CROP EVAPOTRANSPIRATION

Mladen Todorović

CIHEAM – Mediterranean Agronomic Institute of Bari, Italy

mladen@iamb.it

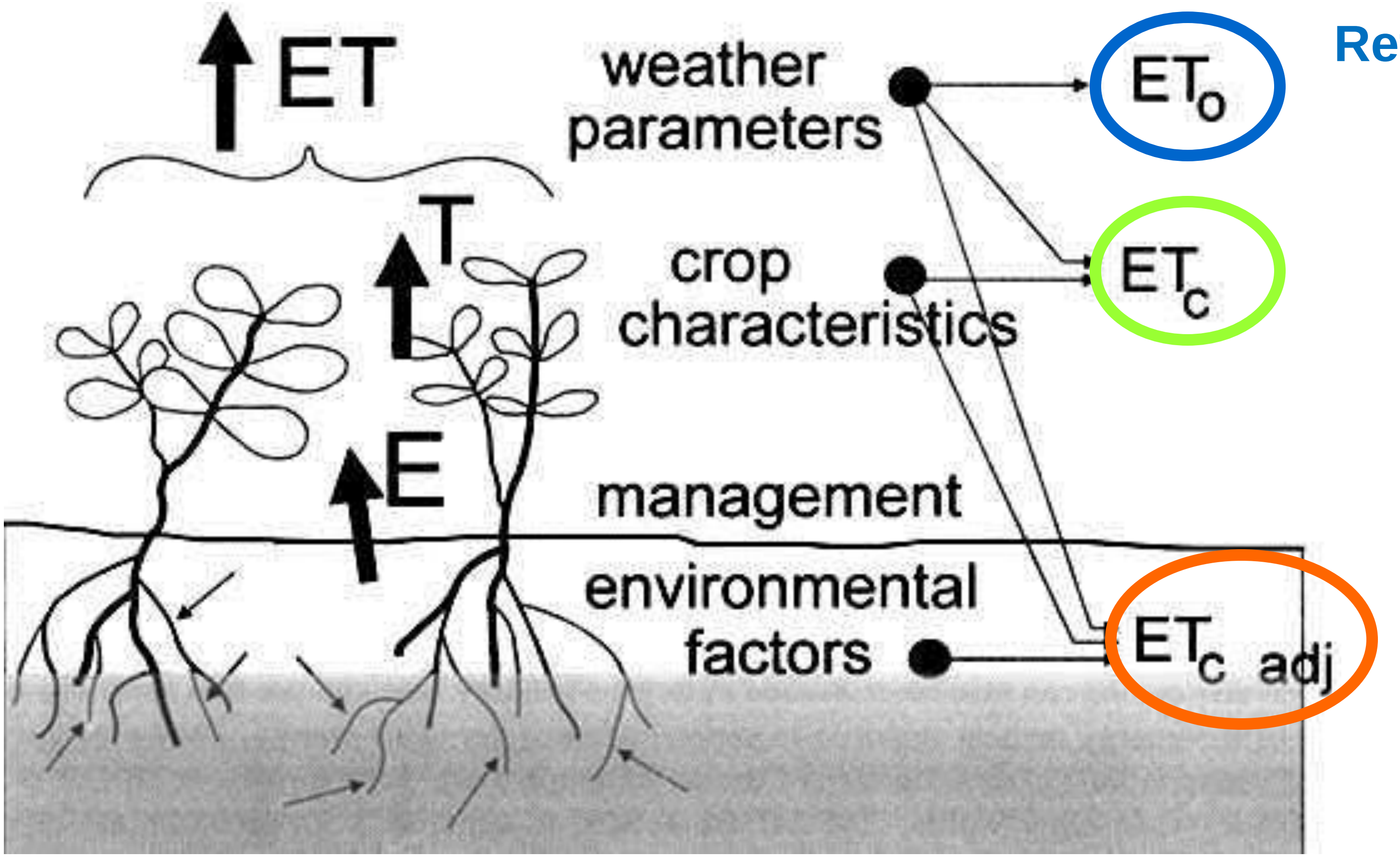
CIHEAM

LAND and WATER
Resource Management

Crop Evapotranspiration ETc

- FAO definition (FAO 56, 1998)
  - the amount of water lost by evapotranspiration process from "disease-free, well-fertilized crops, grown in large fields under optimum soil water conditions, and achieving full production under the given climatic conditions”
- Factors affecting ET
  - weather: radiation, air temperature, humidity and windspeed
  - crop: type, variety, development stage (height, roughness, reflection, ground cover…)
  - management and environmental conditions: soil salinity, land fertility, application of fertilizers, the presence of impenetrable soil horizons, control of diseases and pests, soil management...

Factors affecting ETc

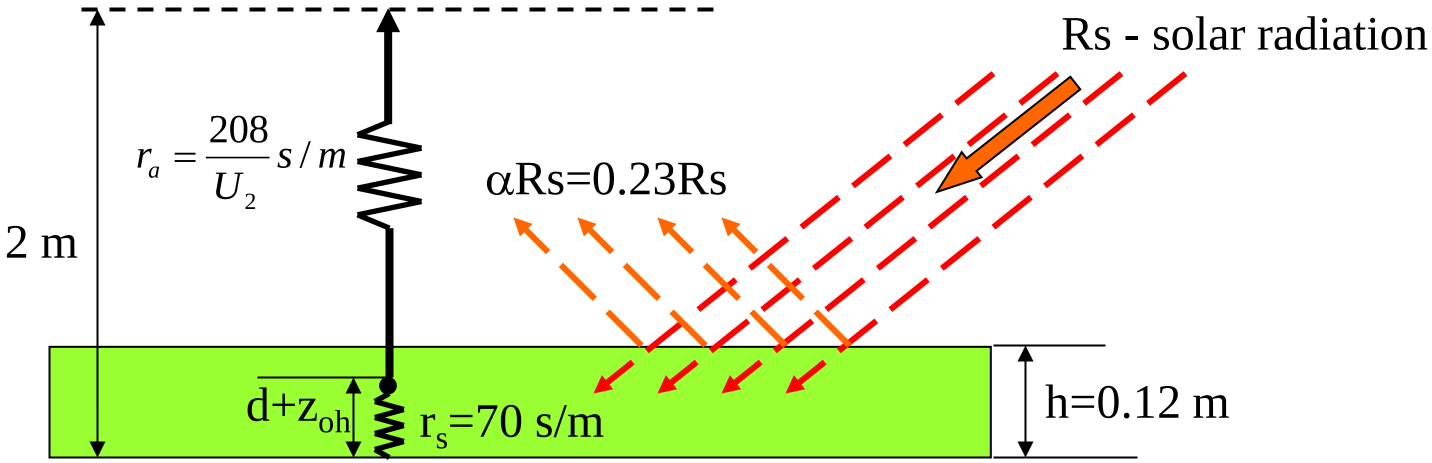


Reference ET

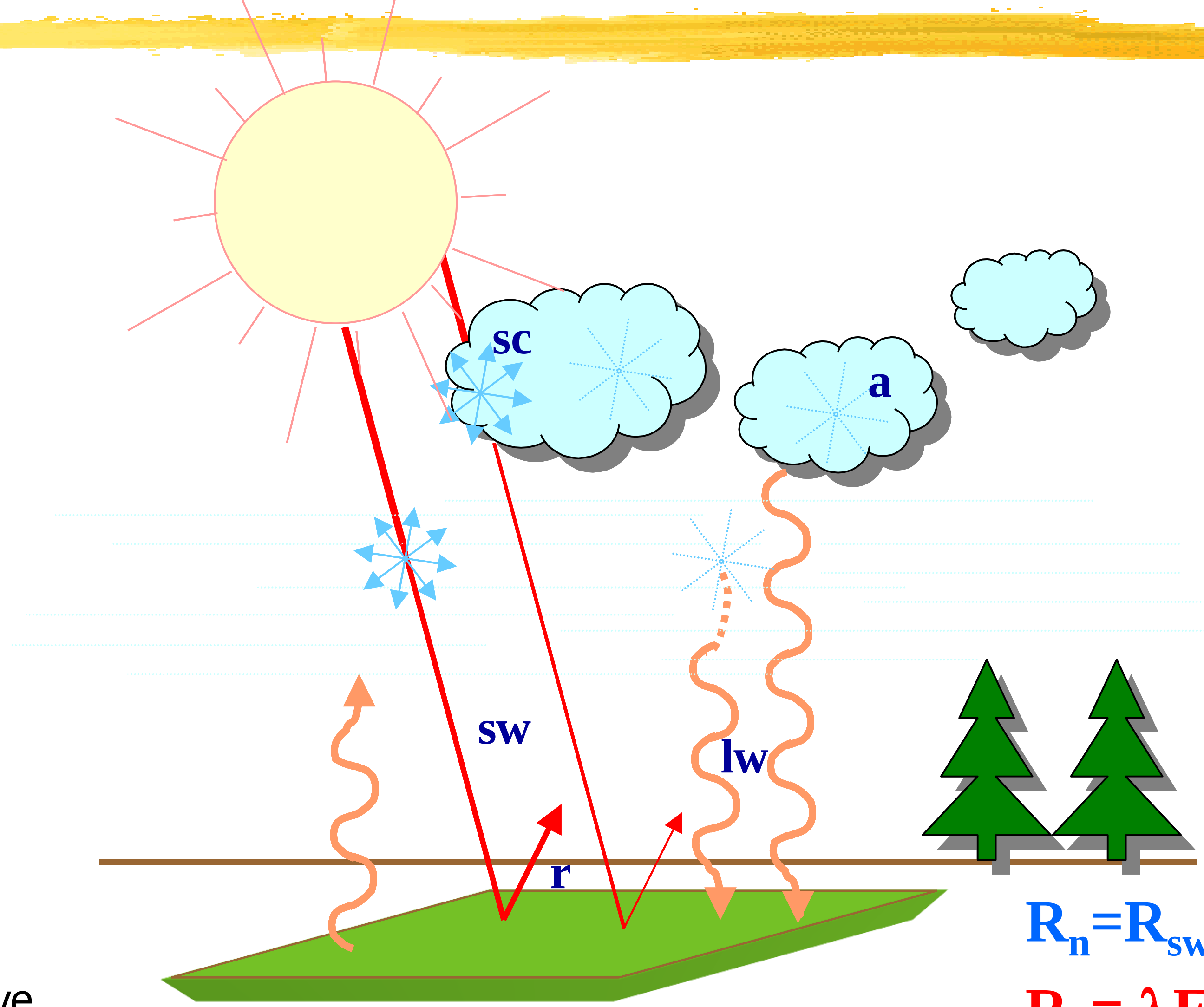
Source: FAO 56, 1998

Reference Evapotranspiration (ETo)

- FAO definition (FAO 56, 1998)
  - the amount of water lost by evapotranspiration process from ”a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s/m and an albedo of 0.23” and maintained under optimal water and nutrient conditions
- ETo provides a standard to which:
  - ET at different periods of the year or in other regions can be compared
  - ET of other crops can be related



Surface radiation (and energy) balance

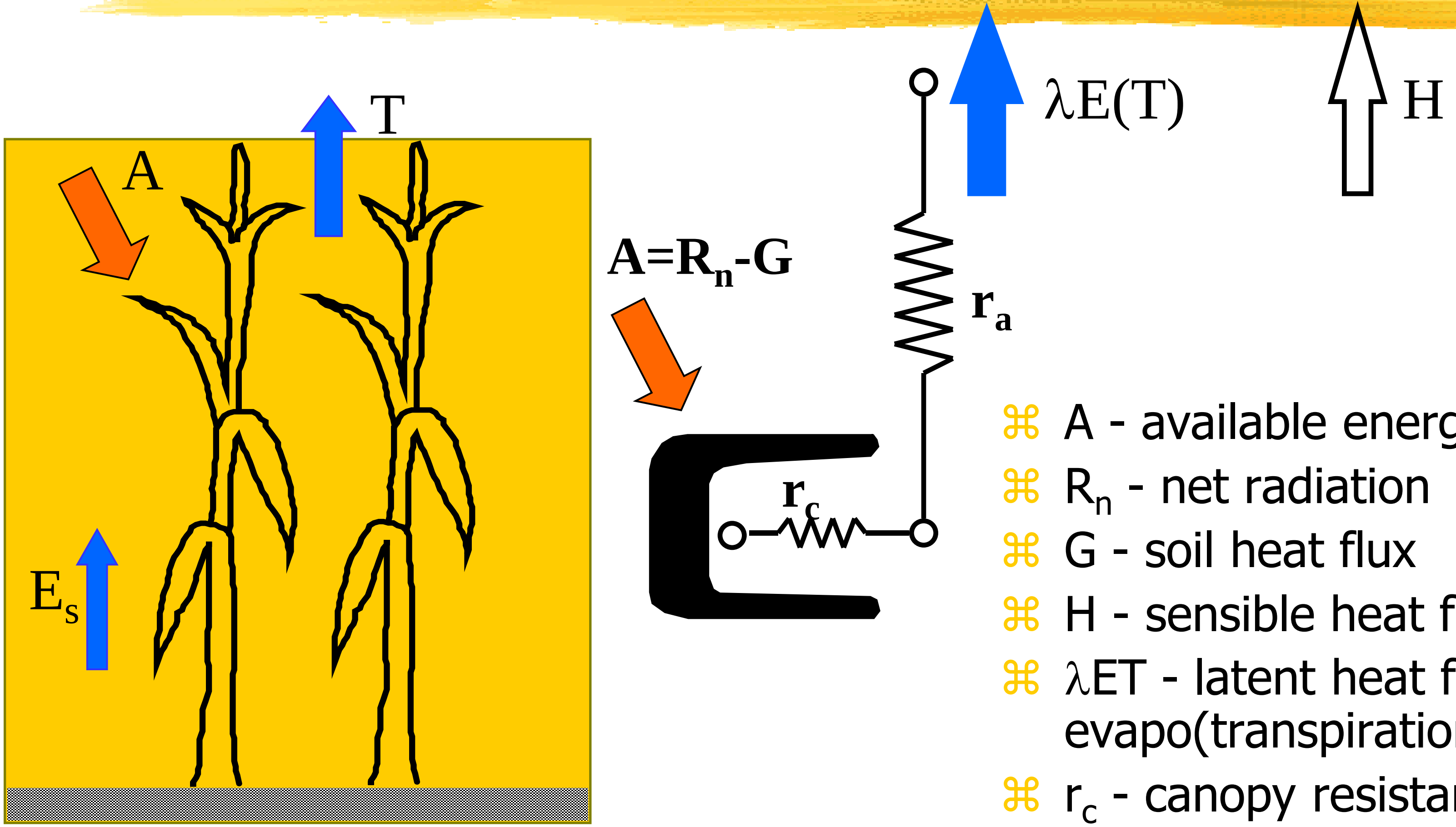


a=absorption
r=reflection
sc=scattering
sw=short-wave
lw=long-wave

$$R_n=R_{sw}+R_{lw}$$

$$R_n= \lambda ET +H+G$$

Plant-Atmosphere Relationship
Crop Evapo-transpiration



$$\lambda ET_p = \frac{\Delta A + \rho c_p (e_s - e_a)/r_a}{\Delta + \gamma(1 + r_s/r_a)}$$

