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A Quantitative Framework for the Systematic Analysis of Potential Water Savings in Agriculture

Theodore C. HSIAO

Dept. of Land, Air and Water Resource
University of California
Davis
USA

Strada Costiera 11, 34151 Trieste, Italy - Tel.+39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it

A QUANTITATIVE FRAMEWORK FOR THE SYSTEMATIC ANALYSIS OF POTENTIAL WATER SAVINGS IN AGRICULTURE

Theodore C. Hsiao

Dept. of Land, Air and Water Resources, University of California
Davis, California 95616, U. S. A.
e-mail: tchsiao@ucdavis.edu

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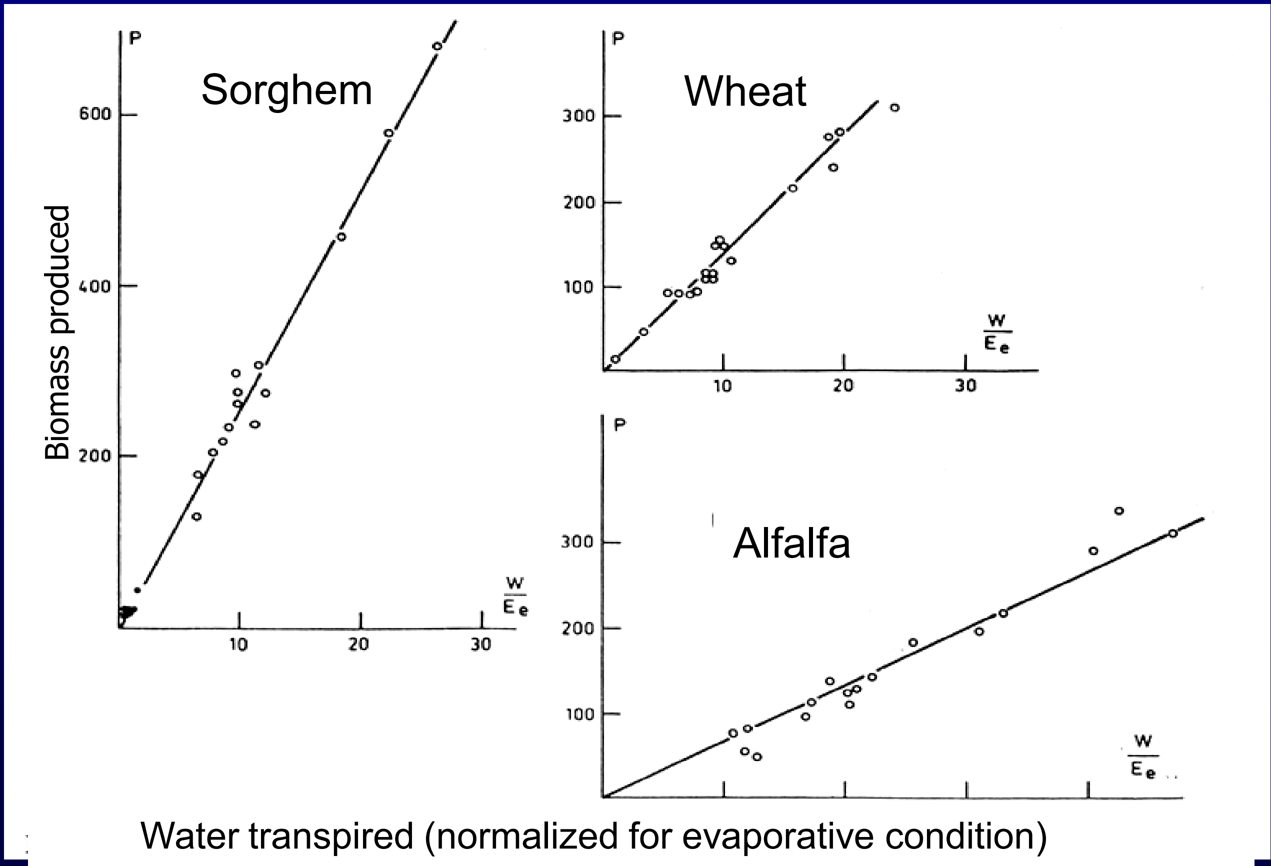
How tightly are plant growth and production linked to water?

