and controlled at short intervals.

Potential evapotranspiration can be estimated in various ways, the best known procedures are according to:

-Penman (1948), which is the most usual one, requires diurnal mean values for air temperature, net radiation, wind speed, and air (relative) humidity (Ref. Summer excercises!).

-Monteith (1964) is less convenient since it requires determination of evaporation resistance down the plant canopy, r_C, and for the zone between the plant stand the air above it, r_A. Therefore, this method is best fitted for research purposes.

-Priestly & Taylor (1972) is the most plain method, since it's based solely on radiation, and thus independent on measurement of wind speed and air humidity.

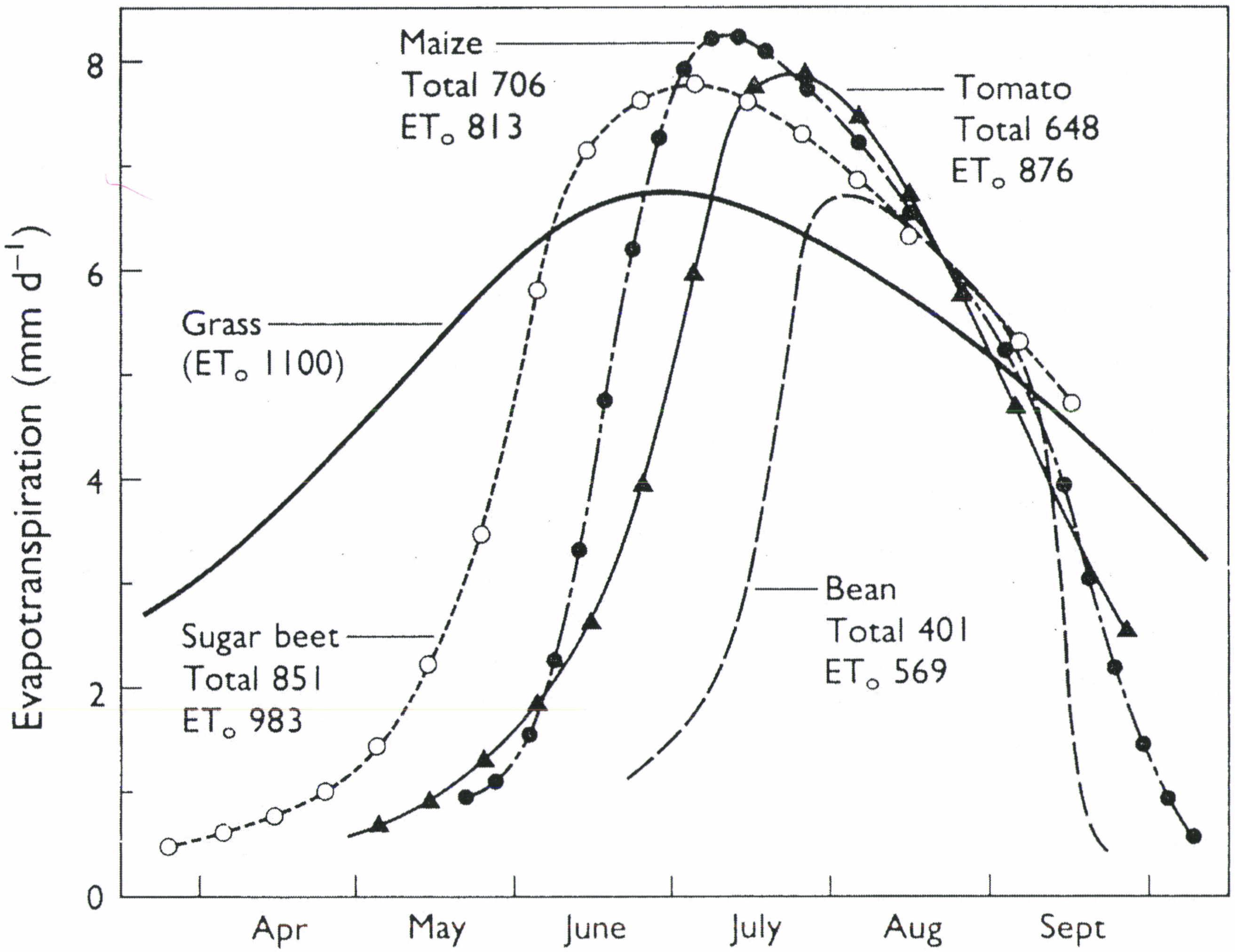


Fig 1. (Fig 9.3 in LC) Seasonal evapotranspiration of various well watered crops compared with a grass reference. The curves represent mean data of seven years' observations at Davies, California. (The values for ET_O (=813, etc.) for each crop are "standard" total seasonal evapotraspiration for the crop in question)

Ideally, potential evapotranspiration should depend solely on environment factors, i.e. weather and soil moisture conditions. But plant transpiration will vary appreciably between crops, even if leaf area is similar, due to variation in e.g. colour, plant height, aerodynamic roughness of canopy surface, and evaporation resistance within the plant stand. Potential evapotranspiration of the particular crop (ET*) can be expressed as a simple function of the reference value:

$$ET^* = cET_0$$

Where c is factor that may vary considerably between crop species and throughout the growing season for the same species, as shown in Fig. 1.

Actual evapotranspiration, symbolized as ET_a or E_a, may be considerably reduced compared to ET*, according to soil water potential, Ψ_s, and root depth, Rd.

$$ET_a = f(ET^*, \Psi_s, Rd)$$

Other important elements in water budget are:

E_s^* = potential evaporation from the soil

E_s = actual evaporation from the soil

E_p = plant transpiration

Soil evaporation, E_s, depends on net radiation above the plant canopy, R_n, and the fraction of this which reaches the soil surface, R_{ns}. The latter depends on the leaf area. When estimating evaporation, the wind or transport factor, in Penman's equation denoted E_t, has been deleted; only the radiation factor E_r, which on average makes out approximately 70 percent of the total potential evaporation, is considered. Thus:

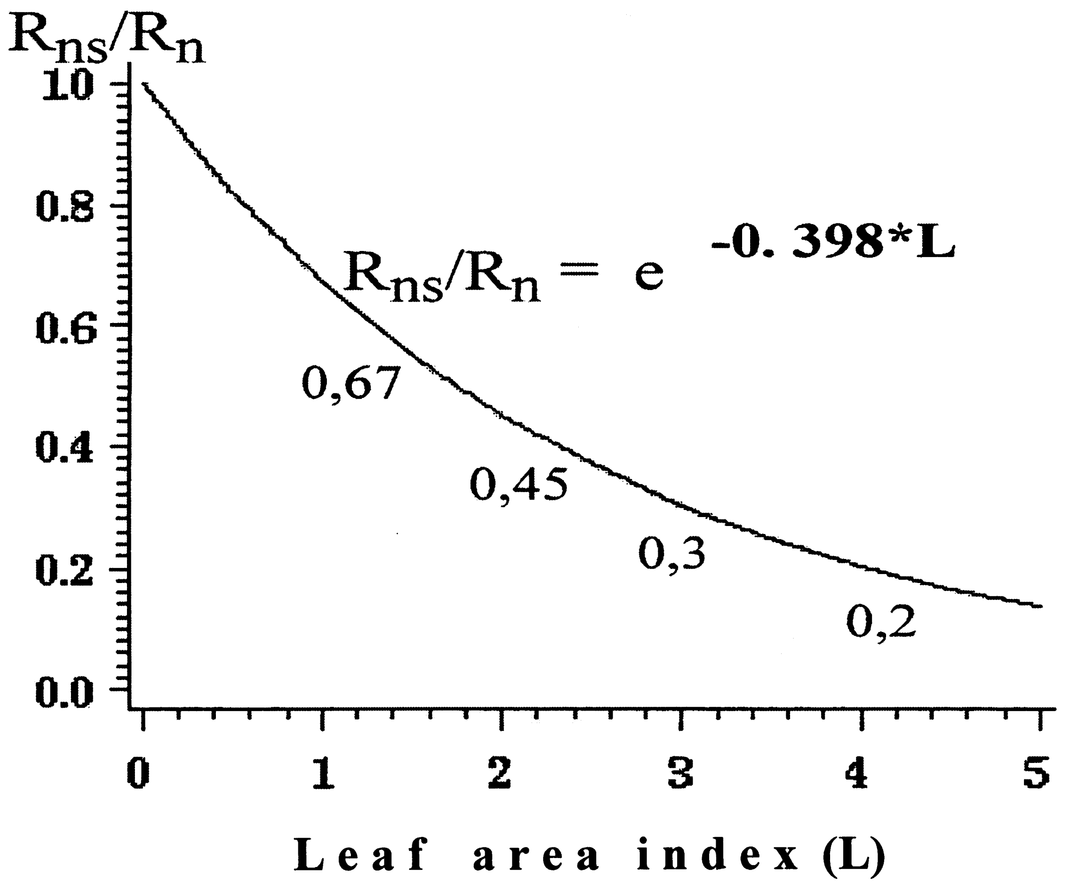
$$E_s = E_r R_{ns}/R_n$$

and:

$$R_{ns} = R_n * e^{-\omega L}$$

Where the factor $e^{-\omega L}$ takes care of the attenuation of the radiation at the surface due to the plant cover, the leaf area index of which equals L.