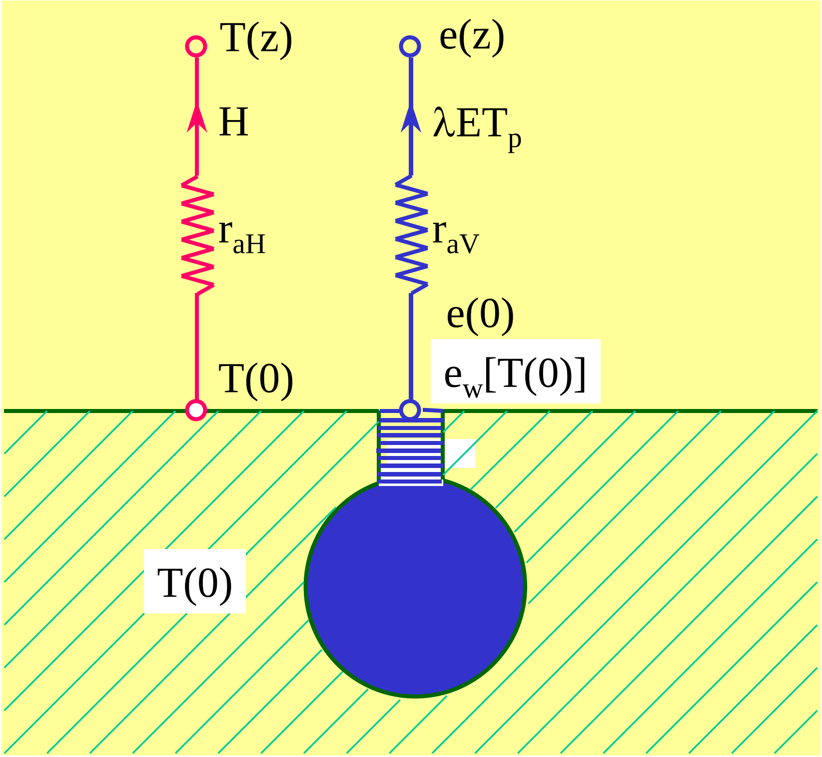
- A - available energy
- R_n - net radiation
- G - soil heat flux
- H - sensible heat flux
- λET - latent heat flux of evapo(transpiration)
- r_c - canopy resistance
- r_a - aerodynamic resistance

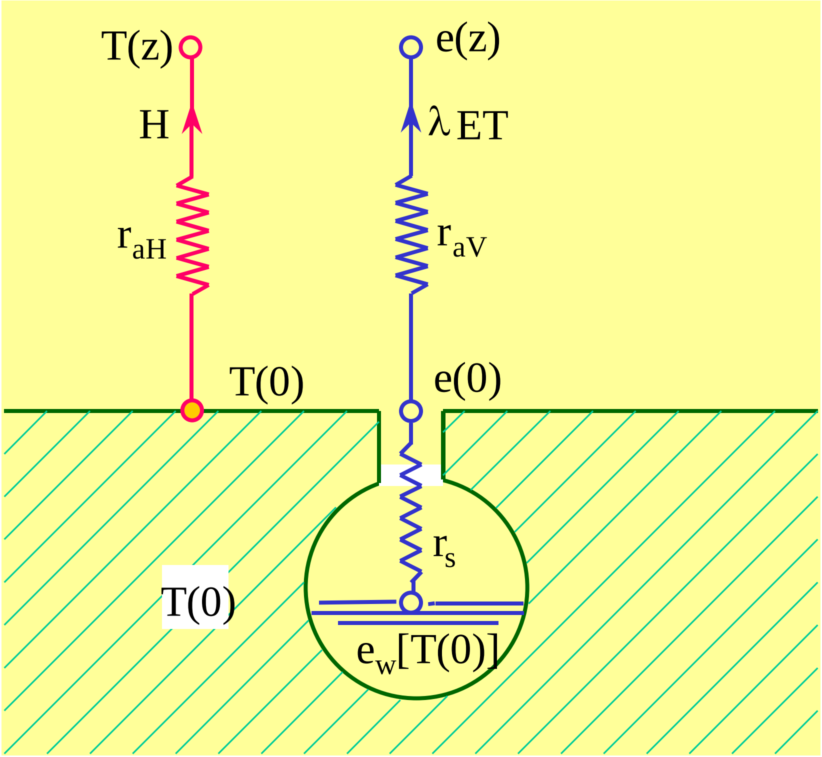
Reference Evapotranspiration
From Penman to Penman-Monteith

$$\lambda ET_p = \frac{\Delta A + \rho c_p (e_s - e_a)/r_a}{\Delta + \gamma}$$

→

$$\lambda ET_p = \frac{\Delta A + \rho c_p (e_s - e_a)/r_a}{\Delta + \gamma (1 + r_s / r_a)}$$





Source: Todorovic, 1998

ETo Estimate methods

Method	Temperature	Humidity	Wind speed	Sunshine or Radiation	Evaporation	Time scale			
						hour	day	week	month
Blaney-Criddle	**+**	**-**	**-**	*****	**-**				**X**
Hargreaves	**+**	**-**	**-**	*****	**-**				**X**
Pan evaporation	**-**	**-**	**-**	**-**	**+**			**X**	**X**
Radiation	**+**	**-**	**-**	**+**	**-**			**X**	**X**
Penman	**+**	**+**	**+**	**+**	**-**		**X**	**X**	**X**
Penman-Monteith	**+**	**+**	**+**	**+**	**-**	**X**	**X**	**X**	**X**
PM-Temperature	+	*	*	*	-	X	X	X	X

+ : must be measured
- : is not necessary

* : estimation required
x : recommended time scale of application

Source: Todorovic, 2004

FAO - Penman-Monteith method for ETo

- On daily basis:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 U_2)}$$

- where
  - ET_o is the reference evapotranspiration, (mm day^{-1}),
  - R_n is the net radiation, (MJ m^{-2} day^{-1}),
  - G is the soil heat flux density, (MJ m^{-2} day^{-1}),
  - T is the mean daily air temperature at 2 m height, (°C),
  - Δ is the slope of the saturated vapour pressure curve, (kPa $°C^{-1}$),
  - γ is the psychrometric constant, 66 Pa $°C^{-1}$,
  - e_s is the saturated vapour pressure at air temperature (kPa),
  - e_a is the prevailing vapor pressure (kPa), and
  - U_2 is the wind speed measured at 2 m height (m s^{-1})
- On hourly basis:
  - replace 900 by 37(=900/24) and
  - express the net radiation and the soil heat flux on hourly basis

Hargreaves-Samani method for ETo estimate

- On daily basis:

$$ET_o = 0.0023 \frac{R_a}{\lambda} (T + 17.8)(T_{\max} - T_{\min})^{0.5}$$

- where
  - ET_o is the reference evapotranspiration, (mm day^{-1}),
  - R_a is the extraterrestrial radiation, (MJ m^{-2} day^{-1}),
  - T is the average air temperature (°C),
  - Tmin is the minimum air temperature (°C),
  - Tmax is the maximum air temperature (°C),
  - λ is the latent heat of vaporization (MJ kg^{-1}),

$$\lambda = 2.501 - \left(2.361 * 10^{-3}\right) T$$

FAO method with only measured T_{air} data

- Wind speed is fixed to 2 m/s (average value of 2000 weather stations around the globe), more accurate data could be used when available
- Solar radiation is estimated as:

$$R_s = k_{Rs}\sqrt{(T_{max} - T_{min})}R_a$$

  k_{Rs} is empirical radiation adjustment coefficient,
  0.16 for “interior” and 0.19 for “coastal” areas

- Assuming that T_{dew} is close to T_{min} at a reference site (at sunrise), actual vapour pressure is estimated as:

$$e_a = e^o(T_{min}) = 0.611 \exp\left[\frac{17.27\ T_{min}}{T_{min} + 237.3}\right]$$

Pan evaporation method: ETo=Kp*Epan

TABLE 5

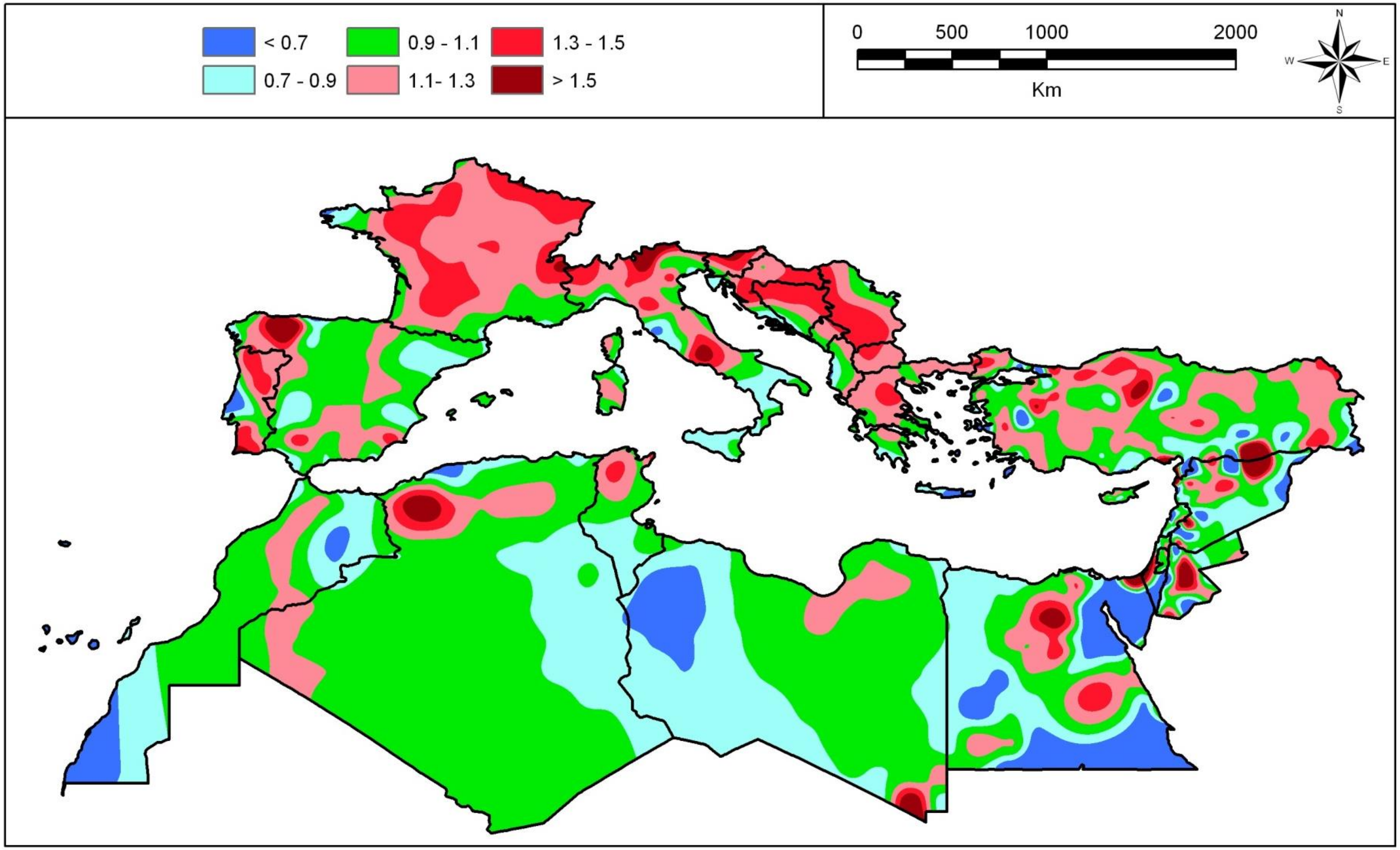
Pan coefficients (K_p) for Class A pan for different pan siting and environment and different levels of mean relative humidity and wind speed (FAO Irrigation and Drainage Paper No. 24)

Class A pan	Case A: Pan placed in short green cropped area				Case B: Pan placed in dry fallow area			
RH mean (%) →		low < 40	medium 40 -70	high > 70		low < 40	medium 40 -70	high > 70
Wind speed ($m\ s^{-1}$)	Windward side distance of green crop (m)				Windward side distance of dry fallow (m)			
Light	1	.55	.65	.75	1	.7	.8	.85
< 2	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	1	.5	.6	.65	1	.65	.75	.8
2-5	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	1	.45	.5	.6	1	.6	.65	.7
5-8	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	1	.4	.45	.5	1	.5	.6	.65
> 8	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

Performances of various ETo methods

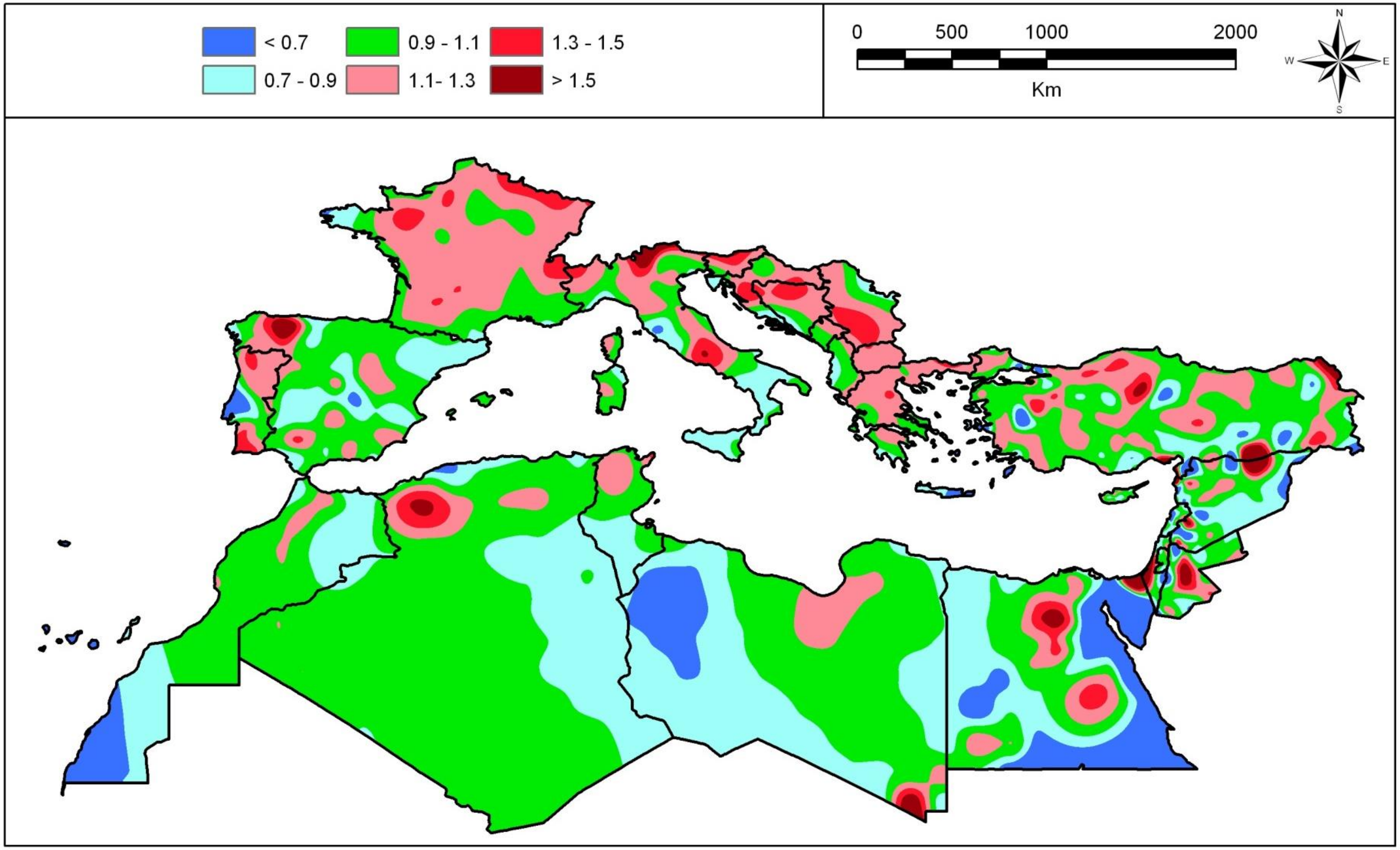
- FAO-PM shows the best performances under both humid and arid conditions, although a slight underestimation is observed in arid zones during the summer months. FAO-PM is recommended as the standard method for ETo estimate.
- Penman method requires local calibration of wind function to achieve satisfactory results
- Hargreaves method shows reasonable results with under different conditions, although the coefficients used in Eq. could require local calibration. Underestimates ET under high wind conditions and overestimates in humid areas.
- Pan evaporation method is susceptible to the local climatic conditions under which the pans are evaporating.
- Radiation and Priestley-Taylor methods show good results in humid climates where the aerodynamic term is relatively small, but they tend to underestimate ET under arid conditions and high wind.

