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

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SUMMARY - Effective management of scarce water resources requires a systems approach. A quantitative framework, termed the chain of efficiencies concept, was described in the previous meeting of WASAMED and proposed for use in the analysis of water use efficiency of production systems. Starting at the source of water, a cascade of events leads to the final production of crops or animal products at the expense of water. These events are mostly sequential, with each process step in the sequence having its own efficiency of output per unit of input. It turned out that the overall efficiency of a whole process is the product of the efficiencies of each sequential step. That is, efficiencies of individual process steps are multiplicative in determining the overall efficiency. Thus, improvement in any one of the efficiency steps has equal effect in improving the overall efficiency, and the overall improvement is more than the sum of the individual improvements. This principle provides a simple and quantitative means to optimize the allocation of limited resources in improving water use efficiency.
In this paper some of the key features of the chain of efficiencies concept are reviewed and some parts of the crop production systems are examined in terms of the framework. Some experimental data are given to illustrate the factors that impact some of the step efficiencies. Included in the consideration are some specialized water management techniques.

Key words: Irrigation, crop productivity, water saving, management, resource allocation, optimization.

INTRODUCTION

There is no question that the relentless growth of human population and the rise in the general living standards are straining the water resources all over the world, especially in the more arid areas. Adding to the strain is the need for water in maintaining the long term sustainability of the environment and ecosystems (Falkenmark, 2000). Since the fresh water resources are essentially finite on earth, making more efficient use of the water must be a major thrust in the global effort to cope with the water scarcity (Gleick, 2003). World-wide agriculture is by far the largest user of water diverted by man (Seckler *et al.*, 1998). On the other hand, the efficiency of water use in agriculture is low. In an assessment of rain-fed agriculture, Wallace (2000) concluded that only 15 to 30% of the rainfall is actually used in crop transpiration. Others (Rockstrom and Falkenmark, 2000) indicated even lower percentages, as low as 5%. Low efficiency has also been indicated for irrigated agriculture. Wallace and Gregory (2002) suggested only 13 to 18% of the irrigation water delivered is actually transpired by crops.

The production of crops and animals in agriculture with water as a key input involves complicated processes with numerous facets that are subjected to the impact of management decisions and environmental variables. To improve the efficiency of water, one needs first to asses where the inefficiencies lie. In most situations the inefficiency is not only in one of the steps, but spread among several or many of the steps in the process of water use for production. A systematic and quantitative approach is needed to analyze where the inefficiency lies, to assess quantitatively the potential improvements, and most importantly, to determine how to allocate limited available resource to maximize the improvement in water productivity. In the previous WASAMED conferences, a relatively simple and yet quantitative and comprehensive framework for the analysis and improvement of water use efficiency was proposed and described. The framework may be termed the “concept of chain of efficiency steps”. For a more complete treatment of this framework and the mathematical details, including how to scale up from fields to farms to watersheds, the reader is referred to a paper in the forthcoming special issue of *Irrigation Science* (Hsiao *et al.*, 2007). The present paper summarizes the essence of this framework and its implications, and illustrates its use and application in the analysis of some common irrigation and crop management practices.

ESSENCE OF THE CHAIN OF EFFICIENCY STEPS CONCEPT

In quantitative terms, efficiency of any process is defined, as done in economics, as the ratio of input to output for that process, with both measured in quantitative units. The units to use vary depending on the situation; if the same units define both, then the efficiency ratio is unitless. When the production of a product is complicated and the starting resource input goes through many processing steps sequentially ending in the product, the overall efficiency for the process chain is the efficiency of each of all the steps multiplied together. Stated as an equation:

$$E_{all} = E_1 \times E_2 \times E_3 \times .... = \prod_i E_i \qquad (1)$$

where E is efficiency, the subscript 'all' stands for 'overall', the subscript i, a running number (= 1, 2, 3, etc., depending on the position of the step), designates each of the sequential steps in the whole process chain, and Π is the multiplication operator (of all the i designated items).

