FRAMEWORK FOR SYSTEMATIC ANALYSIS OF POTENTIAL WATER SAVINGS IN AGRICULTURE, WITH EMPHASIS ON EVAPORATION, TRANSPIRATION AND YIELD WATER PRODUCTIVITY

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- A number of means exist to increase water productivity in agriculture
- Many feasible improvements are minor (e.g., 5 to 20%)
- Professionals in different disciplines tend to focus on their own fields
- Biotechnology is one of the important tools, but not a magic bullet

Much more effective to take a multi-prone approach, go beyond just one or few aspects!

But why? How?

Divide up water use process into sequential steps

Chain of Efficiency Steps – Example: Water from reservoir to root zone:




$$\frac{W_{root\ zone}}{W_{reservoir\ \ in}}$$

Storage efficiency	Conveyance efficiency	Farm efficiency	Application efficiency	Overall efficiency

Sample calculation:

0.90 x 0.85 x 0.72 x 0.75 = **0.413!**

- Although the efficiency of each step is at least reasonable good, the overall efficiency is low

Sample calculation for small improvement in each step:

- The efficiency effects are multiplicative, not just additive

0.92 x 0.885 x 0.86 x 0.87 = **0.610!**

Much improvement

- It follows that minor improvements in several efficiency steps would raise overall efficiency substantially

How do changes in the efficiency steps affect the overall efficiency of the chain?

For any efficiency step

$$E_{new} = (1 + \Delta)\, E_{original}$$

Δ – fractional change in original efficiency

For the overall efficiency

$$E_{all,new} = E_{1\,original}(1 + \Delta_1) \times E_{2\,original}(1 + \Delta_2) \times E_{3\,original}(1 + \Delta_3) \times \ldots\ldots\ldots\ldots$$

Generally then

$$E_{all,\,new} = E_{all,\,original} \times \prod_i \left(1 + \Delta_i\right)$$

For Water Used by Crops to Produce Yield:

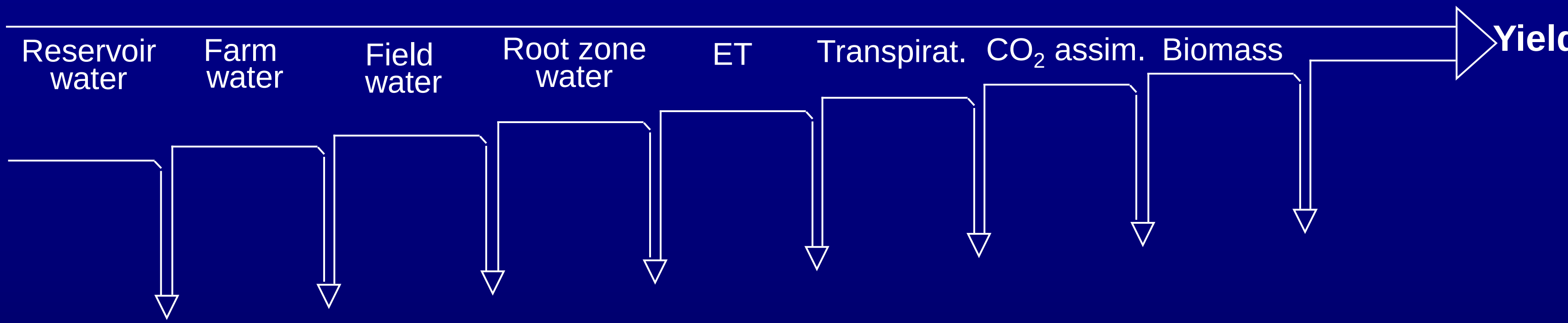
Output (numerator) and input (denominator) are now in terms of water quantity as well as mass of CO_2 or plant material

$$\frac{W_{ET}}{W_{root\ zone}} \times \frac{W_{transp.}}{W_{ET}} \times \frac{m_{CO_2\,assim}}{W_{transp.}} \times \frac{m_{plant}}{m_{co_2\,assim}} \times \frac{m_{harvest}}{m_{plant}} = \frac{m_{harvest}}{W_{root\ zone}}$$

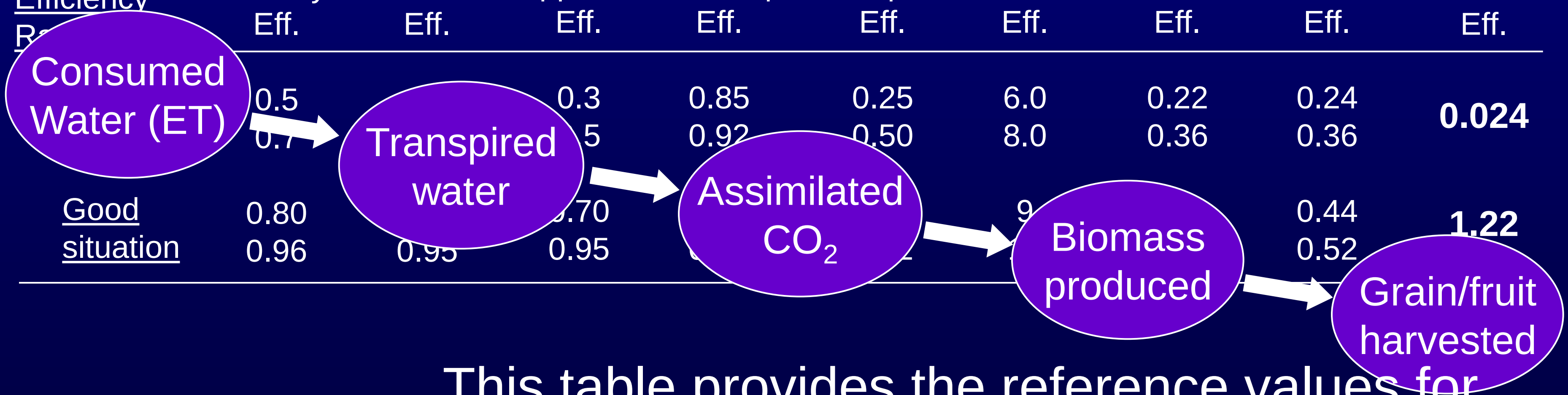
Consumptive efficiency	Transpiration efficiency	Assimilation efficiency	Biomass efficiency	Yield efficiency

Nature of water use for crop production—Chain of efficiency steps

From reservoir water to harvest yield



Efficiency Ra[illegible]	Convey. Eff.	Farm Eff.	Applicat. Eff.	Consumpt Eff.	Transpirat. Eff.	Assim. Eff.	Biomass Eff.	Yield Eff.	Overall Eff.
[illegible]	0.5 0.7	[illegible]	0.3 [illegible]	0.85 0.92	0.25 0.50	6.0 8.0	0.22 0.36	0.24 0.36	**0.024**
Good situation	0.80 0.96	[illegible] 0.95	0.70 0.95	[illegible]	[illegible]	9[illegible] [illegible]	[illegible]	0.44 0.52	**1.22**