Annual ET_o (HS) / ET_o (PM-FAO)



Source: Todorovic et al., 2013

Annual ET_o (PMT) / ET_o (PM-FAO)



Source: Todorovic et al., 2013

Crop coefficient Kc: definition and factors affecting it

- Kc is the ratio of the crop ETc to the reference ETo and it represents the integration of four primary characteristics that distinguish the crop from reference grass:
    - crop height (influences r_a)
    - albedo (reflectance) of the crop soil surface (influences Rn)
    - canopy resistance (affected by LAI, leaf age and conditions, etc.)
    - evaporation from soil (especially from exposed soil)
- Factors determining the crop coefficient
    - crop type (height taller crops and close spacing mean greater Kc,)
    - climate (more arid climate and higher windspeed mean greater Kc)
    - soil evaporation (depends on soil wetness)
    - crop growth stages (initial, crop development, mid-season and late season)

ETc estimates

- using Single crop coefficient approach

$$ET_c = K_c ET_o$$

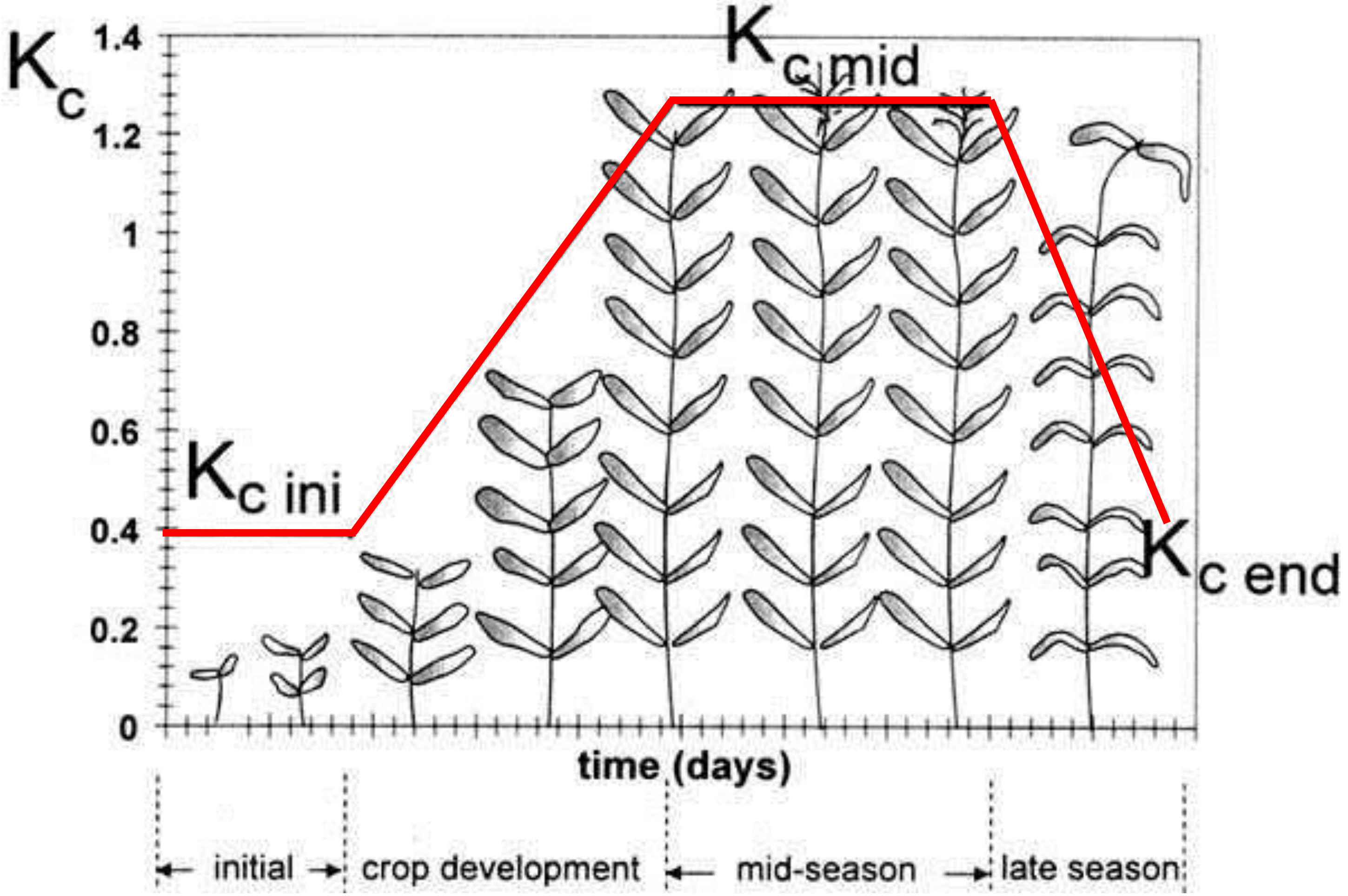
- using Dual crop coefficient approach

  where:

$$ET_c = (K_{cb} + K_e) ET_o$$

  - Kc - crop coefficient
  - Kcb - basal crop coefficient
  - Ke - soil evaporation coefficient
  - ETo - reference evapotranspiration

Generalized Kc curve
for the single crop coefficient approach

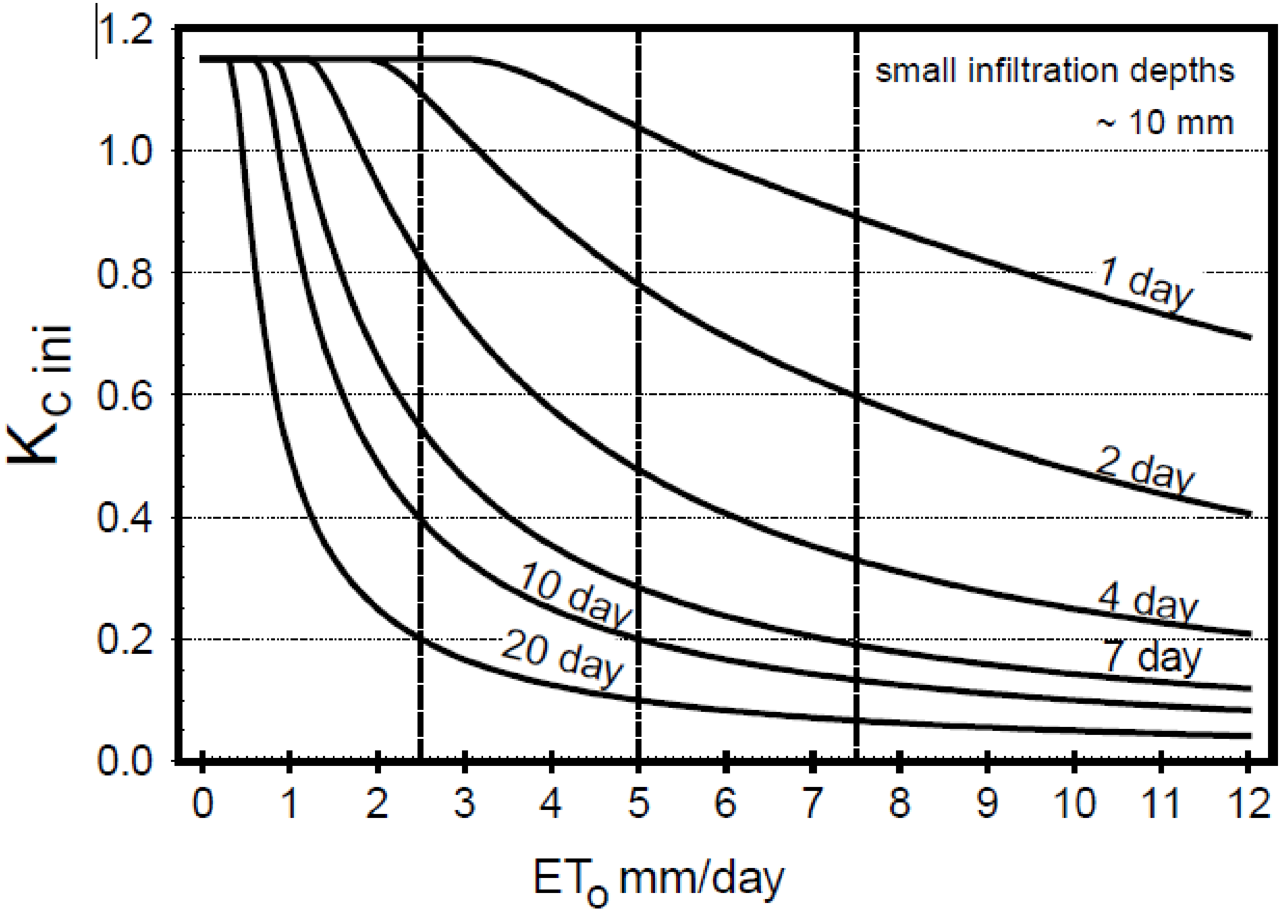


Source: FAO 56, 1998

How to estimate Kc initial? Case 1: small infiltration depths

FIGURE 29

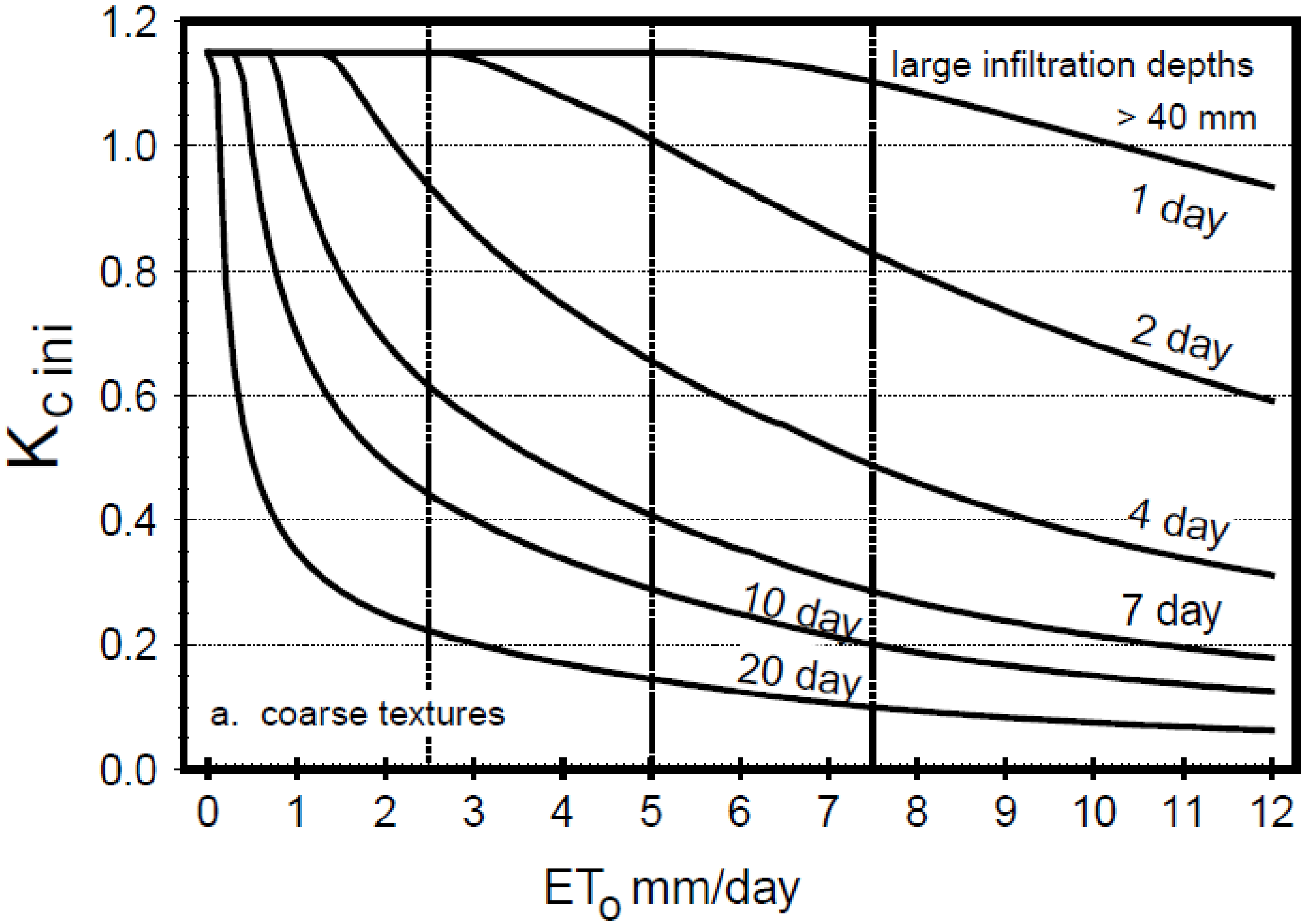
Average $K_{c\ ini}$ as related to the level of ET_o and the interval between irrigations and/or significant rain during the initial growth stage for all soil types when wetting events are light to medium (3-10 mm per event)



How to estimate Kc initial?
Case 2: large infiltration depths and coarse textured soil

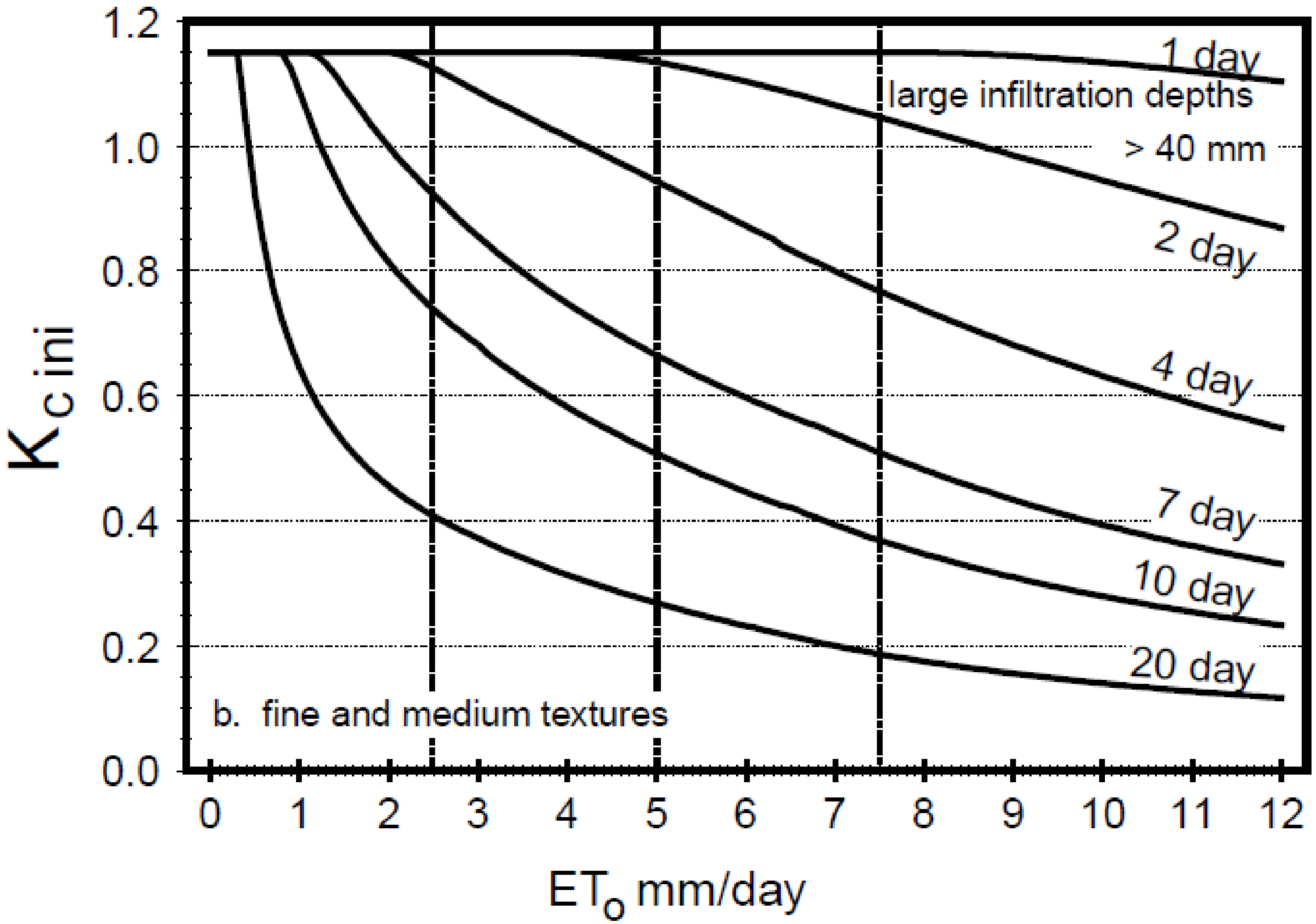
FIGURE 30

Average $K_{c\ ini}$ as related to the level of ET_o and the interval between irrigations greater than or equal to 40 mm per wetting event, during the initial growth stage for a) coarse textured soils; b) medium and fine textured soils



How to estimate Kc initial?