When the coefficient ω is estimated to 0.398, the decrease of surface radiation as a function of leaf area will be as shown below.



Potential transpiration, i.e. evaporation from the plants, Ep, makes out "the rest" of the potential evapotranspiration, when the (potential) evaporation from the soil is subtracted.

$$E_p = ET^* - E_s$$

Estimation of actual evapotranspiration,

an example of which is presented below (see Fig. 3), is based on a water budget schematically shown in Fig. 2. (Fig. 9.1 in LC).

An estimated water budget for a maize crop in Mlingano, Tanzania (6 °N, 130 m a.s.l.) in 1987 is used as an example. The growing season starts with the rainy season which is necessary for sufficient soil moisture to allow germination and growth. Accumulation of soil water is not proportional to cumulative precipitation, because of a certain direct surface runoff, the extent of which can be calculated from soil type and rain intensity.

The leaf area index (LAI) of a maize crop can be estimated from physiological age, cultivar (CV) and plant density:

$$LAI = f(Age, CV, pl/m^2)$$

The physiological age is estimated from a temperature-sum function based on a mean diurnal air temperature (t) with +10°C as basic: the threshold temperature:

$$\text{"physiol. day"} = \sum(t - 10)/21$$

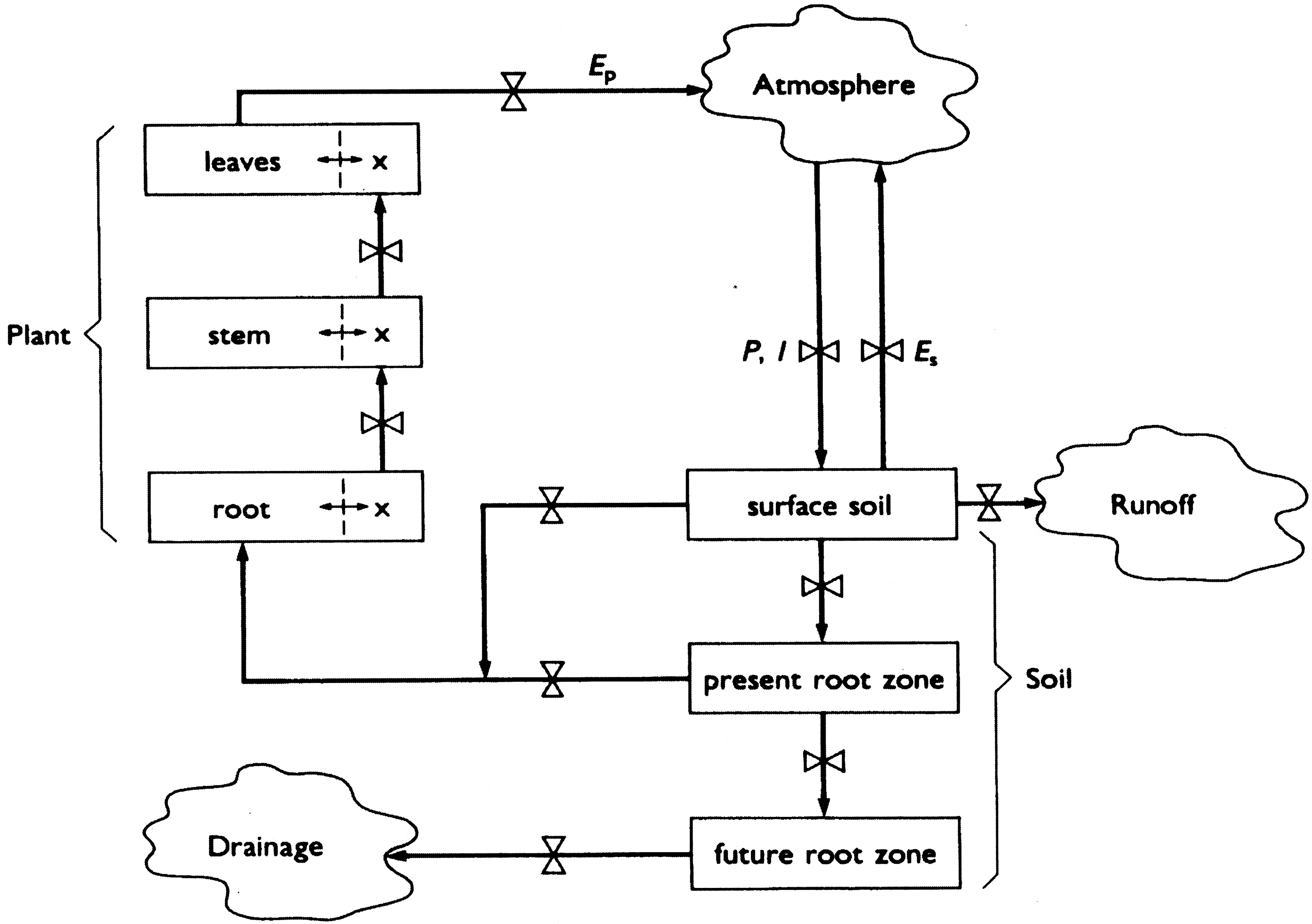


Fig. 2. (9.1 in LC) Model for crop water relation and water balance. The water conducting tissue of the plants, the xylem, is denoted x. P and I are short for precipitation and irrigation, respectively .

The development rate, i.e. change of phenological stage per day, 1/d, is a function of the temperature (somewhat varying between different stages, ref. The lecture “Environmentel factors and plant growth”), so that an integer value of $\sum 1/d$ correspond to an easily recognisable stage:

Stage	$\sum(t-10)$	$\sum 1/d$
Emergence	90	
Flower initiation	800	1
Flower fading	1090	2
Maturity	1400	3

The root depth (RD) is also a plain, linear function of the temperature:

$\sum(t-10)$:	$\leq$ 230	RD = 20 cm
	$\leq$ 1095	RD = linearly increasing
	> 1095	RD = 70 cm

Future water capacity (FVK) is plant available soil moisture between current and maximum (70 cm) root depth.

Readily available water, LTV, is a function of root depth and the pF (soil water potential) curve, which is determined by soil texture and organic matter content:

LTV = f(texture, org. matter, RD) $\quad 2 < pF < 3$

An so is also is the less readily available water, TTV:

TTV = f(texture, org. matter, RD) $\quad 3 < pF < 4.2$

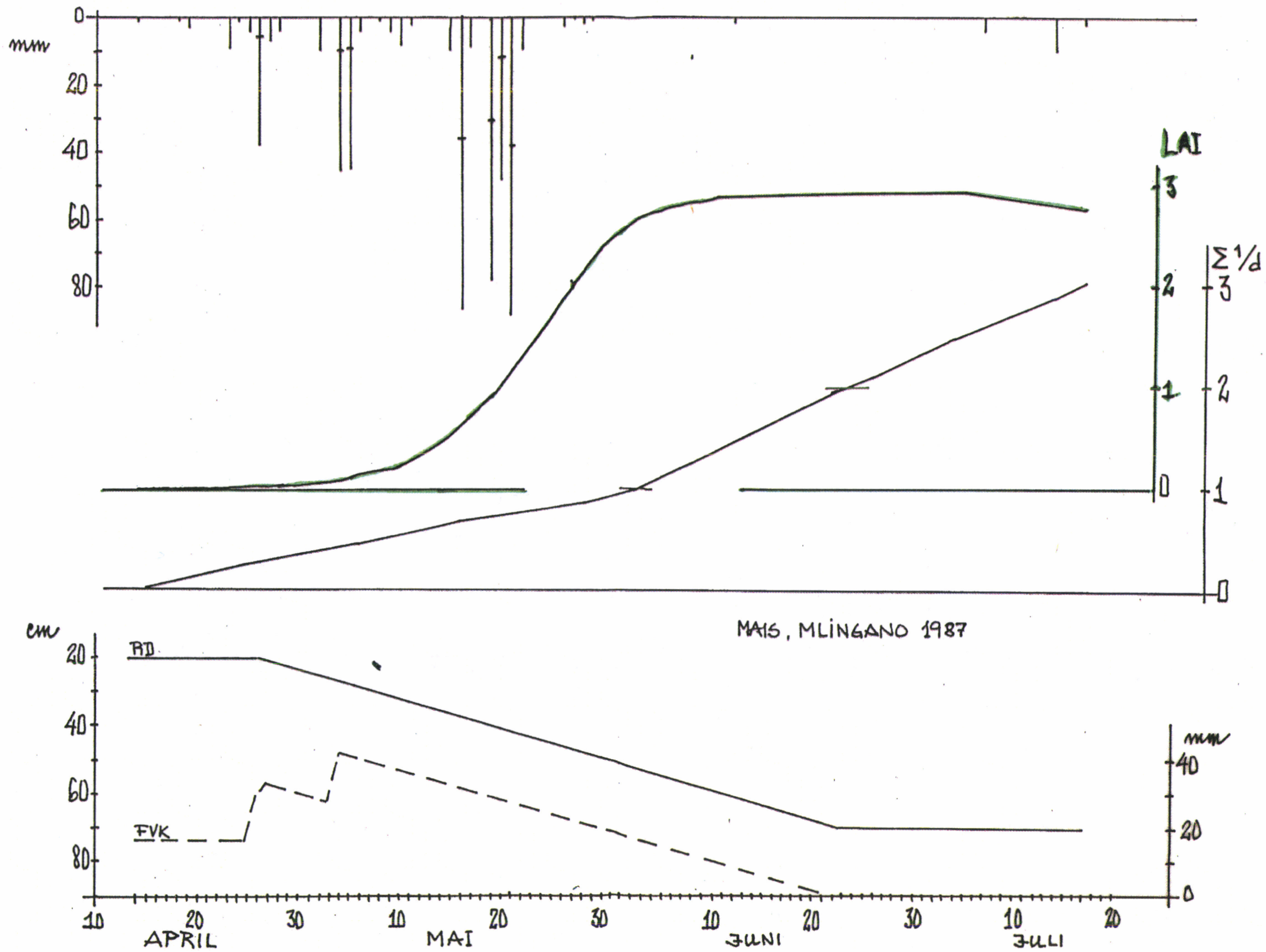


Fig. 3. Precipitation (vertical lines), mm, future soil water capacity (FVK), mm, and estimated maize crop development (see text), including phenological phase (∑1/d), leaf area index (LAI), and root depth (rd), mm. Mlingano, Tanzania, during the growing season 1987.

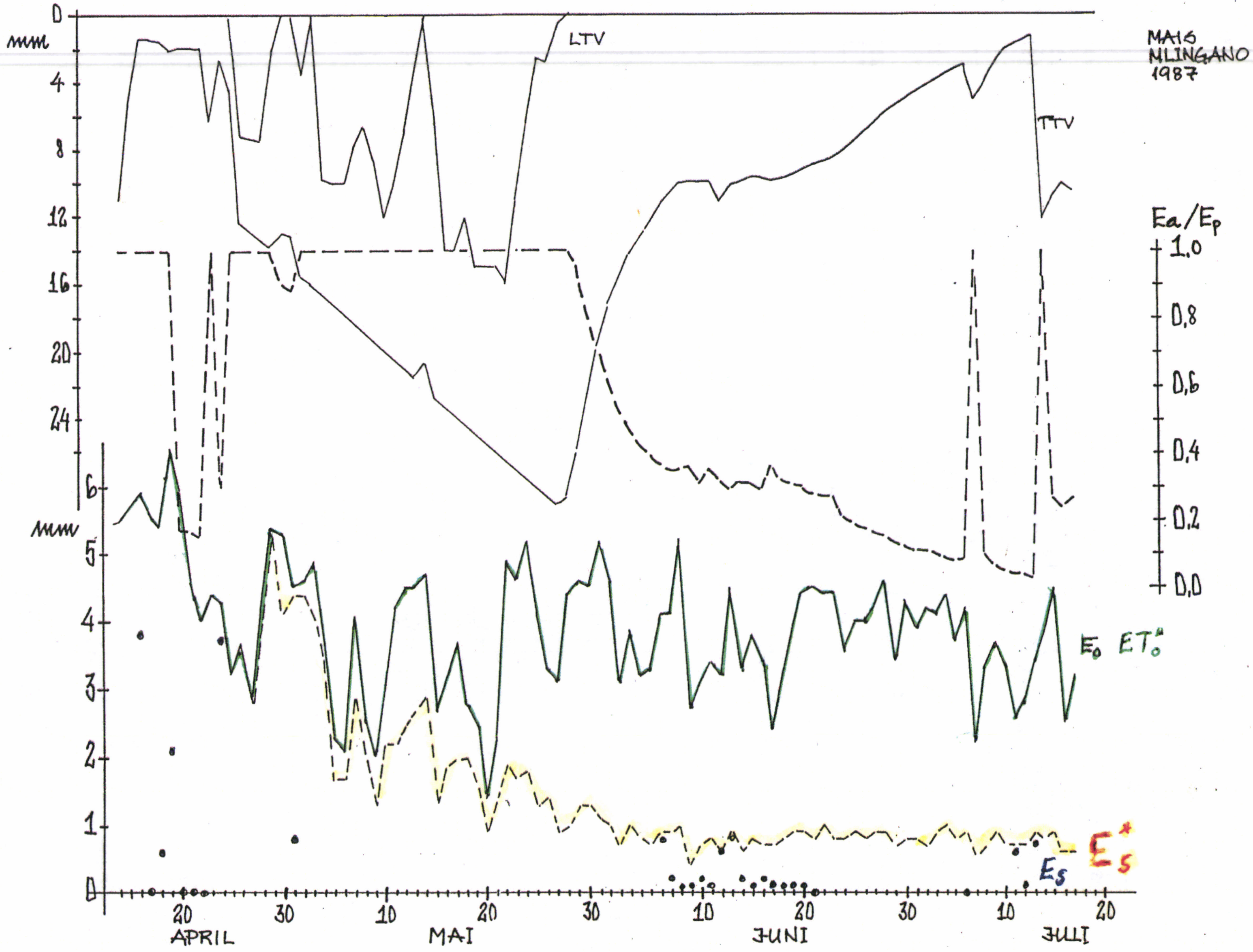


Fig. 4 "Readily available" (LTV) and "Less readily available" soil water (TTV), mm, drought stress (Ea/Ep), and the two main components in water balance estimation, i.e. potential evapotranspiration (ET_o*) (estimated from Penman's equation with a locally adapted wind function) and potential soil evaporation E_s* (see text). Maize crop in Mlingano, Tanzania, 1987.

Potential evaporation from the soil (E_s*) was principally estimated as decribed in LC, pp 229-230, but we included, as mentioned above, only the radiation part of ET_0*. In the summer exercises at Vollebekk, this equation was used to estimate potential evaporation:

$$ET_o^* = \Delta H/(\Delta + \gamma) \; + \gamma\, f(u)(e_s - e_a)/(\Delta + \gamma) \; = \; E_{rad} \; + \; E_{adv}$$

One somewhat different alterative is given in LC, since even soil heat flux (G) is included (and $H = R_n$, $S = \Delta$):

$$ET_o \; = S(R_n + G)/(S + \gamma) \; + \gamma\, f(u)(e^* - e_a)/(S + \gamma) \; = \; E_{rad} \; + \; E_{adv}$$

Thus, both versions imply a sum of two components, one from radiation E_{rad}, and one from advection E_{adv}.

Actual evaporation from soil, E_s.

The soil surface can evaporate water at potential rate only some few mm before the upper layer is too dry to allow sufficient water transport necessary for evaporation at this rate. Maximum accumulated evaporation in the potential phase, stage 1 of soil evaporation, U varies with soil type. The same goes for the parameter α, denoting the evaporation in mm per day at stage 2, which starts as ~~soon as~~ soon as accumulated evaporation in phase 1 has reached U mm:

Soil type	U, mm accumulated	α, mm/day
Sand	6	3.3
Loamy sand	7	3.5
Sandy loam	8	3.7
Loam/sandy clay loam	9	4.0
Clay loam, silty slay loam	10	5.1
Silt loam	13	6.0

U is strongly correlated to soil content of clay particles and is calculated: U = 8 + (0.08 x clay percent). In Mlingano the soil was rich in clay, 47 percent, so that U = 8 + 0.08 x (47/100) = 11.8 mm;

At stage 2 the evaporation declines rapidly. At day t of this stage the estimation will be as follows:

$$Es = \alpha t^{-1/2}$$

The result when U =(>) 10 mm and α = 3.5 mm is shown in Fig. 5.