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

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



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

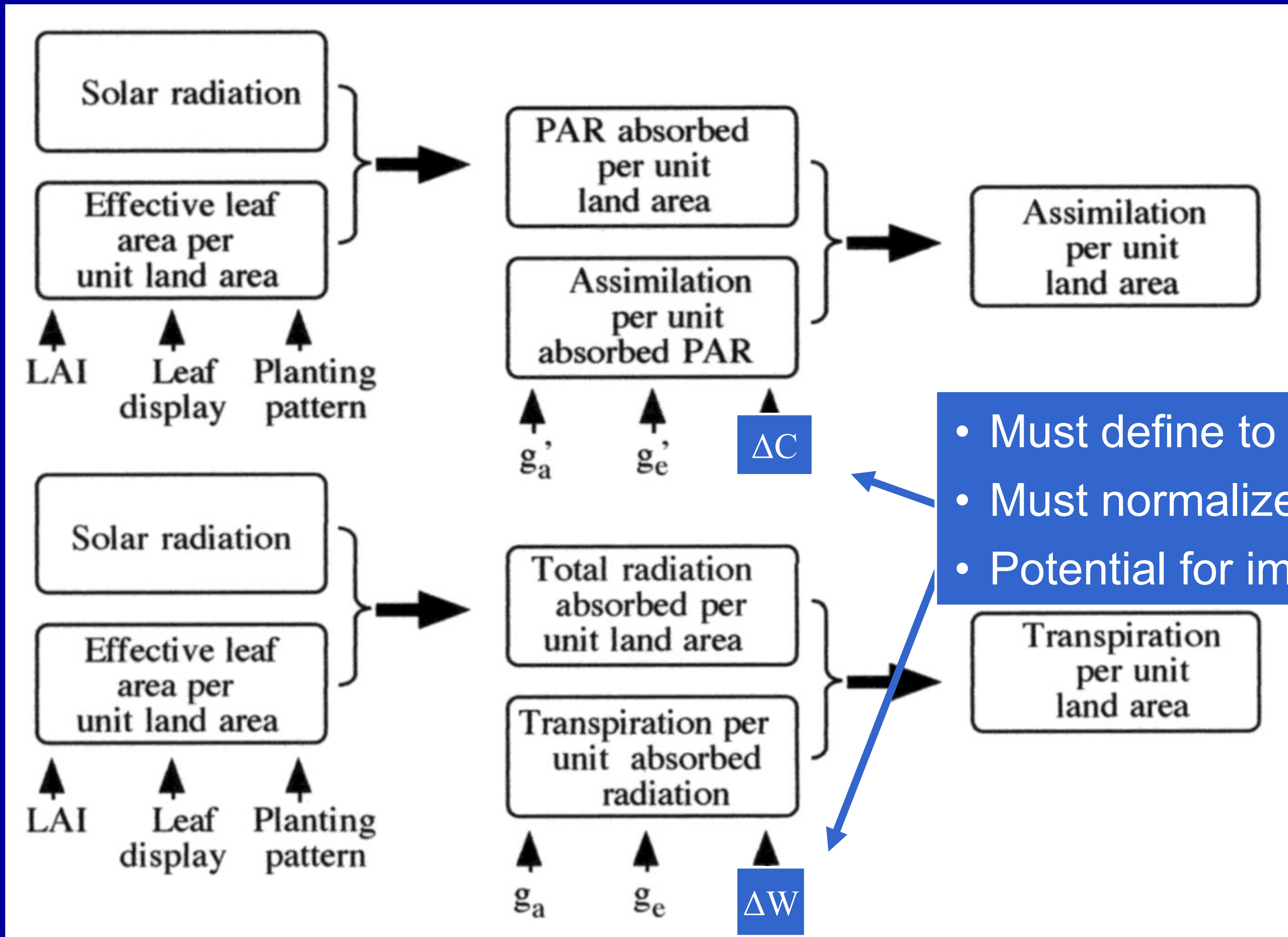
- C4 species (e.g., sorghum) yield more biomass per unit of water transpired than C3 species (e.g., wheat, alfalfa)
- Alfalfa, with large root system, N fixation, and high protein content, requires more assimilates to make its biomass.

