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Quantifying Crop Water Use in Arid and Semi-Arid Regions

- Opportunities Based on Soil-Plant Water Relations -

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Abstract: Proper management of water is vitally important to maintain and sustain crop production in arid and semi-arid regions, where water is often a limiting factor of crop growth. Despite progress made in the past decade, accurate prediction of water flow in the soil-plant system remains challenging. This paper briefly reviews opportunities for improving the precision of water use estimation for field crops considering current knowledge of soil-plant water relations and related multidisciplinary sciences. In addition to making full use of currently available soil/plant sensors and wireless technology, the combined use of crop coefficient-based approach and those involving dynamic modeling of soil-plant-atmosphere system water flow is helpful for robust and sensitive estimation of crop water requirements under variable environmental conditions.

Key Words: Crop coefficient, Root water uptake, Transpiration rate, Water demand, Water supply

1. Introduction

In settings of agricultural production, the amount of water a crop uses is often closely linked to biomass accumulation (Monteith, 1986). Yet, the quantity of water use in different growth stages of the crop can vary greatly depending on various biotic and abiotic factors (Jagtap and Jones, 1989; Ojha *et al*., 2009; Leskovar *et al*., 2012; Djaman and Irmak, 2013). Determining the water requirement of a crop is especially important for optimal irrigation water scheduling, considering the growing trend of water scarcity worldwide. To make the best use of every drop of water in agricultural production, land managers need to effectively regulate soil water status in plant root zone by controlling major components of the soil-plant system influencing water flow. Under certain instances, moderate level of water stress developed in the root zone may not significantly curb crop yield (Fereres and Soriano, 2007). In recent years, with the development of quantitative models, soil/plant sensors, and the wide access of wireless technology, there are opportunities for improving the accuracy of crop water use estimation under field conditions (Greenwood *et al*., 2010). However, a timely synthesis of the related ideas and/or integrated approaches directly applicable to the irrigation management of field crops is lacking. In this mini-review, we discuss current methods of estimating crop water use, soil water flow dynamics and root water uptake with the emphasis of identifying opportunities for the use of relatively simple models of soil-plant system water flow that can directly benefit optimal irrigation scheduling in irrigated agriculture.

2. Demand-based Method for Estimating Crop Water Use

One of the most important components of soil water balance is evapotranspiration (ET). The demand-based crop water use estimation uses a two-step approach, whereby crop ET is computed by potential ET and a crop specific coefficient (K_c) (Allen *et al*., 1989). This approach has been widely used to determine the growth stage-specific crop water use in irrigation management of various crops (Ko *et al*., 2009; Leskovar *et al*., 2012; Djaman and Irmak, 2013; Ghamarnia *et al*., 2013). As shown by Piccinni *et al*. (2009), the application of the crop coefficient method for crop ET estimation can save up to 25% of water use in spinach crop in southwest Texas, USA. As the crop coefficient method of ET estimation is based on potential ET, the crop ET may be overestimated under water-limited conditions as shown by Djaman and Irmak (2013) in maize growing in Nebraska, USA. Also, the crop coefficient for a particular crop may fluctuate under different environmental conditions (Jagtap and Jones, 1989; Annandale and Stockle, 1994), making the application of the crop coefficients developed at one location difficult to use in locations with different climate and/or soil/management conditions. It may be possible to mitigate the shortcomings of the crop coefficient method by considering the water supply to plant roots and the dynamic shoot-root interactions. For example, this is important, under situations of deficit irrigation (Costa *et al*., 2007; Fereres *et al*., 2007).

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3. Supply-Based Method for Estimating Crop Water Use

Monteith (1986) outlined a simplified framework of water supply and demand for crop growth and proposed a scheme for optimal irrigation scheduling. It is unknown, however, if this heuristic understanding has received enough attention in the practice of crop irrigation management. Based on a simplified soil-plant system water flow model of Campbell and Diaz (1998), Annandale *et al*. (2000) proposed a dynamic approach to estimate crop water requirement under both full and deficit irrigation. Soil water potential and root density distribution in the soil profile were used to predict root water extraction from different soil layers. These models also need input data such as crop thermal time requirements for emergence, reproductive development, leaf senescence and maturity, as well as the transpiration-biomass ratio. The authors suggested that their approach may provide a more accurate prediction of crop water use under conditions of variable water availability than the crop coefficient-based ET estimation method.

