Strategies to Maximize Income with Limited Water

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The best economic strategy for water limited agricultural production will often be maximizing income per unit of water available. This requires information about the crop response (yield) to water applied, ways to maximize the effectiveness of rainfall and efficiency of irrigation, forecasts of future weather, the costs and value of production, and strategies to optimally allocate the limited water supply. Growers can make better decisions if they can predict at the beginning of the cropping season what crops and how many acres to plant. Then during the season, they need to know where and when to apply their limited water supply for the next week and the remainder of the season. They also could benefit from understanding the economic risks that result from inaccurate forecasts of irrigation water supply, weather, and crop and input prices. This is a very complex problem best solved with the help of Decision Support Systems that incorporate simulation models of crop growth; projections of weather; and inputs of available irrigation water, production costs, and crop prices.

Water Production Functions

The core information required to best use limited water is the yield response of crops to water. The Water Production Function, WPF (sometimes called water use efficiency, WUE), for a crop in terms of yield produced per unit of water applied, provides basic information needed to best allocate limited water supplies. Yield response to water for numerous crops has been studied by many researchers for many years. However, developing WPFs that are applicable to conditions different from the experimental conditions is difficult. Response of a crop to applied irrigation water depends on rainfall amount, soil water storage and soil type, timing of irrigations, evaporative demand, irrigation method and efficiency, and crop cultivar. Since it is impossible to include all of these variables in experimental trials, trials are often designed to mimic local conditions.

I believe a preferred approach is to base WPF trials on basic water balances so the information is most transferable to other conditions. By basing the function on water consumed by the crop (transpiration, Tc) rather than applied water, most of the effects of irrigation method and rainfall are eliminated. The effects of irrigation method and efficiency, effective rainfall, and soil water storage can then be factored back in based on local conditions. This method requires

measurement of crop transpiration. Crop water transpiration can be calculated by accurate measurement of water applied and stored in the root zone, measured changes in soil water storage, and estimates of soil evaporation. This is most easily done with metered drip irrigation where small irrigations can be accurately and uniformly applied and surface evaporation is small. Lysimeters can accurately measure transpiration, but are too expensive for most applications. Transpiration can also be estimated with micrometeorological measurements such as Bowen Ratio or Eddy Correlation.

Transpiration of a well-watered "baseline" crop (Tc) can be estimated using reference evapotranspiration equations (ETo) and a basal crop coefficient (Kcb) based on growth stage and planting configuration. By calculating water transpiration of a deficit irrigated crop relative to that of the well-watered crop, much of the influence of weather during the experiment (temperature, humidity, wind, and solar radiation) can be accounted for. Reference ET for an area and time period is then used to modify the transpiration level in the relative WPF for local weather conditions, and the crop coefficient, Kcb, is used to adjust for crop conditions. The well-watered crop should produce maximum yields for a given set of conditions (soils, fertility, cultivar, and climate). It is convenient to also calculate WPF yields relative to the maximum yield of the well-watered crop. Thus, the yields of cultivars that respond similarly to water stress but have different yield potential can be estimated based on their potential yield. Figure 1 shows an example of a generic "normalized" WPF that can be converted to a WPF for local conditions using actual or predicted irrigation efficiencies, effective rainfall, climatic conditions, and yield potential.
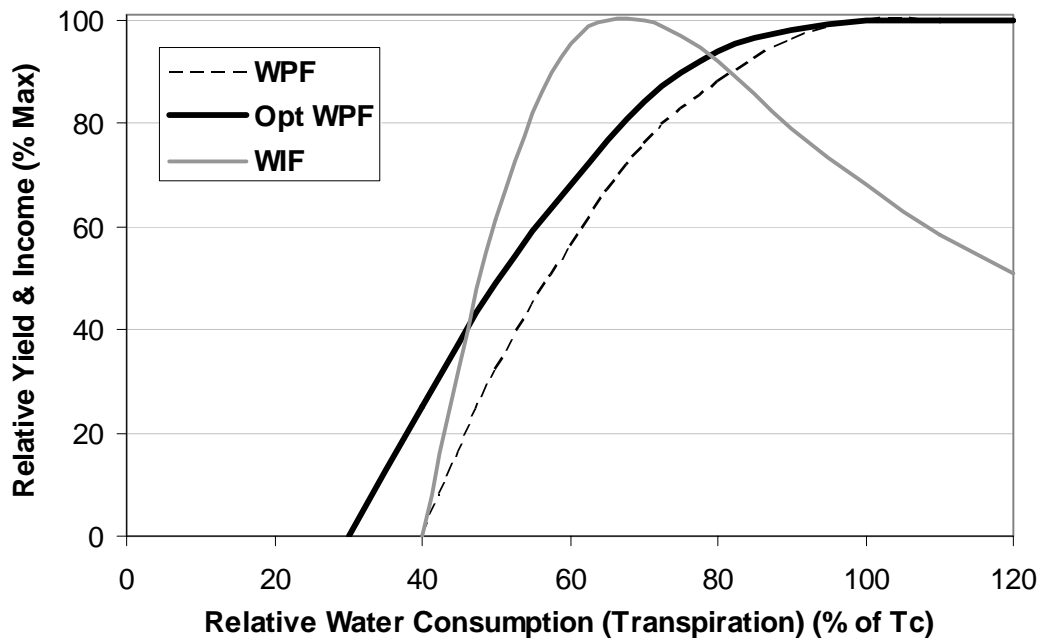