To see why Eq. 1 is valid, it is best to take a simple example of a process that consists of only three steps, each with its efficiency defined as the ratio of output to input. Because the processing steps are in sequence and come one after another, the output of the first step is the input of the second step, and the output of the second step is the input of the third step. Applying Eq. 1 with i = 1, 2, and 3,

$$E_{all} = \frac{\text{Output}_1}{\text{Input}_1} \times \frac{\text{Output}_2}{\text{Output}_1} \times \frac{\text{Output}_3}{\text{Output}_2} = \frac{\text{Output}_3}{\text{Input}_1} \qquad (2)$$

In Eq. 2, the first three ratios are the efficiency of each of the three steps, and the last ratio is the overall efficiency. The product of the first three ratios is equal to the ratio of output_3 to input_1, the overall efficiency, because the numerator of the preceding ratio cancels out the denominator of the following ratio, leaving only the numerator of the third ratio and the denominator of the first ratio. It is obvious that this treatment can be extended to processes consisting of many more than three steps, as long as the steps are sequential. Since Eq. 1 is the straight forward outcome of simple mathematics, it is fundamental and has wide and general applicability. Important is the fact that because the overall efficiency is the product of the individual step efficiencies, it is generally low in spite of the fact that the efficiencies of the steps may be relatively high. On the other hand, this multiplicative nature also means that if relatively minor improvements are made in several of the steps making up the whole process, the improvement in overall efficiency can be quite substantial. These points will be illustrated by examples later.

When analyzing a production process, it is important not only to know the efficiencies of the different component steps, but also to know how improvements in the efficiency of the steps affect the overall efficiency. To obtain a simple equation to calculate the new overall efficiency, we start by expressing the improvement in a step as a fraction of the original efficiency ($E_{original}$) of the step. Denoting the fractional improvement by Δ, an expression for the improved (or new) efficiency of the step (E_{new}) is:

$$E_{new} = (1+\Delta)\ E_{original} \qquad (3)$$

Applying Eq. 3 to all the steps in an efficiency chain and designating each step by the running number i as before, a general expression of the new overall efficiency ($E_{all,new}$) in terms of Δ and the original overall efficiency ($E_{all,\ original}$) is as follows:

$$E_{all,\,new} = E_{all,\,original} \times \prod_{i} (1+\Delta_i) \qquad (4)$$

where Π is the multiplication operator over items i. Expressed in words, one plus the fractional improvement for each step, when multiplied together, and multiplied again by the original overall efficiency, is the new overall efficiency. Eq. 4 is general, and can be applied to any efficiency chain. Importantly, it also applies to cases where there is a reduction in efficiency of some or all the steps. In that case, the impact on overall efficiency is calculated simply by denoting the fractional reduction in efficiency (Δ) as negative.

Several important features of Eq. 1 and 4 need to be emphasized:

(1) The treatment is quantitative, and by simple mathematics, demonstrates the fact that the overall efficiency is the products of the efficiencies of individual steps (and not the average of the efficiencies).

(2) Even though the efficiency of each step may be high, the overall efficiency is considerably or much lower because of the multiplicative effect of individual efficiencies.

(3) By the same token, the same multiplicative effect makes it possible to improve the overall efficiency substantially by making minor improvement in several of the individual efficiencies. In practice this means that one should not concentrate on the improvement of a single efficiency, but focus more on at least several of the weaker steps.

(4) The impact of a change in the efficiency of one step on the overall efficiency is strictly according to the fractional change in the efficiency of that step, regardless of where the step is located in the efficiency chain or how efficient the step is originally. For example, a 20% improvement in an efficiency step with an original efficiency of 0.8 (from 0.8 to 0.96) has exactly the same effect on the overall efficiency as a 20% improvement in another efficiency step with an original efficiency of 0.5 (from 0.5 to 0.6).

(5) The ability to quantify the impact of changes in the efficiency of individual steps on the overall efficiency provides the means to optimize mathematically resource use to improve the overall efficiency of a complex system.

APPLYING THE CHAIN OF EFFICIENCIES FRAMEWORK TO IRRIGATED CROPPING

In the previous WASAMED conference, the steps of the process leading from water diverted out of storage reservoir to the final yield of the crop were described. The steps are now schematically depicted in the top portion of Figure 1, with the narrow downward arrows representing the loss of water or production potential for each step along the chain. Below each arrow is given the name of the particular efficiency step.