Why nearly constant basic 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)

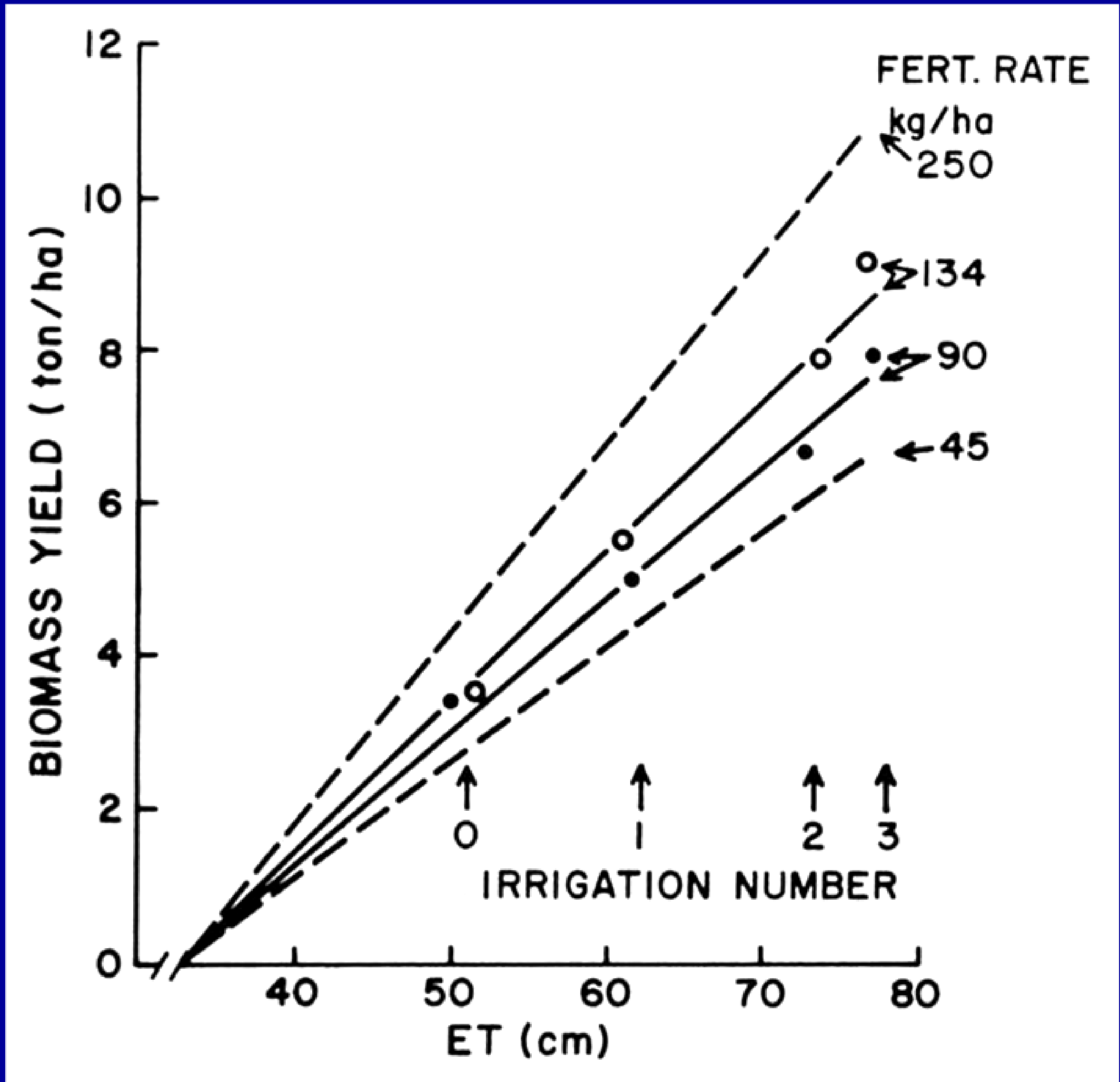
- There is much commonality between CO_2 assimilation and transpiration
- Because of these shared features, biomass production is closely linked to crop water use
- But a couple of features not shared provide opportunity for improvement:
  - ΔC – Difference in CO_2 pressure between the air and the leaf interior
  - ΔW – Difference in water vapor concentration between the leaf interior and the air, a measure of evaporative demand of the atmosphere

Near constant basic WUE being the case, then how to get more crop 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

- A number of means exist to increase basic WUE of plants
- These improvements are mostly minor (e.g., 4 to 15%)
- Biotechnology is one of the important tools, but not a magic bullet

Much more effective to take a multi-prone approach, go beyond basic WUE!