Case 3: large infiltration depths and fine and medium textured soil



Approximate values of Kc initial for medium wetting events (10-40 mm) and a medium textured soil

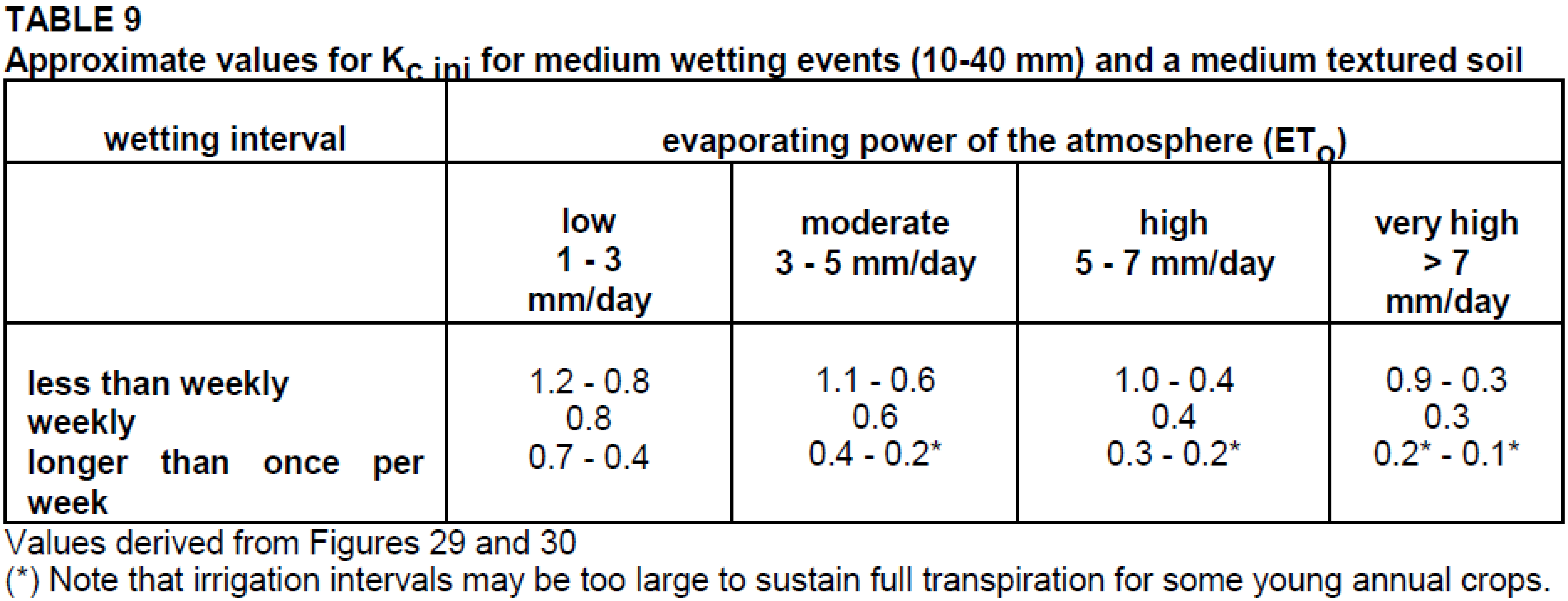


TABLE 9

Approximate values for $K_{c\ ini}$ for medium wetting events (10-40 mm) and a medium textured soil

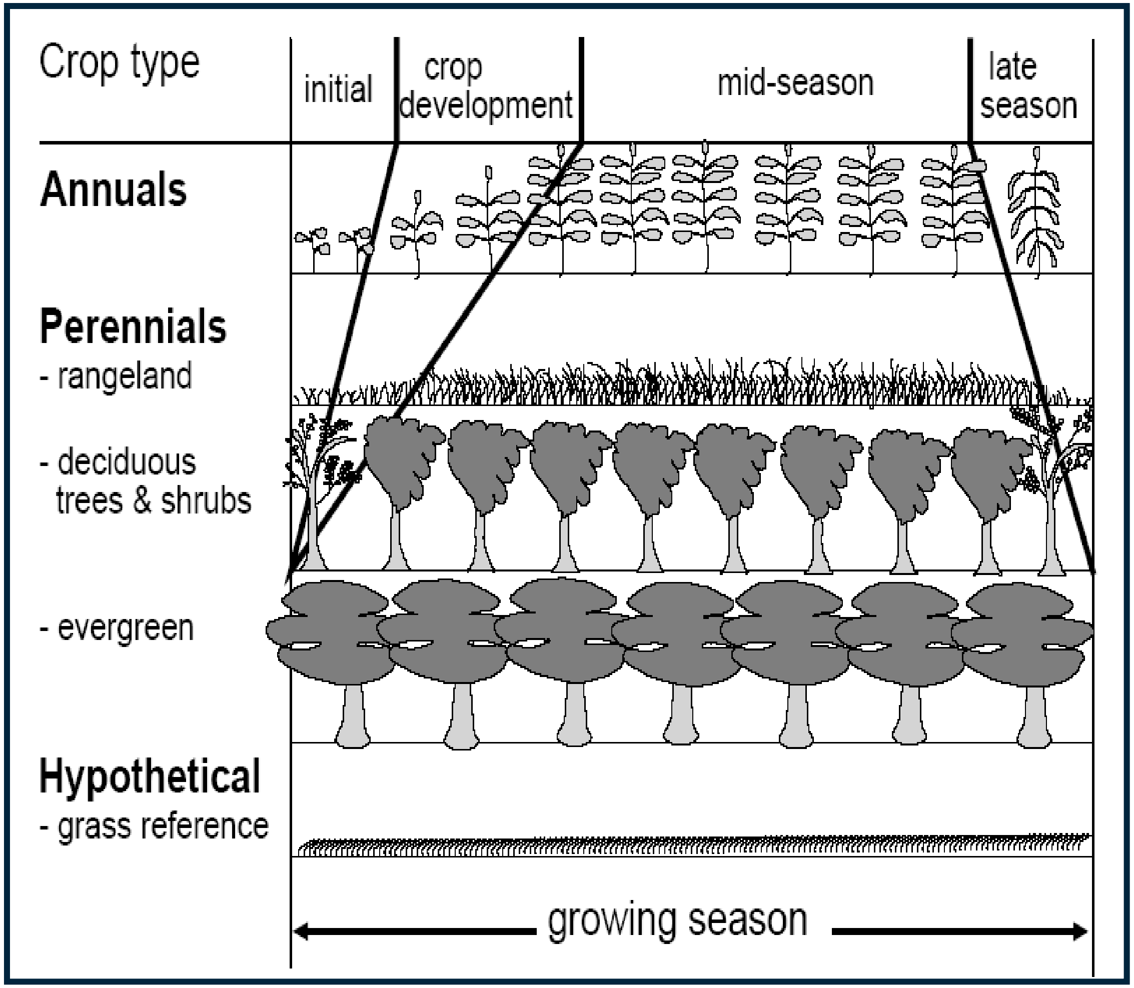
wetting interval	evaporating power of the atmosphere (ET_o)			
	low 1 - 3 mm/day	moderate 3 - 5 mm/day	high 5 - 7 mm/day	very high > 7 mm/day
less than weekly	1.2 - 0.8	1.1 - 0.6	1.0 - 0.4	0.9 - 0.3
weekly	0.8	0.6	0.4	0.3
longer than once per week	0.7 - 0.4	0.4 - 0.2*	0.3 - 0.2*	0.2* - 0.1*

Values derived from Figures 29 and 30

(*) Note that irrigation intervals may be too large to sustain full transpiration for some young annual crops.