Water, the input, is first conveyed from the reservoir outlet to the farm gate, and this constitutes the first efficiency step. The efficiency of this step is conveyance efficiency (E_{conv}) and is calculated as the ratio of the quantity of water (W) diverted out of the reservoir (W_{vo}) for that farm, to the quantity of water received at the farm gate (W_{fg}). After the water arrives at the farm, it is stored or not stored depending on the farmer, and distributed to the fields for irrigation. For simplicity, we will combine the storage and on farm conveyance to the field into one step and call its efficiency farm efficiency (E_{farm}). The output is water at the field edge (W_{fd}) and the input is water at the farm gate (W_{fg}). Once the water is at the field edge, it is applied as irrigation to the crop in the field. The crop can only use the water retained in its root zone (W_{rz}), water that runs off the surface of the field or drains below the root zone represents losses. This step is well known in irrigation engineering and its efficiency is application efficiency (E_{appl}). The output is W_{rz}, and the input, W_{fd}. The next step is consumptive efficiency ($E_{et} = W_{et}/W_{rz}$), a measure of the proportion of water in the root zone removed by evapotranspiration (W_{et}). The loss of efficiency in this step is due to water left in the soil at harvest time. The next step is transpiration efficiency ($E_{tr} = W_{tr}/W_{et}$), a measure of the proportion of water consumed that is actually taken up by the crop and transpired (W_{tr}). The loss is due to water evaporated from the soil. The next step is assimilation efficiency ($E_{as} = m_{as}/W_{tr}$), a measure of the mass of carbon dioxide assimilated by photosynthesis (m_{as}) relative to the volume of water transpired. The measurements here now include the mass of assimilated carbon dioxide as well as the volume of water. The next step is biomass conversion efficiency (E_{bm}), a measure of the plant biomass produced (m_{bm}) relative to the mass of carbon dioxide assimilated. This efficiency is primarily determined by the chemical composition of the crop and is not easily changed. The last step is yield efficiency (E_{yld}), a measure of the proportion of plant biomass that ends up in the harvested yield (m_{yld}), and is equivalent to harvest index (HI), a well known parameter in the crop and agronomic literature.

Eq. 5 below expresses the overall water use efficiency (E_{all}) of irrigated grain crop production as the product of the efficiencies of the component steps, with the efficiencies given as ratios of output to input.

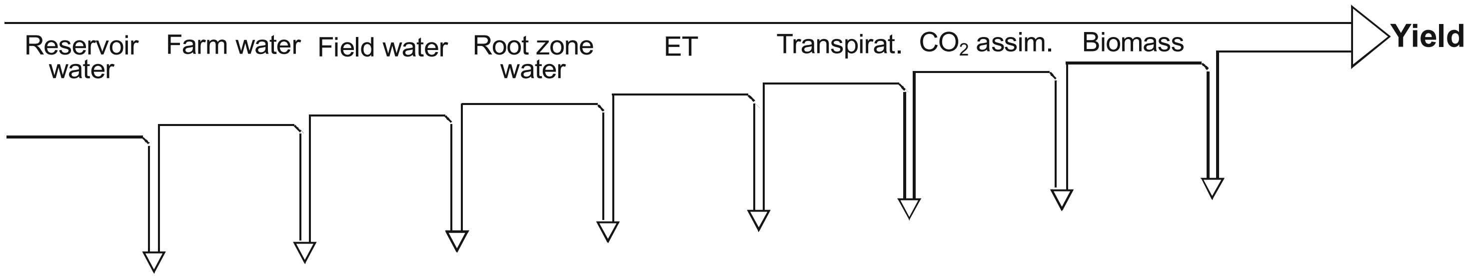
$$E_{all} = \frac{m_{yld}}{W_{vo}} = \frac{W_{fg}}{W_{vo}} \times \frac{W_{fd}}{W_{fg}} \times \frac{W_{rz}}{W_{fd}} \times \frac{W_{et}}{W_{rz}} \times \frac{W_{tr}}{W_{et}} \times \frac{m_{as}}{W_{tr}} \times \frac{m_{bm}}{m_{as}} \times \frac{m_{yld}}{m_{bm}} \tag{5}$$

In the lower part of Figure 1 the range of efficiency for the individual steps are given, one for poor situations where the efficiencies are low, and one for good situations where the efficiencies are high. These ranges are based on literature and our general understanding and do not include the more extreme values, especially the extremes in the poor situation category. Also given in the figure are the overall efficiency (E_{all}) for the poor and good situations, calculated according to Eq. 5 from the mid-value (average of the two limits of the range) of each step efficiency. In addition, the units for each efficiency are also given.