Transpiration in exchange for assimilation and yield

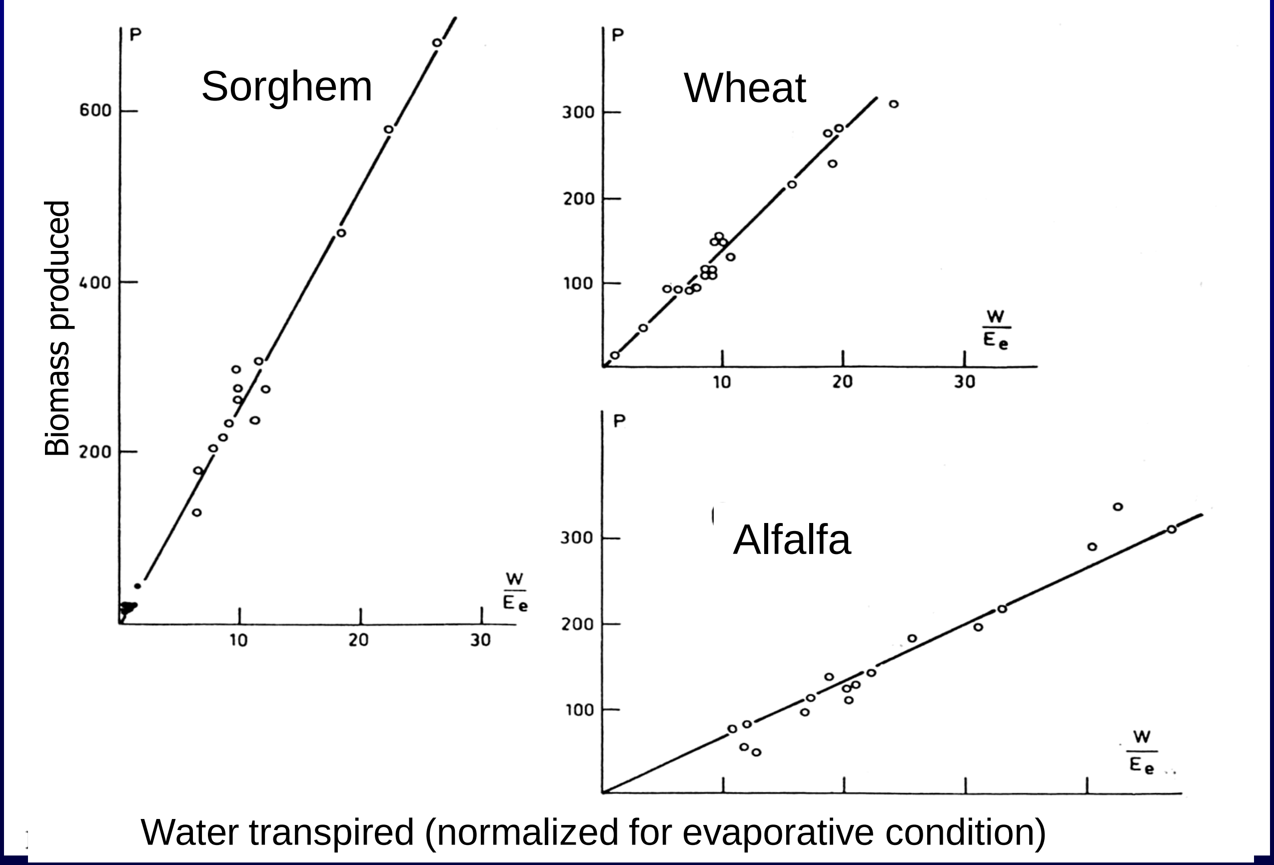
This table provides the reference values for assessing WP of most situations

Overall efficiency is in units of kg yield per m^3 water

How tightly are plant growth and production linked to water?

Classical study shows plant dry matter production is proportional to water transpired. Original data obtained in 1900s-1920s

Slope of the line is basic WP (biomass/water transpired)



Analyzed and normalized for different evaporative demands by De Wit (1958)

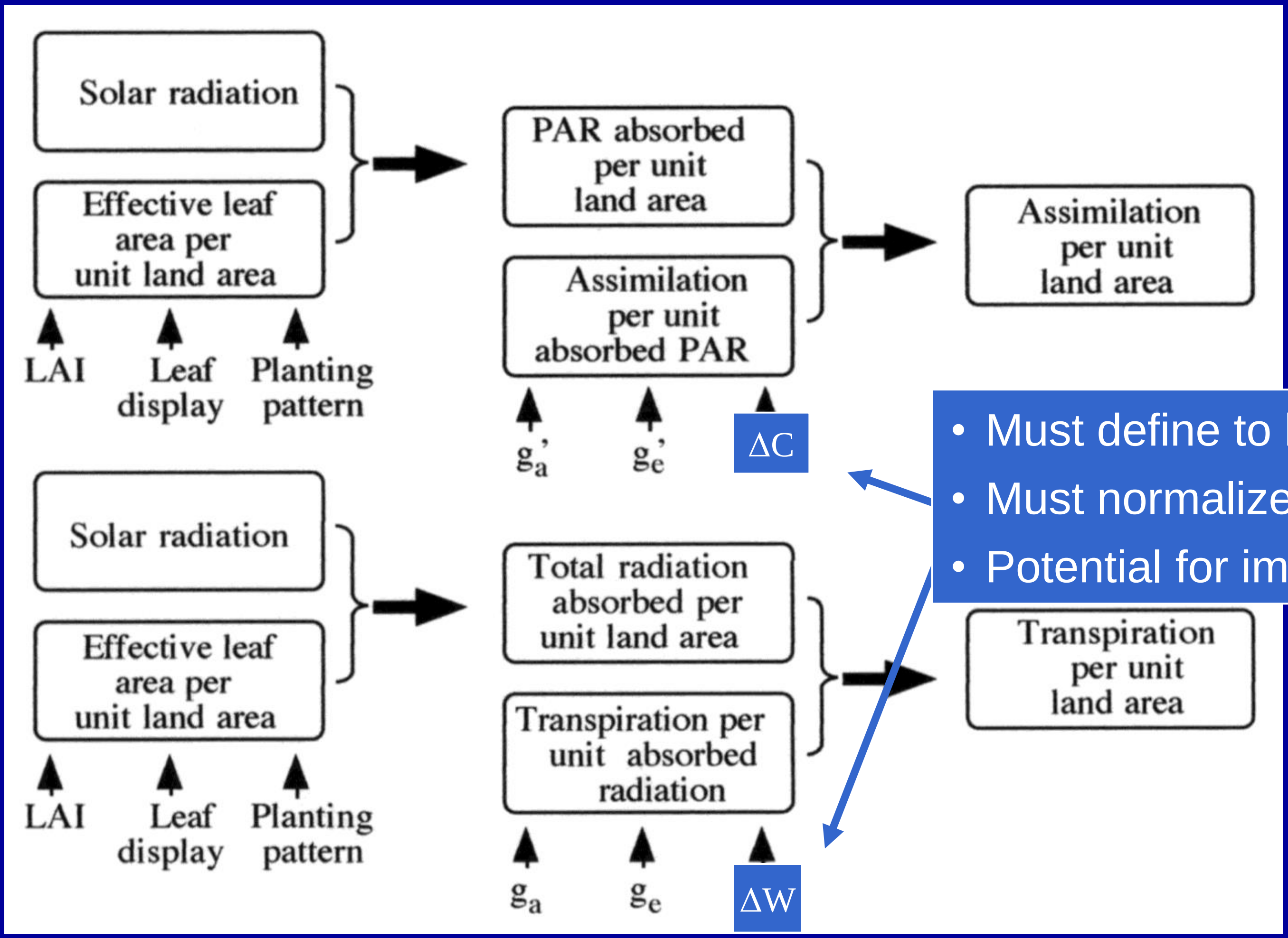
- C4 species (e.g., sorghum) yield more biomass per unit of water transpired than C3 species (e.g., wheat, alfalfa)
- Alfalfa, with large root system, N fixation, and high protein content, requires more assimilates to make its biomass.

