Incorporating knowledge of soil moisture into understanding of paddock variability – A case study from a paddock on Jordy Wilksch's farm at Yeelanna

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Background

Like any paddock on any farm, those used for agronomic trials in the EP Smart Farms project are variable. A useful way of understanding how this variability impacts on management and, in particular, how management might be tailored to it, is to conduct simple strip trials in which the strips cross the important within-paddock variation (Bramley et al. 2013, 2022a; Colaço et al., 2022). It therefore follows that some prior knowledge of variation is valuable, especially if sufficient data (yield maps, high resolution soil survey, etc) are available to generate so-called 'management zones' characterising the different areas in the paddock which can be expected to be agronomically different. Combining the results from the trials with knowledge of these zones provides a good basis for the targeting of differential management, such as variable rate fertilization and seeding.

In a companion case study focused on Todd Matthews' farm (Bramley et al. 2023), we illustrated how information from a soil moisture probe might be extrapolated away from the location of the probe to give information of possible value for decision-making at other locations in the field or farm. Of note was the observation that at times of likely key agronomic decision making, such as at GS31 – when a mid-season nitrogen (N) fertilizer decision might be made – the range of spatial variation in soil moisture status at any given depth was considerably less than the range of soil moisture status down the soil profile at any given location (this result was obtained at both the Matthews farm and also in another contrasting paddock in the mid-north region; Bramley et al., 2022b). We therefore suggested that the value of a soil moisture probe was probably greater in highlighting differences between seasons, than in being the basis for a targeted management decision at any one time. However, the Matthews case study should be nuanced by the fact that it dealt predominantly with measures of soil moisture content. Whilst such measures are important, knowing the 'size of the bucket' in which the soil is at a particular moisture content is also important because the total amount of soil moisture that is available to support crop growth is what sets potential yield. In this case study, we consider how including information on soil moisture and 'bucket size' along with yield and other data can contribute to understanding of paddock variation and therefore how variable paddocks might be optimally managed.

Generating management zones

By coincidence and good fortune, the Wilksch 'focus paddock' is one that CSIRO worked in as part of a previous project focussed on the selective harvesting of barley. Accordingly, quite a lot of information was already available for the Wilksch 'focus paddock' (Figure 1) – 94 ha of rolling country at Yeelana and part of the Wilksch family's much larger 3000 ha cropping program.

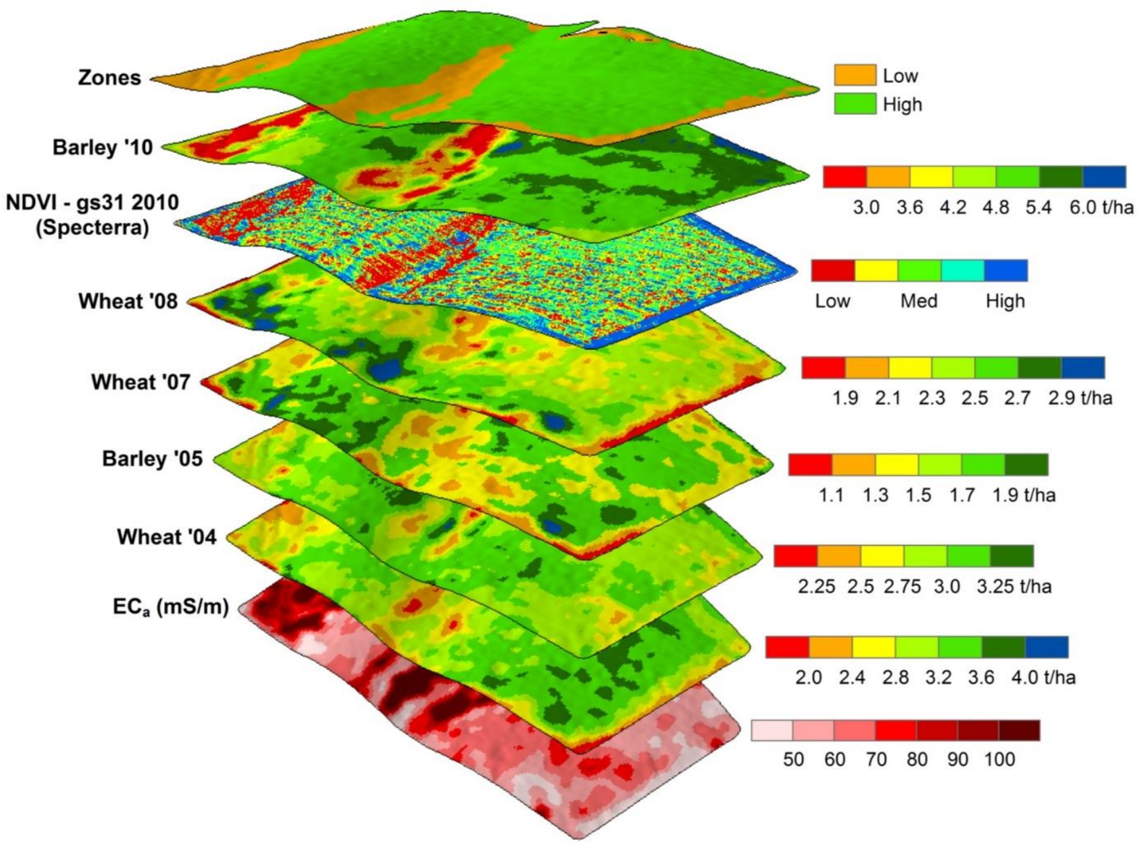

Figure 1. Management zones identified in the 94 ha Wilksch 'focus paddock' (Front SW) during a previous project using cereal yield maps (2004-2010), electromagnetic soil survey (EM38) of bulk electrical conductivity (ECa), a mid-season (GS31) image and a digital elevation model derived from the guidance system on the Wilksch machinery.