It is seen in Figure 1 that the difference in overall water use efficiency (last column, Figure 1) between the poor situation and the good situation is huge, in spite of the fact that for each efficiency step the difference between the two situations is not that large or even minor. It should also be noted that the comparison is not between the extremely poor and the extremely good situations, but between the mid-values of the efficiency steps for the two situations. Nonetheless, E_{all} for the poor situations is only 2% of E_{all} for the good situations. The reason for this huge difference lies in the multiplicative nature of the efficiency chain, as already noted. This 50 fold difference in water use efficiency to produce yield (grain or fruits of annual crops) indicate that there is much room for improvement in many situations.

The chain of efficiency steps concept, by dividing the whole process into sequential steps and providing the means to integrate the individual efficiencies into the overall efficiency, is ideal as a framework for the analysis and assessment of the efficiency of production systems. The ranges of efficiencies provided in Figure 1 should serve as useful references by which the water use efficiency of any irrigated crop system can be compare with and potential improvement assessed.

Figure 1. Range of efficiencies for the steps in the irrigated cropping efficiency chain, from water diverted out of the reservoir to yield of annual grain (or fruit) crops. See Eq. 5 for the output to input ratio for each of the efficiency steps. Two ranges of efficiencies are given, one for poor circumstances and practices, and the other for good circumstances and practices. Also given are the overall efficiency for the two situations, calculated from mid-values of the efficiency steps.



Situation:	Convey. eff.	Farm eff.	Applicat. eff.	Consumpt. eff.	Transpirat. eff.	Assim. eff.	Biomass eff.	Yield eff.	Overall eff.
Poor	0.5–0.7	0.4–0.6	0.3–0.5	0.85–0.92	0.25–0.5	6.0–8.0	0.22–0.36	0.24–0.36	**0.0243**
Good	0.8–0.96	0.75–0.95	0.7–0.95	0.97–0.99	0.7–0.92	9.0–14	0.4–0.5	0.44–0.52	**1.22**
Efficiency units	unitless	unitless	unitless	unitless	unitless	kg_{CO2}/m^3_{water}	$kg_{biomass}/kg_{CO2}$	unitless	kg/m^3

SAMPLE APPLICATIONS OF THE FRAMEWORK

There are at least hundreds of published papers reporting the amount of biomass produced by a crop per unit of water evapotranspired. Additional papers on the same subject are coming out nearly weekly, including some being reported at this conference. This efficiency ratio (biomass/ΣET) may be termed biomass consumptive water use efficiency and denoted by $E_{bm/et}$. In terms of the efficiency steps listed in Figure 1 and Eq. 5, this efficiency is a combination of the 5th, 6th, and 7th step efficiencies in Eq. 5. That is:

$$E_{bm/et} = \frac{W_{tr}}{W_{et}} \times \frac{m_{as}}{W_{tr}} \times \frac{m_{bm}}{m_{as}} = \frac{m_{bm}}{W_{et}} \qquad (6)$$

In many of the reports $E_{bm/et}$ tends to be nearly constant for a given crop and climate, regardless of the watering regimes. In other comparisons, however, $E_{bm/et}$ can be quite variable. These apparently divergent observations are now examined in terms of the three efficiency steps making up $E_{bm/et}$ and discussed in terms of the options available for improving $E_{bm/et}$.