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:

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

Much improvement

- The efficiency effects are multiplicative, not just additive
- 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

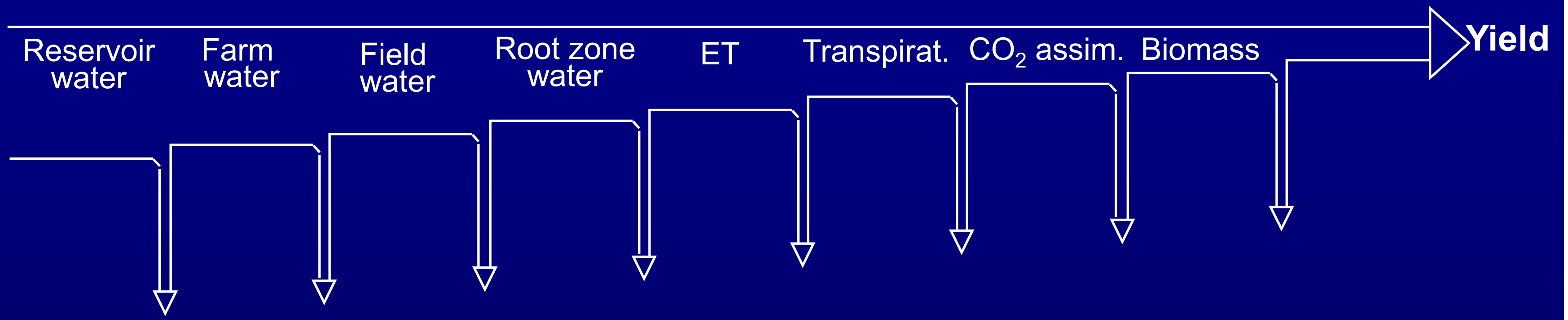
$$E_{all,new} = E_{1\,original}(1+\Delta_1) \times E_{2\,original}(1+\Delta_2) \times E_{3\,original}(1+\Delta_3) \times \ldots\ldots\ldots\ldots$$

Generally then

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

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

From reservoir water to harvest yield



Efficiency Range for:	Convey. Eff.	Farm Eff.	Applicat. Eff.	Consumpt Eff.	Transpirat. Eff.	Assim. Eff.	Biomass Eff.	Yield Eff.	Overall Eff.
Poor situation	0.5 0.7	0.4 0.6	0.3 0.5	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	0.75 0.95	0.70 0.95	0.97 0.99	0.70 0.92	9 14	0.4 0.5	0.44 0.52	**1.22**

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

For Water Used by Crops to Produce Yield:

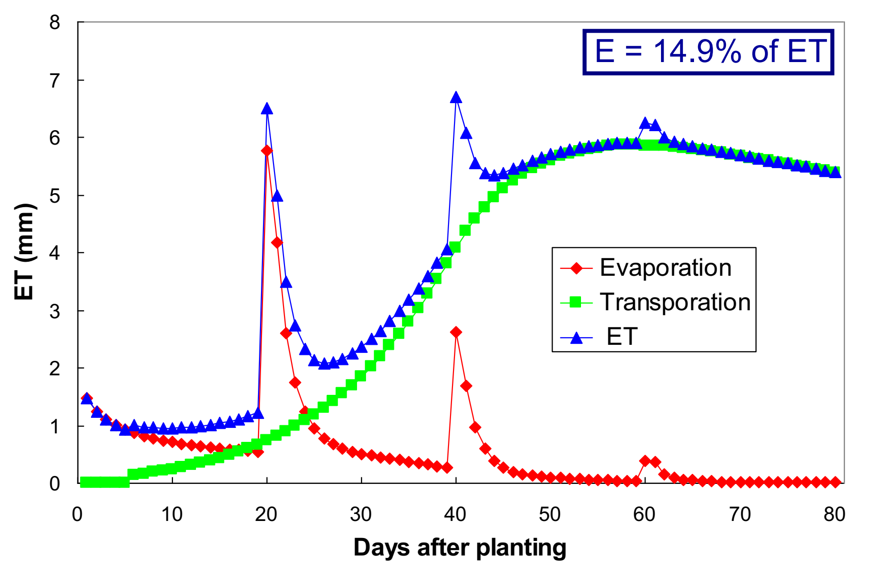
- Output (numerator) and input (denominator) are now in terms of water quantity as well as mass of CO_2 or plant material

