Technologies to estimate plant available soil water storage capacities at high spatial resolution

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Abstract

Grain yields in the Mediterranean-type environment of Western Australia are often limited by insufficient water. Water needs to be stored between rainfall events for crop use. The plant available water storage capacity of a soil (PAWC) is therefore an important yield determinant in this environment. PAWC is used to simulate crop growth, grain yield, water loss by deep drainage and nitrate leaching. Tactically this simulation allows nitrogen requirement to be determined and strategically, the long term yield and environmental performance of the field can be assessed. PAWC can vary from 30 to 150 mm across a field mainly due to differences in soil texture and root distribution. Direct measurement of this variation is time consuming and costly. This work aimed to develop geophysical methods to estimate PAWC at metre resolution across paddocks. Apparent soil electrical conductivity (EC_a) and gamma-ray emission from the natural abundance of radioactive potassium (^{40}K), thorium and uranium isotopes were measured by electromagnetic (EM38) sensing and gamma-spectrometry respectively, carried out at 30 m line spacing. In areas devoid of superficial rocks, gravels and salt, linear regressions were obtained between EC_a or gamma-emission from ^{40}K and PAWC. Salt-affected areas resulted in large EC_a values unrelated to PAWC. In these areas, only gamma-emission from ^{40}K could be used to estimate PAWC. For shallow sandy soils overlaying gravel and rock, soil depth was estimated from the attenuation of gamma-rays emitted by superficial the rock and gravels. This approach allowed us to estimate PAWC from soil depth.

Key Words

Gamma-ray spectrometry, apparent soil electrical conductivity, EM38, precision agriculture, yield variation

Introduction

Yield monitoring in Western Australia (WA) typically measures large variation in grain yield ranging by a factor of about ten from about 0.4 to 4.0 t/ha across a paddock (Wong and Asseng 2006). The implication of such large yield variations common across the WA wheatbelt is that low yielding parts of the paddock may receive too much fertiliser whereas the high yielding parts may be over-fertilised because fertiliser requirement is dependent on both the size of the crop and the soil test value for the nutrient (Wong et al 2001). In paddocks with large yield variations, it is financially beneficial to adjust nitrogen (N) to the anticipated size of the crop and the plant available N content of the soil profile (Robertson et al 2006). Fine tuning N application may not only be financially beneficial but can also decrease N leaching by matching application to site-specific requirement (Wong et al 2005, Stoorvogel and Bouma 2005).

Insufficient water is an important limitation to grain yield in the Mediterranean-type environment of Australia and is the underlying cause of both spatial and temporal yield variability (Wong and Asseng 2006). The amount and distribution of rainfall across a cropping season determines the water-limited yield potential of the crop. The different capacities of soils to store water for crop use between rainfall events greatly influences spatial yield variability across a paddock. They also significantly influence the extent of temporal yield variation since soils with larger plant available soil water storage capacities (PAWC) store more water, minimise loss to deep drainage and allow a bigger crop response to rainfall (Wong and Asseng 2006). It is time-consuming and costly to measure PAWC directly at spatial resolutions needed to interpret yield maps and to fine-tune paddock management. One option to minimise costs is to measure PAWC within contrasting yield zones across the paddock and assume (1) that the yield zones were due to variation in PAWC and (2) acceptable uniformity in PAWC within each zone (Oliver et al 2006). The ability of a soil to store plant available water is predominantly governed by soil texture and root length distribution down the soil profile. Our ability to sense soil texture by electromagnetic (EM38) and gamma-ray sensing provides a means to estimate PAWC for the typical root distribution of the crop. When a root-impenetrable layer such as a compacted or acidified soil layer occurs within the potential rooting depth of the crop, then PAWC is decreased by depth of the soil over the impenetrable layer. Our aim was to use these geophysical techniques to develop another option to estimate PAWC at high spatial resolution similar to those of yield maps (5 m grid). Development of this new option requires us to overcome geophysical shortcomings such as salt interference on measurements of soil apparent electrical conductivity (EC_a) by EM38 and gamma-ray emissions from materials such as rocks and gravels that are unrelated to the clay content of the soil. It also requires us to develop an effective means to estimate soil depth over a root-impenetrable layer.

Methods

Geophysical surveys

EM38 and gamma-emission surveys were carried out at paddock-scale on one farm in Three Springs and two farms (A and B) in Buntine, WA. EM38 survey was carried out on wet soil in winter and gamma-emission on dry soil in summer to maximise signal strength measured on-ground using a quad-bike travelling slowly at 30 m line spacing. The paddock in Three Springs had soil texture ranging from grey sand to loam. The paddocks on both farms in Buntine sloped down to a salty creek that formed their north-west boundary. Soil texture in these Buntine paddocks ranged from pale yellow sand to deep yellow sand and sandy loams and gravely soils. There are occasional occurrences of alkaline red clay soils on farm B. Soil depth across the paddock on farm A was very variable due to shallow compacted gravels at 10 to 60 cm depth.

