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The available water holding capacity of soils under pasture

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ABSTRACT

The concept of available water holding capacity (AWHC) is important to many aspects of soil water management, particularly those involving a soil water balance calculation. In New Zealand AWHC estimates are commonly based directly or indirectly on laboratory measured pressure plate data. Such retentivity based values for AWHC are relatively similar across a range of soil types. Less often, AWHC values have been measured under rye grass/white clover pasture in the field. We critically discuss an important earlier New Zealand study. It noted that field-measured values are commonly about twice the laboratory-based estimates. We conclude that variable rooting depth, due to the presence or absence of compacted soil at depth and/or variable pasture vigour or species composition, usually has a greater effect on the AWHC than does the soil properties in the top 760 mm depth. Finally, it is claimed that this uncertainty around the exact size of AWHC need not undermine its utility. The one exemption to this assurance is where reliable predictions of drainage (and leaching) below the root zone are required: in this case there is the likelihood that use of the often quoted values for AWHC in the water balance will result in a significant overestimation of drainage (and leaching).

1. Introduction

The available water holding capacity (AWHC) is an important feature of many aspects of soil water management. This is particularly true of those components of soil water management which are informed by the use of a soil water balance. Soil water balances are calculated for a wide variety of reasons, such as; to assist in soil classification (Hurst, 1951), the development of models of water movement, crop growth and nutrient leaching (Cichota et al., 2013), quantifying the response to irrigation and the irrigation water requirement, scheduling irrigation, identifying when dairy shed effluent can be applied to land without environmental damage, when a paddock can be cultivated without damaging the soil structure, and how large a dam to install in a sub-catchment. This illustrates the level of interest in soil water balances and therefore AWHC.

To calculate a daily soil water balance at least three things need to be known or estimated. The first is the rainfall. The second is the evapotranspiration. The third is the AWHC, that is the maximum amount of stored water that the vegetation can extract from the soil during periods when the rainfall is less than the evaporative demand.

The AWHC, expressed like rainfall as an equivalent depth, is the difference between the volumetric soil water contents at the upper and lower storage limits integrated over the rooting depth. The upper storage limit is the maximum amount of water the soil profile can hold on to during a rain-free period, while the lower storage limit is the water left in the soil when the vegetation has extracted all the water that it can from the soil.

We consider here the ways the AWHC is estimated or measured for soils growing a typical rye grass/white clover pasture in New Zealand, the wide range of values obtained, and the uncertainty in determining the best estimates. We see the paper by Woodward et al. (2001) as being a significant contribution to research on this topic, so discuss it in some detail. We reformat Woodward et al.'s soil water balance model and critique their suggested approach to AWHC estimation. Lastly we discuss how important it is, or is not, to use a reasonably accurate AWHC value in the common applications of soil water balances. While New Zealand data are presented, the principles discussed and conclusions reached have wider relevance. But first we need to consider the upper and lower limits referred to above.

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2. Defining terms—the upper limit and lower limit

The upper storage limit for plant available soil water is usually referred to as field capacity. We start by saying what field capacity is not. Despite what is stated in some elementary soil science textbooks, field capacity is not the equilibrium water content when the downward gravity force is balanced by the upward capillary forces. Such equilibrium is only reached in the metre or so of soil immediately above a water table. Kirkham (2014, p. 153) describes the attainment of field capacity following the excessive wetting of the soil profile in the following manner: "after one or two days the water content . . .. will reach, ... for many soils, a nearly constant value. This somewhat arbitrary value . . .. is called the field capacity." Field capacity is not always reached in two days. Nielsen et al. (1959) showed that two silt loam and two clay loam 1.5 m deep soil profiles, which had been wet to excess and then covered with plastic, lost a further 10 mm to 50 mm of water via drainage following the first two days.

Gardner (1960) defined field capacity somewhat differently as the soil water content at which the unsaturated hydraulic conductivity is so small that further gravity induced drainage is negligible and Twarakavi et al. (2009) presented a detailed analysis of this approach. It also has its problems. A negligible drainage rate is usually taken as being significantly less than the evapotranspiration rate (which is typically between 1 and 5 mm/d in New Zealand),but there is no agreement on the specific rate at which drainage becomes negligible. Assouline and Or (2014) reported that negligible rates ranging from 0.01 mm/d to 1 mm/d have been assumed. However, despite the above problems, the concept of field capacity has proven to be so useful that it persists and the literature abounds with estimated values for it.

The lower limit for plant available soil water, often misleadingly referred to as the permanent wilting point, is commonly estimated as the laboratory measured water content at a matric potential of −1.5 MPa (Kirkham, 2014, p. 157). The limitations of such estimates are discussed below.