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

Consumptive efficiency	Transpiration efficiency	Assimilation efficiency	Biomass efficiency	Yield efficiency

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

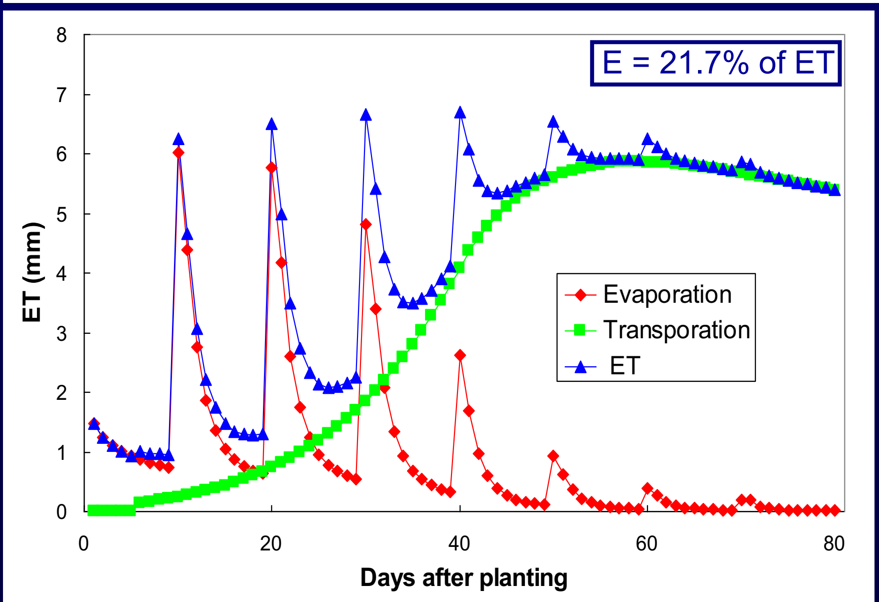
Simulation model of Hsiao & Madson (unpublished)