Figure 1 summarises a classification of management zones which we generated in 2010 using a mixture of yield maps, a mid-season remotely sensed image of crop vigour, and an EM38 soil survey; we also had access to elevation data acquired through the use of guidance on the Wilksch machinery. As can be seen in Figure 1, two zones were identified – a low yielding zone, covering two low-lying areas in which sodic soils with subsoil boron toxicity were limiting production, and the higher yielding remainder of the paddock; the low yielding zone in the centre of the paddock was also an area (at that time) of ryegrass infestation.

Through the EP Smart Farms project, we were provided with additional and more recent data relating to this paddock (Figure 2). Thus, in addition to the data shown in Figure 1, yield monitor data for the 2014-2019 period were made available, in addition to further electromagnetic and gamma radiometric surveys conducted in 2015 (Figure 3). Note that we also conducted a gamma radiometrics soil survey in 2010 but did not include this in the clustering shown in Figure 1 because we found that, for this paddock, it did not provide any useful information beyond that provided by the simpler apparent electrical conductivity (EC_a) data obtained from the EM38 survey.

As can be seen in Figure 2, a few artefacts are visible in the available maps. In 2013, the paddock was harvested in two harvest events which, even after correction for differences in grain moisture, were

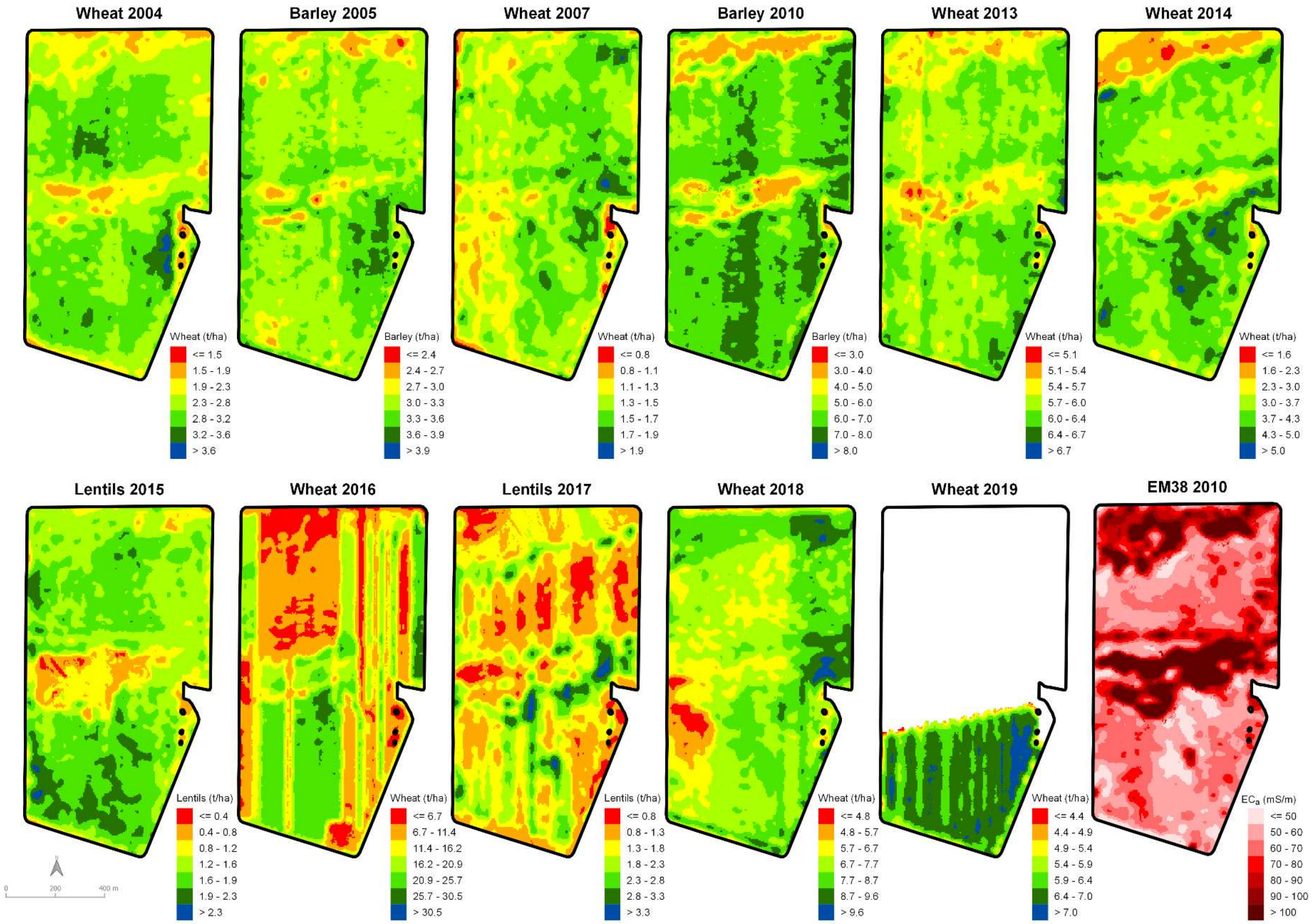

Figure 2. Map layers available for a revision of the 2010 clustering shown in Figure 1.

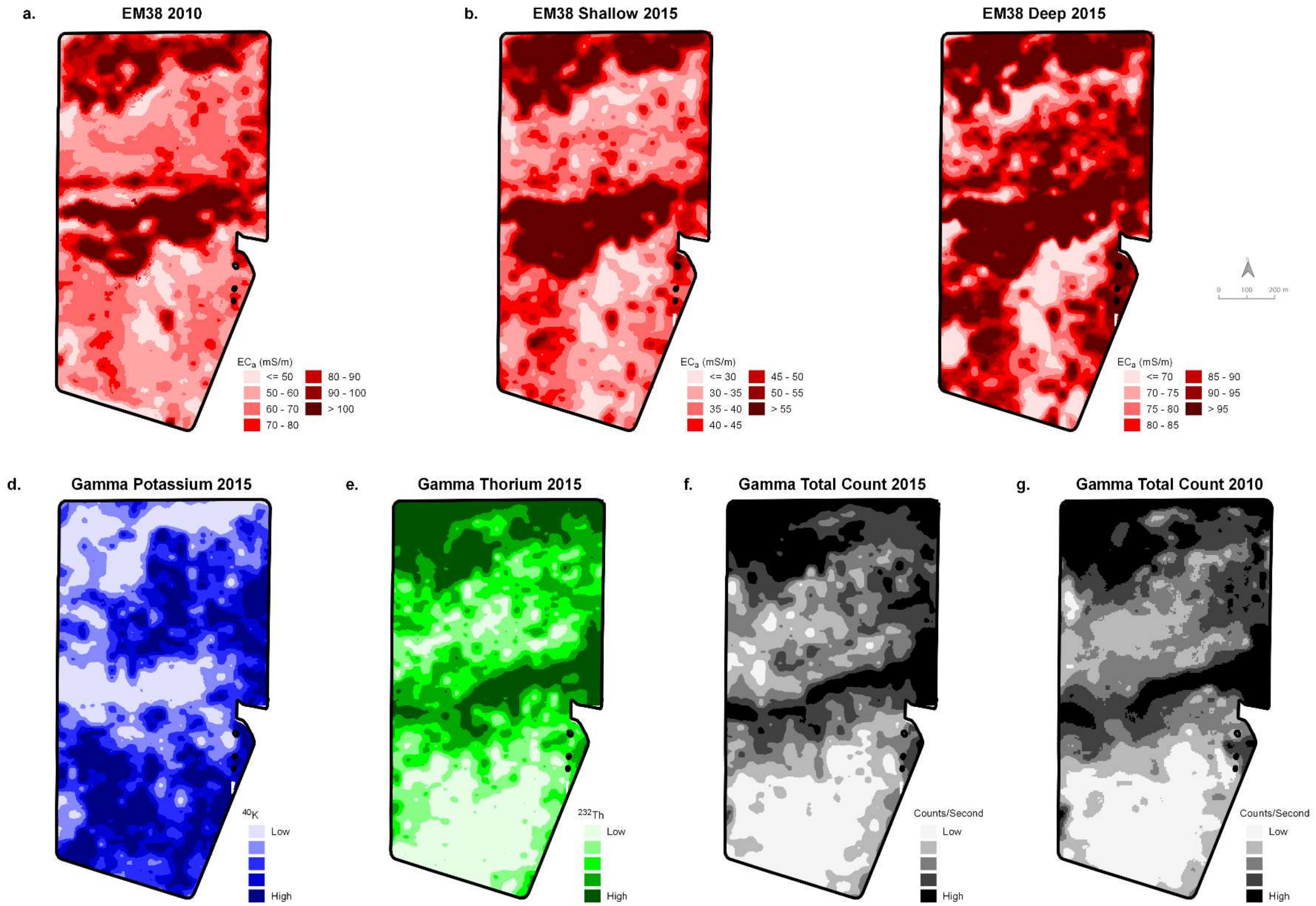

Figure 3. High resolution soil survey data obtained in either 2010 (a, g) or 2015 (b-f) using either electromagnetic soil sensing (a-c) or gamma radiometrics (d-g). In (a) an EM38 sensor was used; the data in (b-c) were obtained using a DualEM sensor. It is not known what type of gamma sensor was used for (d-f) but we do know that it was different to the sensor used for (g).

still apparent. Clearly, something went wrong in 2016 and 2017, whether as a result of a yield monitor error or something else, whilst in 2019, only about a quarter of the paddock was harvested.