Of course the AWHC is not just a soil property. The vigour of the pasture, and the species it contains, will affect the root distribution and so the amount of extractable water in a soil profile at the upper limit. For example, in a four year study on a deep silt loam, Brown et al. (2005) found a maximum soil water deficit of around 340 mm under red clover and chicory forages, but a maximum deficit of 400 mm under lucerne, with the extra 60 mm of uptake all coming from below 1.6 m depth. However, in this study we will focus on the influences of soil attributes and the characteristics of rye grass/white clover pasture that affect AWHC.

As well as the AWHC it is useful to define another water holding capacity, the readily available water holding capacity. This is the difference in root zone storage at the upper limit and the storage when the evapotranspiration rate is first affected by water stress. As water held in larger pores is more easily extracted than the water held in smaller pores, some water is more readily available, some is less readily so. Also, water in the topsoil where root density is greatest, and less energy is required to lift it, is more readily extracted than water deeper down in the soil profile. The readily available water can be extracted from the soil fast enough for the evapotranspiration rate to equal what is called the reference evapotranspiration crop rate. A pasture behaves as a reference crop when it fits the description of "an extensive surface of green grass of uniform height, actively growing, completely shading the ground, and with adequate water" (Allen et al., 1998, p. 23). The reference crop evapotranspiration rate is independent of the soil, and can be estimated from meteorological data. Once all the readily available water is exhausted, the soil partly controls the evapotranspiration rate, which in the absence of rain or irrigation, gradually reduces from the reference crop rate to near zero as more and more of the remaining available soil water store is used up. It is commonly assumed that about half of the AWHC is readily available (Allen et al., 1998, p. 162), although that will not be the case for all soils, all plants and all climatic conditions.

3. The common approach to estimating AWHC

One method is used so commonly to obtain AWHC estimates that it has come to be regarded as the standard procedure for identifying AWHC. It is discussed and adopted in the widely used FAO manual for computing crop water requirements (Allen et al., 1998). In a series of papers, Gradwell (1968, 1971, 1974, 1976) used it to obtain AWHC estimates for nearly 100 soil profiles in New Zealand. He took soil samples from each horizon into the laboratory to obtain estimates of the upper and lower limit moisture contents using pressure plate retentivity measurements. Currently such retentivity values are often not measured but instead inferred from other soil properties using pedo-transfer functions (Lilburne et al., 2014). A rooting depth is then assumed in order to obtain an AWHC value for the soil.

There is some basis to the assertion that the soil water content at a certain matric potential will approximate the field capacity or upper limit. Near saturation, almost all of the water flow through a soil is via a network of interconnected macropores. At a matric potential of around −20 kPa, these macropore networks have emptied and the hydraulic conductivity has usually decreased by several orders of magnitude. So the water content at about this matric potential often corresponds to the upper limit at which further drainage can be considered negligible, as demonstrated for example by Gradwell (1985).

One problem with this laboratory based procedure for estimating AWHC is that there is no widespread agreement on what matric potential value best approximates the upper limit or field capacity. Gradwell (1968) reported that values ranging from −4 to −50 kPa had been used by other workers, before selecting a value of −19.6 kPa (−2 m head of water) in his studies. More recently, Assouline and Or (2014) report a similar range of values from the literature (from −5 to −33 kPa) with −33 kPa being the *de facto* standard value employed in the USA. As there is usually a large difference between the water contents at −5 and −33 kPa, the matric potential value chosen makes a significant difference to the estimates of AWHC. Another problem is that the presence of either a relatively impermeable horizon (Scotter, 1977), or a coarser-textured horizon (Clothier et al., 1977), enhance the field capacity in the soil horizon above it, and these effects are not taken into account in the laboratory estimates.

Similar problems exist with the laboratory estimate of the lower limit. As indicated above there is widespread agreement that the lower limit can be estimated as the soil water content at a matric potential of −1.5 MPa. However there is no good reason for choosing this particular matric potential. As Czyz and Dexter (2012) commented "it is not a coincidence that the commonly assumed wilting point suction is the same as the greatest value of air pressure that was used in the pressure cell extractors." Furthermore, no single matric potential value is likely to apply over the whole rooting depth. As shown below, pasture is less effective at drying out the subsoil than the topsoil, presumably due in part to decreasing root density with depth. The lower limit also depends on climatic conditions to some extent.

As already mentioned, Gradwell (1968, 1971, 1974, 1976) used the retentivity method to obtain AWHC values for 96 New Zealand soil profiles. He assumed a rooting depth of 760 mm. The cumulative probability distribution of the values Gradwell obtained is shown in Fig. 1. The mean AWHC value is 109 mm, and the standard deviation is only 27 mm. It will be argued below that the variability