**Within field variability of soil penetration resistance**

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**Abstract**

Spatial variability of penetration resistance and soil wetness across a centre-pivot irrigated dairy farm in the northern Midlands of Tasmania, Australia was mapped from intensive ground sampling. The mean penetration resistance over the 0 – 400 mm depth layer was 1940 kPa with 42 % of all data being greater than the widely accepted root growth inhibiting 2000 kPa. The mean depth to 2000 kPa resistance was 182 mm, with a range from 20 to 400 mm indicating that root growth was restricted to very shallow depths at many locations.

Penetration resistance showed considerable spatial variability and there was a strong negative relationship between soil wetness and penetration resistance indicating that irrigation is necessary to optimise grass growth at the site. Sixty one randomly selected sample points would be required to represent our full data set with 95% confidence. The spatial variability of both penetration resistance and moisture content indicates that there are likely to be plant growth advantages in targeting irrigation application with the use of variable rate irrigation.

**Key words**: penetration resistance, spatial, wetness, growth

1. **Introduction**

The knowledge of soil strength variability at the field scale is of potential value as decision support information for modifying site-specific irrigation, tillage and stock management within the context of precision farming (Hanquet et al. 2004). The ability to make predictions over a large area from a single point measurement ranges from good to unsatisfactory, depending on the particular prediction parameter of interest (Nielsen et al. 1973). Understanding the spatial variability of soil strength requires the collection of relatively large amounts of data, making it not cost-effective at large scale (Clark 1999). Soil strength is one factor known to influence crop yield (Tola et al. 2017) and soil structure degradation, as compaction limits plant growth by restricting root elongation (Taylor and Ratliff 1969). It also limits the range of tillage options for soil preparation. Soils also need to be kept at an appropriate wetness so as to not limit plant growth through water deficit.

Soils with degraded structure are difficult to manage due to a restricted range of soil wetness for tillage operations, resulting in low yields (Cotching et al. 2004). If a soil has poor structure this can lead to problems with drainage due to the blocking of soil pores, resulting in a decrease in the rate at which water can enter the soil (infiltration rate) and the rate at which water can drain through the soil (hydraulic conductivity). Compaction can lead to reduced aeration when wet, particularly on heavier textured soils, resulting in restricted
volumes of soil available for root growth (Letey 1985). The ability of plants to penetrate the soil is also reduced when the structure is poor, affecting access to both soil nutrients and moisture, and therefore crop yields. Poorly structured soils are more likely to form a surface crust after heavy rainfall and are more easily eroded by wind or water.

Assessment of soil strength is often performed by measuring the soil resistance to a penetrometer probe. Penetration resistance is a measure of soil resistance to root penetration, indicating the magnitude of energy a plant can divert from root penetration to other plant growth functions. Penetration resistance is strongly dependent on soil wetness (Cass 1999; Fredlund et al. 1978; Vaz et al. 2001), and so it is important to have an understanding of the relationship between structural degradation and soil wetness because farming practices can influence both attributes. Structural degradation can be caused or avoided by management practices including tillage, trafficking and irrigation (Cotching 1997), which are normally used to optimise crop and pasture production in Tasmania, Australia during summer. Penetration resistance measurements have been used to distinguish compacted from well-structured Ferrosols (Cotching and Belbin 2007) and Vertosols (McKenzie 2001), and has been correlated with crop yields (Hamza and Anderson 2002) and with plant emergence (Altuntas et al. 2005).

The objective of this study was to evaluate the magnitude of spatial variation of soil strength, as measured by penetration resistance, and soil wetness on an area under a single pivot irrigator used for intensive dairy production. The study also aimed to make an assessment of how many point measurements would be needed to give useful information. This information can be of value when assessing and evaluating the properties of an entire centre pivot circle on the basis of limited data from only a few locations.

2. Methods
The site was a 110 ha centre-pivot irrigated dairy farm in the northern Midlands of Tasmania, Australia (147° 0'32.19"E; 41°39'59.70"S). The site was mapped with a dominant soil series of Cressy soils that contained four different soil types or variants that were classified as Brown Dermosols (Isbell 2002). Smaller areas of Kinburn clay soils (Hydrosols) were mapped in low-lying depressions (Fig. 1). Perennial pasture containing ryegrass (Lolium perenne) and white clover (Trifolium repens) was growing over the experimental site.