Why nearly constant basic WP (WUE)?

Over 96% of plant biomass is derived from photosynthetic assimilates

At the Canopy Level:

Commonality and differences between assimilation and transpiration



- Must define to have constant WUE
- Must normalize if they vary
- Potential for improvements in WUE

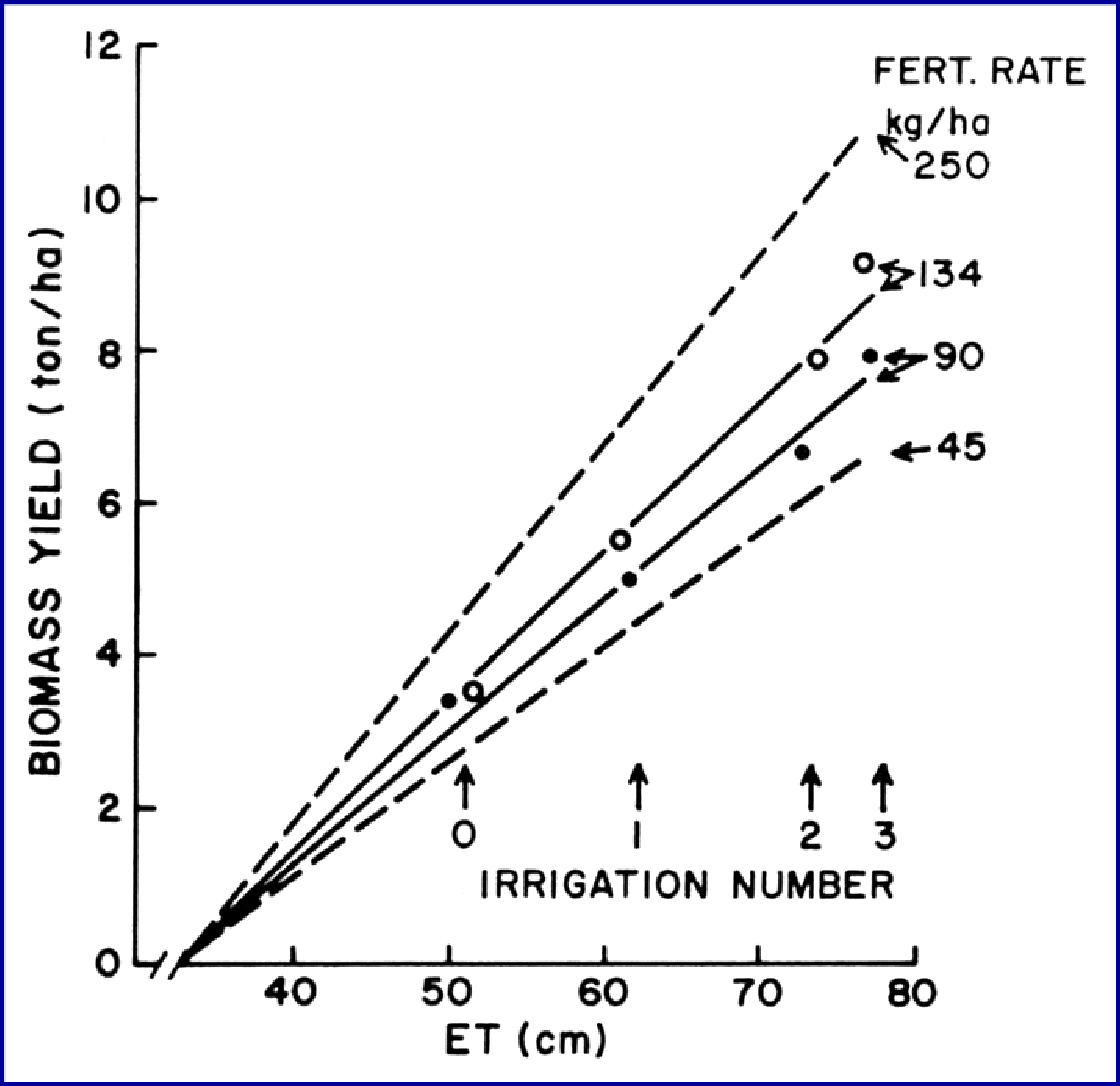
Hsiao (1993)

Near constant basic WUE (Assim Eff. x Biomass Eff.) being the case, how to get more biomass per drop?

There are some leeways:

- Change from a C3 to a C4 crop –ΔC increases
- Change to a CAM crop –ΔC increases and ΔW decreases
- Improve nitrogen nutrition –ΔC increases
- Shifting to cooler part of the season when evaporative demand is lower –ΔW decreases
- Biotechnology and genomics –extremely long term prospect

Biomass production of wheat vs. cumulative evapotranspiration: effects of nitrogen nutrition



Data of Jensen and Sletten (1965), estimates by J. Ritchie (1983)

- Nitrogen makes up the photosynthetic machinery (enzymes, etc.)
- Better N nutrition, better photosynthetic capacity
- Hence, higher assimilation rate, higher biomass production and little direct impact on transpiration
- Hence, higher basic WUE with better N nutrition

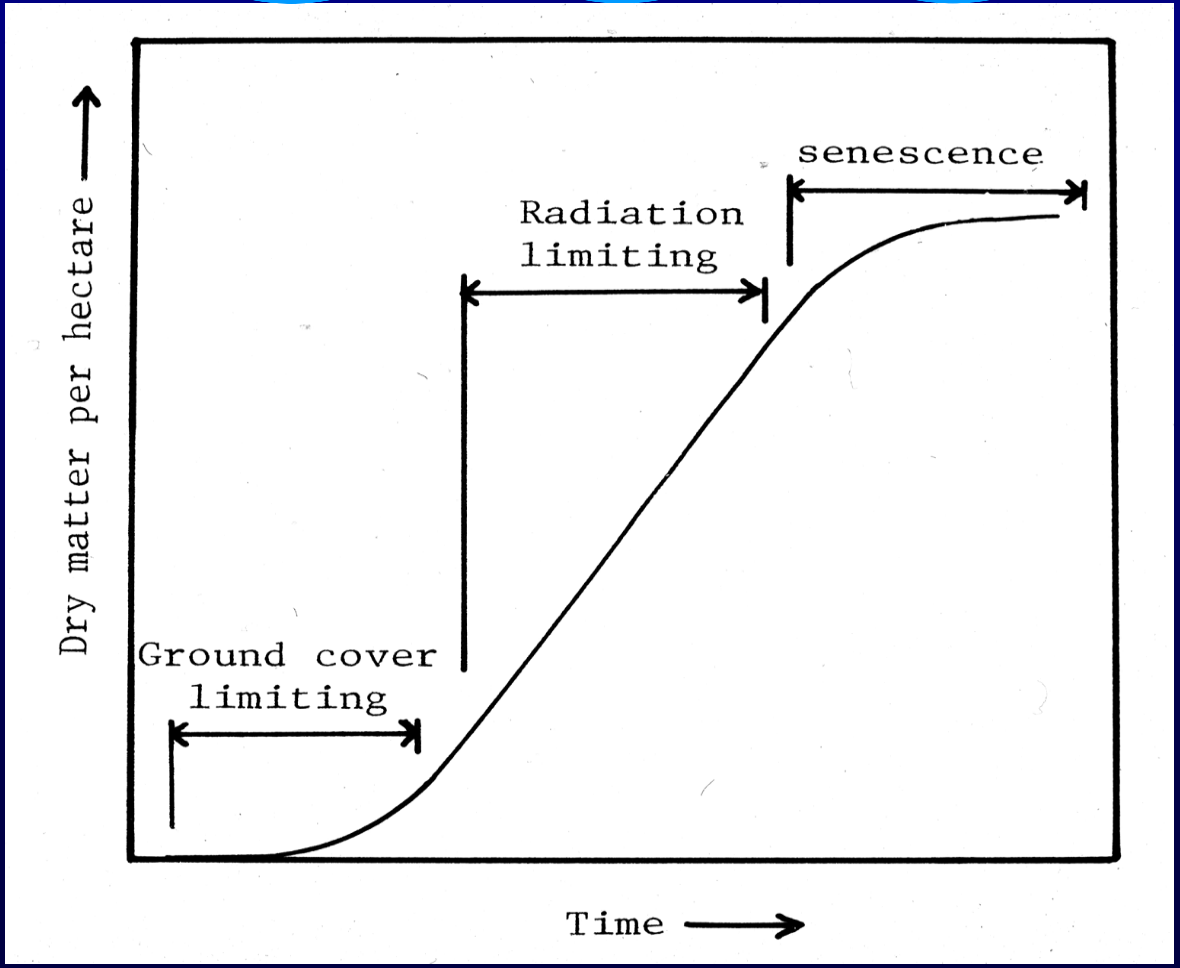
The crop coefficient approach to estimate ET