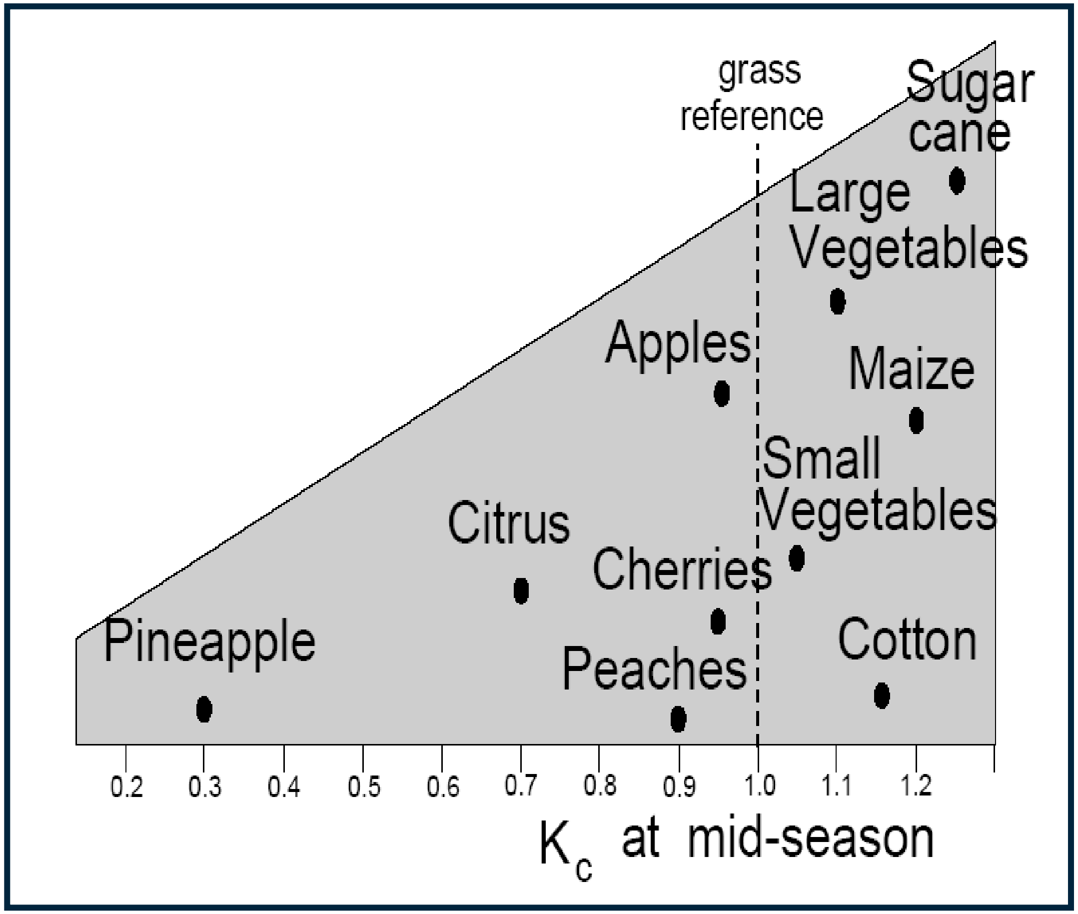
Source: FAO 56, 1998

Crop coefficient Kc: a function of crop type and growing stages



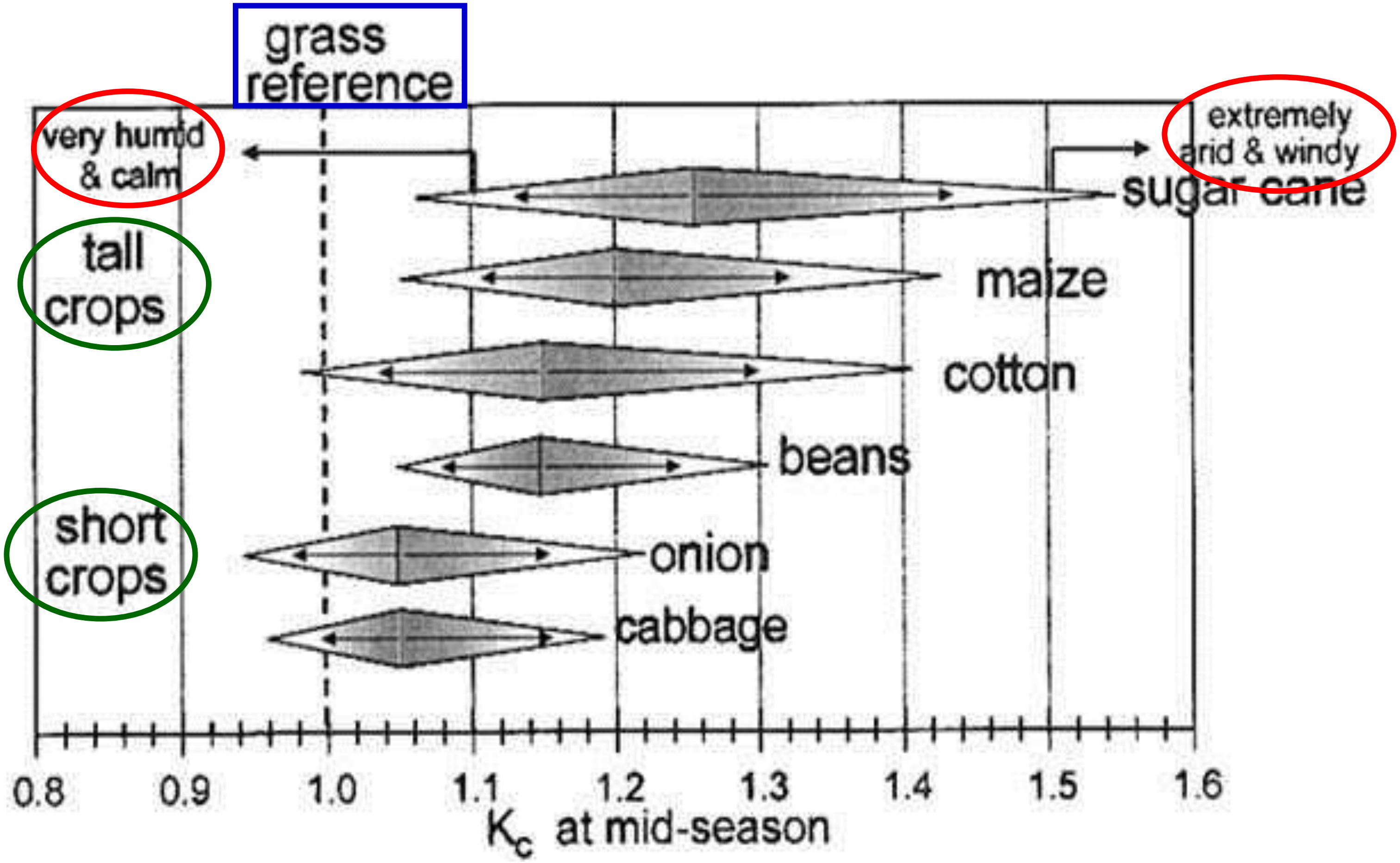
Source: FAO 56, 1998

Crop coefficient Kc: a function of crop type



Source: FAO 56, 1998

Extreme ranges expected in Kc for full grown crops as climate and weather change



Source: FAO 56, 1998

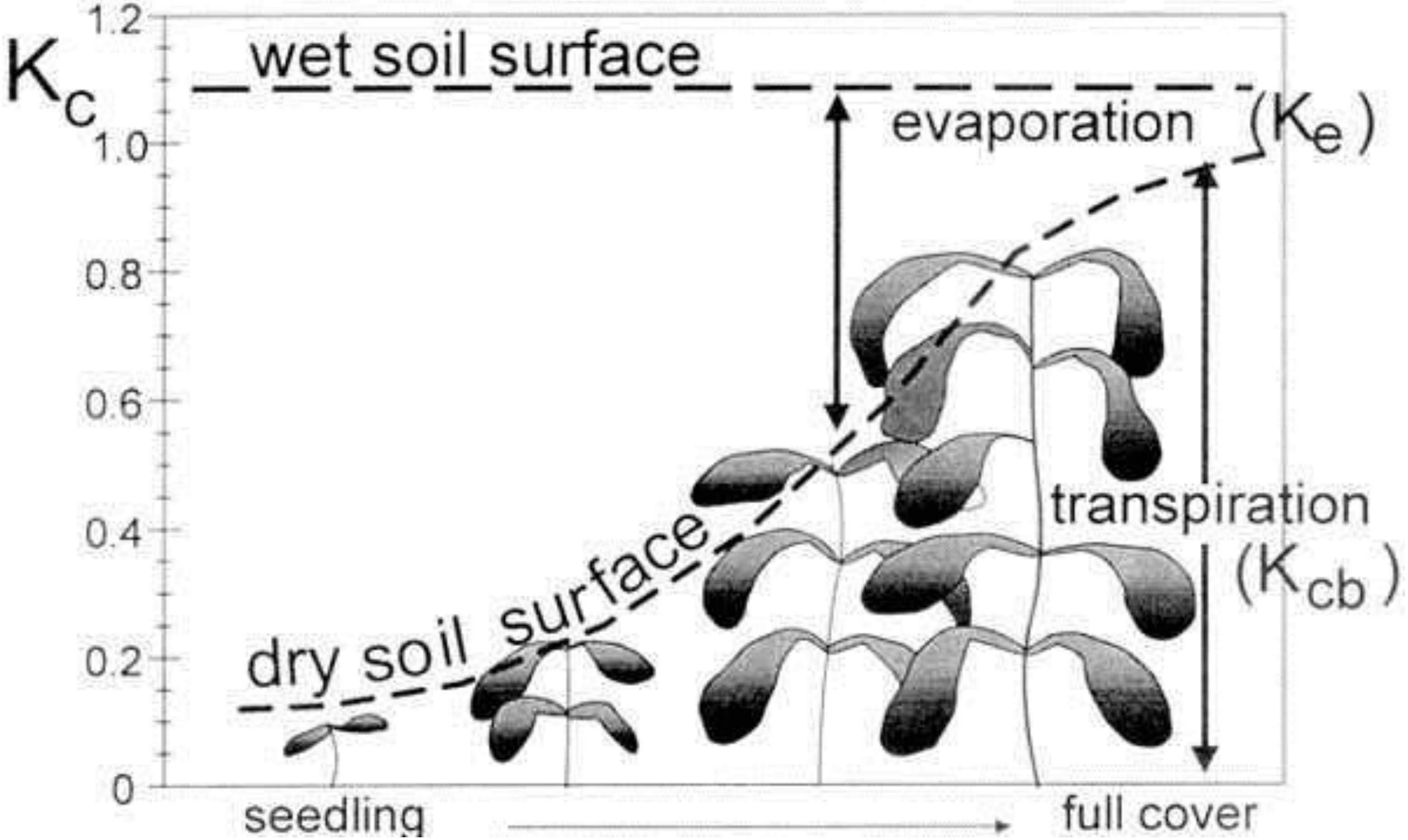
Kc adjustment for climate

$$K_{c\ mid} = K_{c\ mid\ (Tab)} + [0.04\,(u_2 - 2) - 0.004\,(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3}$$

- The adjustment should be applied where
  - RH_{min} differs from 45% or where
  - u_2 is larger or smaller than 2.0 m/s
- $K_{c\ (Tab)}$ is the Kc value from the FAO56 database
- h is canopy height in m

Source: FAO 56, 1998

Dual Kc approach – the effect of surface wetting on Kc



Source: FAO 56, 1998

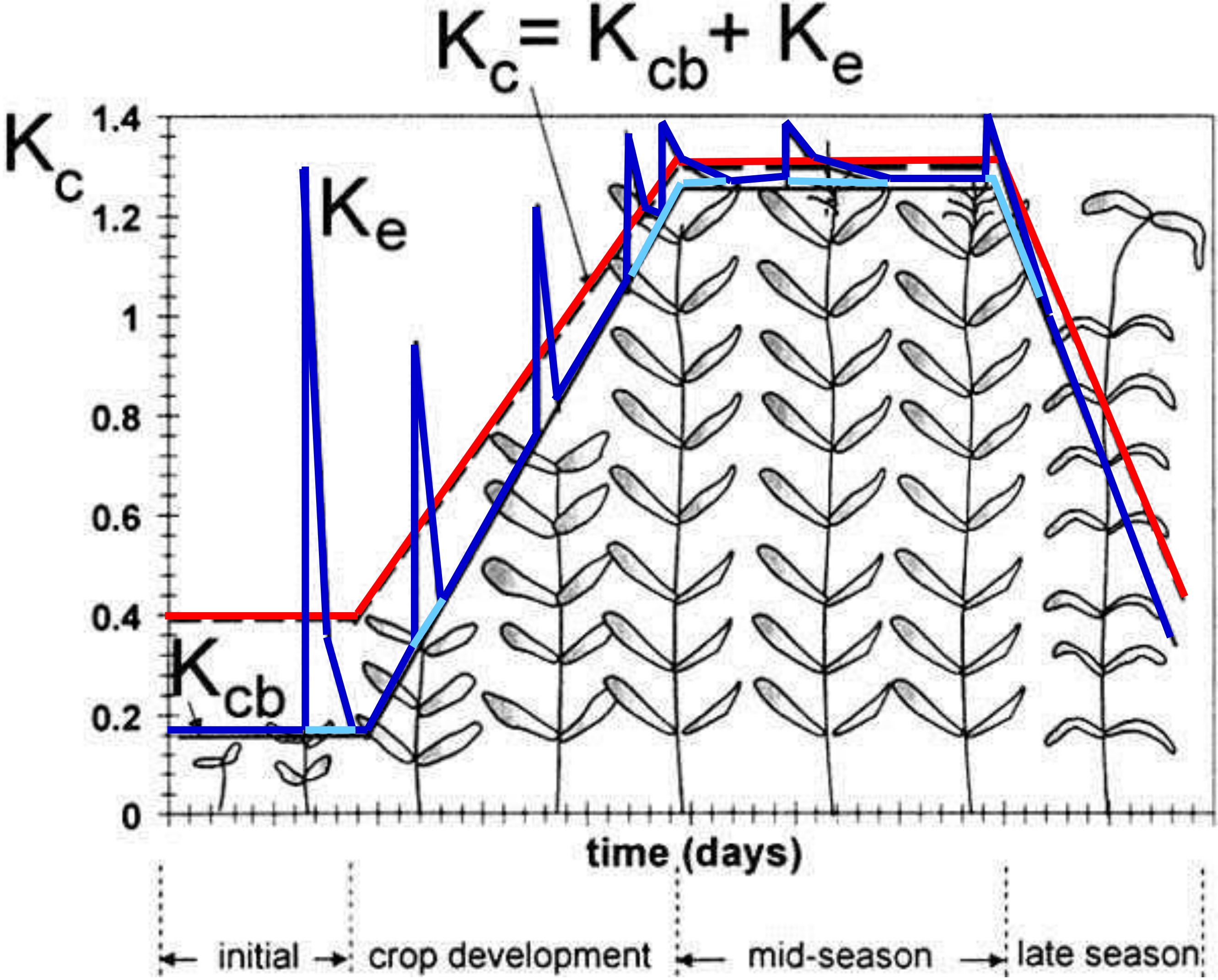
Dual crop coefficient approach

$K_c=K_{cb}+K_e$

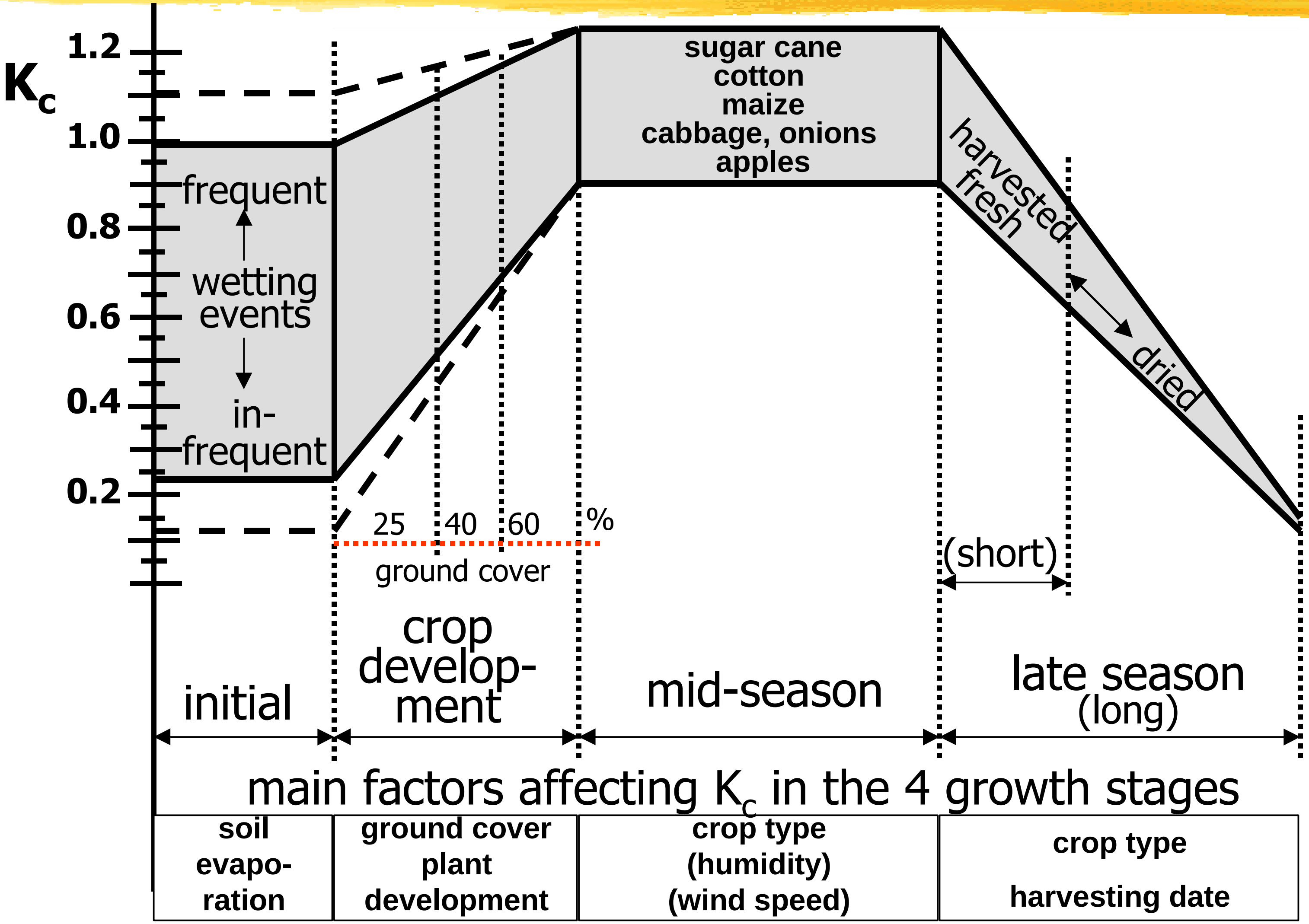
- The basal crop coefficient (Kcb)
  - describes plant transpiration
  - represents the ratio of ETc to ETo when the soil surface layer is dry but where the average soil water content of the root zone is adequate to sustain full plant transpiration
- The soil water evaporation coefficient (Ke)
  - describes evaporation from the soil surface
  - if the soil is wet following rain or irrigation, Ke may be large
  - as the soil surface becomes drier, Ke becomes smaller and falls to zero
- The sum (Kcb+Ke) can never exceed a maximum value Kc,max, determined by the energy available for evapotranspiration at the soil surface.

The Kc curves

for single and dual Kc approaches



Main factors affecting Kc & typical ranges expected in Kc for the four growth stages



main factors affecting K_c in the 4 growth stages

initial	crop development	mid-season	late season
soil evapo-ration	ground cover plant development	crop type (humidity) (wind speed)	crop type harvesting date

General selection criteria for the single and dual crop coefficient approaches

	Single crop coefficient K_c	**Dual crop coefficient $K_{cb}+K_e$**
Purpose of calculation	- Irrigation planning and design - Irrigation management - Basic irrigation scheduling - Real time irrigation scheduling for non-frequent water applications (surface and sprinkler irrigation)	❑ Research ❑ Real time irrigation scheduling ❑ Irrigation scheduling for high frequency water application (micro-irrigation and automated sprinkler irrigation) ❑ Supplemental irrigation ❑ Detailed soil and hydrologic water balance studies
Time step	❑ Daily, 10-days, monthly	❑ Daily
Solution method	❑ Graphical ❑ Pocket computer ❑ PC	❑ PC

Source: adapted after FAO 56, 1998

Mean monthly crop coefficient (Kc) values for ETc estimate of some important crops grown in Southern Italy

Crops	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Tree Crops											
Citrus	0.75	0.75	0.7	0.7	0.7	0.65	0.65	0.65	0.65	0.65	0.7	0.7
Cherry	-	-	-	0.75	0.9	0.95	0.95	0,9	0,86	-	-	-
Olive tree	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Peach	-	-	0.53	0.71	0.81	0.86	0.86	0.84	0.78	0,73	-	-
Grapevine	-	-	-	0.48	0.59	0.68	0.68	0.68	0.68	-	-	-
Vegetables Crops												
Autumn Sugar Beet	0.5	0.5	0.5	0.87	1.20	1.30	1,30	-	-	-	0.4	0.4
Spring Sugar Beet		0.35	0.62	1.10	1.20	1.24	1.24	0.95	-	-	-	-
Artichoke	1.25	1.15	0.95	-	-	-	0.6	0.7	0.8	1.05	1.22	1.3
Carrot	-	-	-	-	-	-	0.4	0.7	0.9	1	1.05	1.00
Cereals (durum wheat)	0.8	1.0	1.1	1.15	0.85	0.35	-	-	-	-	0.4	0.6
Broad bean	0.8	0.9	0.95	0.95	0.9	-	-	-	-	-	0.4	0.65
Sunflower	-	-	-	0.4	0.85	1.20	1.02	0.45	-	-	-	-
Lettuce	1	1	0.9	-	-	-	-	-	-	-	0.75	0.9
Maize	-	-	-	0.45	0.6	1.05	1.2	0.6	-	-	-	-
Eggplant	-	-	-	0.30	0.45	0.7	1	1.15	1.00	-	-	-
Early Potato	0.5	0.8	1.1	1.15	0.9							
Common Potato	-	-	0.5	0.8	1.1	1.15	-	-	-	-	-	-
Tomato	-	-	-	0.5	0.87	1.2	1.1	0.8	-	-	-	-
Pepper	-	-	-	0.64	0.75	1	1	0.8	-	-	-	-
Soya	-	-	-	0.4	0.51	0.9	1	0.4				
Watermelon*	-	-	-	0.45	0.85	1	0.8	-	-	-	-	-