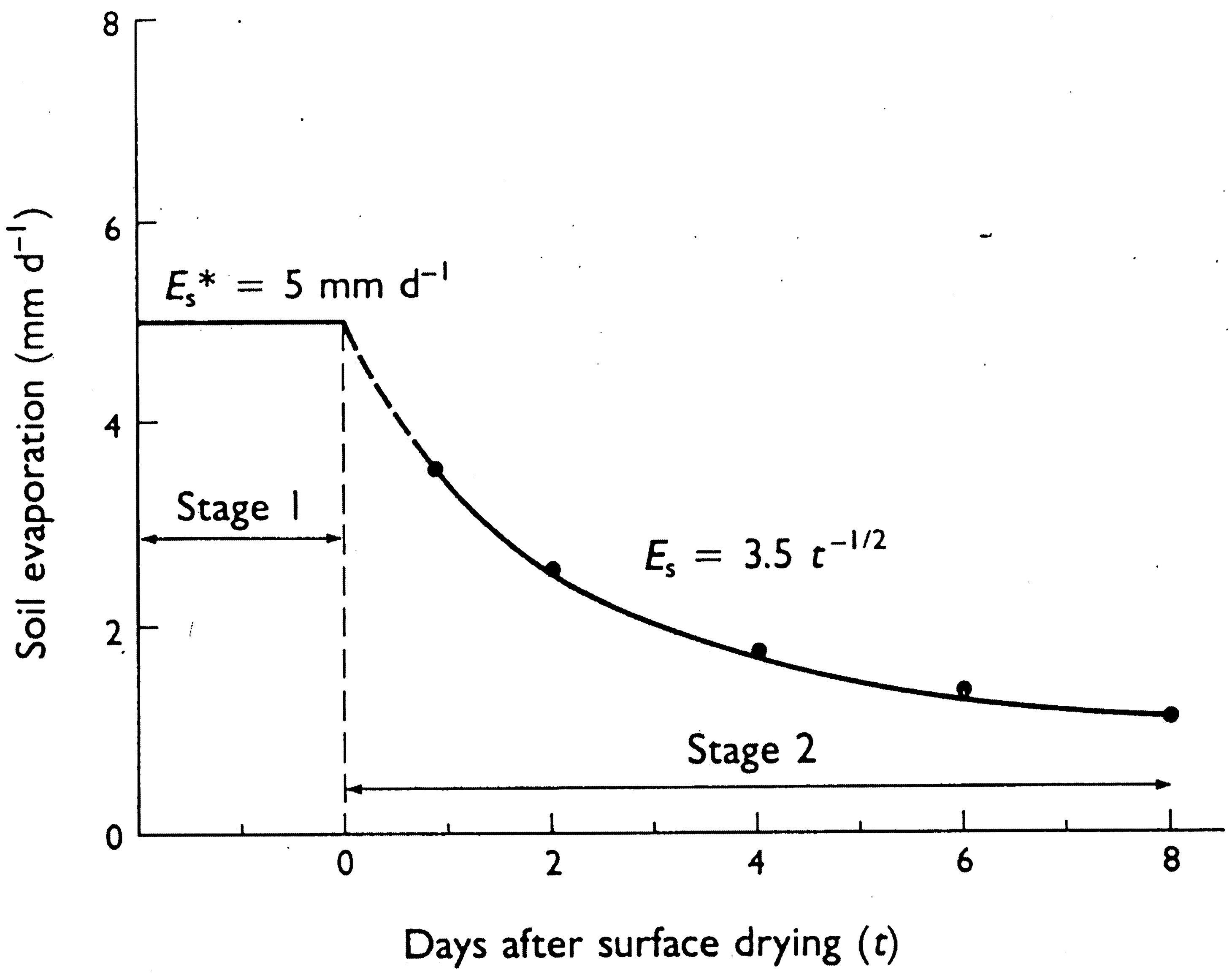
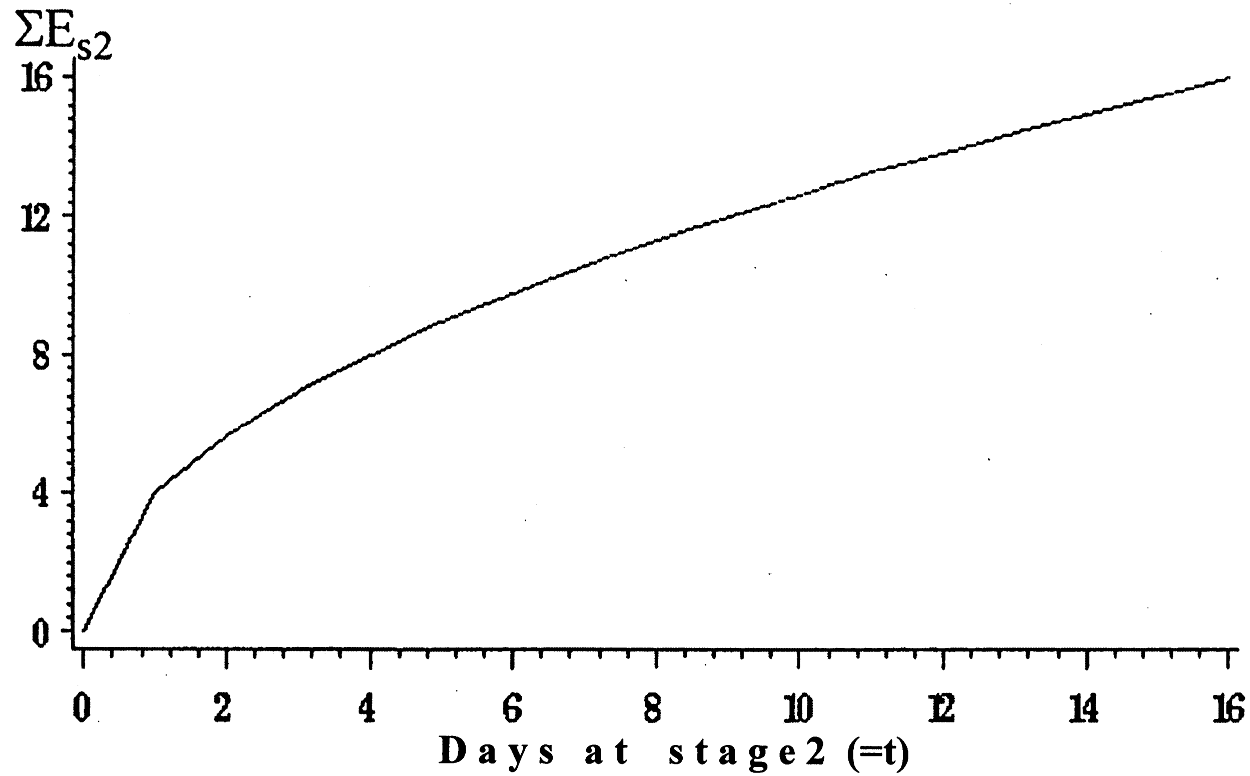


Fig. 5. (9.5 in LC). The two stages of evaporation from a bare soil (Es) following wetting.

Thus, total accumulated evaporation forwards at stage 2, $\sum E_{s2}$, will increase at a declining rate according to a logarithmic curve, when day number makes the abscissa in a figure like the one below:

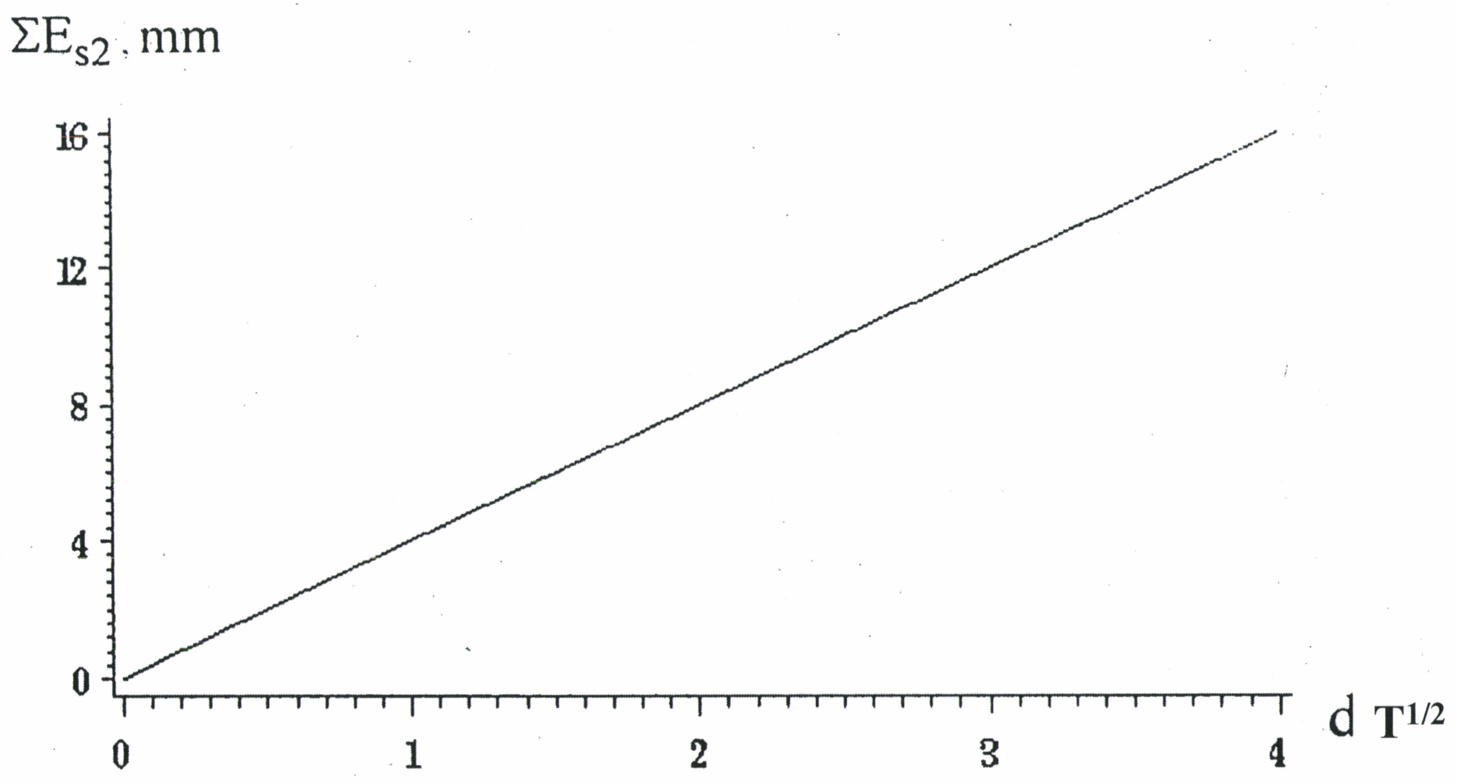


If, as an alternative, the square root of day number in stage 2, $t^{1/2}$, is used as the abscissa the curve will make a straight line (see figure below), since the relevant functional relations are:

$$t = (\sum E_{s2}/\alpha)^2$$

and:

$$\sum E_{s2} = \alpha t^{1/2}$$



<u>Potential transpiration from plants</u>, E_p (E_{pp} in the demonstration model), is calculated as the difference between potential evapotranspiration (according to Penman's equation) and potential evaporation from the soil:

$$E_p(E_{pp}) = ET_o^* - E_s^*$$

and is shown as the area between the two lowest curves of Fig. 4. This difference is strongly correlated with leaf area (see Fig 4) up to an LAI of approx. 3, for most crops, e.g. sorghum and cotton, as shown in Fig. 5. Further increase of leaf area beyond an LAI of 3, seem to imply minor increase of plant transpiration (Fig.6).