Measurements of plant available soil water storage capacities

Geophysical survey and paddock yield data were use to decide the locations of PAWC measurement to cover the range of data values. Soil samples were taken to a maximum depth of 2.1 m wherever possible at these sampling locations to measure soil bulk density and soil water contents at crop lower limit and drained upper limit. The crop lower limit is the water content of the soil after harvest and is a measure of the ability of the crop to take up water from the soil and to dry it down prior to harvest in a dry finish year. The drained upper limit is the field capacity of the soil and was measured in winter by wetting the soil down to the sampling depth, allowing it to drain under cover for several days and sampling for soil moisture determination. The amount of water (mm) contained between the crop lower limit and the drained upper limit is the PAWC (Dalgliesh and Foale, 1998).

Estimating soil depth from attenuation of gamma-rays

Soil depth was measured at the interface between the sand and compacted gravel layer on farm A. This interface was readily noticeable but could be confirmed by sudden increase in cone penetrometer resistance to > 5MPa. Assuming that the underlying root-impenetrable gravel layer had similar chemical composition across the paddock then, in the absence of an overburden, one would measure a uniform rate of gamma emission from the gravel layer. This layer is unlikely to be horizontal, and on farm A was covered by a non-uniform depth of sand. Sand will attenuate gamma radiation reaching the surface and the thickness required to decrease the radiation by half is called its half thickness. The half thickness of dry sand at bulk density 1.6 g / cm^3 is approximately 10 cm (Grasty, 1979). The overlying sand layer is itself a weak emitter of gamma-rays. Its emission was ignored compared with the much stronger emission from compacted gravels. The exponentially decreasing relationship between gamma-K and soil depth was used to estimate soil depth spatially.

Results

The PAWC data reported here are for the 0-90 cm layer to account for the maximum depth of sensing (< 90 cm). Strong correlations (r^2 >0.7) were obtained between PAWC in the 0-60 cm layer and the corresponding values in the 0-90 cm layer. At Three Springs, PAWC could be estimated from its linear relationships with both EC_a and gamma-emission from ^{40}K (gamma-K). This paddock was mostly devoid of salt incursions but only had small areas of superficial gravels where PAWC was not measured. Estimation of PAWC in those areas is dealt with separately below. Outside those areas, the regression equations for PAWC were:

PAWC = 22.6 EC_a – 25, r^2 = 0.78.

PAWC = 1.9 gamma-K – 81.8, r^2 = 0.69

Occurrence of salt and of shallow compacted gravels across paddocks on farm A and B in Buntine resulted in poor correlations between PAWC and EC_a (Figure 1a, c). There was a stronger but poor (r^2 = 0.5) correlation between PAWC and gamma-K that followed opposite directions on these two farms (Figure 1 b, d). On farm B, areas with red clay gave gamma-K counts > 70 counts /100 s and these areas were associated with high PAWC values. Shallow gravels also gave high counts but this was unmatched by PAWC values. This weakened the local correlation between gamma-K and PAWC. On farm A, shallow compacted gravels also resulted in increased gamma-K emission. Here, the extensive area of shallow gravels varied in depth with shallow depths resulting in increased emission and decreased PAWC.