It is unclear why the additional 2015 soil surveys were conducted because as Figure 3 shows quite clearly, the patterns of variation in the maps obtained in 2015 are the same as those seen in 2010 as would be expected; the numbers change for various reasons (soil moisture, type of sensor used, etc), but it is the patterns in the maps that are important. Note that gamma radiometrics is affected by clay mineralogy which ought not to change measurably other than in geological time; EC_a values are affected by various factors, but unless there is active salinisation or desalinisation occurring, the patterns in EM38 maps should also be stable in time. Indeed, in re-analysing the zones for this paddock we have not used the 2015 soil survey data and instead just used the EM38 data from 2010 shown in Figures 1 and 2.

Figure 4 shows the results of the revised zone analysis using data spanning 2004-2019; two, three and five zone solutions have been generated. As can be seen, the two zone solutions (Figure 5a, d) appear almost identical to those seen in Figure 1 thereby strongly supporting the idea that the patterns of variation are temporally stable. This is not a surprising result given that the variation in crop performance is driven by the soil variation (i.e. soil sodicity and boron toxicity) which in turn is driven by the variation in elevation (as seen in Figure 1). Back in 2010 we did not include pulse or legume crops in the zone analysis due to a suspicion that these may follow different patterns of variation to cereals. However, the 2015 lentil yield map (Figure 2) suggests that this concern may have been unfounded. Nonetheless, Figure 4 shows the zone analysis repeated both with and without the 2015 lentil crop included.

It is not for us to say how many zones should be used in managing this paddock – that is a decision for Jordy Wilksch. However, we note the following.

- The mean zone yields in the two zone (Figure 4a, d) solution are statistically significantly different in all years except the very high yielding 2018, with bulk electrical soil conductivity similarly statistically significantly different between the zones.
- Given the previous work done in 2010, including detailed soil analysis, we can be confident that a combination of sodicity, boron toxicity and early season waterlogging in the low-lying parts of the paddock are the drivers of the poor crop performance, with annual ryegrass in the centre of the paddock a possible additional low yield-causing factor, especially in 2010 and earlier.
- When we go to a three-zone solution, the low-lying areas are unsurprisingly identified as lower yielding than the other zones. However, in most years, the other higher yielding zones do not have statistically significantly different yields, nor (ignoring statistics) yield differences which are of sufficient magnitude that differential management might be justified. This is why in the five-zone solution, the picture is somewhat confused, albeit with the low yielding, low lying areas still clearly identified, which is also why we did not bother to assess the statistical significance of between-zone differences.
- In terms of this paddock being one in which a strip trial is conducted, the sensible approach would be to run the strip aligned with the north-south tramline orientation along the length of the paddock so that, along the strip, there are both 'low' and 'high' zone areas included. The locations where samples (biomass cuts, soil samples, etc..) would be taken should then cover these zones so that the zones can be meaningfully compared, and inferences about how they might be differentially managed can be made.