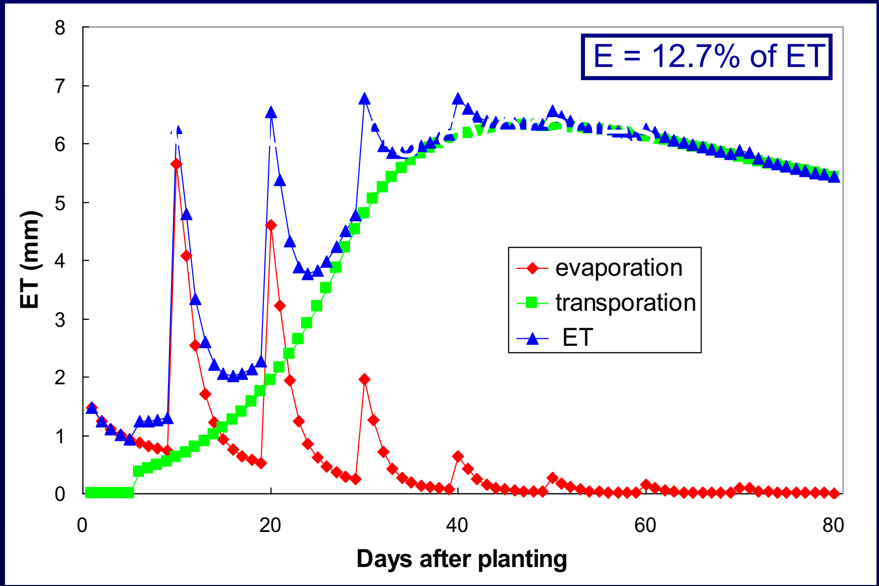


More frequent applications before canopy covers the soil allows more soil E

Note more irrigation spikes means more soil E

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



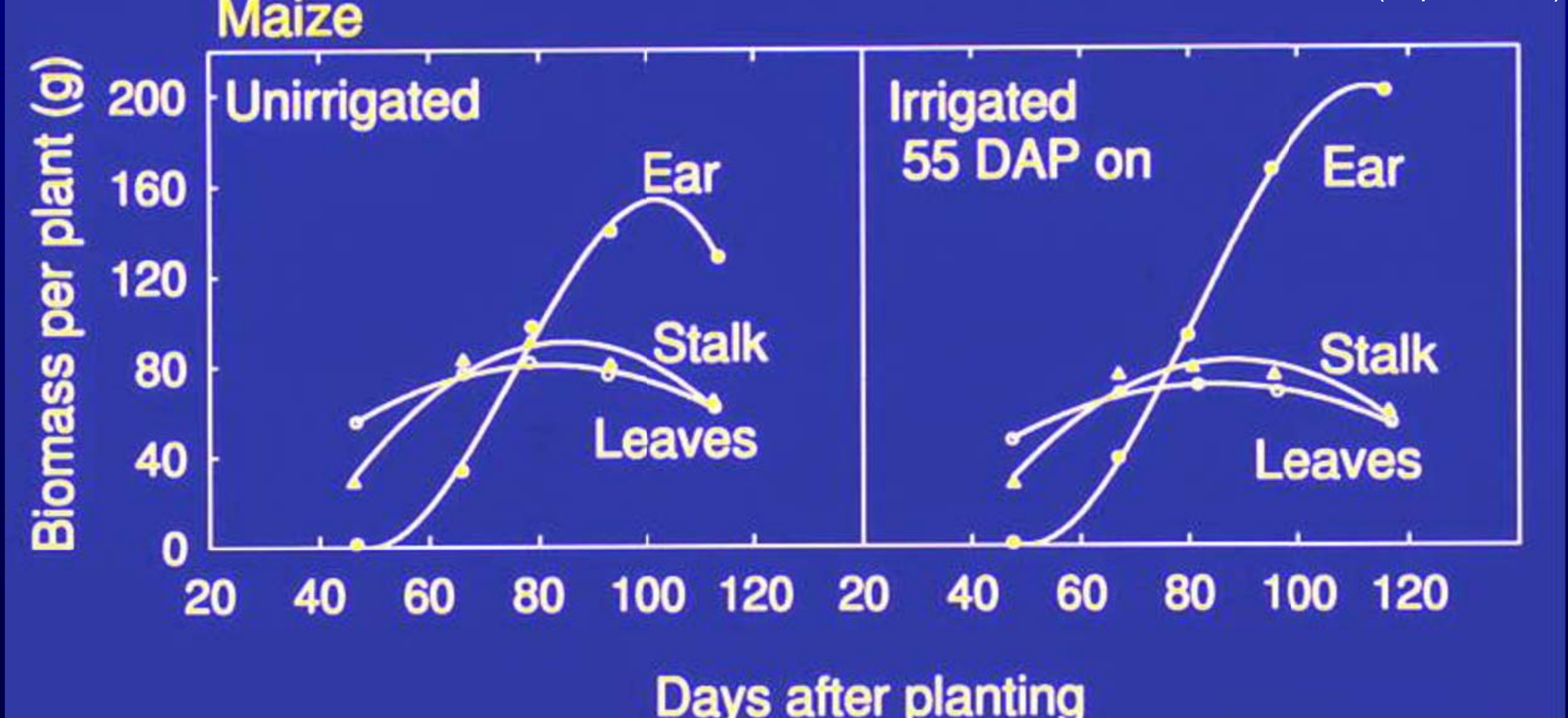


When water supply is limited, strategic timing of irrigation can save water by raising harvest efficiency (HI).

	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

- Small increases in several efficiency steps make a large increase in overall WUE
- Generally, the more steps improved (even if each only by a small percentage), the larger is the overall improvement
- To meet the future challenges in saving water and increasing WUE, must look as the system as a whole
- Being quantitative, a good tool for economic analysis and optimization