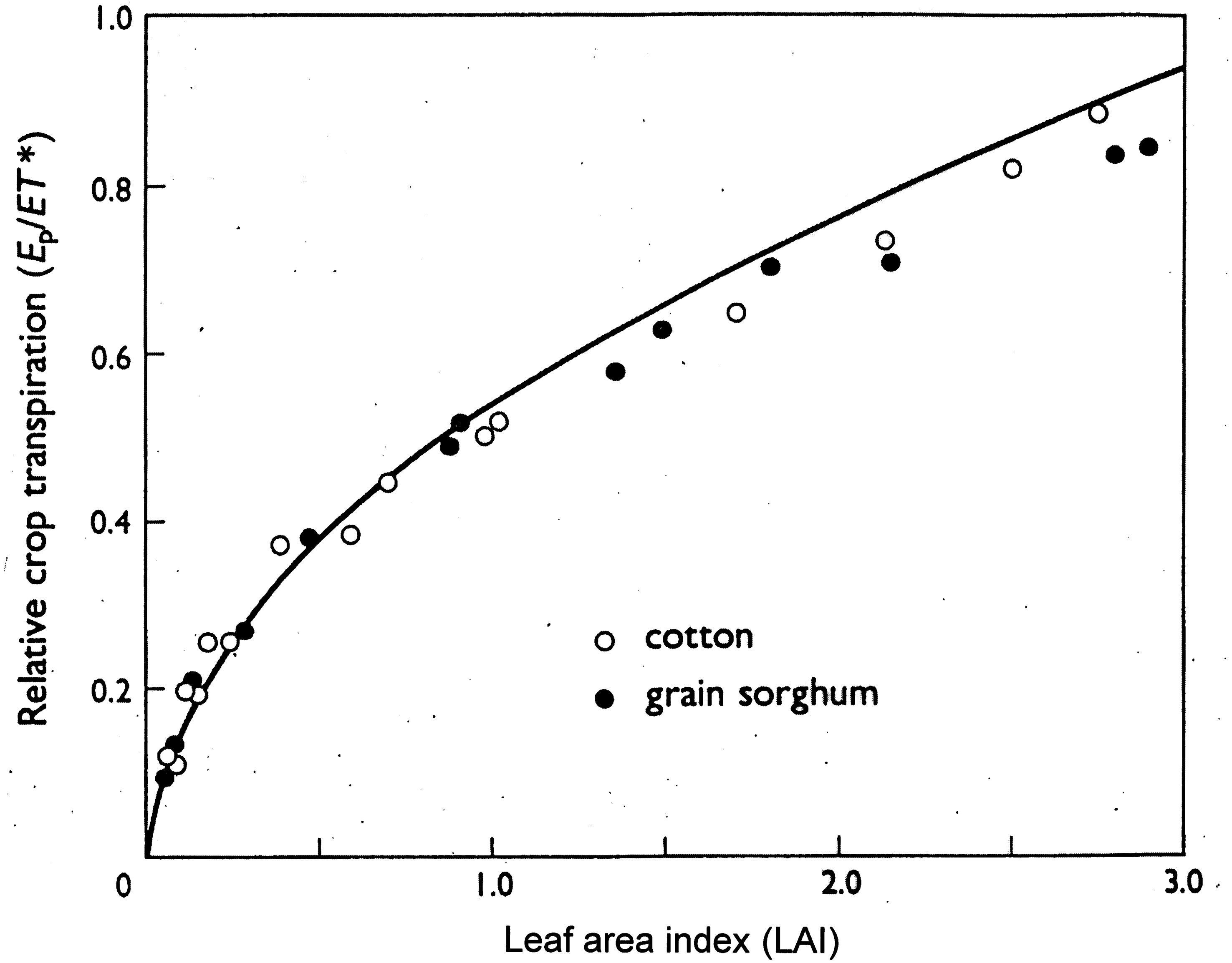


Fig. 5. (9.14 in LC) Potential crop transpiration in relation to potential evapo-transpiration ($E_p/ET*$) as a function of leaf area in cotton and grain sorghum

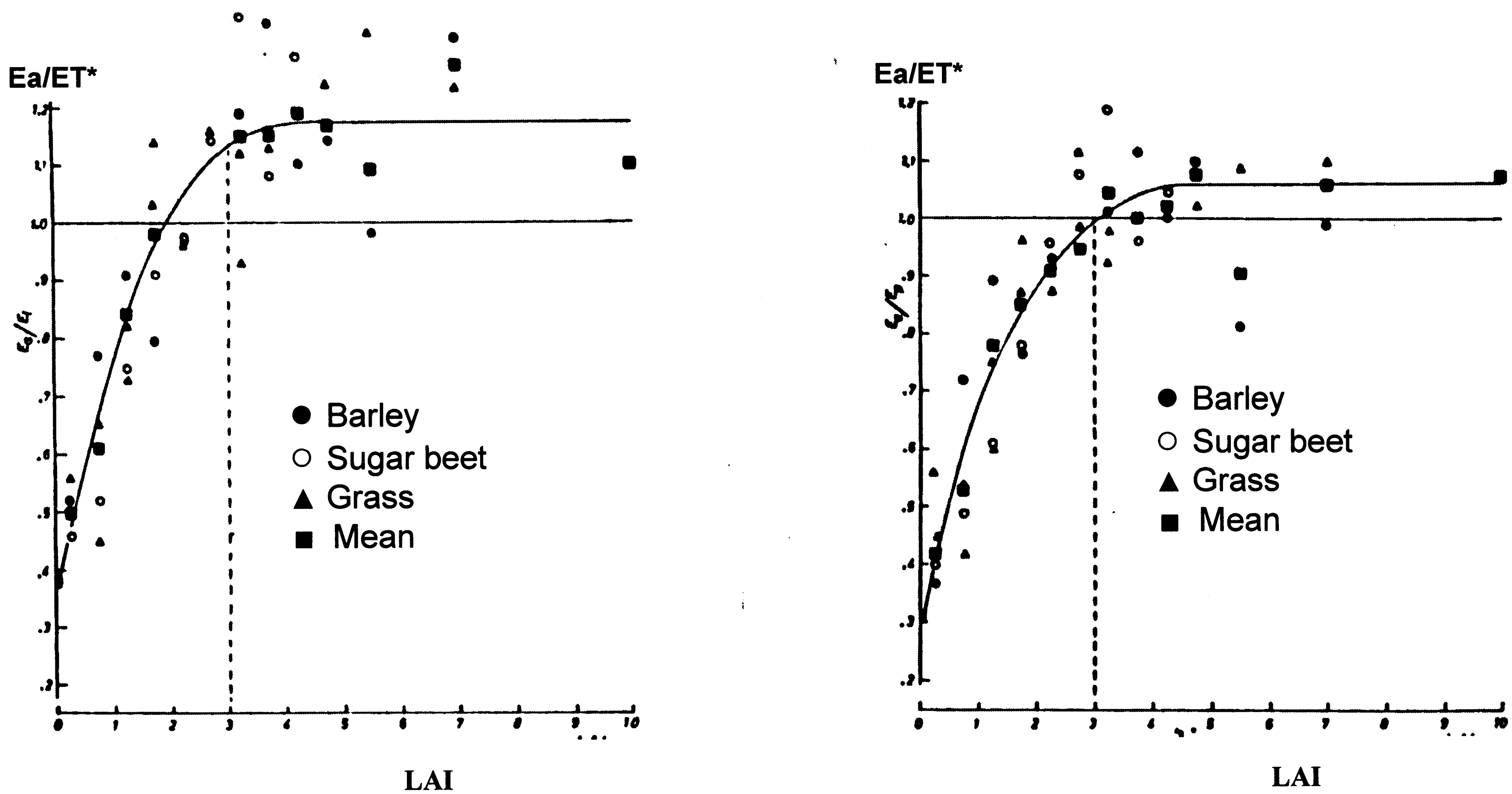
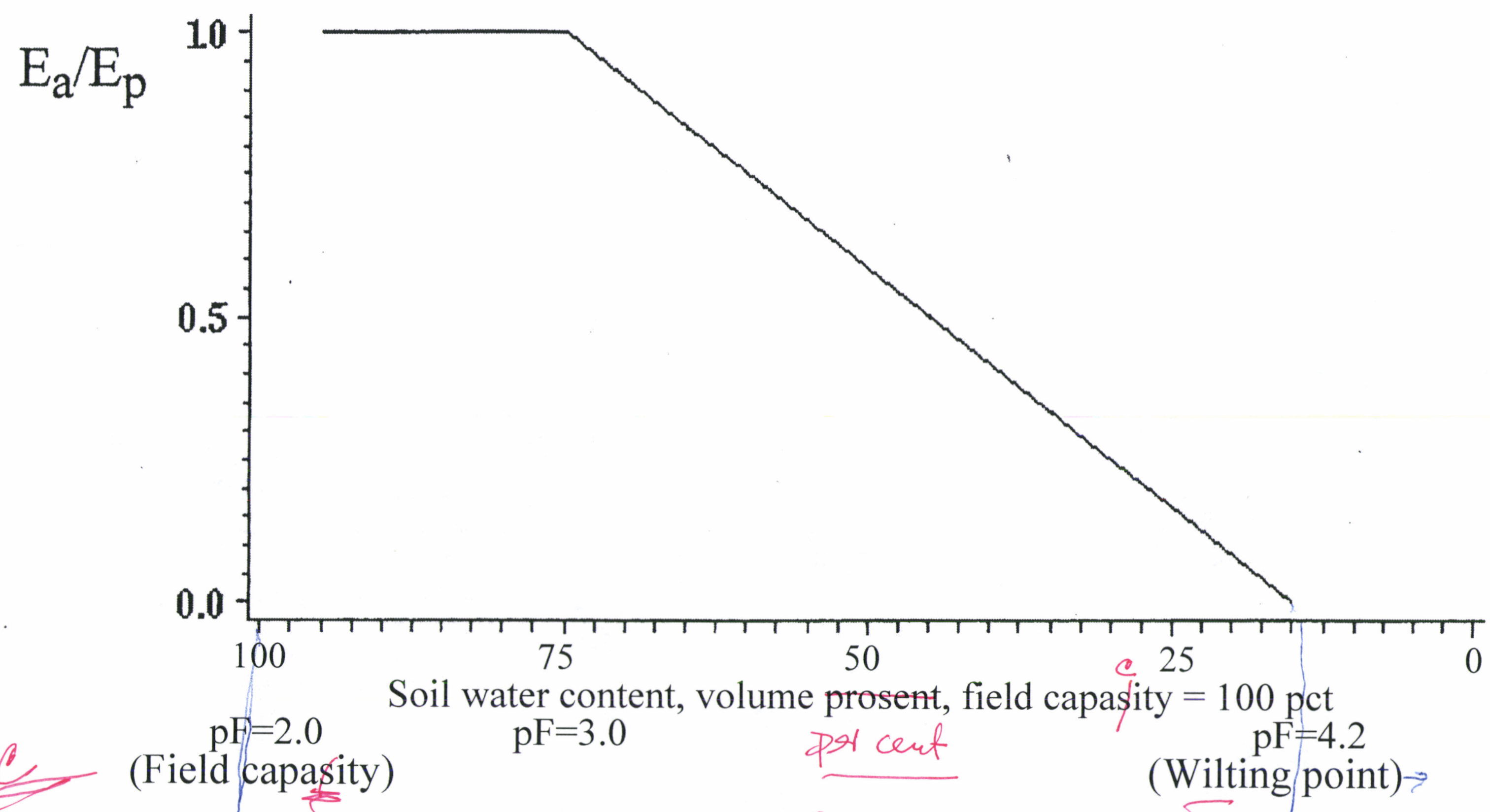