$$ET = K_c\, ET_o$$

- ET_o (reference ET) is a measure of the evaporative demand of the atmosphere and depends on climatic factors.
- K_c (crop coefficient) is a measure of the effective wetness of the field surface, a composite of surface of the plants and of the soil.

Three Phases of Seasonal Crop Cycle—Link between Crop Coefficient and Biomass Production Rate

Phase 1	Phase 2	Phase 3
$K_c < 1.0$	$1.0 < K_c < 1.2$	$K_c < 1.0$
rising	steady	falling



The three phases of crop coefficient (K_c) correspond to the three phases of biomass production.

The rise in K_c with time in phase 1 is mostly the result of canopy development.

Phase 2 is reached when the canopy closes.

The fall in K_c with time in phase 3 is the result of leaf senescence as the crop matures.

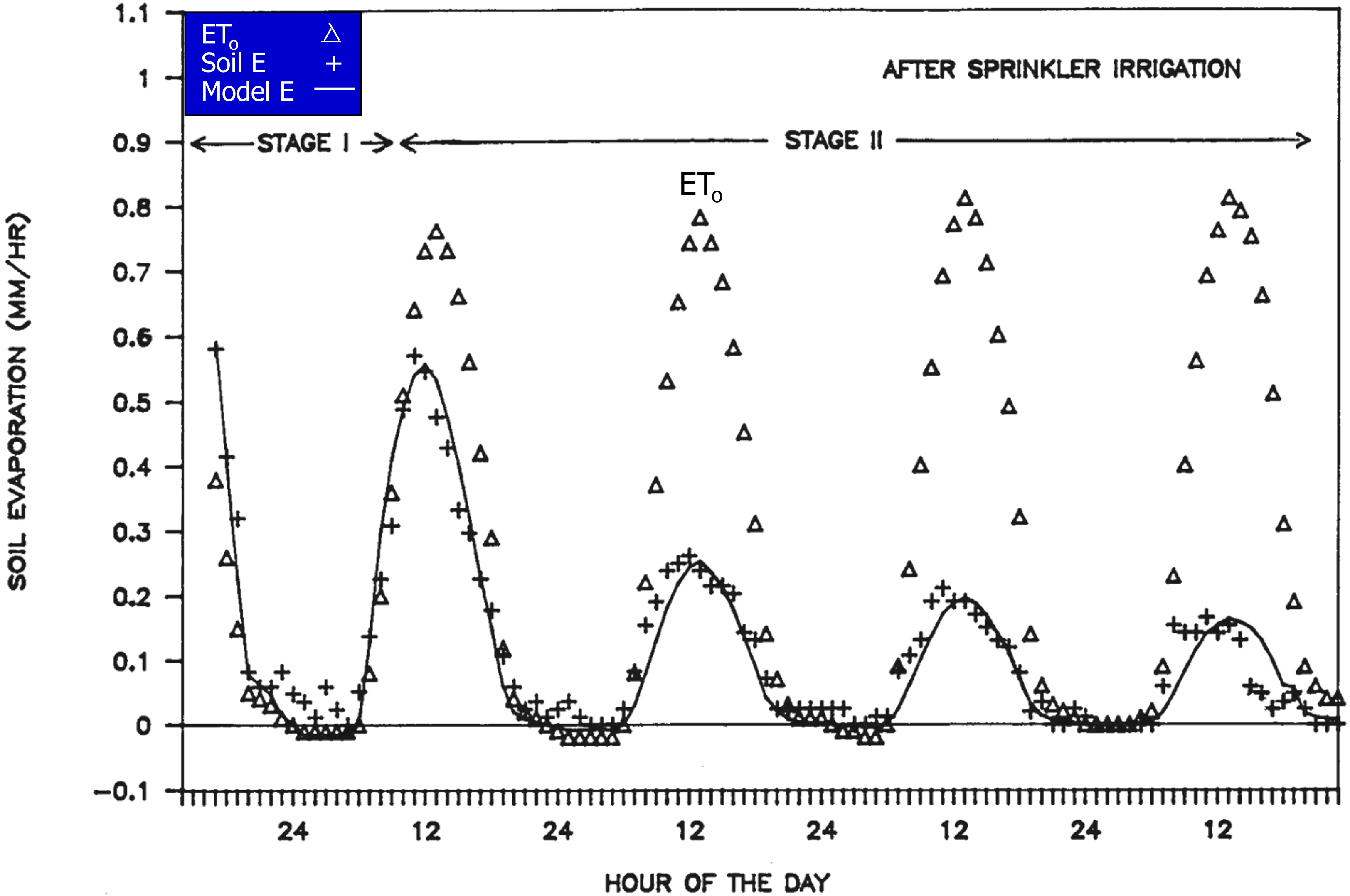
The extent of canopy cover is dependent largely on planting density