Nonetheless, similar to the crop coefficient-based approach, the model of Annandale *et al*. (2000) also relies on computed potential (instead of actual) transpiration. In addition, transpiration modeling based solely on root distribution may bypass some subtle but important mechanisms by which plant roots absorb water and nutrients from the soil medium under conditions of water stress. One example is the compensated and active uptake of water and nutrients by plant roots, as shown both by theoretical analysis (Lai and Katul, 2000) and computer simulations supported by field observed data of soil water contents (Adiku *et al*., 2000; Li *et al*., 2001; Skaggs *et al*., 2006; Šimůnek and Jopmans, 2009; Yadav *et al*., 2009; Dong *et al*., 2010). The compensated root uptake of water and nutrient is defined as the increased uptake from one part of soil depth (where water or nutrient is readily available) to compensate for the reduced uptake at soil depths where water or nutrient is limiting. It emphasizes the importance of root activity (as opposed to root mass/length density) in taking up water and nutrients (Lai and Katul, 2000). The degree of compensation may reflect a crop's ability of maintaining water uptake under moderate stress. This mechanism may be utilized to yield additional water saving in deficit irrigation, including the technique of partial root drying (Costa *et al*., 2007; Pereres and Soriano, 2007; Leskovar and Piccinni, 2005), if the amount of water a crop can mine from the soil through compensated uptake can be quantified under field conditions. To our knowledge, few studies have investigated this possibility.

Most of the models and analysis leading to the compensated uptake mechanism have some important differences from the simplified transpiration models of Campbell and Diaz (1998) and Annandale *et al*. (2000). The first difference is that these models typically employ additional empirical parameters to modify root water uptake (in addition to having a root distribution function similar to the latter models). Despite increased flexibility in adjusting root water uptake capacity (and correctly simulating root uptake compensation), it is usually difficult to link the compensated uptake with specific biological mechanisms (Šimůnek and Jopmans, 2009), primarily due to the empiricism of using the additional modifying parameters. These 'compensated' models also differ from the model of Annandale *et al*. (2000) in that the Richards equation, instead of the cascade scheme, is used in describing water flow. For management-orientated applications, however, these models may sometimes have stability problems due mainly to the highly nonlinear nature of the soil hydraulic functions as used in association with the Richards equation. The difficulty of obtaining complete information of the hydraulic functions from different soil depths and across a study field will further limit the application of these 'compensated' models. Fortunately, with the availability of the wireless-enabled soil water sensors (Greenwood *et al*., 2010) and the appropriate data assimilation technique (Lü *et al*., 2011; Shin *et al*., 2012), the problem of uncertainty in soil hydraulic properties will to some extent be ameliorated. Finally, similar to the models of Campbell and Diaz (1998) and Annandale *et al*. (2000), in these 'compensated' models water to be partitioned among roots located in different soil layers comes from potential transpiration, instead of actual transpiration. The problem with the approaches using potential transpiration is that stomatal control of transpiration may sometimes override the effect of root water uptake compensation under drought stress conditions.

4. Field Measurements in Support of the Estimation of Actual Crop Transpiration

Dong *et al*. (2010) showed that plants growing in the mixed-grass prairie of North Dakota, USA exhibited compensated root water uptake, which enabled the plants to efficiently absorb soil water both during a dry period and under ample water supply following a heavy rain event. In the meantime, some other models not including the mechanism for compensated uptake (such as that by Annandale *et al*., 2000) also accurately simulated soil water depletion during the growing season of a crop. A question that arises naturally is that if there is a water stress threshold that triggers the uptake compensation in a crop under particular growing condition? Answering this question may (a) help to clarify the physiological mechanisms responsible for the root water uptake compensation, and (b) lead to more accurate prediction of crop transpiration and assist in efficient delivery of deficit irrigation to field crops. This also motivates the use of simple models describing stomatal control of water loss, because, similar to the situation in root water uptake, the most likely situation for canopy water loss is that both the total leaf area index (LAI) and stomatal conductance play a role under water limited situations. Models developed by Johnson *et al*. (1991) and Gao *et al*. (2002) are of heuristic value for this efforts because they are relatively simple and consider the stomatal function from a "macroscopic" perspective. Yet, the simplicity goes along with the requirements of experimental data needed to estimate model parameters. This calls for reliable field measurements of leaf stomatal conductance, leaf area index, soil water content and evapotranspiration, as can be determined using a lysimeter (Marek *et al*., 2006). Due to non-linearity, the model of Gao *et al*. (2002) may not be giving reliable results under very dry conditions. It should be beneficial to calibrate several models (demand-, supply- and stomatal-based) within the same field experimental system for improved estimation of crop water use under varied field conditions. This may also offer opportunities for identifying conditions under which the water use estimation from particular models becomes off-bound (unreliable). The combined use of different classes of models can offer both robustness and sensitivity in crop water use estimation, with the crop coefficient-based method (demand-based) providing base-line values for the growth-stage specific ET, and the supply- and stomatal-based models giving further fine-tuning for the ET estimations and the possibility of saving additional amount of irrigation water while maintaining crop harvest index. Field experiments of crop water use are needed to substantiate this scheme.