Figure 1. Depiction of a normalized Water production Function (WPF) with uniform water application, an "optimum" WPF with water strategically allocated among growth stages, and a Water Income Function (WIF)

Water Production Functions are based on water applied or consumed over an entire season. However, timing of water applications and the resulting water deficits experienced by the crop through the growing season can greatly affect the yield response. Irrigation applications in WPF experiments should be sufficiently frequent that impacts of fluctuating soil water content and crop stress are small. Drip irrigation allows frequent, efficient irrigation. The preferred scheduling approach would be to trigger frequent water applications based on plant stress indicators such as canopy temperature, leaf water potential, stomatal conductance, or soil water potential. However, these stress indicators are difficult to measure accurately and yield response to stress is not well quantified for most crops. An alternative scheduling approach is to base water applications (irrigation + effective rainfall) on a fraction of predicted water use of the well-watered crop (ie. replace percentages of Tc after each x mm of water use or x days). The plant phenological (growth rate, yield) and physiological (canopy temperature, leaf water potential, stomatal conductance, soil water potential) responses can be measured for the target deficits (ie. 50% of full water). Stress indicators can then be compared to measured deficits and yield. These scheduling methods assume water applications can be controlled and scheduled. Rainfall will sometimes exceed intended application levels and temporarily increase soil water content above targeted levels. Irrigation must be delayed after rainfall until the desired water deficit levels are reached again.

The response of crop yield and quality to water stress varies with the stage of growth. For example, many grain crops are less sensitive to stress during vegetative growth than during reproductive development. Some minimum soil water content is required to germinate and establish a stand. Deficits during maturation may positively or negatively effect crop quality and value. Thus, uniformly applied deficits often do not produce the maximum yield or value for a given water consumption. To maximize the WPF for many crops, the target deficit or stress level must be varied with stage of growth. For example, if the target seasonal water consumption is 70% of Tc, the best strategy might be to apply at 50% of Tc during vegetative and 90% of Tc during the reproductive stage. Because these relative growth stage responses to stress are not well known, it is possible that a given seasonal WPF could be improved with better allocation of water among growth stages. A goal of research is to quantify the relative response to stress at each growth stage so that a given seasonal allocation of water can be optimally applied.

Crop simulation models provide the opportunity to incorporate complex plant physiological processes that determine response to stress over time. They can also incorporate the effect of water supply limitations during certain portions of the season. Currently, most simulation models do not adequately model stress effects, but improvements based on improved understanding of plant physiology and data from well designed WPF experiments are being made. All WPF studies

should include adequate plant measurements to allow calibration and improvement of simulation models.

Water *Income* Functions

A Water Income Function, WIF, can be calculated from the WPF using input costs and crop prices. Because water costs (and possibly fertilizer and pest control costs) may increase with increasing water applications, the maximum income may occur at less than maximum yield, as depicted in Figure 1. With this WIF, the marginal return to water can be calculated and the amount of land that should be planted for a given water supply to maximize income can be predicted. If a grower has potential to grow several crops, the WIF for each crop can be combined in a system that optimizes the amount of each crop that should be grown. This Decision Support System, DSS, will predict the crop mix and intensity for a predicted water supply and other conditions. Constraints on the cropping mix such as availability of equipment and labor or market limits can be imposed to meet specific situations of growers.

As the season progresses, water supply, rainfall, weather, input costs and crop prices, and crop growth may deviate from the initial projections. Crop simulation models within the DSS can then update the WPFs for current conditions and project how to best allocate the remaining water. Such systems can consider more complex factors than is otherwise possible. Models and DSS must adequately incorporate the biology, physics, and economics of the farming operation and environment to make good predictions of yields and income.

Research Plans

The ARS Water Management Research Unit is carrying out field experiments to develop WPFs for 4 crops in rotation (corn, dry beans, wheat, sunflower) under two tillage systems (conventional and minimum tillage). Irrigation water will be applied through a metered drip irrigation system to maximize uniformity and minimize evaporative losses. Measurements will include:

- Irrigation water applications
- Rainfall
- ETo calculated with an on-site weather station
- ETc with Bowen Ratio Equipment
- Crop growth, canopy cover and Leaf Area Index (LAI) measured weekly
- Soil water content measured weekly (neutron probe and TDR)
- Crop stress (canopy temperature, leaf water potential, stomatal conductance) measured weekly.
- Yield and quality

The research will be closely coordinated with the ARS Agricultural Systems Research (ASR) unit who will use the results to improve and validate existing crop simulation models (RZWQM and DSSAT). They will also predict optimal allocations of irrigations among growth stages and how to allocate remaining water. The research will also be coordinated with a CSU agricultural economist who will carry out the economic analysis. The final objective is to develop a DSS that incorporates WPFs, crop simulation models, and economics into one system.