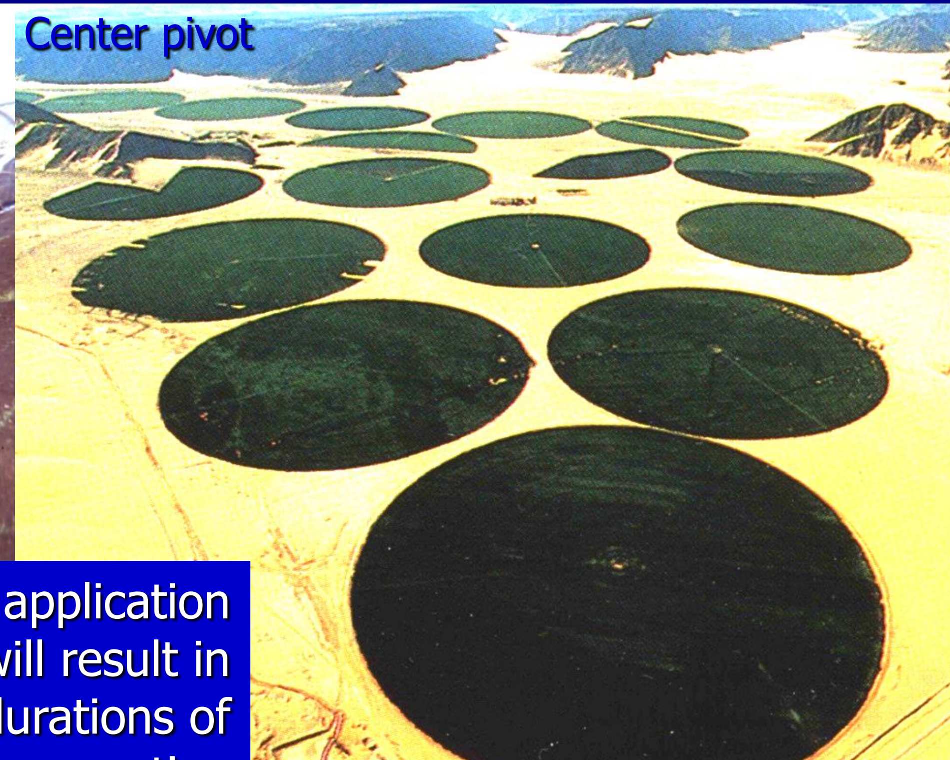
Soil evaporation

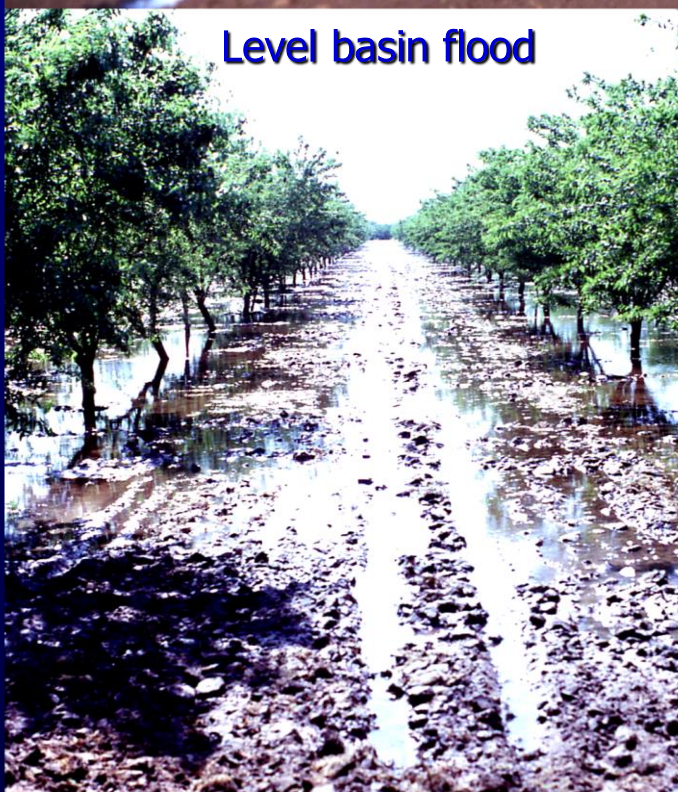
Consists of two stages, each characterized by different behavior

- Stage 1 is when the soil surface is full wet and surface soil Ψ is zero or somewhat lower. This means the absolute humidity or vapor pressure at the surface is near the same as that of water at the same temperature. Evaporation from the soil is essential the potential rate because energy supply to the surface is determining the rate and water supply to the surface is not limiting
- Stage 2 is when the soil surface begins to dry and vapor pressure at the surface begins to decrease significantly compared to vapor pressure at the surface of water at the same temperature. Evaporation at the stage declines exponentially with time

Soil (Yolo clay loam) evaporation measured hourly on large (6.1 m diameter) lysimeter after a sprinkler irrigation







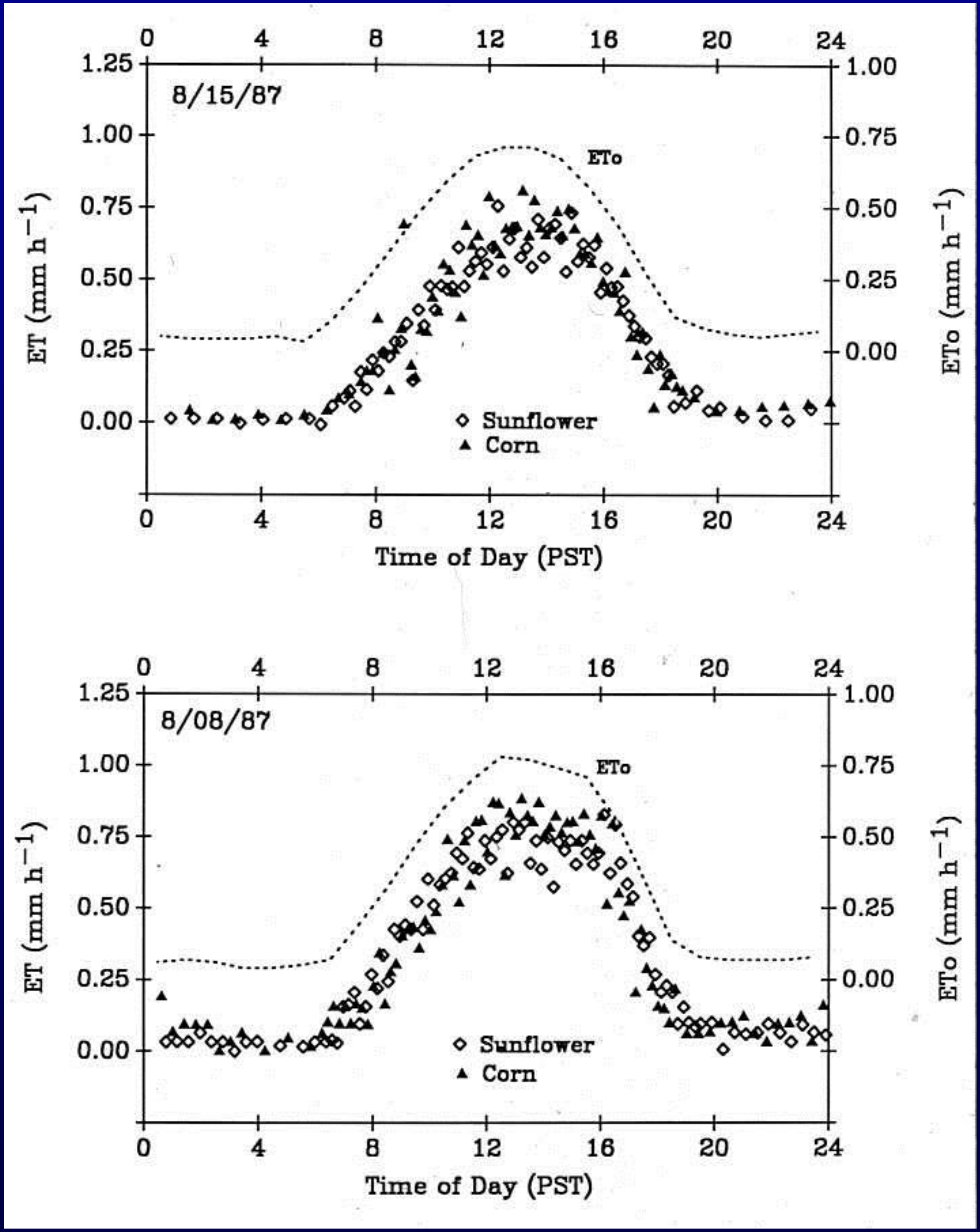
Different application methods will result in different durations of Stage 1 evaporation