It turned out that assimilation efficiency (E_{as}, the 2nd step in Eq. 6) is inversely related to the evaporative conditions of the atmosphere, with E_{as} being higher for conditions of low evaporative demand. The implication is that water use efficiency would be higher if one grows the same crop in the cooler part of the year as compared to the hottest part of the year. When normalized for evaporative demand of the atmosphere, however, E_{as} tends to be nearly constant for a given species. This conservative behavior lies in the fundamentals of leaf photosynthetic assimilation and transpiration process (Steduto *et al.*, 2007) and is illustrated in Fig. 2. In fact, large difference in E_{as} under similar climate can only be found between the C3 and C4 crop groups, with E_{as} being substantially higher for C4 than for C3. In fact, many C3 species exhibit nearly the same E_{as}, at least when data were obtained on single leaves (Steduto *et al.*, 2007). On the other hand, better nitrogen nutritional status of the crop can enhance E_{as} but not markedly (Ritchie, 198; Steduto *et al.*, 2007). So other than switching crops or changing the evaporative demand regimes, nutrient management is the only option to enhance E_{as} within a narrow range. As for biomass efficiency (E_{bm}, the 3rd step in Eq. 6), it depends mostly on the chemical composition of the crop (hence energy content per unit biomass) and cannot be easily altered except possibly by the impact of temperature regimes on crop respiration (Steduto *et al.*, 2007). In contrast, transpiration efficiency (E_{tr}, the 1st step in Eq. 6), can vary substantially with management practices. This is because the proportion of total ET that goes to transpiration is highly dependent on the degree of foliage canopy cover of the crop and the frequency of wetting of the soil surface. If canopy cover over the soil is sparse and the exposed soil surface is wetted frequently by irrigation or rain, there would be much soil evaporation and little transpiration, resulting in low E_{tr}. On the other hand, if the canopy cover is nearly complete and shades most of the soil surface, E_{tr} would be high even when irrigation or rainfall is frequent. That is because the shaded soil does not receive enough net radiation to supply the energy needed to sustain high soil evaporation rate.

Overall then, if $E_{bm/et}$ is low and the compounds making up the particular crop's biomass is not especially high in energy content, the probably cause is either poor nitrogen nutrition (can also be other nutrient deficiencies) or low canopy cover and frequent wetting of exposed soil surface. Of course, nitrogen nutrition can be improved by fertilization. Canopy cover can be manipulated to a certain degree by altering planting density. Same can be said for altering the frequency of irrigation

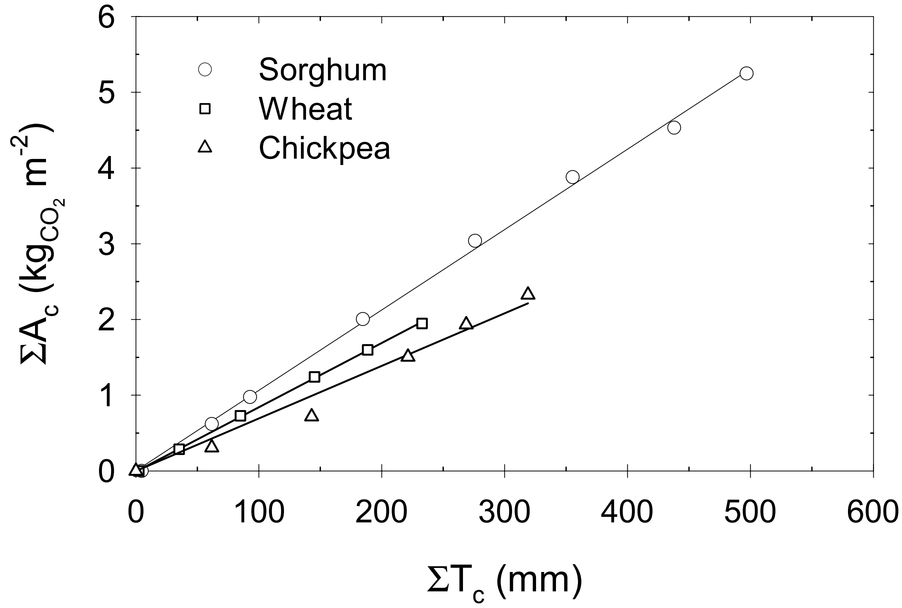


Figure 2. Relationships between cumulative daytime canopy net assimilation (A_c) and cumulative daytime canopy transpiration (T_c) for sorghum, a C4 crop, and wheat and chickpea, two C3 crops. The slope of the relationships represents E_{as}. Measurements were taken when the crops were all at full canopy cover, and soil evaporation was assumed to be negligible (redrawn from Steduto and Albrizio, 2005).