For dryland cropping, the first 2 efficiency steps are different

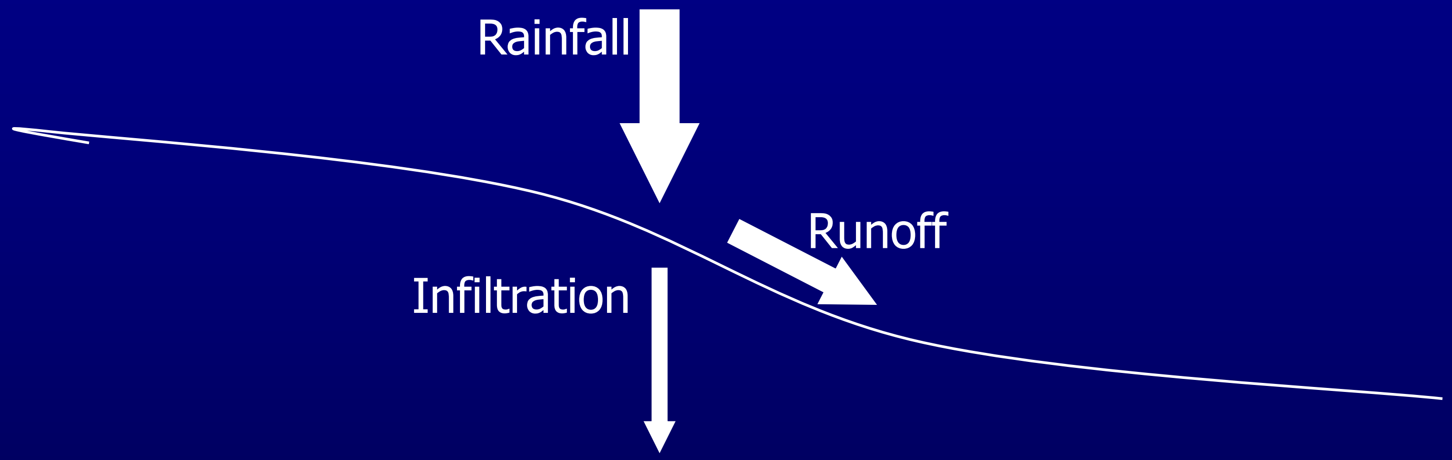
For animal production, more steps are needed at the end

Different first 2 steps in efficiency chain for dry land cropping

Capture efficiency	$= \frac{W_{soil\ in}}{W_{rain}}$	<u>Medium/steep slope, low cover, low IR, intense rain</u> 0.1—0.6	<u>Flat/gentle slope, good cover, high IR, gentle rain</u> 0.7—1.00
Soil storage efficiency	$= \frac{W_{root\ zone}}{W_{soil\ in}}$	<u>Shallow soil/root, coarse texture, prolonged & heavy rain</u> 0.4—0.6	<u>Deep soil/root, fine texture, well distributed rains</u> 0.7—0.98
Followed by the same 5 steps as for irrigated crops, to biomass and yield			