And also, in some cases, the percentge of soil surface wetted

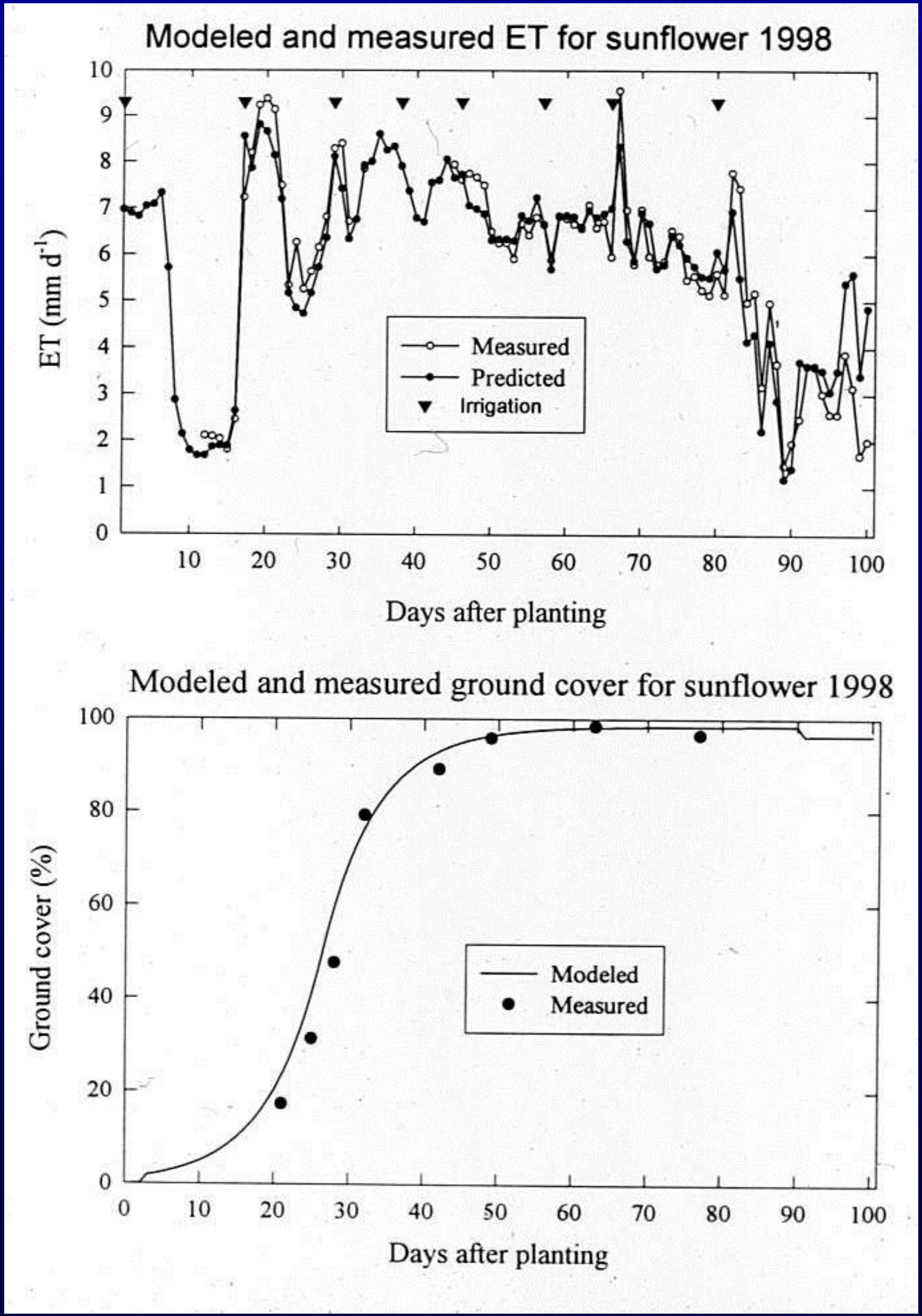
$$K_c = f\,(\text{soil surface wetness},\ \text{canopy cover extent},\ \text{stomatal opening})$$

- Soil surface wetness:
  - Irrigation & rainfall frequency & amount
  - Soil hydraulic properties
  - Evaporation rate
- Canopy cover extent:
  - Plant density and pattern
  - Canopy growth rate
- Stomatal opening:
  - Leaf senescence
  - Water stress
  - Nutrient deficiency

Very little soil evaporation if covered by canopy



After canopy fully covers the soil, most crops have a K_c between 1.0 and 1.15 under non-stressed conditions

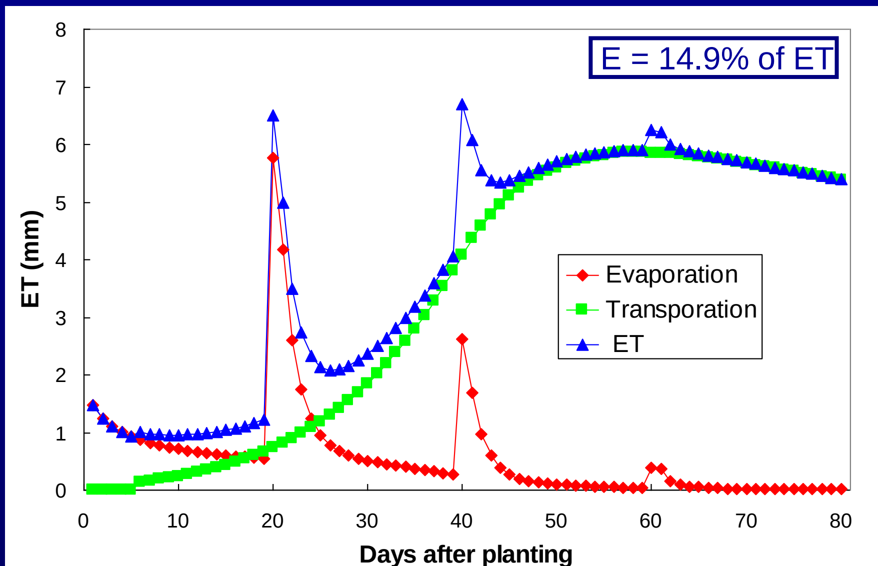


Comparing the measured ET with simulated E+T using the simple model

- ET was overestimated late in the season because the simple model does not take senescence into account.

Frequency of irrigation and canopy cover make a difference in soil E (transpiration efficiency)

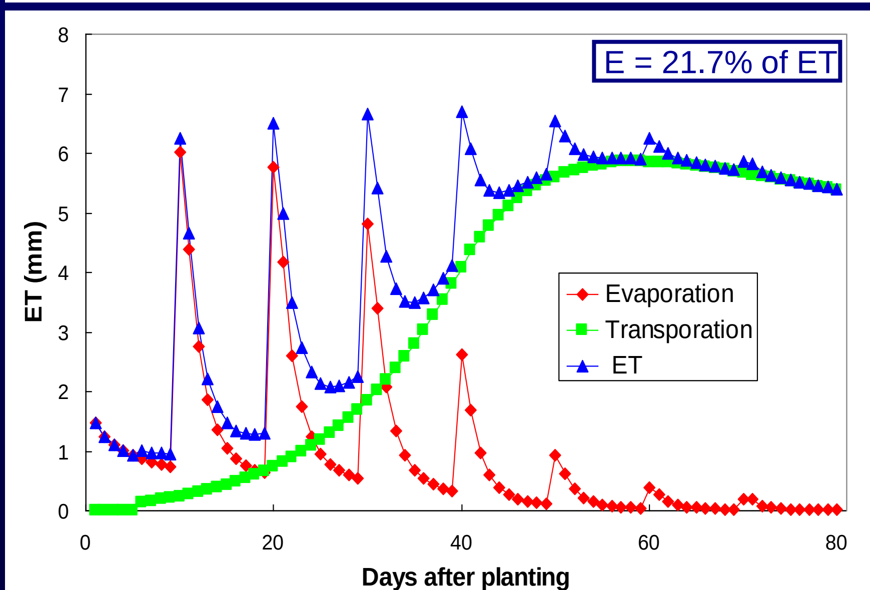
Simulation model of Hsiao & Madson (unpublished)

