Evaluation of Soil Hydraulic Limitations in Determining Plant-Available-Water in Light Textured Soils

Thesis submitted by

Sukhpal Singh Chahal

BSc. Agri. (Hons.) and Master of Science (Agronomy) from
Punjab Agricultural University, Ludhiana, Punjab, India

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Table of Contents

Summary

Chapters 1 and 2 identify the aims and objectives of the study, as well as the hypotheses and assumptions required. The relevant literature on soil water availability and plant-response to water stress is explored. In particular these two chapters explain that plants extract water from soils by regulating a host of physiological mechanisms at their disposal – some plants are more efficient than others at doing this. As soil dries out, plants must ‘sense’ and gradually integrate the net effect of many soil conditions including: increasing soil aeration, as well as matric and osmotic suctions and soil strength, but also diminishing soil hydraulic conductivity. Plants, therefore, gradually take up water more slowly as the soil dries, depending on environmental conditions and other factors, all of which vary enormously on an hourly basis and which are difficult to predict let alone measure. Groenevelt *et al*. (2001; 2004) proposed a model, the Integral Water Capacity (IWC) to predict the effects of soil physical and chemical restrictions on water availability, but this model has not yet been tested against the performance of real plants. Evaluation of this model forms the primary focus of this study.

The IWC uses the soil water retention curve, $\theta(h)$, to produce a differential water capacity, $C(h) \equiv d\theta/dh$, which is then reduced using various weighting functions, $\omega(h)$, to account for the above limiting physical and chemical properties, then integrated to produce a total amount of water that can be extracted from the soil by plants. The key, of course, is to identify robust weighting functions for each of the limiting soil conditions, yet this is no easy task because the limiting soil conditions often interact. For example, as the soil dries out, the hydraulic conductivity drops while aeration, strength and salinity all increase to varying extents – this makes it difficult to quantify the effect of any one limitation. In the present study it was therefore decided to focus solely on the unsaturated soil hydraulic conductivity as the major limiting soil condition. A significant drop in the soil hydraulic conductivity during a dry period after rainfall or irrigation can make the difference between crop success and failure, particularly in Mediterranean and arid environments. The aims of the study were to:

1) Evaluate the effect of declining soil hydraulic conductivity on soil water availability in the absence of all other known soil physical limitations.

2) Evaluate the link between real plant response to water stress and that predicted using the IWC model of Groenevelt *et al*. (2001) for a range of different plant species, planting densities, soil types and environmental conditions.

3) Evaluate the utility of the hydraulic conductivity function of Grant *et al*. (2010) in weighting the water capacity.

Chapter 3 identifies the main methods used in the study. It explains that two different, light-textured soils were selected (*Very fine sand* and *Loamy sand*)[1], for some pot experiments designed to compare the predicted and measured amounts of water that two contrasting plants (maize v. sorghum) could extract from the soil under different environmental conditions (low and high evaporative demand). In the first instance, the water retention curves were measured on soil samples packed to the same bulk densities used in the plant experiments. The water retention curves were then modelled to produce the differential water capacities and the relative hydraulic conductivities for the two soils. The IWC was then calculated based upon experimental data describing plant responses to environmental conditions (see below).

A large number of pots holding 5 kg soil and different numbers of maize or sorghum seeds were well watered until plants reached a critical stage, after which half the pots were no longer supplied with water while the other half were maintained at ideal water contents. An identical set of control pots containing no plants was monitored to separate evaporation from plant transpiration, and to thus determine the soil matric suction at which the rate of water loss from the planted pots declined to the rate of natural evaporation – indicating the point at which transpiration effectively stopped. Stomatal conductance, g (mmol m^{-2} s^{-1}), and soil water content, θ (m^3/m^3) were measured first thing each morning every day until this was no longer possible. When stomatal conductance on the stressed plants could no longer be measured (ranging between 5 and 21 days depending on conditions) the experiments were terminated and the fresh weights of roots and shoots measured.

Chapter 4 describes how the stomatal conductance of the stressed plants, g, was expressed as a fraction of that for the well-watered control plants, g_c, and plotted as a function of the soil water suction, h (cm). At a certain stage the decline in relative

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[1] both soils had no significant physical or chemical restrictions other than relatively low unsaturated hydraulic conductivity

stomatal conductance, g/g_c, changed from a curved to a linear form and continued in this way until it was no longer possible to take measurements, at which point g/g_c was judged to be zero. The transition between the curved and linear decline in g/g_c was considered to mark the soil matric suction, h_t, at which plants began to experience terminal water stress. When plants finally stopped transpiring, the soil matric suction, h_w, was noted as the end point of the experiments.

The stressed plants stopped transpiring across a large range of soil matric suctions, demonstrating that plant-response is strongly influenced by soil texture, plant species, root-length density, and environmental conditions. By far the most important factor, however, was soil texture; plants grown in the *Very fine sand* (coarser-textured) perished at suctions much smaller than the classical wilting point of 15,000 cm, while plants grown in the finer *Loamy sand* persisted to matric suctions of nearly 27,000 cm in some cases. The other variables appeared to be less important and somewhat complicated by interactions. For example, when averaged across soil texture (and in most cases, regardless), sorghum extracted water to greater matric suctions at all planting densities than did maize; however at higher planting densities and under higher evaporative demand, maize extracted water to greater matric suctions than sorghum. The large difference in behaviour of plants between the two soils demonstrated that a primary cause of water stress was a limitation in the unsaturated hydraulic conductivity. This highlighted the importance of hydrodynamics in controlling water-availability to plants and indicated the potential usefulness of the unsaturated hydraulic conductivity function in weighting the differential water capacity.

Chapter 5 explores the extent to which dynamic plant responses to water stress can be used to calculate the IWC. The best function for weighting the soil water capacity was found to be a modified quadratic relation that incorporated the critical soil matric suctions at the onset and end of hydraulic stress, as well as the root-length density. The onset of hydraulic stress shifted toward lower matric suctions as temperature and evaporative demand increased, and transpiration stopped at lower matric suctions as well – particularly in the *Very fine sand* (well before the classical permanent wilting point of 15,000 cm). The effects were more modest in *Loamy sand* where plants (particularly sorghum) survived well beyond the classical wilting point. Both sorghum and maize extracted greater amounts of water from the *Loamy sand* than from the *Very fine sand*, and sorghum extracted more water from both soil types than did maize.

Chapter 6 explores how soil properties combined with plant response can be used to calculate the IWC. In the first instance, the model of Grant *et al*. (2010) was applied to obtain the relative hydraulic conductivity of the two soils, which provided useful parameters to develop a simple weighting function for the water capacity. The functional form was based on two factors: the shape of the unsaturated hydraulic conductivity and the soil matric suctions at which plants experienced the onset of water stress and then cessation of transpiration. The IWC's predicted by applying this weighting function were closer to the actual amounts of water extracted by the plants than were the IWC's produced in Chapter 5, and were more accurate in the coarser of the two soils, the *Very fine sand*. The combination of soil and plant factors in predicting IWC appears to produce superior estimates than either soil or plant factors alone.

Chapter 7 draws some general conclusions, highlights the implications of the work conducted in this study and identifies potentially fruitful lines of future research.

Declaration

Name: **Sukhpal Singh Chahal** **Program:** **Doctor of Philosophy**

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Dedication

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