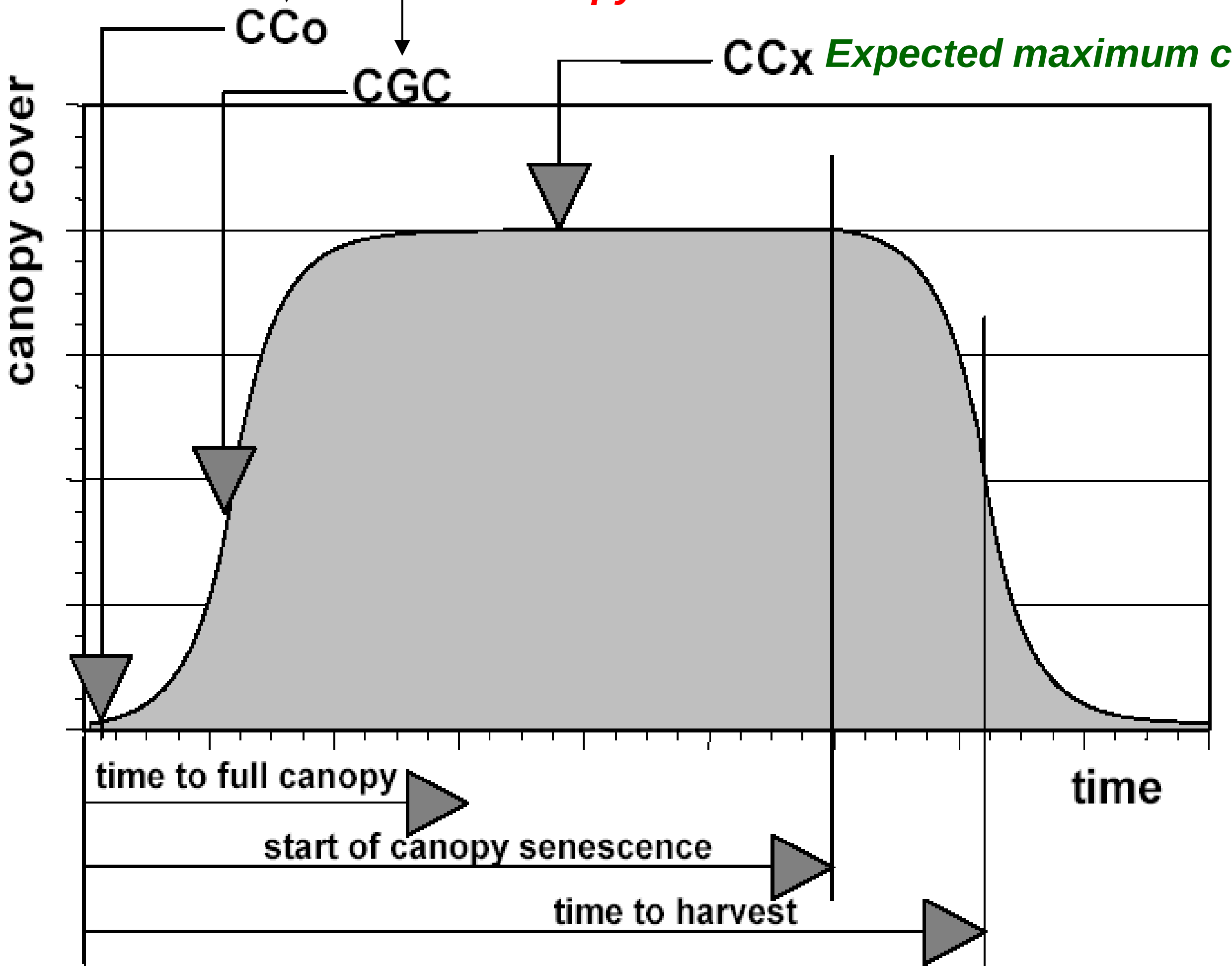
Data are based on the experimental works carried out in Apulia (University of Bari) and on other databases (FAO 56).

How to improve Kc approach? AquaCrop approach
Using Green Canopy Cover instead of Kc!?

Starting canopy size

Canopy Growth Coefficient

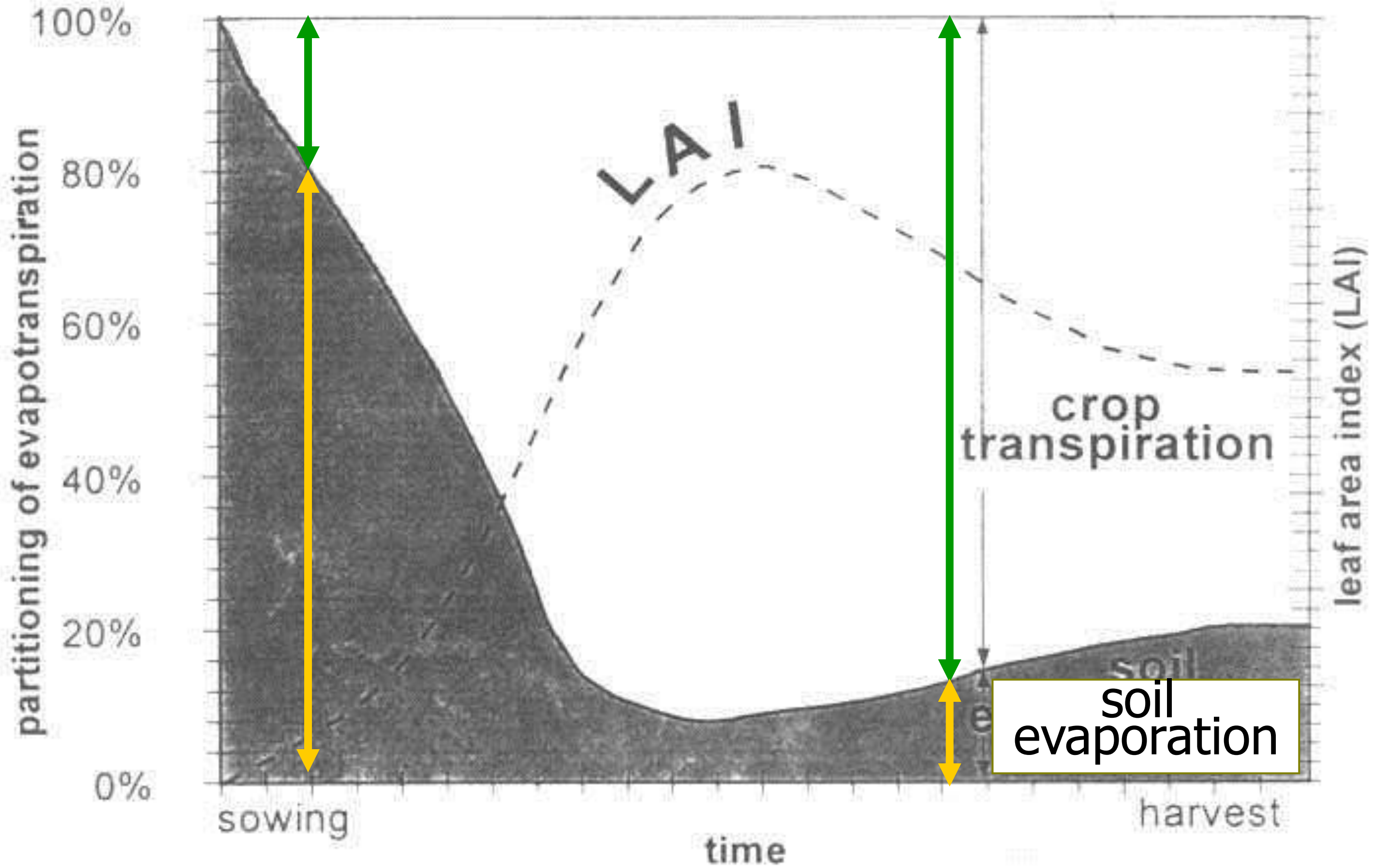
Expected maximum canopy



CGC is derived from the required time to reach full canopy

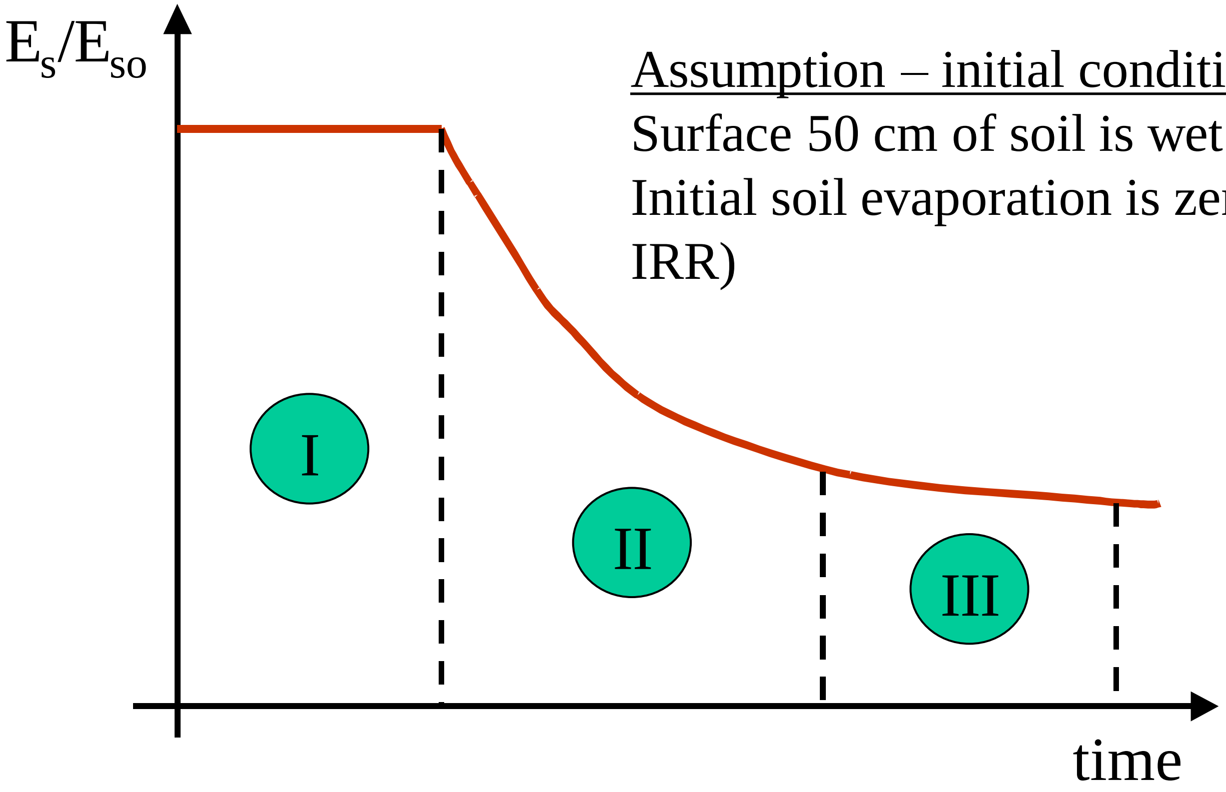
The partitioning of evapo-transpiration

over the growing period for an annual field crop



Source: FAO 56, 1998

RITCHIE evaporation MODEL from bare soil



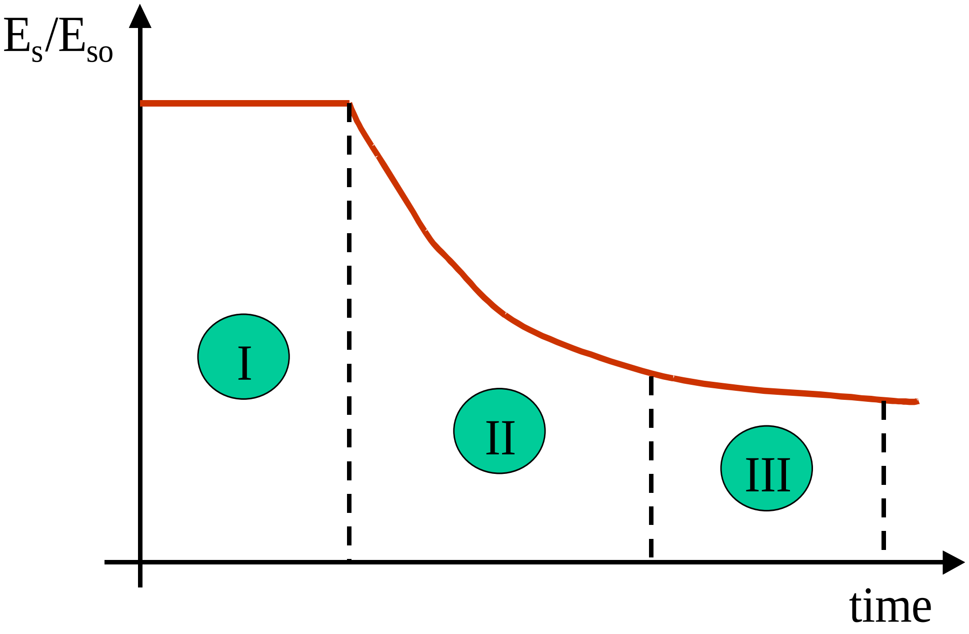
Assumption – initial conditions:
Surface 50 cm of soil is wet to field capacity
Initial soil evaporation is zero (for day of P or IRR)

Stage I – constant rate stage, completely wet surface, $E_s=E_{pot}$

Stage II – falling rate stage, soil starts to dry, $E_s<E_{pot}$

Stage III – soil is almost completely dry, $E_s \rightarrow 0$

RITCHIE MODEL – stage I – constant rate stage



Completely wet surface

Constant soil evaporation rate depends on energy supply reaching the soil surface

Soil evaporation E_s =equal to potential evaporation rate when E_o (VPD→0; WS→0))

ET_{eq} - equilibrium

E(T)

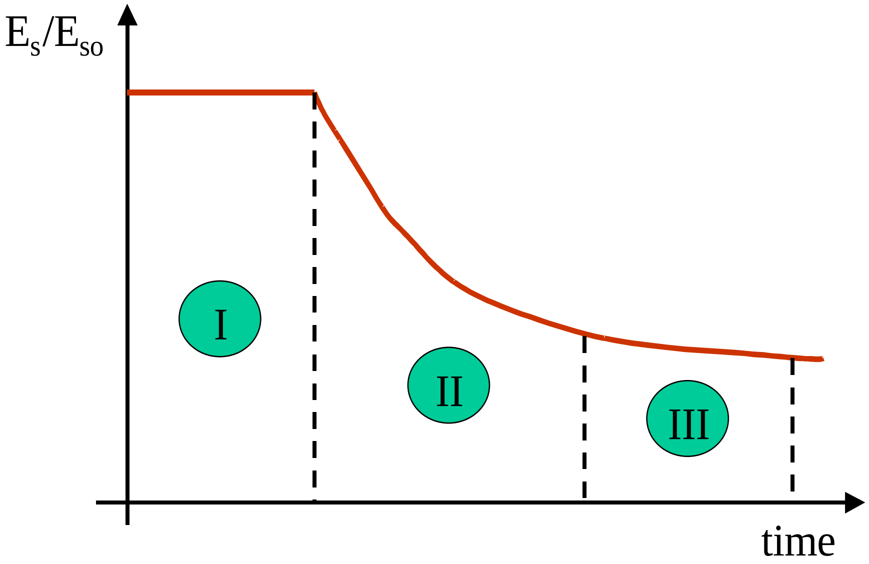
$$E_s = E_{so} = E_o = \frac{s}{s+\gamma} R_n$$