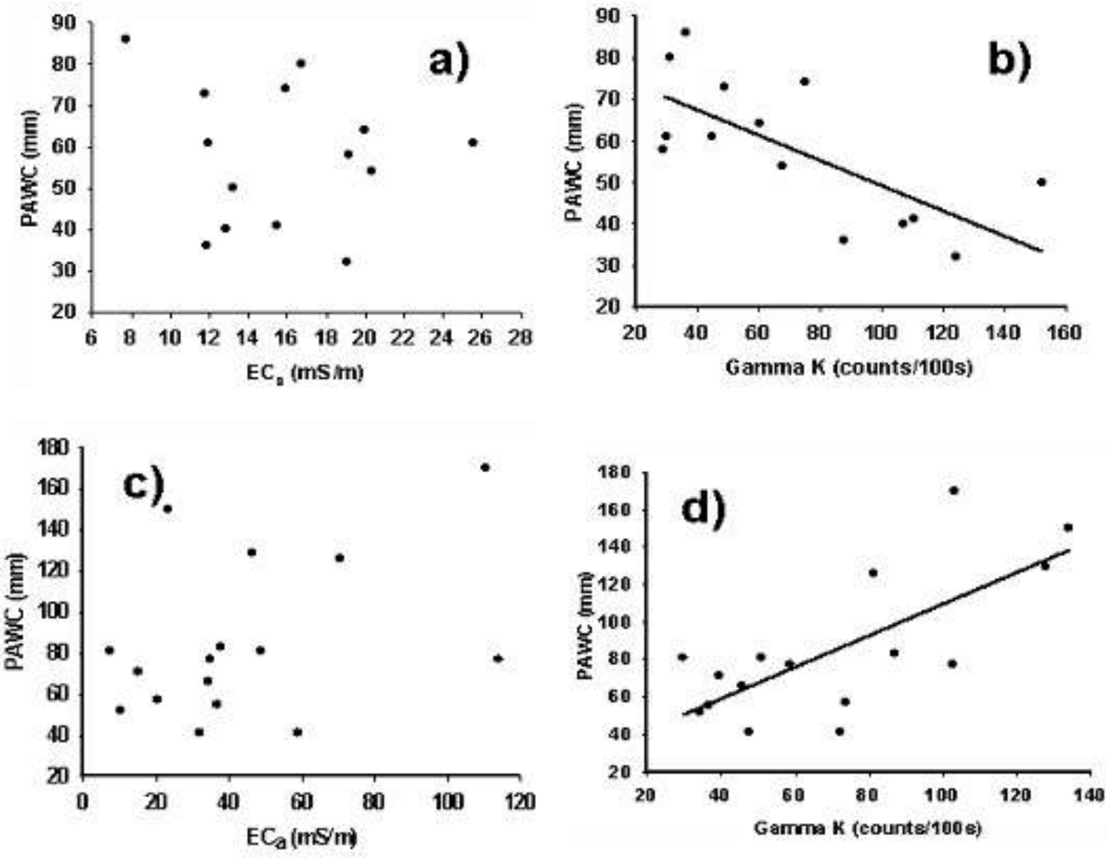

Figure 1. Relationships between PAWC and geophysical data on farm A (a, b) and B (c, d)

Gamma-attenuation estimated soil depth accurately (Figure 2a) with RMSE of 6.2 cm based on 36 paired comparisons for 10-50 cm soil depths. The intensity of the geophysical survey allowed soil depth to be mapped at 5 m resolution by kriging. In turn, we used the regression equation shown in Figure 2b to estimate PAWC at this spatial resolution.

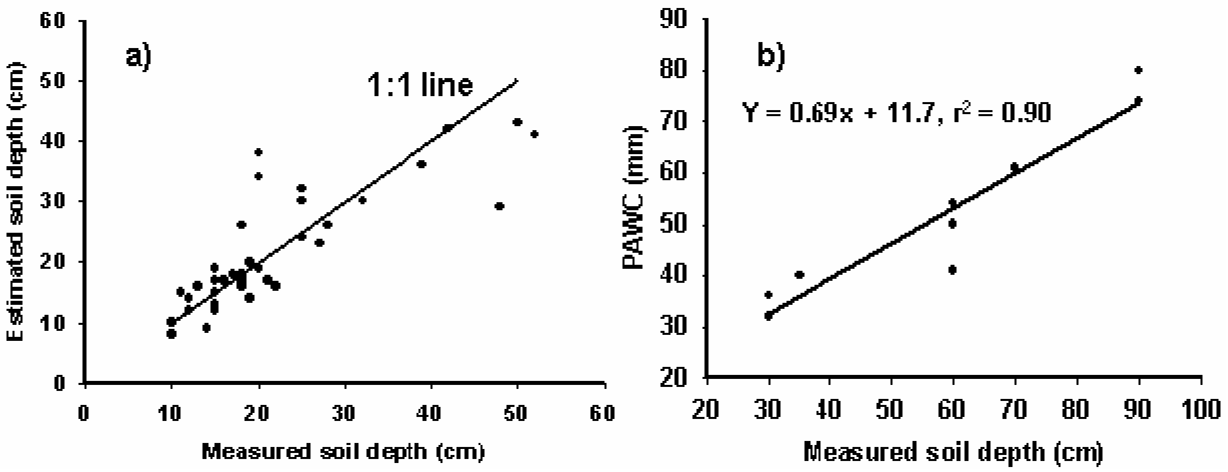

Figure 2. Goodness of estimation of soil depth (a) and regression (b) of PAWC (y) on measured soil depth (x)

Conclusion

PAWC is difficult to measure directly but is an important soil property that determines yield, deep drainage and nitrate leaching in our Mediterranean-type environment. It can be estimated from geophysical surveys. A sound knowledge of the paddock is required to interpret the data as high geophysical measurements can mean low or high PAWC depending on the specific situation faced. Gamma surveys seems to have an advantage on EM38 surveys in this study as it is insensitive to salt and emission from shallow rocks and gravels can be use advantageously to estimate soil depth and hence PAWC. However, EM38 is able to sense more deeply into the profile than Gamma and will have advantages on other situations.

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