and wetting of the soil surface. Data illustrating the effects of canopy cover and wetting of the soil on soil evaporation relative to transpiration are shown in Figure 3 and Table 1. Features attributable to the development of crop canopy cover and changes in soil surface wetness stand out in Figure 3. For the first half of the graph, there is a gradual rise in base-line ET that can be visualized if one draws an imaginary smooth curve connecting the lowest ET rates for the first half of the graph. Added to this base line are several skewed ET peaks occurring after each irrigation. The peaks (referred to simply as irrigation spikes) are due to evaporation from the exposed soil surface after it is wetted by the irrigation water. As the soil surface begins to dry one or two days after an irrigation, soil E declines with time. The basal ET is due mostly to transpiration from the crop, plus some residual evaporation from the exposed soil at its driest point. In the first two or three weeks after planting, the plants have only very few leaves and the canopy covers only an insignificant portion of the ground. Therefore soil E accounts for virtually all of the ET. As the canopy of the crop develops, more and more of the ground is covered by the canopy, which continues to transpire regardless of the wetness of the soil surface, as long as the crop is obtaining sufficient water from the deeper part of the soil to keep its stomata open. Hence, base line ET rises with time in Figure 3, until the canopy covers the ground nearly fully.

With full ground cover, the canopy intercepts nearly all the radiation energy and accounts for most of the ET and soil E is not of much significance. ET is then insensitive to the wetting of the soil surface under the canopy, and hence is not affected perceptively by irrigation. In Figure 3, the soil was mostly covered by the crop canopy about 55 days after planting. There were therefore no marked