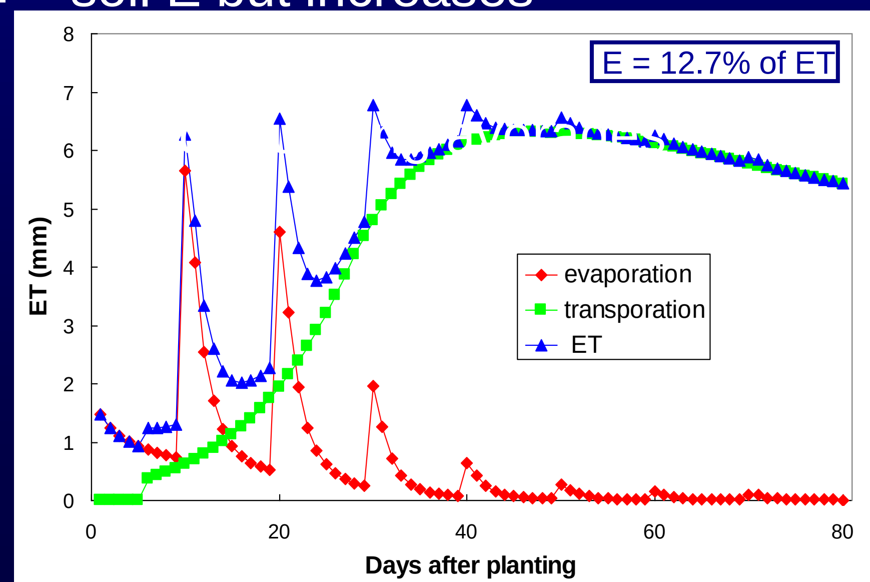


More frequent applications before canopy covers the soil allows more soil E

Note more irrigation spikes means more soil E

Higher plant density and faster canopy development reduces soil E but increases

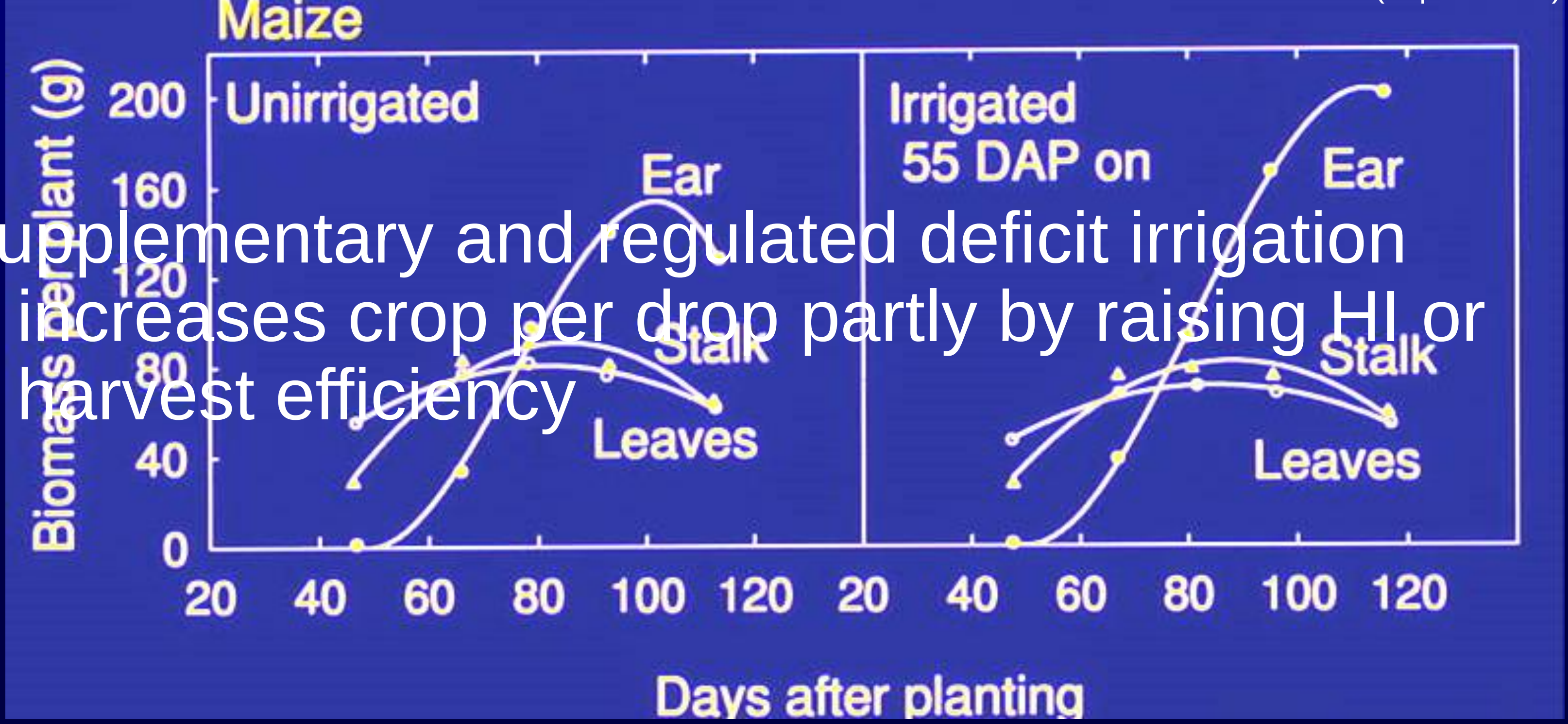




When water supply is limited, strategic timing of irrigation can save water by raising harvest efficiency (HI).

	HI
Well irrigated	0.47
Unirrigated	0.31
Late irrigation	0.49

- Unirrigated ran out of water near maturation and leaves senesced early, shortened grain filling time, reducing HI
- Late irrigation allowed full grain filling while stalk and leaf weight remained low and similar to unirrigated, raising HI



Acevedo & Hsiao (unpublished)

Supplementary and regulated deficit irrigation increases crop per drop partly by raising HI or harvest efficiency

Total ET of a crop depends on:

- Climate and weather
- Life cycle length
- Green canopy cover (CC) duration
- Frequency of rain & Irrigation when CC is partial
- Degree of stomatal closure due to water stress—usually minor

E as % of ET depends on:

- Canopy cover (the lack of)
- Frequency of rain & Irrigation when CC is partial

Range of crop ET (mm)

• Overall	100-1200
• Majority of crops	450-850
• Sugar cane	800-2000
• Rice (paddy culture), tropics	400-700
• Rice (paddy culture), temperate	800-1100
• Alfalfa	200-1000
• Soybean	300-800
• Radish (guestimate)	180
• Barley	100-500

Methods to reduce E:

- Reduce irrigation frequency—need care to avoid water stress
- Plant at higher density—only if water is adequate
- Subsurface drip irrigation—expensive to install & maintain

Less frequent irrigation and higher plant density may save 5-30% of E, at most 45%. Not a large saving