Stage I ends on day when

$\Sigma E_s \geq U$

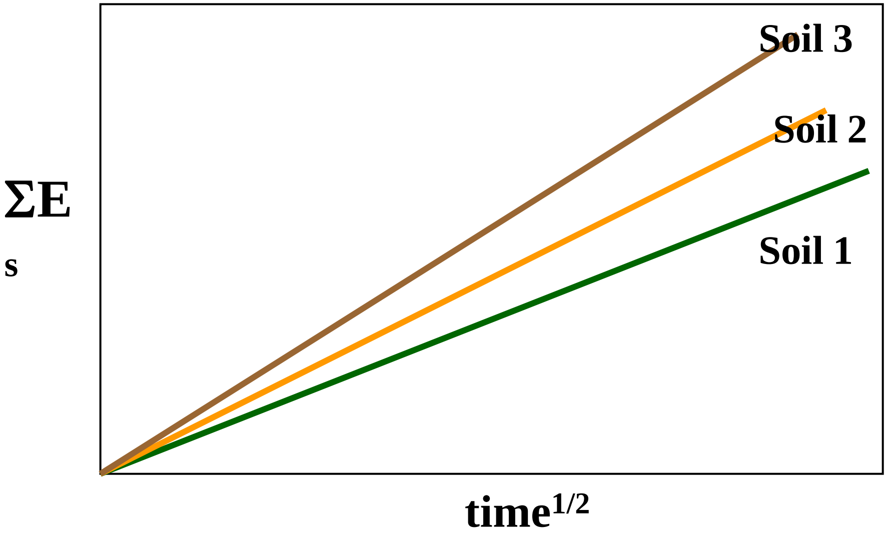
U is an empirical parameter (threshold), depends on soil characteristics

RITCHIE MODEL – stage II – falling rate stage



Stage II starts when
$\Sigma E_s \geq U$

E_s is more dependent on the soil hydraulic properties and less dependent on the available energy



E_s is based on equation

$$E_s = \alpha\sqrt{t}$$

α - empirical parameter in $mm*day^{-1/2}$, depends on soil hydraulic characteristics

t – time in *days* from the start of stage II

RITCHIE MODEL – parameters

Some indicative values of Ritchie model parameters

Soil	K	U	α	Reference
	cm/day	mm	mm/days	
Clay Loam	0.15	12	5.08	Van Bavel et al. (1968)
Loam	0.10	9	4.04	LaRue et al. (1968)
Sandy	0.05	6	3.34	Black et al. (1969)

K is hydraulic conductivity

Some formulas suggested by USDA-SCS for estimating U (mm)*:

If Sand<80%, Clay<50%	**then**	**U=8+0.08*(%Clay)**
If Sand>80%	**then**	**U=5+0.15*(%Sand)**
If Clay>50%	**then**	**U=5+0.06*(%Clay)**

***** *The above values should be increased for poorly drained soils***

Ritchie soil evaporation model – how it is working…

<u>Assumptions:</u>

U=12mm, α=5mm/day$^{1/2}$, precipitation refilled 50 cm soil depth at F.C. (initial E_s=0), P=0 for all days after and potential evaporation is constant for all days E_{so}=5mm/day;

<u>Calculation:</u>

Day 1 → E_s=5 mm/day; ΣE_s=5 mm/day; ΣE_s<U

Day 2 → E_s=5 mm/day; ΣE_s=10 mm/day; ΣE_s<U

Stage I

Day 3 → E_s=3.8 mm/day; E_{s_I}=2 mm/day and E_{s_II}=1.8 mm/day

$E_s=E_{so}-0.4(\Sigma E_s-U)=5-0.4(15-12)=3.8$

$E_{s\_II}=0.6(\Sigma E_s-U)=0.6(15-12)=1.8$ mm/day

$E_{s\_I}=E_s-E_{s\_II}=3.8-1.8=2.0$ mm/day

passage
from Stage I
to stage II

Empirical equations

Day 4 → $E_s=\alpha*t^{1/2}-E_{s\_II\_(day\ before)}$= 5 - 1.8 = 3.2 mm/day (t=1)

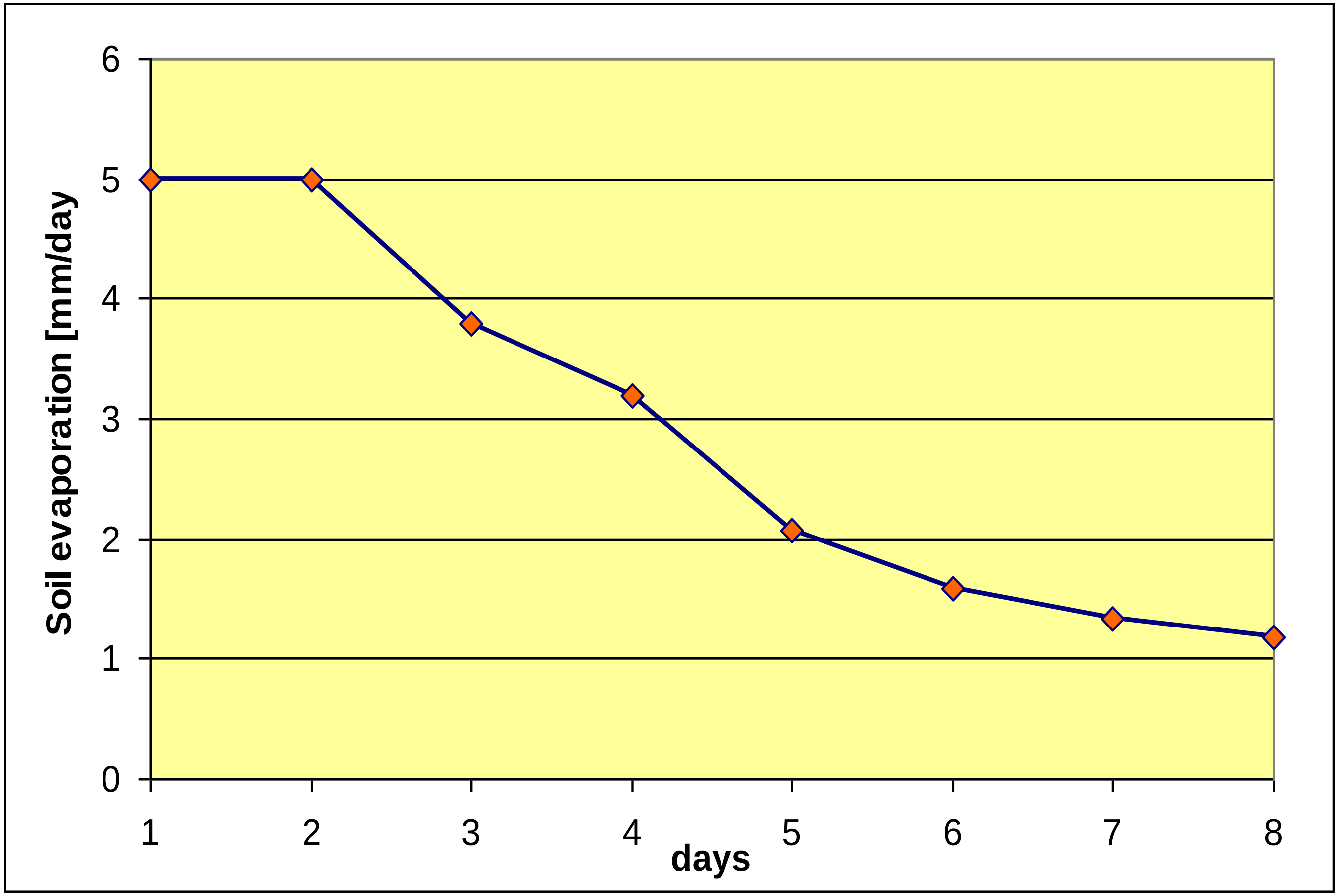
Day 5 → $E_s=\alpha*t^{1/2}-\alpha*(t-1)^{1/2}$= 7.07 - 5.0 = 2.07 mm/day (t=2)

Day 6 → $E_s=\alpha*t^{1/2}-\alpha*(t-1)^{1/2}$= 8.66 - 7.07 = 1.59 mm/day (t=3)

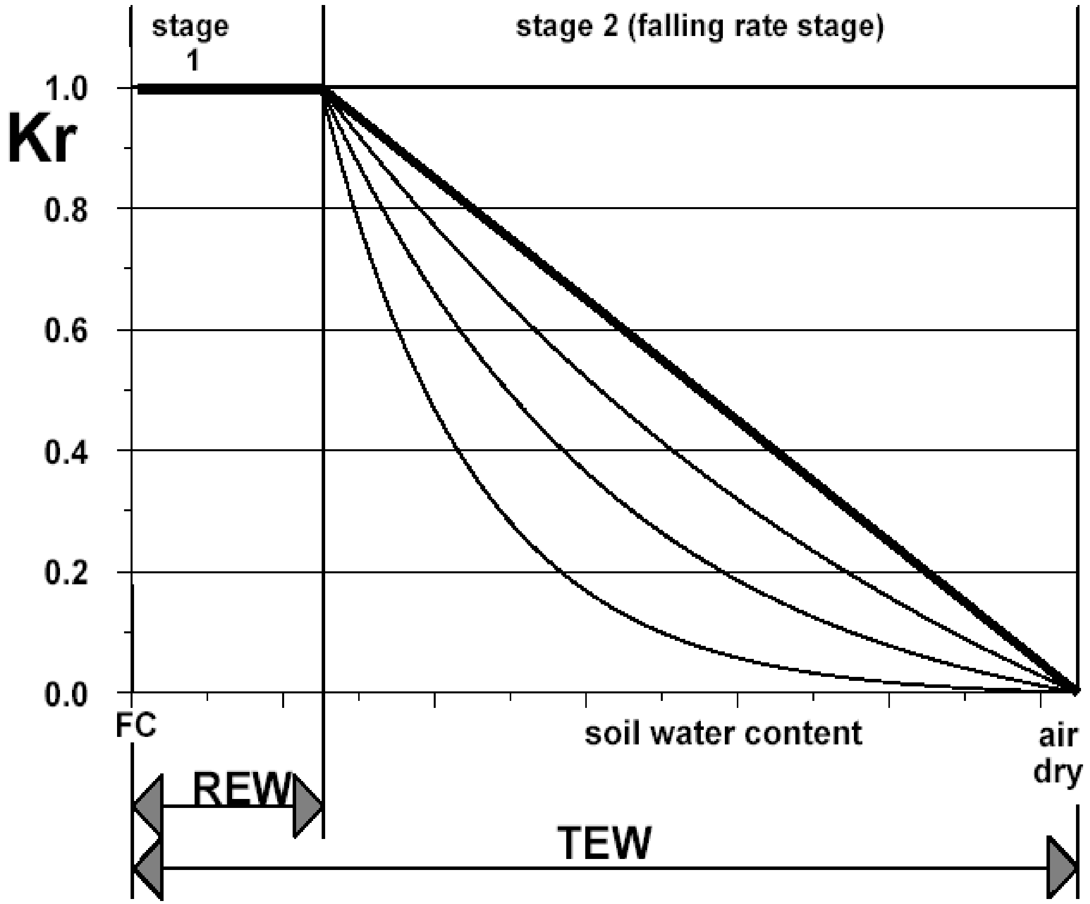
Day 7 → $E_s=\alpha*t^{1/2}-\alpha*(t-1)^{1/2}$= 10.0 - 8.66 = 1.34 mm/day (t=4)

Stage II

Ritchie model – graph with results



AQUACROP approach –
Soil Evaporation estimate



Soil type	REW default
Sandy	4 mm
Loamy	10 mm
Clay	12 mm

Falling rate stage decrease functions – program parameters

Readily Evaporable Water (REW)

Ritchie model – pros & cons

- **Advantages:**
  - It can be applied for evapo-transpiration estimate from a crop with incomplete cover (if LAI and light extinction coefficient are known) and under optimum water supply
  - Many on-field experiments have confirmed its validity (after calibration)
- **Disadvantages:**
  - Model should be started when the profile is wet to F.C. to a depth ≥ 50 cm – a solution is proposed for $E_{s\_initial}$ when depth $<$ 50 cm as:

$$E_{s\_initial}=U(D/50)$$

  - When rainfall occurs during stage II, Es does not return to stage I until the profile is refilled – this could lead to an underestimation

Ritchie model – evapo-transpiration from a crop with incomplete cover

- **Basic standpoint theory:**
  - Upper limit ET is assumed as $ET_{max}=\alpha_{\_ET}*ET_{eq}$, where $ET_{eq}=E_{so}$
  - $\alpha_{\_ET}\cong 1.26$ for several crop under non-advective conditions
  - Pruitt's experiments on ryegrass stand $\alpha_{\_ET}\cong 1.4$ (using R_{n_24}) and $\alpha_{\_ET}\cong 1.2$ (using R_{n_12})
- **Evaporation:**
  - $E_{max} = \alpha_{\_E}\,\tau\;\; ET_{eq}$, where $\tau = R_{nG}/R_n \cong e^{(-\beta LAI)}$, $\alpha_{\_E} \cong 1.0$
- **Transpiration:**
  - $T_{max} = \alpha_{\_T}\,(1-\tau)\; ET_{eq}$
  - Ritchie & Burnett (1971), experimental results:
    - $T_{max}=(-0.21+0.70LAI^{1/2})ET_{max}$, for $(0.1\leq LAI\leq 2.7)$

Evapo-transpiration

- Partitioning of ET_{crop} :

$$ET_{crop} = E_{pot} + T_{pot}$$

- E_{pot} is estimated by means of a Ritchie-type equation:

$$E_{pot} = f * e^{(-c * LAI)} * ET_{crop}$$

f : regression coefficient ≅ 1.0
c : regression coefficient, between 0.6 and 0.7
LAI : leaf area index $[m^2 m^{-2}]$

- When LAI=0 then :

$$E_{pot} = Kc_{wet,\ bare\ soil} * ET_o$$

$[Kc_{wet,bare\ soil} \cong 1.1]$

- ***Effects of mulches*** on the soil evaporation from non-cropped fields :

$$E_{pot} = (1 - f_m \frac{\%covered}{100}) Kc_{wet\_bare\_soil} ETo$$

$f_m \approx 0.5$ for organic mulches; $f_m \approx 1.0$ for plastic mulches

Evapo-Transpiration

- **Actual evaporation** is obtained by integrating E_{pot} over the entire topsoil and introducing weighing factors and wetness coefficient (α)

$$\boxed{E_{act} = \int \alpha . fw.E_{pot} dz}$$

- **Actual transpiration** is calculated by means of S_i (water uptake by root) - the amount of water extracted by the roots per unit of bulk volume of soil, per unit of time [$m^3 m^{-3} day^{-1}$]

$$\boxed{S_i = K_{s,i} * S_{max}}$$

S_i : sink term [m^3 m^{-3} day^{-1}] at soil depth *i*
$K_{s,i}$: water stress factor [non-dimensional, from 0 to 1] for soil water conten
S_{max} : maximum water uptake by roots

- **Actual transpiration** is obtained by integrating water uptake over the entire root depth

$$T_{act} = \int_{\textbf{top}}^{\textbf{bottom}} S_i dz$$

Errors in measurements

- All agro-meteorological/evapotranspiration measurements contain error.
- **Systematic error:** associated with sensor calibration bias, improper sensor functioning/operation/placement, inaccurate sensor recording, inadequate or incorrect model associated with data interpretation or processing, unrepresentative vegetation characteristics, improper data reduction procedures, and improper use of time-step integration.
- **Random error:** associated with resolution of sensor readings, electronic noise, mechanically induced noise, thermal responses of sensors, vegetation and soil water management, as well as other random error specific to the type of measurement system.
- **Human induced errors:** associated with data-logger error and data reduction programming, error in equipment assembly, error in equipment and sensor maintenance, error in managing the environment of the measurements, and error in sensor placement.