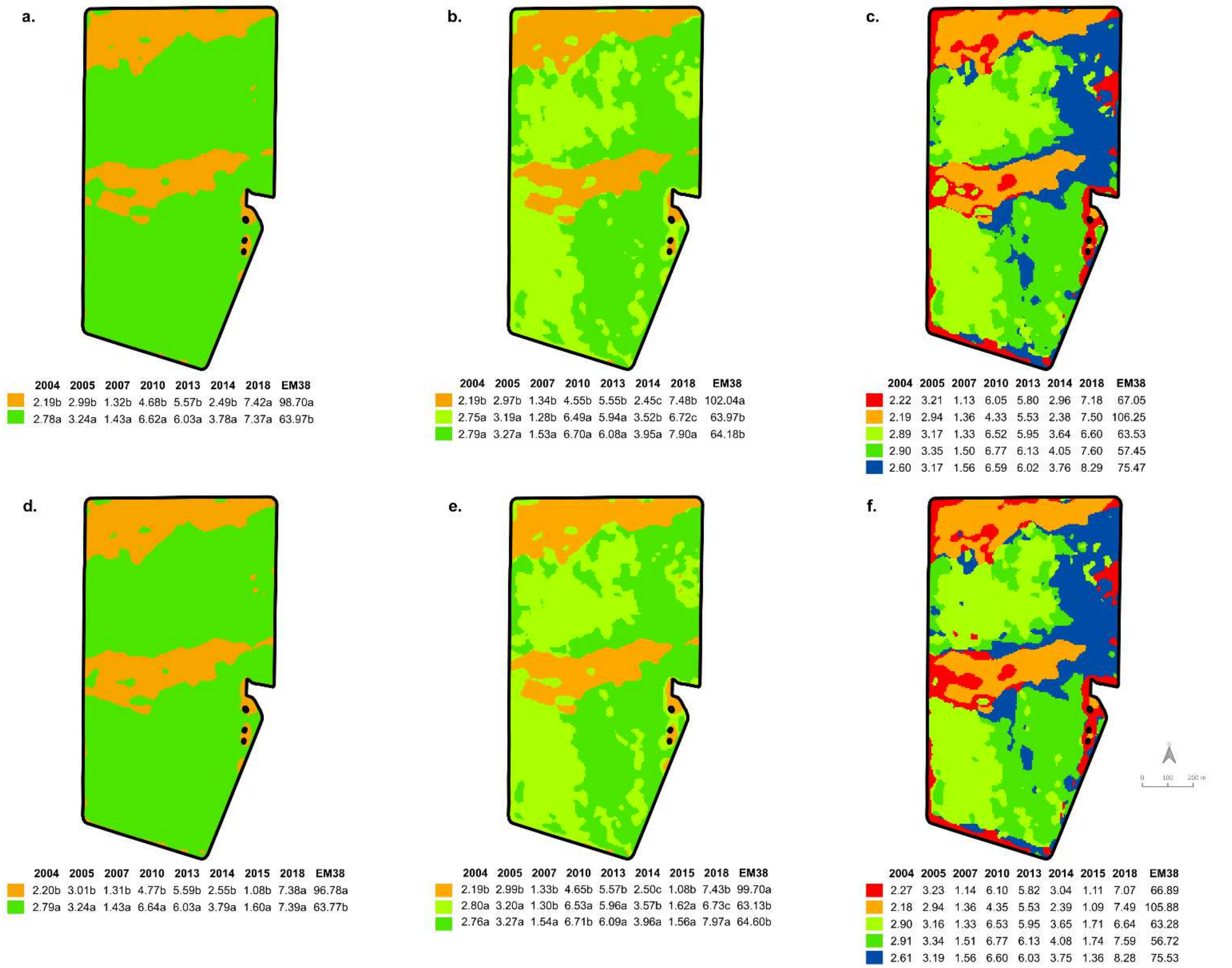

Figure 4. Zone analysis of the Wilksch 'focus paddock' using data collected between 2004 and 2019. Here we have generated either two, three or five zones and run the analysis twice – in (a-c) data for cereals only are used, whilst in (d-f) the yield map for lentils grown in 2015 were included. The numbers in the legends are zone means; those not connected by the same letter are statistically significantly different (P<0.05).

- Finally, and following from the last point, it is common in PA to hear people talking about "homogenous management zones". It is important to realise – as comparison of Figures 3 and 4 illustrates very clearly ! – that there is no such thing as a homogenous or uniform zone. Rather, zones are much less variable than the paddock as a whole, and in large paddocks such as this one, being able to work with less variable areas is valuable.

Of interest here is how knowledge of soil moisture dynamics might contribute to targeted decision-making within the paddock.

Variation in soil moisture characteristics

Figure 5 shows the same data as presented in Figure 4d, but with the locations of a number of soil sampling points also indicated. Soil samples collected from these locations were analysed for their moisture contents using pressure plate equipment to measure field capacity, otherwise known as the drained upper limit (DUL) and the lower limit (LL15) for water extraction, defined by imposition of suction at -10 and -1500 kPa; LL15 is an approximation of the crop lower limit (CLL) – the lowest soil moisture content at which the crop is able to extract water from the soil. Note that this procedure uses disturbed and sieved soil samples and not intact cores but is nonetheless an accepted practice for determining the boundaries of soil water availability. The difference in moisture content at these lower and upper limits defines the size of the 'bucket' in which water that is plant available can be held. In an unconstrained soil, the depth of the bucket is defined by the rooting depth, but in soils such as those encountered on the Wilksch farm, sodic subsoils place a potential restriction on the depth of soil within which the roots are able to function (i.e. extract water). Accordingly, the soil samples were also analysed for their content of exchangeable cations (Ca^{2+}, Mg^{2+}, K^{+} and Na^{+}) from which the exchangeable sodium percentage (ESP) was calculated. Here, we assume that ESP > 15 % sets a limit for root function which, in turn, defines the depth of the soil water bucket. Figure 6 shows the result of the soil moisture pressure plate analysis with the blue lines denoting the moisture profile at field capacity (DUL) and the red lines denoting moisture status at LL15. Note that two sets of graphs are shown; one in which soil moisture content is expressed on a gravimetric basis (%; Figures 6a, c, e, g, i) and another in which the data have been converted to a volumetric (mm/mm) basis (Figures 6b, d, f, h, j); the pairs of graphs reflect the five sampling sites shown in Figure 5 organised on a north-south basis.