Penetrometer and soil moisture readings were taken at 193 predetermined sampling points on a rectangular grid at a spacing of 75 m along defined transects as the soil dried by evapotranspiration following irrigation (Fig. 2). At each sampling point, penetrometer readings were taken to a depth of 400 mm at 20 mm increments using a Rimik Agricultural Electronics CP20 Cone Penetrometer. The Hydraprobe Data Acquisition System (HDAS) was used to measure point-based water content of the top 50 mm soil layer at the same time as the penetrometer readings were taken. The system included a Hydraprobe soil moisture sensor and a handheld computer to control the sensor and record soil moisture measurements together with their locations from a built-in GPS. A GIS interface was used for display, navigation, and manually typing other ancillary information about the land surface. During the experiment, three replicate soil moisture measurements were taken within 1 m distance at each sampling point, in order to account for sampling uncertainty and spatial heterogeneity. The point-based soil moisture measurements were collected at the predefined points over three days in January 2017. To confirm the calibration of the Hydraprobe soil moisture sensor, four gravimetric soil moisture samples were collected with soil moisture ranging from dry to very wet. The soil samples were weighed at field moisture content and then oven-dried.
(105°C) for 24hr to determine soil wetness. A Root-Mean-Squared Error (RMSE) of 0.03 m$^3$m$^{-3}$ was achieved for the HDAS used during the experiment, using the manufacturer supplied probe calibration. The continuous penetrometer data fields were segmented by depth with maps generated after averaging the three readings at any one location for the multiple depths. A gridded surface was created from the point data with a four-neighbour krigging process.

3. Results and discussion
Mean penetration resistance typically increased steadily to 2000 kPa at 160 mm depth, with a steady state to 260 mm depth and then a further increase to greater than 2300 kPa by 380 mm depth (Fig. 3). The shape of the resistance curve is different to that reported on a clay loam textured soil by Cotching et al. (2002) who found that resistance remained less than 1500 kPa to 180 mm depth under long term pasture when the soils were at field capacity. The mean penetration resistance over the 0 – 400 mm depth layer was 1940 kPa (median 1841 kPa; std dev 564 kPa), with the data distribution positively skewed (skew 0.47) with 42 % of all data and 40 % of mean data being greater than 2000 kPa. The mean depth to 2000 kPa resistance was 182 mm (median 140 mm; std dev 137 mm) with a bimodal distribution (skew 0.46 mm). Much of the depth data was concentrated in the ≤ 40 mm (21%) and > 360 mm (17%) depths. The deeper category indicates that 2000 kPa was not reached within the sampling depth while the shallow data indicates strong resistance at, or close to, the soil surface.

Penetration resistance showed considerable spatial variability. The lowest mean penetration resistance values were concentrated on Cressy clay loam soils on the western section of the experimental circle while the greatest resistance occurred on Cressy gravelly clay loam soils on the eastern section (Figure 3A). The depth to 2000 kPa penetration resistance tended to be in opposite locations to the mean penetration resistance (Fig. 4B), i.e. the less the mean penetration resistance the greater the depth to 2000 kPa resistance ($r^2$ = -0.54).

The critical penetration resistance of 2000 kPa is the field capacity value at which root growth is impeded except through cracks, channels and points of weakness in the soil. It is also likely that above this value the moisture uptake by the plants will be restricted (Cass 1999). Published critical values of resistance that retard root growth and seedling emergence are 720-3000 kPa, with values varying between crops (Taylor and Ratliff 1969, Cass 1999). At penetration resistances between 1000–2000 kPa seedling emergence may fail without the presence of surface cracks and root growth may be restricted. This is due to the likelihood of greater resistance values being reached as plants use the soil moisture. The available moisture in soil with greater resistance is also limited.