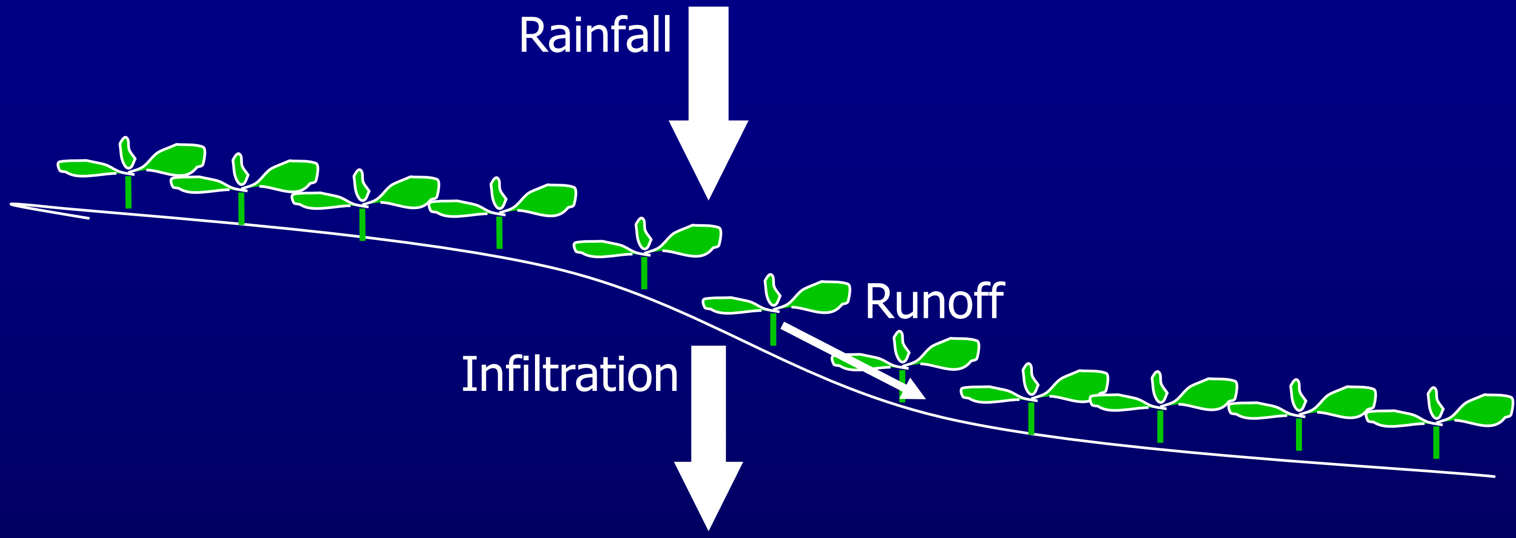
Factors affecting capture efficiency

Effects of Vegetative Cover on Infiltration, Runoff, and Erosion



- Without vegetative cover, mechanical impact of rain drops breaks the surface soil aggregates
- Large pores between the aggregates are destroyed, reducing water infiltration into the soil and increasing runoff
- With the soil deaggregated and faster runoff, there is more erosion

Effect of Vegetative Cover on Infiltration, Runoff, and Erosion



- With mulch or minimum tillage, mechanical impact of rain drops on the soil aggregate is greatly reduced and many aggregates remain
- Some large pores between aggregates remain, permitting rapid water infiltration into the soil
- More infiltration and less runoff and soil erosion

Efficiency steps improved by some water management techniques and potential impact on overall WUE

Management Technique	Specific step efficiencies that may be improved	Likely potential improvement in E_{all}
Localized irrigation	E_{appl}, E_{tr}	5 – 40%
Regulated deficit irrigation	E_{appl}, E_{et}, E_{tr}, E_{yld}	20 – 140%
Supplemental irrigation at planting	E_{et}, E_{tr}	20 – 220%
Supplemental irrigation, late stages	E_{appl}, E_{et}, E_{yld}	20 – 300%
Water harvesting	E_{infil}, E_{rzstor}, E_{tr}, possibly E_{yld}	100 – 900%

Efficiency chain for range animal production

Capture efficiency	$= \frac{W_{soil\ in}}{W_{rain}}$	Medium/steep slope, low cover, low IR, intense rain 0.1—0.6	Flat/gentle slope, good cover, high IR, gentle rain 0.7—1.00
Soil storage efficiency	$= \frac{W_{root\ zone}}{W_{soil\ in}}$	Shallow soil/root, coarse texture, prolonged & heavy rain 0.4—0.6	Deep soil/root, fine texture, well distributed rains 0.7—0.98
Followed by the same 4 steps as for cropping, to biomass			
Grazing Efficiency	$= \frac{m_{plants\ eaten}}{m_{plant}}$	Unpalatable spp. or old plants 0.02—0.2	Desired spp. & young growth 0.6—0.9
Conversion Efficiency	$= \frac{m_{animal}}{m_{plantseaten}}$	Sparse plants, low digestibility 0.03—0.1	Dense plants, high quality 0.2—0.3

Overgrazing reduces water use efficiency drastically

Even replanted desirable species are eaten and have no chance to improve the range vegetation

Grazing in Accordance to Carrying Capacity of the Range

Controlled rotation allow desirable vegetation to develop canopy and capture the sun to produce biomass before foliage is eaten, increasing biomass production and suppressing undesirable species.

- More canopy cover protects soil aggregates from rain drop impact, leading to higher IR and higher **infiltration efficiency**, and less erosion
- More plant biomass means more root growth and depth, leading to higher soil **retention efficiency**
- More canopy cover of the soil reduces soil evaporation. **Transpiration efficiency** is increased.
- Less unpalatable and inedible plants allow more biomass to be eaten, increasing **grazing efficiency**
- More biomass per land area means less distance for animals to graze, leaving more nutrients to convert to meat, milk, etc., higher **conversion efficiency**

One management improvement raises 5 efficiencies in the chain, with multiplicative enhancing effects on the overall efficiency!

Without going into details, one reasonable estimate is that overall efficiency can be improved about 45 folds!

- The efficiency chain concept is also a powerful tool to analyze rangeland WP in terms of animal products
- The degraded rangelands offer the greatest potential for improving WP in the dry areas of the world
- These improvements can only come about when supported by changes in political, social and economical policies

- A systematic way to evaluate different parts of the paths of water use efficiency or productivity
- A precise way to calculate the overall efficiency and the impact of improvement in any of the steps
- A means to do economic analysis and optimization of resource allocation in the improvement of water use efficiency

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 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!