Many farmers and agronomists like to work with soil moisture data on a volumetric basis because they can they make judgements as to how many mm of moisture is available and relate this to likely crop production using a rule of thumb such as that generated by French and Schultz (1984) or the more recent update of Sadras and Angus (2006). Soil moisture probes also tend to generate data on a volumetric basis. However, it is much easier to make gravimetric soil moisture determinations. Converting between the two is straightforward, but it requires a commitment to also determine the soil bulk density which requires very careful sampling and analysis. Here, we assumed that the soil bulk density throughout the paddock was represented by that measured at a site close to the probe as a part of a site characterisation undertaken by project partners. Of course, bulk density may be spatially variable, which would impact on the spatial variability of soil moisture status. It may also vary down the profile, especially in texture contrast or otherwise layered soils. As can be seen in Table 1, for a location near the moisture probe (Figure 5), bulk density does not vary substantially down the profile, which is why the shape of the moisture curves shown in Figure 6 are similar whether expressed on a gravimetric or volumetric basis. Similarly, the curves for the probe location are similarly shaped

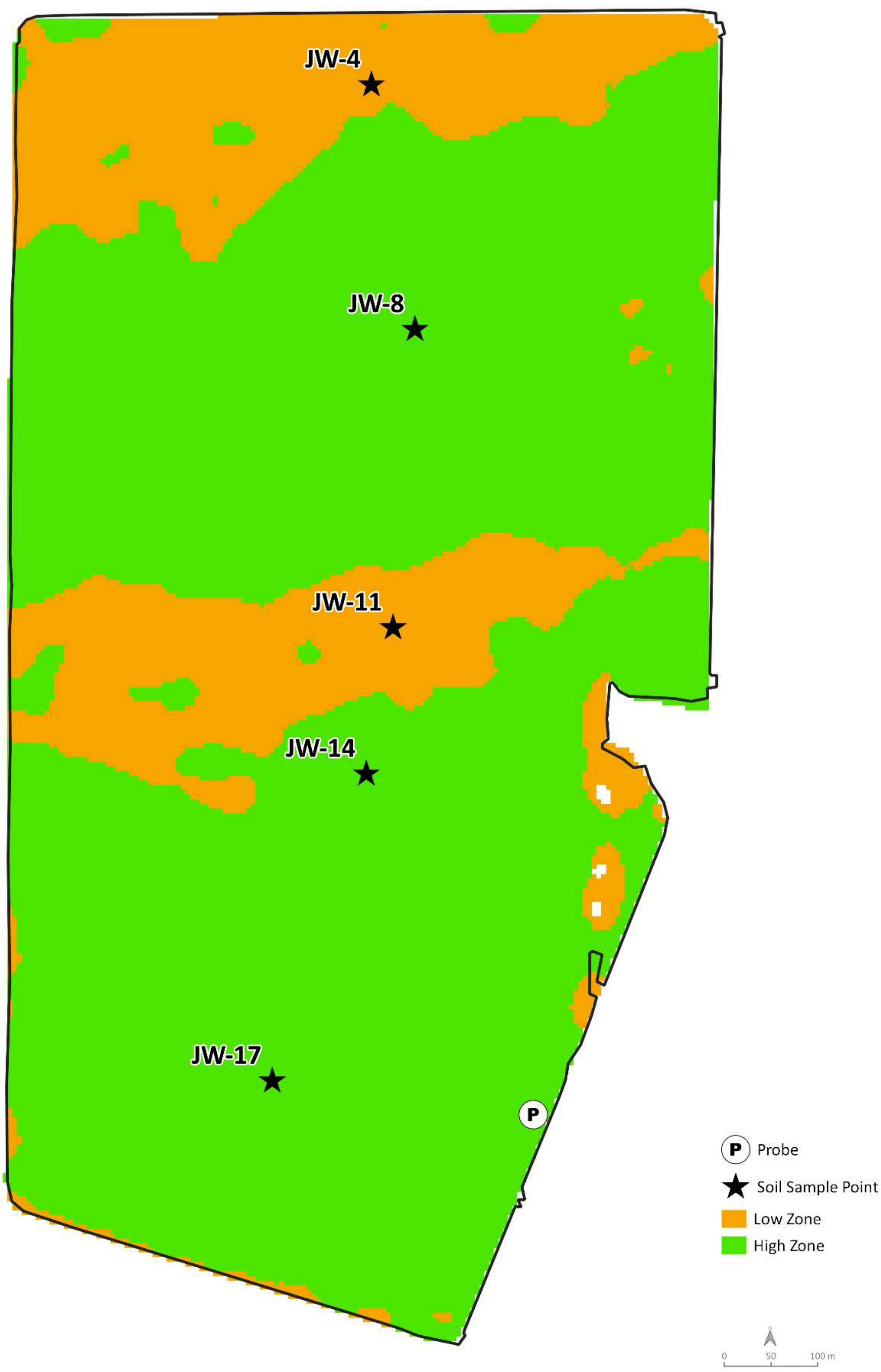

Figure 5. The Wilksch focus paddock showing the location of the soil moisture probe, five locations at which soil samples were collected for analysis and the 'zones' identified in Figure 4d.