5. Opportunities for Future Research

The development and availability of soil/plant sensors and wireless technology provide opportunities for deploying a large number of soil sensors in the field for measuring soil water and salinity. This will significantly expand researchers' ability of calibrating soil-plant system water flow models aimed at irrigation management. The availability of high quality data of soil water can to some extent compensate for the lack of soil hydraulic properties for solving the water flow equations.

Future availability of high resolution satellite-based surface soil water data (such as that from the Soil Moisture Active Passive (SMAP) satellite, which will provide top 5 cm soil water content at a 2-3 days cycle and 6 square mile spatial resolution for the globe; http://smap.jpl.nasa.gov), along with applications of new data assimilation methods (Shin *et al*., 2012), will facilitate improved prediction of crop evapotranspiration.

The release of new crop varieties with improved traits for drought/heat stress tolerance will provide opportunities for testing different crop water use models considering genotype, environment, and management interactions (Jones *et al*., 2003; Sinclair and Muchow, 2009; White, 2009; Boote *et al*., 2013).

The most desirable models of crop water use for assisting farmer's decision-making in irrigation water management in world's dryland regions should be relatively simple ones, the use of which should not require an extensive user input, but can give a robust prediction of water dynamics while reducing the risk of yield loss under uncertain climate. The combined use of conceptually different transpiration models in conjunction with experimental data, computing (Shin *et al*., 2012; McCarthy *et al*., 2013) and web support (Geogiev and Hoogenboom, 1999) may allow this to happen sooner.

References

Adiku S.G.K., Rose C.W., Braddock R.D., Ozier-Lafontaine H. (2000): On the simulation of root water extraction: examination of a minimum energy hypothesis. *Soil Science*, **165**: 226-236.

Allen R.G., Jensen M.E., Wright J.L., Burman R.D. (1989): Operational estimates of reference evapotranspiration. *Agronomy Journal*, **81**: 650-662.

Annandale J.G., Stockle C.O. (1994): Fluctuation of crop evapotranspiration coefficients with weather: a sensitivity analysis. *Irrigation Science*, **15**: 1-7.

Annandale J.G., Campbell G.S., Olivier F.C., Jovanovic N.Z. (2009): Predicting crop water uptake under full and deficit irrigation: An example using pea (*Pisum sativum* L. cv. Puget). *Irrigation Science*, **19**: 65-72.

Boote K.J., Jones J.W., White J.W., Asseng S., Lizaso J.I. (2013): Putting mechanisms into crop production models. *Plant, Cell and Environment*, **36**: 1658-1672.

Campbell G.S., Diaz R. (1998): Simplified soil-water balance models to predict crop transpiration. *In* Bidinger F.R., Johansen C. eds., *Drought Research Priorities for the Dryland Tropics*. ICRISAT, India, pp 15-26.

Costa J.M., Ortuño M.F., Chaves M.M. (2007): Deficit irrigation as a strategy to save water: Physiology and potential application to horticulture. *Journal of Integrative Plant Biology*, **49**: 1421-1434.

Djaman K., Irmak S. (2013): Actual crop evapotranspiration and alfalfa and grass reference crop coefficients of maize under full and limited irrigation and rainfed conditions.

Journal of Irrigation and Drainage Engineering, **139**: 433-446.

Dong X., Patton B.D., Nyren A.C., Nyren P.E., Prunty L.D. (2010): Quantifying root water extraction by rangeland plants through soil water modeling. *Plant and Soil*, **335**: 181-198.

Fereres E., Soriano M.A. (2007): Deficit irrigation for reducing agricultural water user. *Journal of Experimental Botany*, **58**: 147-159.

Gao Q., Zhao P., Zeng X., Cai X., Shen W. (2002): A model of stomatal conductance to quantify the relationship between leaf transpiration, microclimate and soil water stress. *Plant, Cell and Environment*, **25**: 1373-1381.

Geogiev G.A., Hoogenboom G. (1999): Near real-time agricultural simulations on the web. *Simulation*, **73**: 22-28.