One irrigation event prior to sampling and the progressive sampling over three days meant that penetration resistance was recorded as the soil dried giving rise to the wide range in soil moisture contents (0.02 – 0.66 m$^3$m$^{-3}$; Fig. 4C). The majority of the data was between 0.3 – 0.5 m$^3$m$^{-3}$ moisture (mean 0.38; median 0.39; std dev 0.13) and the data distribution was slightly negatively skewed (skew -0.135) (Fig. 5). The values derived from this population of 575 sample points indicate that a subset of 61 randomly selected sample points would be required to represent our full data set with 95% confidence according to Slovin’s formula $n = N/(1+N e^2)$, where n is the sample size, N is the population size and e is the margin of error. Although much less than the total observed, this would still require considerable time input if gathered manually as in this experiment due to walking distance between points and the time to collect data at each point. Alternative remote sensing technologies, such as passive microwave, would seem to be a more appropriate means of spatial sampling, subject to the
applicability of suitable paddock-scale resolution of observations at short time intervals (Rao and Ulaby 1977; Mohanty et al. 2017).

The soil moisture contents indicate that the experimental site had 34% of observations wetter than field capacity (0.44 m³ m⁻³, Marcus Hardie pers. comm.), and 44% of observations were drier than the recommended refill point of 0.37 m³ m⁻³. These observations are to be expected under a centre pivot irrigator with sites in front of the moving irrigator requiring water and those behind having just received water. Seventy two percent of observations were at moisture contents at or less than the plastic limit of 0.46 m³ m⁻³ (Cotching et al. 2002), the moisture contents below which damage due to traffic and tillage will not occur (Spoor 1979).

There was a strong negative relationship between soil wetness and penetration resistance. The relationship was strongest for the mean resistance 0 - 400 mm depth \( (r = -0.61) \) (Fig. 6), weaker at 0 - 120 mm depth \( (r = -0.57) \) and 140 - 240 mm depth \( (r = -0.58) \), and weakest at 260-400 mm depth \( (r = -0.43) \). This indicates that measuring moisture content at 0 – 50 mm depth is suitable to determine its control over penetration resistance variability for the 0 – 400 mm depth layer in a surface applied irrigation environment. This strong relationship emphasises the importance of irrigation in keeping the soil moist enough for root elongation as well as the supply of water requirements for growing plants. The spatial variability of penetration resistance (Fig. 3) that is due in large part to soil wetness indicates that there are likely to be advantages in targeting irrigation application with the use of variable rate irrigation (VRI) technology (Lo 2015).

The strong negative relationship between soil wetness and penetration resistance indicates that topsoils at the experimental site may be in poor structural condition, as drying has been found to increase resistance much more in the poorly structured soils than in well-structured soils (Cotching and Belbin 2007). Moisture content has a much greater control on penetration resistance in poorly structured soils than in well-structured soils.

4. Conclusions

Mapped distribution of penetration resistance at paddock scale showed wide variability under irrigated pasture with resistance values exceeding plant root penetration capability over 40% of the area mapped. Strong negative relationships between penetration resistance and soil wetness indicate that keeping the soil optimally wet via variable irrigation will allow for enhanced plant growth through drier seasonal conditions. Detailed sampling on a closely spaced grid is logistically inappropriate and expensive for agricultural purposes, however remote sensing technologies using suitable sensors is likely to provide an appropriate means of spatial sampling. The spatial variability of both penetration resistance and moisture content indicates that there are likely to be plant growth advantages in targeting irrigation application with the use of variable rate irrigation.

References


Captions

Fig. 1. Soil types mapped at the experimental site.

Fig. 2. Grid sampling map of experimental site.

Fig. 3. Penetration resistance at the experimental site

Fig. 4. Penetration resistance and moisture content at the experimental site

Fig. 5. Distribution of soil moisture contents at sampling points.

Fig. 6. Correlation of soil moisture content to penetration resistance.

Fig. 1. Soil types mapped at the experimental site.

Cs = Cressy clay loam
Cbcl = Cressy black clay loam
Cgr = Cressy gravelly clay loam
Cpw = Cressy perched water variant
Kb = Kinburn clay
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Fig. 3. Penetration resistance at experimental site.
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