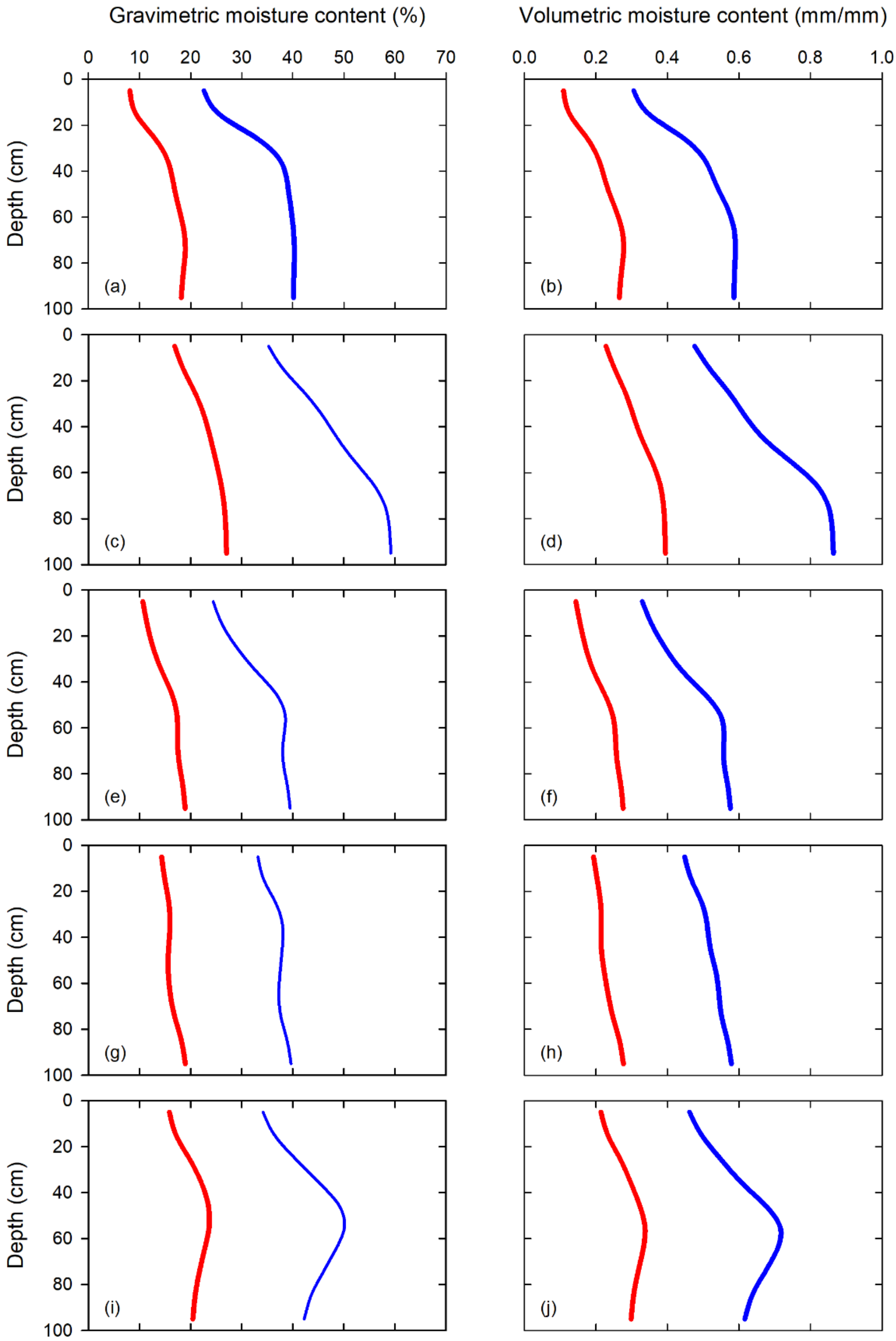

Figure 6. Soil moisture curves for the sampling sites shown in Figure 5; (a, b) JW-4, (c, d) JW-8, (e, f) JW-11, (g, h) JW-14 and (I, j) JW-17. Blue lines represent field capacity or the drained upper limit, red lines represent the crop lower limit.