Need to look at the whole efficiency chain, not focus on one or two steps

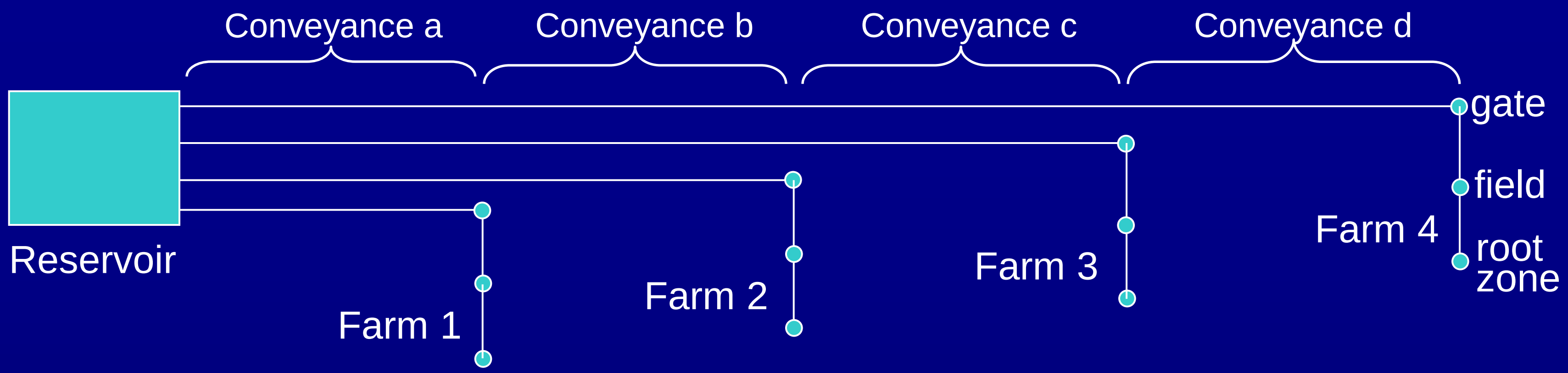
Optimization features of chain of efficiency approach

- The same percentage of improvement in the efficiency (in fractions) of any step in the chain will result in the same improvement in the overall efficiency, regardless of the location of the step in the efficiency chain
- For example, a 20% improvement in a step with 0.4 efficiency (to 0.48) has exactly the same impact on overall efficiency as a 20% improvement in a step with 0.8 efficiency (to 0.96)
- Resource should be allocated to steps with the least cost for each relative unit (percent) of improvement in its existing efficiency
- It is more effective to improve several or more steps instead of concentrating on one step

Reference:

Hsiao, T. C., P. Steduto, and E. Fereres, 2007. A Systematic and quantitative approach to improve water use efficiency in agriculture. Irrig. Sci. 25: 209-231

Thank you!



Efficiency chain

Farm 1:

$$\frac{W_{fg,1}}{W_{vo,1}} \times \frac{W_{fd,1}}{W_{fg,1}} \times \frac{W_{rz,1}}{W_{fd,1}} = \frac{W_{rz,1}}{W_{vo,1}}$$

Farm 2:

$$\frac{W_{a,2}}{W_{vo,2}} \times \frac{W_{fg,2}}{W_{a,2}} \times \frac{W_{fd,2}}{W_{fg,2}} \times \frac{W_{rz,2}}{W_{fd,2}} = \frac{W_{rz,2}}{W_{vo,2}}$$

Farm 3:

$$\frac{W_{a,3}}{W_{vo,3}} \times \frac{W_{b,3}}{W_{a,3}} \times \frac{W_{fg,3}}{W_{b,3}} \times \frac{W_{fd,3}}{W_{fg,3}} \times \frac{W_{rz,3}}{W_{fd,3}} = \frac{W_{rz,3}}{W_{vo,3}}$$

Farm 4:

$$\frac{W_{a,4}}{W_{vo,4}} \times \frac{W_{b,4}}{W_{a,4}} \times \frac{W_{c,4}}{W_{b,4}} \times \frac{W_{fg,4}}{W_{c,4}} \times \frac{W_{fd,4}}{W_{fg,4}} \times \frac{W_{rz,4}}{W_{fd,4}} = \frac{W_{rz,4}}{W_{vo,4}}$$

Generalized equation

$$\frac{W_{rz,i}}{W_{vo,i}} = \prod_{j} E_j$$

Overall WUE for the system

$$\frac{W_{rz}}{W_{vo}} = \sum_i A_i \left(\frac{W_{rz,i}}{W_{vo,i}} \right)$$

Efficiency of each branch must be weighted by the amount of water that branch draws

W_{rz} — water applied in the root zone, whole system

W_{vo} — water drawn out of the reservoir, whole system

$W_{rz,i}$ — water applied in the root zone for branch i

$W_{vo,i}$ — water drawn out of the reservoir for branch i

A_i — fraction of water allocated out of the reservoir to branch i

Root zone water to crop yield chain: Comparing poor and good situations

		Poor circumstance, management or technology	Good circumstance, management or technology
Comsumptive efficiency	$= \frac{W_{consumptive}}{W_{root\ zone}}$	Fine texture soil o.86—0.94	Coarse texture soil o.95—0.99
Transpiration efficiency	$= \frac{W_{transp.}}{W_{consumptive}}$	Poor cover, frequent rain 0.3—0.5	Good cover, infrequent rain 0.6—0.95
Assimilation efficiency	$= \frac{m_{CO_2\ assimil.}}{W_{transp.}}$	C3 spp. Of low assim. cap. 0.003—0.004	C4 spp. Of good assim. cap. 0.004—0.006
Biomass efficiency	$= \frac{m_{plant}}{m_{CO_2\ assimil.}}$	Hot environment 0.4—0.5	Cool environment 0.54—0.64
Harvest efficiency	$= \frac{m_{harvest}}{m_{plant}}$	Tall, indeterminant, stress 0.3—0.4	Short, determ., optimal stress 0.46—0.52

Comparing overall efficiency between the "poor" and the "good", using mean values of each efficiency in the efficiency chain (above):

Poor: 0.90 x 0.40 x 0.0035 x 0.45 x 0.35 = 0.198 kg m^{-3}

Good: 0.97 x 0.775 x 0.0050 x 0.59 x 0.49 = 1.087 kg m^{-3}

More than a five-fold difference in overall efficiencies!

Optimization features

- The same percentage of improvement in the efficiency (in fractions) of any step in the chain will result in the same improvement in the overall efficiency, regardless of the location of the step in the efficiency chain
- For example, a 20% improvement in a step with 0.4 efficiency (to 0.48) has exactly the same impact on overall efficiency as a 20% improvement in a step with 0.8 efficiency (to 0.96)
- Resource should be allocated to the step with the least cost for each relative unit (percent) of improvement in its existing efficiency.

Defining water productivity (Water use efficiency)

General definition of efficiency: $$Efficiency = \frac{Output}{Input}$$ Must use quantitative units

Depends on numerator and denominator selected. So define them with subscripts:

$$WUE_{m/t} = \frac{Biomass}{\Sigma T}$$ Biomass transpiration efficiency

$$WUE_{y/ET} = \frac{Yield}{\Sigma ET}$$ Yield consumptive efficiency

$$\mathrm{WUE}_{\mathrm{y/ap\,w}} = \frac{\mathrm{Yield}}{\Sigma \mathrm{W}_{\mathrm{applied}}}$$ Yield applied water efficiency

$$WUE_{y/\ farm\,w} = \frac{Yield}{\Sigma W_{farm\ gate}}$$ Yield farm water efficiency