Ghamarnia H., Jafarizade M., Meri E., Gobadei M.A. (2013): Lysimetric determination of *Coriandrum sativum* L. water requirement and single and dual crop coefficients in a semiarid climate. *Journal of Irrigation and Drainage Engineering*, **139**: 447-455.

Greenwood D.J., Zhang K., Hilton H.W., Thompson A.J. (2010): Opportunities for improving irrigation efficiency with quantitative models, soil water sensors and wireless technology. *Journal of Agricultural Science*, **148**: 1-16.

Jagtap S.S., Jones J.W. (1989): Stability of crop coefficients under different climate and irrigation management practices. *Irrigation Science*, **10**: 231-244.

Johnson I.R., Melkonian J.J., Thornley J.H.M., Riha S.J. (1991): A model of water flow through plants incorporating shoot/root 'message' control of stomatal conductance. *Plant, Cell and Environment*, **14**: 531-544.

Jones J.W., Hoogenboom G., Porter C.H., Boote K.J., Batchlor W.D., Hunt L.A., Wilkens P.W., Singh U., Gijsman A.J., Ritchie J.T. (2003): The DSSAT cropping system model. *European Journal of Agronomy*, **18**: 235-265.

Ko J., Piccinni G., Steglich E. (2009): Using EPIC model to manage irrigated cotton and maize. *Agricultural Water Management*, **96**: 1323-1331.

Lai C.T., Katul G. (2000): The dynamic role of root uptake in coupling potential to actual transpiration. *Advances in Water Resources*, **23**: 427-439.

Leskovar D.I., Agehara S., Yoo K., Pascual-Seva N. (2012): Crop coefficient-based deficit irrigation and planting density for onion: growth, yield and bulb quality. *HortScience*, **47**: 31-37.

Leskovar D.I., Piccinni G. (2005): Yield and leaf quality of processing spinach under deficit irrigation. *HortScience*, **40**: 1868-1870.

Li K.Y., De Jong R., Boisvert J.B. (2001): An exponential root-water-uptake model with water stress compensation. *Journal of Hydrology*, **252**: 189-204.

Lü H., Yu Z., Zhu Y., Drake S., Hao Z., Sudicky E.A. (2011): Dual state-parameter estimation of root zone soil moisture by optimal parameter estimation and extended Kalman filter data assimilation. *Advances in Water Resources*, **34**: 395-406.

Marek T., Piccinni G., Schneider A., Howell T., Jett M., Dusek D. (2006): Weighing lysimeters for the determination of crop water requirements and crop coefficients. *Applied Engineering in Agriculture*, **22**: 851-856.

McCarthy A.C., Hancock N.H., Raine S.R. (2013): Advanced process control of irrigation: the current state and analysis to aid future development. *Irrigation Science*, **31**: 183-192.

Monteith J.L. (1986): How do crops manipulate water supply and demand? *Philosophical Transactions of the Royal Sociery of London A.*, **316**: 245-259.

Ojha C.S.P., Prasad K.S.H., Shankar V., Madramootoo C.A. (2009): Evaluation of a nonlinear root water uptake model. *Journal of Irrigation and Drainage Engineering*, **135**: 303-312.

Piccinni G., Ko J., Marek T., Leskovar D.I. (2009): Crop coefficients specific to multiple phenonogical stages for evapotranspiration-based irrigation management of onion and spinach. *HortScience*, **44**: 421-425.

Shin Y., Mohanty B.P., Ines A.V.M. (2012): Soil hydraulic properties in one-dimensional layered soil profile using layer-specific soil moisture assimilation scheme. *Water Resources Research*, **48**: W06529.

Šimůnek J., Jopmans J.W. (2009): Modeling compensated root water and nutrient uptake. *Ecological Modelling*, **220**: 505-521.

Sinclair T.R., Muchow R.C. (2009): System analysis of plant traits to increase grain yield on limited water supplies. *Agronomy Journal*, **93**: 263-270.

Skaggs T.H., van Genuchten M.Th., Shouse P.J., Poss J.A. (2006): Macroscopic approaches to root water uptake as a function of water and salinity stress. *Agricultural Water Management*, **86**: 140-149.

White J.W. (2009): Combining ecophysiological models and genomics to decipher the GEM-to-P problem. *NJAS - Wageningen Journal of Life Sciences*, **57**: 53-58.

Yadav B.K., Mathur S., Siebel M.A. (2009): Soil moisture dynamics modeling considering the root compensation mechanism for water uptake by plants. *Journal of Hydrologic Engineering*, **14**: 913-922.