Fig 6. The relation of actual (E_a) to potential evapotranspiration (ET*) as a function of leaf area for different crops, as measured in a lysimeter (left) or as estimated from Penman's equation (right).

Actual transpiration from plants is estimated from the figure below, which shows the ratio actual/potential transpiration (E_a/E_p):



Thus, the fact that E_a/E_p varies with potential ecapotranspiration (fig 7), is not taken into account. In addition, the actual evapotranspiration is supposed to decline in relation to potential rate at a higher soil water potential, i.e. By a less dry soil, than shown in Fig. 8. According to this figure, the transpiration both of wheat and soybeans keeps at potential rate until approx. 75 percent of plant available water is used, whereas the above figure indicate a decline already at around 30 percent soil water reduction.

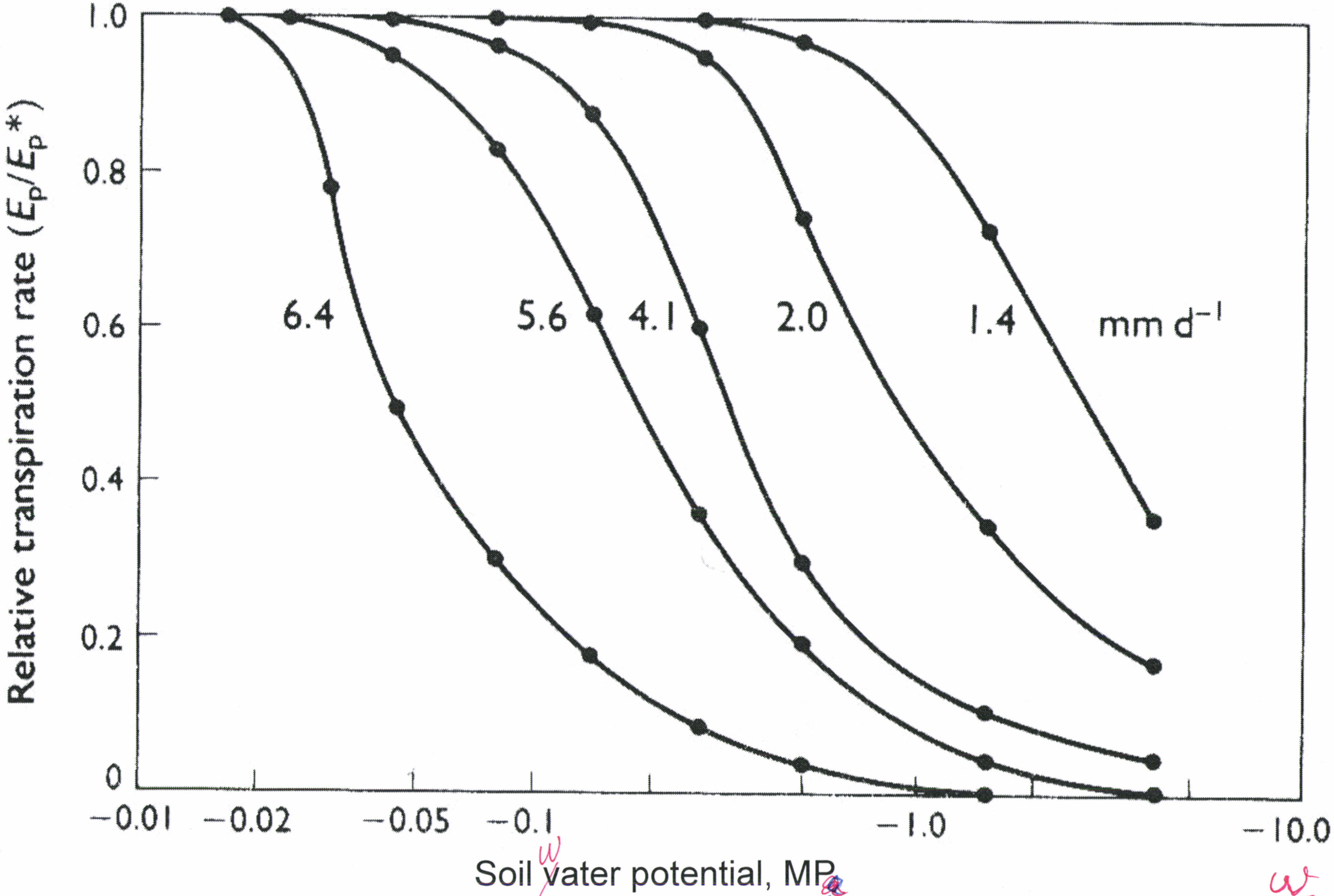


Fig. 7 (9.7 in LC). Relative transpiration rate as functions of soil water potential at varying levels (1.4-6.4 mm/d) of potential evapotranspiration. NB: -0.01 MP = pF 2.0 (= field capacity), -0.1 MP = pF 3.0, pF 4.2 (wilting point) = -1.5.