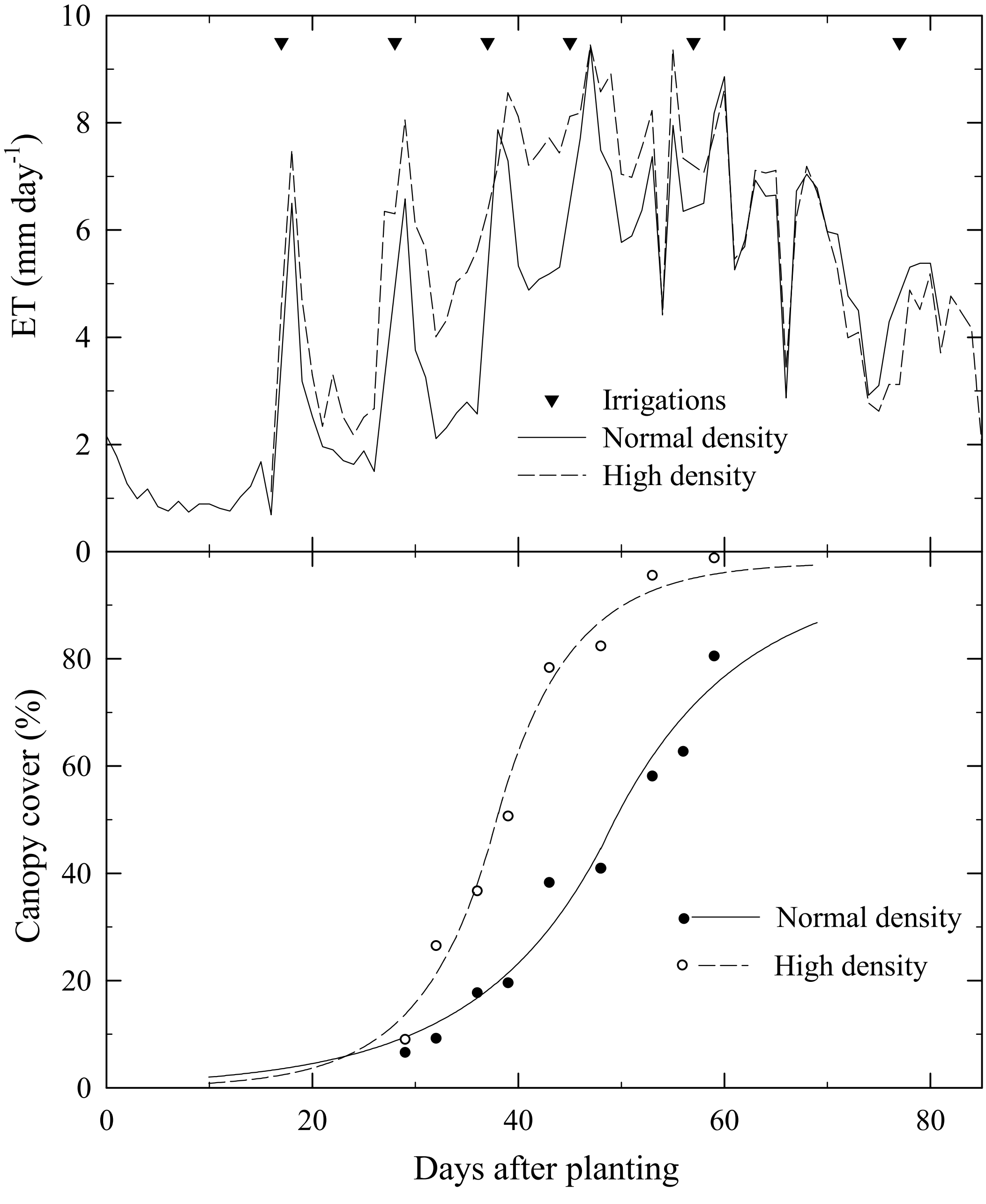


Figure 3. Daily evapotranspiration and canopy cover of bean (*Phaseolus vulgaris*) planted at two densities, 19 plants m^{-2} (normal, with 76 cm row spacing) and 38 plant m^{-2}.(high, with 38 cam row spacing). Inverted solid triangles indicate sprinkler irrigations. Measured canopy cover is given as circles; lines are fitted using the canopy growth model. ET was measured on two 6.1 M diameter lysimeters in the same field at the same time, at Davis, California. Summer, 1982. Reproduced from Hsiao and Xu (2005).

irrigation spikes in ET after that time, in spite of the irrigations. It is seen that by doubling the plant density and reducing the space between plant rows, the crop canopy develops faster. The faster canopy development is associated with a faster rise in base line ET. This supports the interpretation that when canopy cover is incomplete, base line ET is mostly due to canopy T when irrigation intervals are long enough to permit the drying of exposed soil surface. After most of the soil is covered by the canopy (day 55 onward), there was very little difference in ET between the two densities.

The model of Hsiao and Henderson (1985) that calculates E and T separately was used to simulate the ET of the two densities. As shown in *Table 1*, the simulated soil E for the low density planting was 101 mm or 28% of the total ET for the low density, and 44 mm or 11% of the total ET for the high density. The simulated results appear to be realistic in that the simulated total ET for the low and high density were, respectively, 362 mm and 406 mm, values surprisingly close to the measured total ET of 358 mm for the normal and 395 mm for the high density. A reasonable conclusion would be that the percentage of ET going to soil E can be reduced substantially by narrower row spacing and higher planting density. On the other hand, this would result in a higher total ET because of the increase in canopy T. Higher canopy T, however, is associated with higher CO_2 assimilation and hence higher productivity.

Table 1. Cumulative soil E and canopy T and ET as predicted by the model of Hsiao and Henderson (1985) in comparison with cumulative ET as measured by lysimeters, for fields of beans planted at two different densities. Data are for a period of 79 days starting 1 day after planting. Reproduced from Hsiao and Xu (2005).

	Plant Density			
	19 plants m^{-2}		38 plants m^{-2}	
	(mm)	(% of ET)	(mm)	(% of ET)
	Model			
Soil E	101	28	44	11
Crop T	261	72	362	89
ET	362	100	406	100
	Measurement			
ET	358	----	395	----

Returning now to the variations in and improvement of $E_{bm/et}$. For simplicity we start with the step efficiencies at the Poor Situation range. As mentioned, of the three constituent step efficiencies making up $E_{bm/et}$, E_{as} is conservative but can be changed by changing atmospheric evaporative demand and improving mineral nutrition, if the same species is grown. A reasonable fractional improvement that could be achieved there would be 0.1 (i.e., Δ = 0.1, see Eq. 4). The other step efficiency, E_{bm}, is even more conservative because it is determined mostly by the biochemical composition of the crop. No significant improvement can be expected there. This leave E_{tr} as the only step efficiency that can be manipulated to a fair degree. Starting with the poor situation range, a reasonable fraction improvement would be 0.8. According to Eq. 4, the overall improvement would be 98% (i.e., $\prod_i (1+\Delta_i) = 1.98$).. If for the original poor situation $E_{bm/et}$ is 0.76 kg biomass per m^3 of water consumed, the improved $E_{bm/et}$ would be 0.76 x 1.98 = 1.51 kg biomass per m^3 of water. Although this improvement is substantial, it is about the maximum improvement that can be practically achieved. Here we are limited by making improvements only in two of the three steps. To improve further, we need to consider other steps in the chain.