Size of errors in measurements

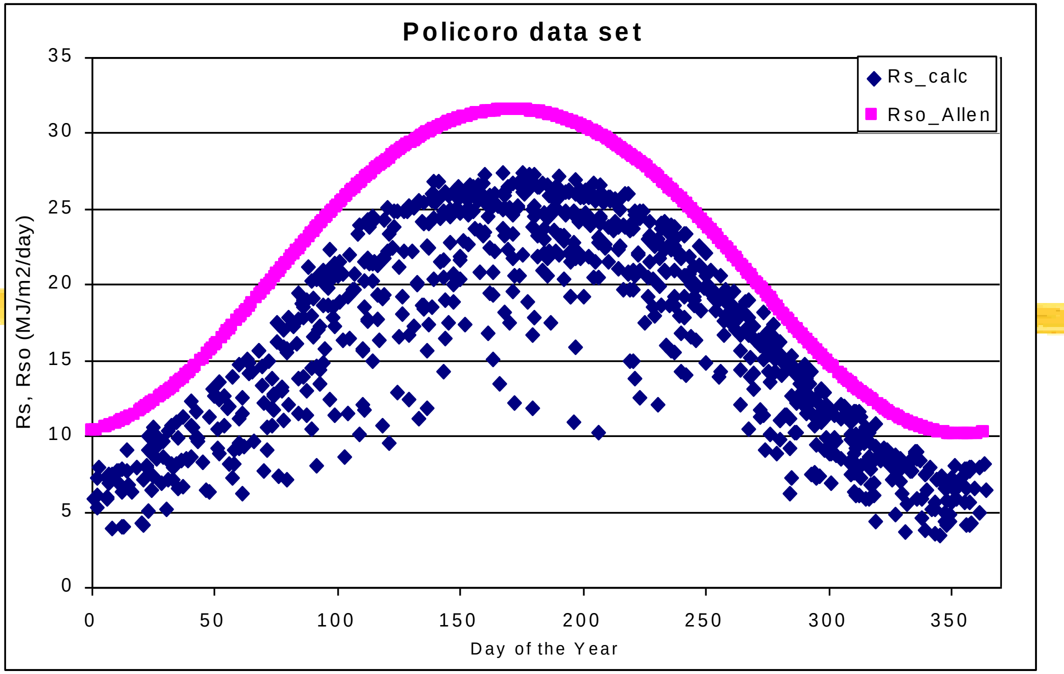
- **Systematic error** does not necessarily reduce with repeated sampling.
- Systematic error associated with a specific component of a measurement process may be additive to systematic error of another component, or may even multiply the other's error, or may partially mitigate the other error by partial compensation in a different direction.
- **Random error** are typically dual-signed and distributed about a mean of 0.
- Repeated sampling over time can reduce random error, often in proportion to the square root of the number of samples.
- **Human-induced error** can be even larger than other systematic error, and is often unavoidable, but is expected to reduce with operator experience, education and training.
- Substantial experience and understanding of the measurement process can partially offset some non-human-associated error components through proactive intervention and adjustment by cognizant operators.

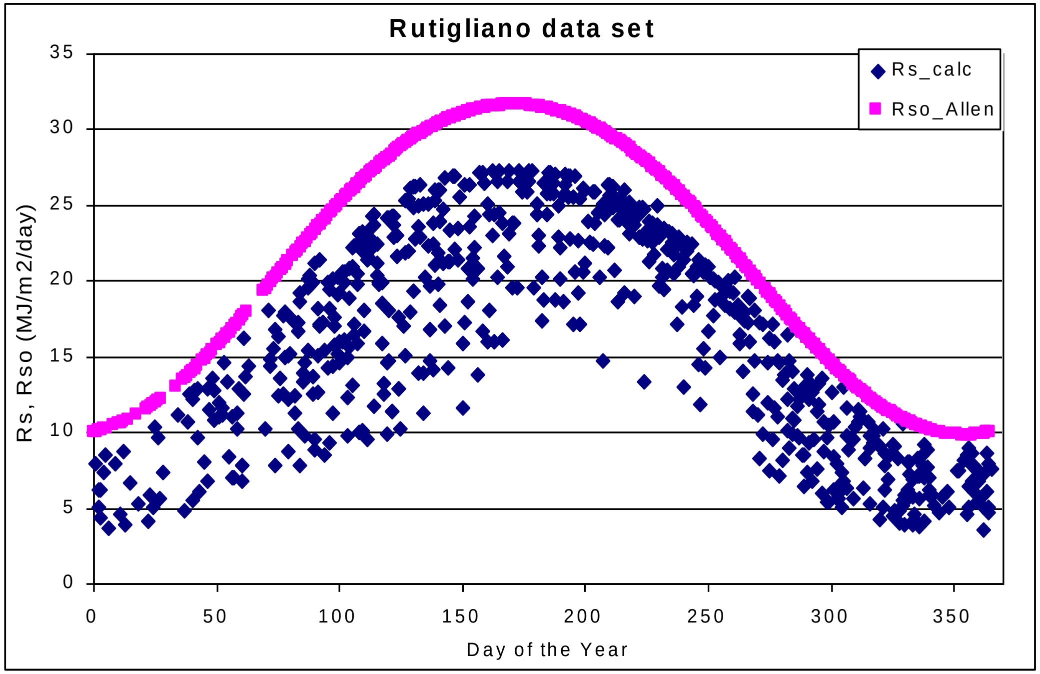
Error, expressed as one standard deviation from the true mean value, expected for various types of ET measurement

Method	Typical error, %	Error for an experienced expert, %	Error for a beginner, %	Additional error caused by equipment malfunction, %
Lysimeter	5-15	5	20-40	5-40
Soil water balance	10-30	10	20-70	10-40
Bowen ratio	10-20	10	20-50	5-40
Eddy covariance	15-30	10-15	30-50	10-40
Remote sensing energy balance	10-20	5-15	30-40	5-10
Remote sensing using vegetation indices	15-40	10-30	20-40	5-10
Sap flow	15-50	10-40	40-200	20-100

Source: Allen et al., 2011

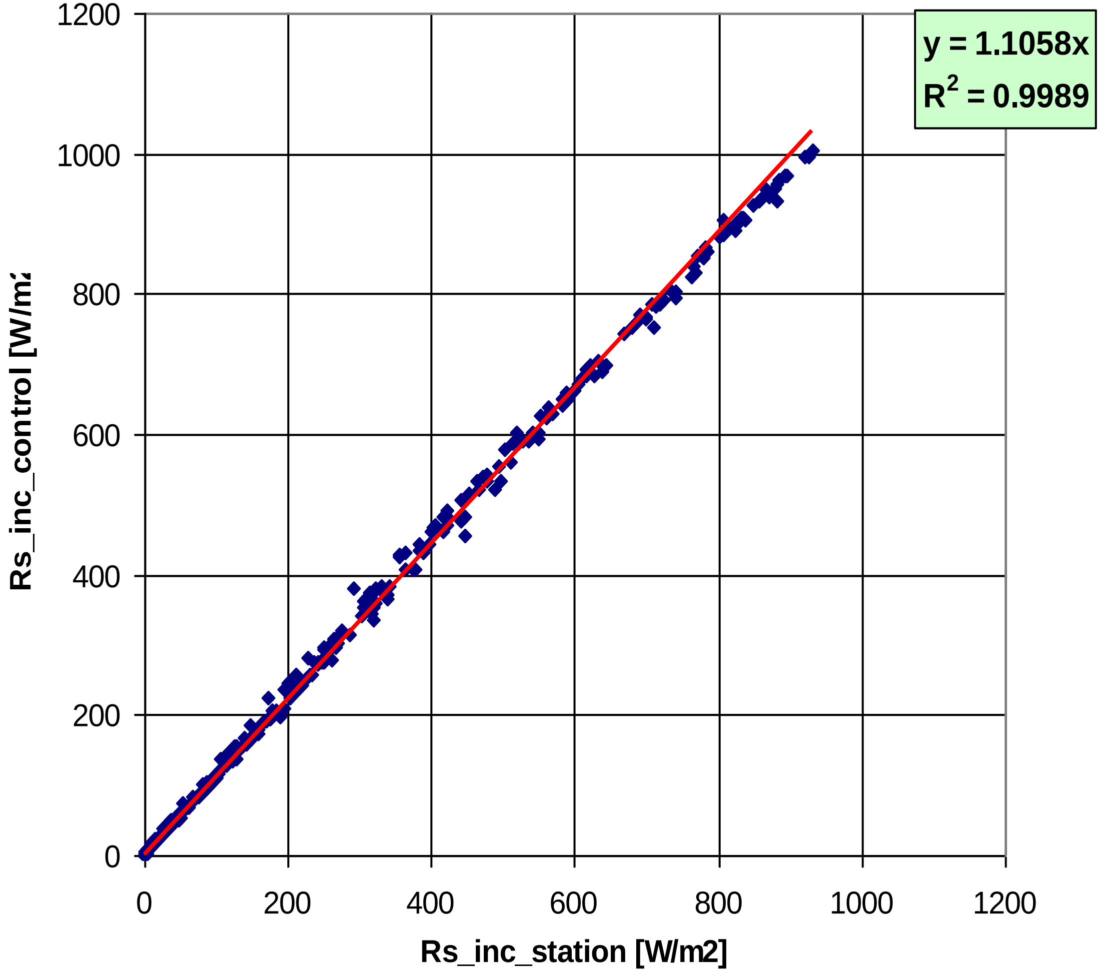
Rs_inc measured vs. maximum theoretically possible values (Policoro, Southern Italy, 1984-1987)



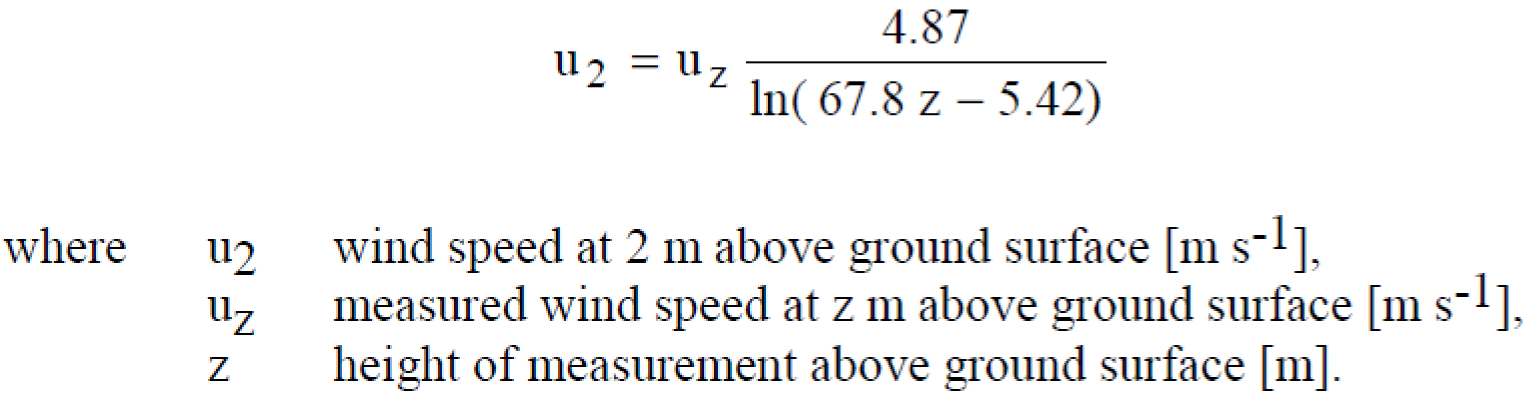


Source: Todorovic, 1998

Rs_inc measured by two radiometers at the same location (Southern Italy, April, 2005)



Wind speed adjustment when measured at height different than 2 m



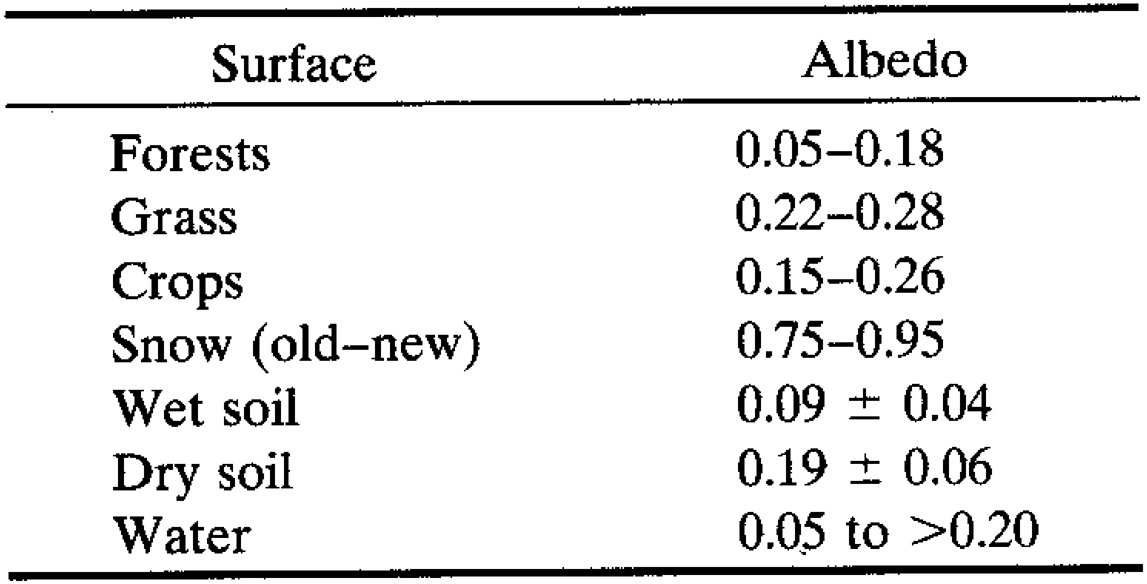
$$u_2 = u_z \frac{4.87}{\ln(67.8\,z - 5.42)}$$

where	u_2	wind speed at 2 m above ground surface [m s^{-1}],
	u_z	measured wind speed at z m above ground surface [m s^{-1}],
	z	height of measurement above ground surface [m].

Reflection coefficient - albedo

varies a lot depending on
species, canopy structure and growing stage

Albedo of various surfaces



Surface	Albedo
Forests	0.05–0.18
Grass	0.22–0.28
Crops	0.15–0.26
Snow (old–new)	0.75–0.95
Wet soil	0.09 ± 0.04
Dry soil	0.19 ± 0.06
Water	0.05 to >0.20

Source: Jones (1992) and Lowry (1969)

How to correct the measurement of precipitation at the rain gauge?

- In most cases, the precipitation amounts are under-measured by rain-gauges
- The correction of P measurements can be done by the following type of equation (site specific, to be verified)

$$\boxed{\mathbf{P_{corrected} = P_{gauge}(exp(0.062WS{\wedge}0.58))}}$$

- WS is wind speed at gauge height, m/s
- The height of rain-gauge is relevant because the precipitation can be under-measured due to WS increases with height

Source: Yang et al., 1996