1 MPa = 10 bar

1 bar = pF 4 1 bar

MP = 1000 000

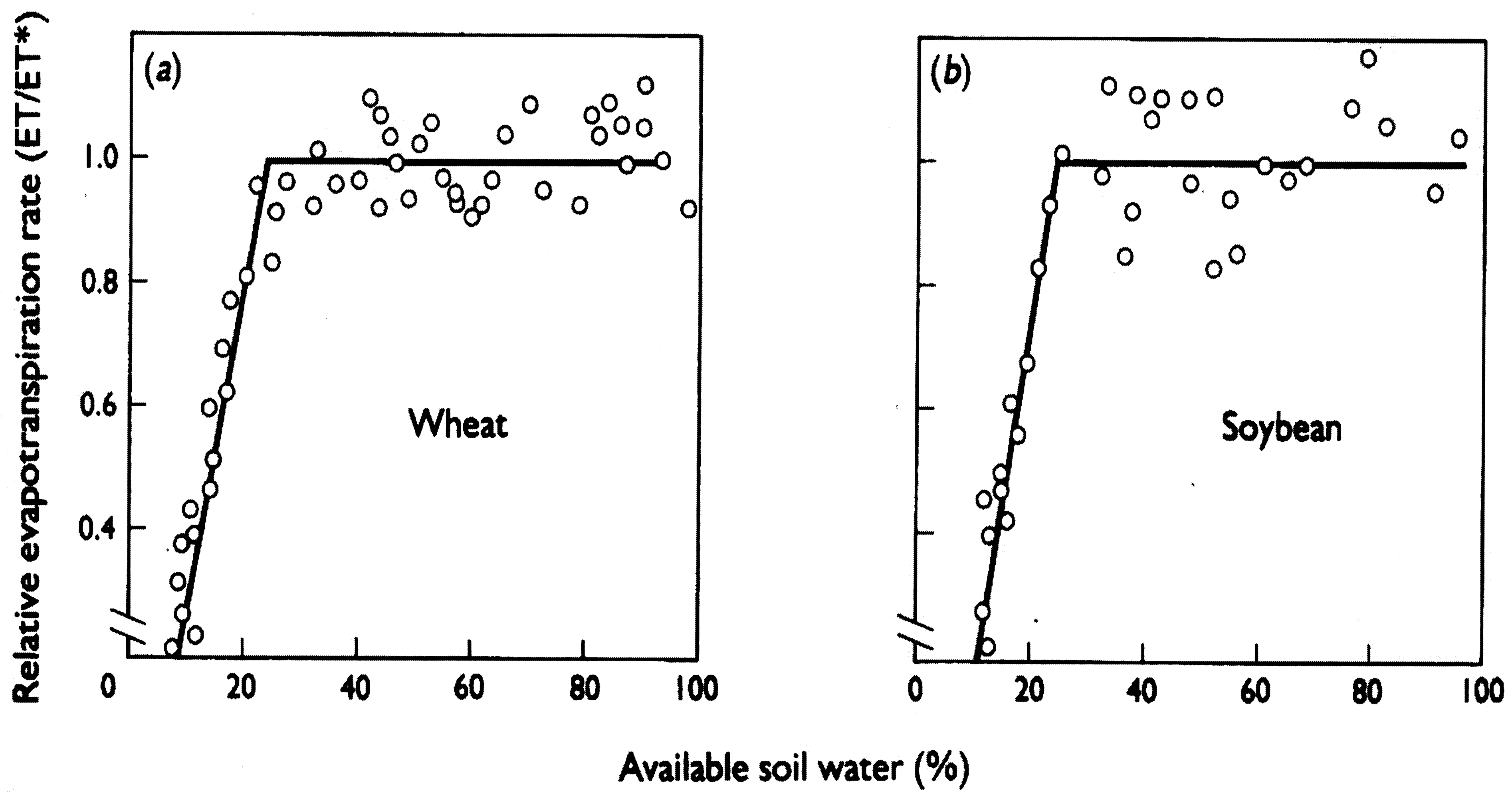


Fig 8 (9.8 in LC) Relative evapotranspiration rate (ET/ET*) as functions of available soil water content (in percent) for wheat (a) and soybean (b).

Relative transpiration and crop production

The efficiency in water utilization for DM production of different crops, is expressed as the transpiration coefficient, or WUE, ”Water Use Efficiency”, and is measured as kg water consumed per kg DM produced, totally or in the product harvested.

Fig 9 shows the relation between the dry matter production of a potato crop and transpiration during the period from the start of tuber formation. At this stage, the foliage is fully developed, so that almost all evapotranspiration goes via the leaves, whilst the evaporation from the soil is minimal. The production is (linearly) proportional to transpiration from the 0-level at the starting point mentioned. The tilt of the curves, indicating the water use efficiency, vary between the years. From the 1976-curve a final DM yield of approx.17 tonnes per hectare can be red. To obtain this, an amount of water corresponding to 350 mm, which can be calculated to: 0.35 m x10000 m^2=3500 m^3 or 3500 tonnes per hectare is transpired. The resulting WUE-value will be: 3500/17 ≈ 200.

Fig. 9 gives a corresponding description for sunflower, but in this case from the start of the growing season, including even the first part without or with only partly established foliage. The curves' intercepts with the abscissa at points mainly expressing the amount of water evaporating directly from the soil surface. This part of the total evapotranspiration is highest by frequent irrigation (curves 1, 2, 3), because the soil here most frequently is moistened up to the surface and thus evaporate at potential rate, i.e. in the first stage as described above (see Fig. 5). An estimation similar to that for the potato crop above shows a DM production of 11 tonnes per hectare when 650 mm of water is evapotranspired, i.e. a WUE-value of 600 kg water per kg DM.

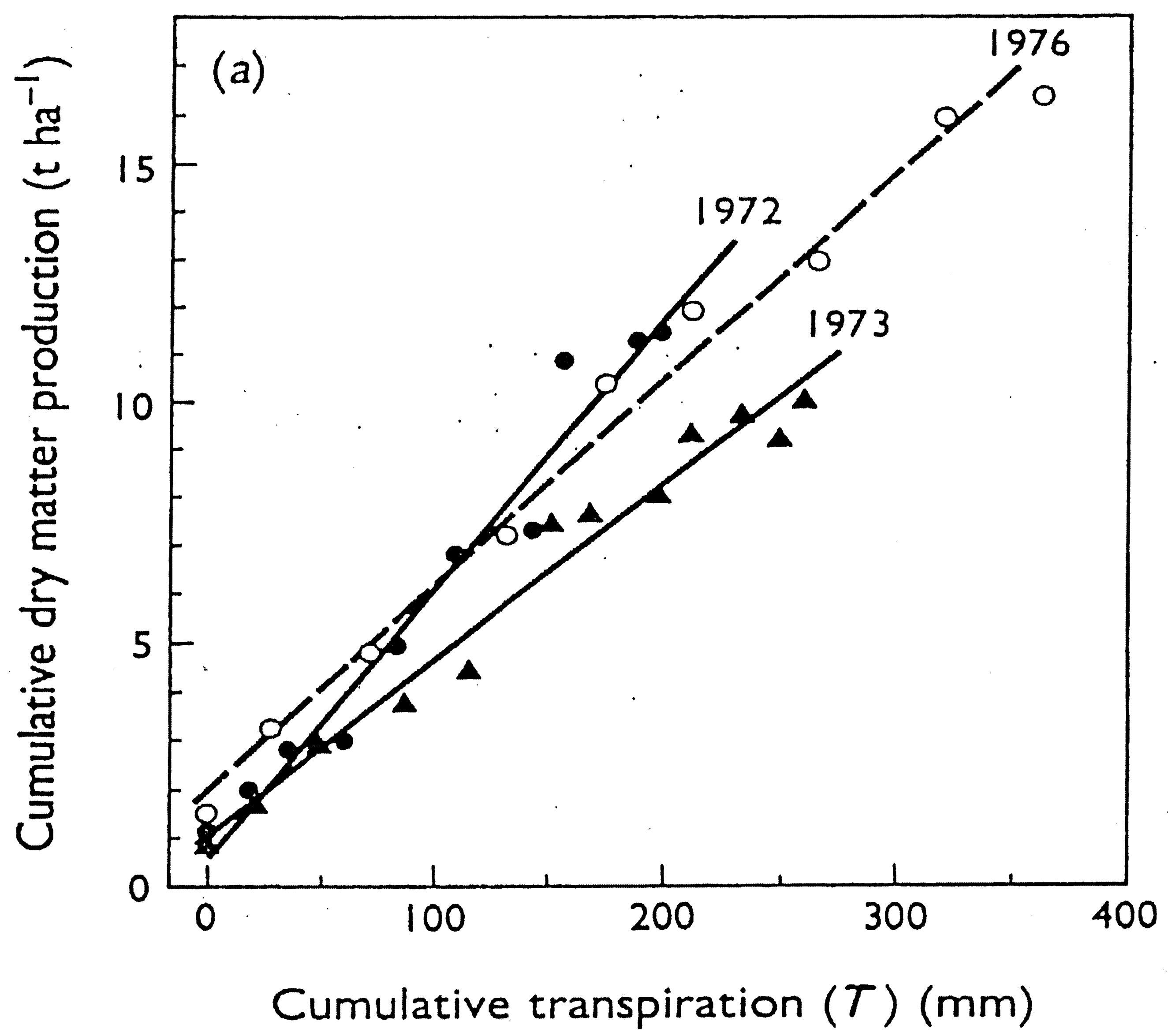


Fig 9 (9.19 in LC) Relation of total dry matter to water consumption in a potato crop from the start of tuber formation to harvest.