The other step to consider is farm efficiency, E_{farm}. This step efficiency is chosen for an additional reason, to show how an efficiency step can be divided into more steps when warranted. Previously we illustrated how adjacent steps can be combined to form a single step when necessary. On some farms the farmer store the water in a pond before conveying the water to the field for application. Thus, the processes can be considered to be consisting of two sequential steps, storage followed by conveyance in ditches to the field. Hence,

$$E_{farm} = \frac{W_{po}}{W_{fg}} \times \frac{W_{fd}}{W_{po}} = \frac{W_{fd}}{W_{fg}}$$

where W_{po} is the outflow from the storage pond, with the other symbols already defined. In a poor situation, the fractional improvement in storage efficiency, the 1st of the two step efficiencies, may easily be 0.6 if fine clay was disperse in the pond to seal the leaky coarse soil forming the bottom. The fractional improvement in the 2nd step efficiency, ditch efficiency, may be 0.8 if the ditches are lined with plastic sheeting. Thus, $\prod_i (1+\Delta_i) = 1.6 \times 1.8 = 2.88.$ In other words, the improvement in farm efficiency is 2.88 folds. If these improvements are carried out in addition to the improvements in $E_{bm/et}$ described earlier, the improvement in overall efficiency of the system would be 5.7 folds. Note that by making modest but not dramatic improvements in a number of steps, we managed to improve the overall water use efficiency several folds. .

APPLICATION TO MANAGEMENT TECHNIQUES AND OTHER PRODUCTION SYSTEMS

Because the principle and equations are general, the chain of efficiency steps framework is application to any production management technique or systems, as long as the steps in the production process are largely sequential. Since space does not allow detailed elaboration, the application of the chain of efficiency concept to two special water management techniques are summarized in *Table 2.*

Table 2. The step efficiencies for crop production which are likely to be enhanced by the listed water management techniques, and the likely range of potential improvement in the overall efficiency as the results of the improvements in the listed step efficiencies.

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%

the chain of efficiencies framework is equally useful for other production systems. Water is of paramount concern in rainfed cropping systems in less humid areas. To apply the chain of efficiencies approach, the engineering aspects of irrigated cropping, from conveyance from the reservoir to placing water in the root zone, are replaced by a couple of efficiency steps involving infiltration of rain water into the soil and retention of the water in the root zone. From that point onward the steps are the same as those starting on 4th efficiency step (E_{et}) of Eq 6. The concept is also valid for animal production. By adding animal production steps following the biomass step (for forage fed animal) or yield step (for grain fed animal), the final outcome is animal product instead of crops. These interesting applications are discussed in Hsiao *et al.* (2007).

The treatment here is confined implicitly to the local scale. In fact, the unit considered is a single field. For practical use, it is necessary to account for more complex situations such as a farm with a number of fields of different crops, or an irrigation district comprised of many farms and several distribution canals. These situations certainly make the calculations more complicated, but the principle and basic equations still apply. A way to integrate the basic equations for application at large scale has been worked out and is discussed in Hsiao *et al.* (2007). Another complication is the need to account for the use of recycled runoff and drainage water, also discussed in Hsiao *et al.*

USE IN ECONOMICAL ANALYSIS

The ability to quantify the contribution of improvement in any efficiency step to the improvement in overall efficiency makes this approach extremely useful. Different steps have difference efficiencies and the cost of their improvement also differ. Often the cost of raising a step efficiency to a top level is very high, but raising it to a modest level is low or moderate. Eq. 4 indicates that generally it is better to allocate resources to improve the steps with the lowest efficiencies, because the overall improvement is proportional to the fractional improvement of a step. So a given percentage improvement (e.g., 20%) in a low efficiency step (e.g., from 0.4 to 0.48) has exactly the same effect on the overall efficiency as the same percentage improvement in a relatively high efficiency step (e.g., from 0.8 to 0.98). When many step efficiencies are less than the good situation, how to allocate the limited resources for improvement among the steps is not simple and requires optimization. The approach here provides the quantitative fundaments for that process.

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