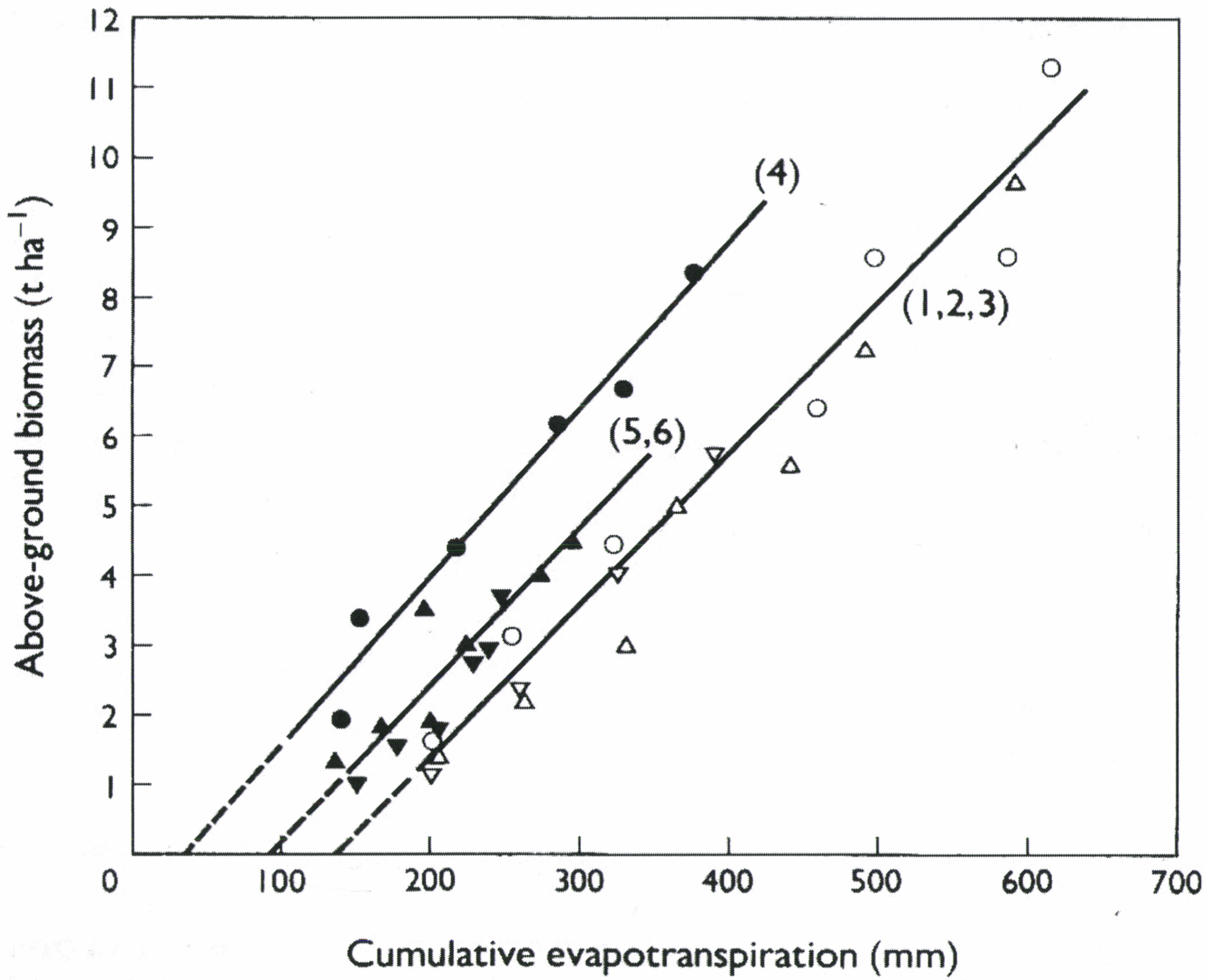


Fig 9 (9.19 in LC) Relation of total dry matter to water consumption from the start of the growing season to harvest in sunflower crops subjected to six different irrigation regimes (1 – 6).

The sensivity parameter λ.

Usually the relative reduction of DM production by drought stress (Y) compared to the production by optimal water supply (Y_o) is considered as equal to the reduction of plant transpiration:

$$Y/Y_o = E_a/E_p{}^*$$

However, the plants may have different strategies for maintaining a high production even under drought conditions. This can only to a limited degree be the case for <u>gross assimilation</u>, which depends on open stomata, but may go for <u>net production</u>, and especially for <u>participation</u> to and growth of above ground plant parts, including those which are harvested and utilised. For such parts (Y) of the total production the alternative equation may be:

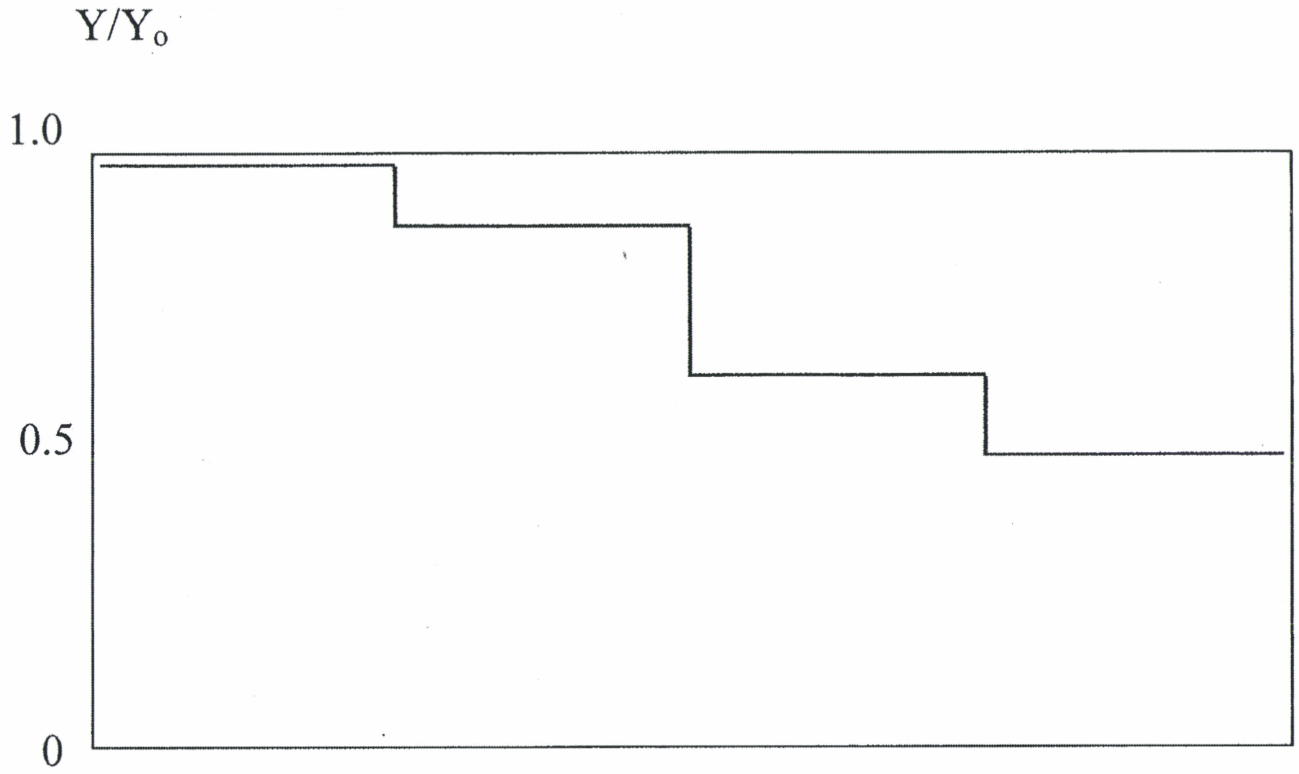
$$Y/Y_o = (E_a/E_p{}^*)^\lambda$$

Where λ, which expresses the sensitivity to drought for the actual part of the total production, may vary between 0 and 1. For maximum sensitivity λ=1, i.e., the reduction in production is equal to the transpiration decrease. When λ=0, production is independent of drought. Many trials has shown that the effect of drought on the end production depends on which growth or development phase the drought exposition occurs. The cereals may be specially sensitive during the heading period (see Fig 9.12 in LC, p243). For maize, the value of λ has been assessed for 4 stages from emergence to maturity (LC, Tab. 14.4, p 385). The effect on the end production, is estimated by a cumulative multiplication (expressed by the symbol Π, analogous to ∑ for cumulative summing) of the effect of drought stress during each of the four phases (i=1 to i=4):

$$Y/Y_o = \Pi(Ea/Ep^*)\lambda i$$

λi (ultimate) yield

If the mean drought stress for each phase is set to 1.0, 0.8, 0.5, and 0.3, respectively, the ~~result~~ will be ~~as~~ shown below. reduced to 49 percent of that with no drought stress



Phase	1	2	3	4
Ep/Ep*	1	0.8	0.5	0.3
λ	0.25	0.5	0.5	0.21
$(Ea/Ep^*)^{\lambda i}$	1	0.89	0.71	0.77
$\Pi(Ea/Ep^*)^{\lambda i}$	1	0.89	0.63	0.49