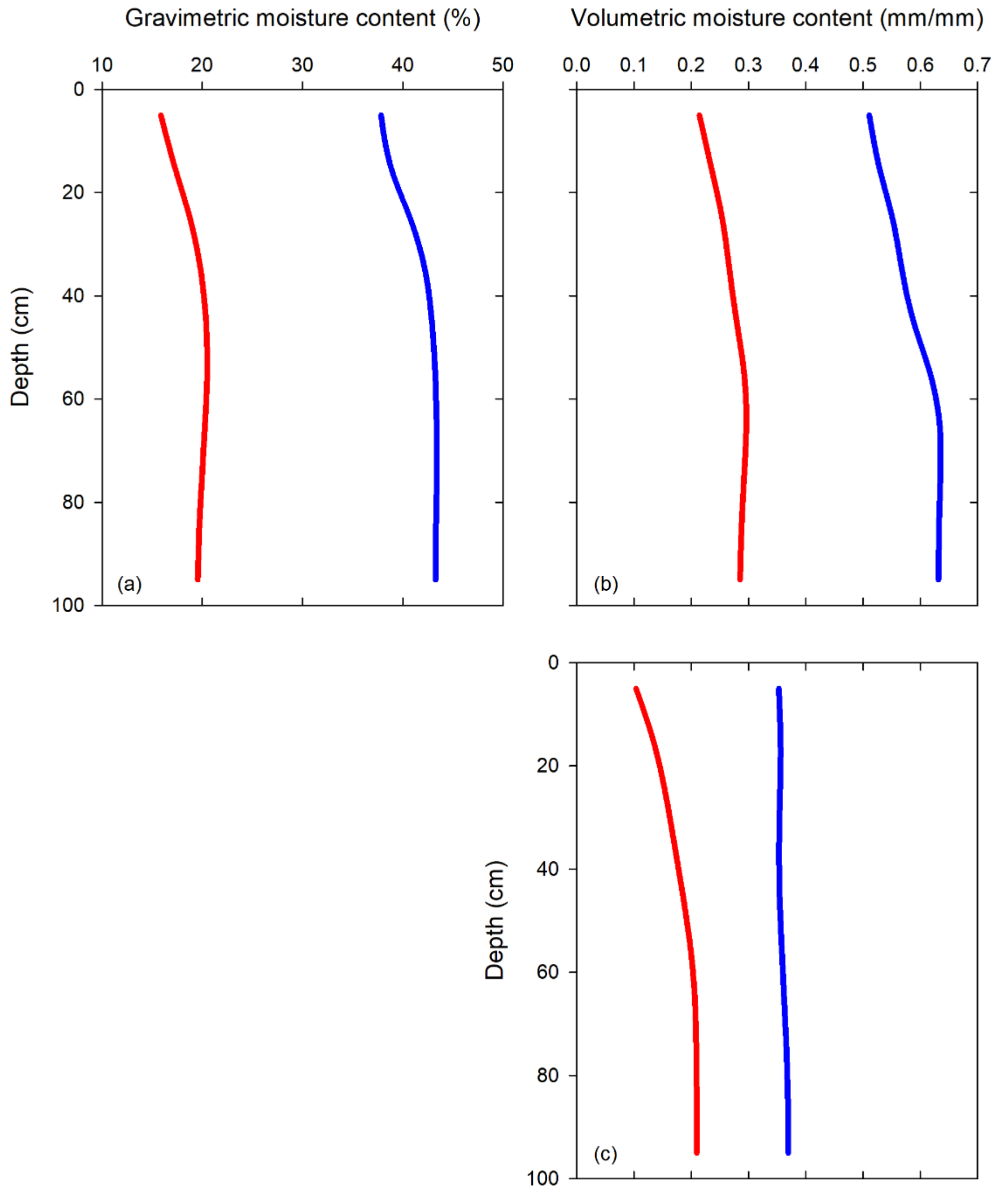

Figure 7. Soil moisture curves for a location near the moisture probe (Figure 5) at which a site characterisation (Table 1) was undertaken. (a, b) shows the moisture curves determined in the lab using sieved and re-packed soil samples on pressure plates, whilst (c) shows the results obtained using undisturbed soil in a field-based characterisation. Blue lines represent field capacity or the drained upper limit, red lines represent the crop lower limit.

Table 1. Site characterisation data for the Wilksch focus paddock (site close to the soil moisture probe) and estimates of plant available water capacity at the sampling locations shown in Figure 5.

Depth	**Bulk density**[A]	**DUL**[A]	**CLL**[A]	**Plant available water capacity**		**F:L**[B]	**Plant available water capacity**					**Adjusted plant available water capacity**[C]				
cm	g/cm3	mm/mm	mm/mm	mm/10 cm			mm/10 cm					mm/10 cm				
				Probe - F	Probe - L		JW-4	JW-8	JW-11	JW-14	JW-17	JW-4	JW-8	JW-11	JW-14	JW-17
0-10	1.35	0.35	0.10	24.91	29.83	0.84	19.62	24.83	18.61	25.49	24.77	10.99	13.91	10.42	14.27	13.87
10-20	1.36	0.36	0.13	22.23	29.67	0.75	22.10	26.65	20.00	26.37	26.24	12.38	14.93	11.20	14.77	14.70
20-30	1.35	0.35	0.15	20.06	29.94	0.67	26.74	28.95	22.19	28.34	28.02	14.97	16.21	12.42	15.87	15.69
30-40	1.35	0.35	0.17	18.30	30.23	0.61	29.62	31.16	24.78	29.66	30.78	16.59	17.45	13.88	16.61	17.24
40-50	1.37	0.35	0.19	16.89	31.07	0.54	30.64	34.11	27.97	30.50	34.95	17.16	19.10	15.66	17.08	19.57
50-60	1.43	0.36	0.20	15.94	33.03	0.48	31.40	38.73	30.24	31.25	37.84	17.58	21.69	16.93	17.50	21.19
60-70	1.46	0.36	0.21	15.59	35.02	0.45	31.39	43.58	30.31	31.01	37.48	17.58	24.41	16.98	17.37	20.99
70-80	1.46	0.37	0.21	15.74	36.36	0.43	31.28	46.18	29.87	30.43	35.41	17.52	25.86	16.73	17.04	19.83
80-90	1.46	0.37	0.21	15.91	37.40	0.43	31.71	46.84	29.90	30.23	33.13	17.76	26.23	16.75	16.93	18.55
90-100	1.46	0.37	0.21	15.96	37.99	0.42	32.04	47.00	30.01	30.19	31.81	17.95	26.32	16.80	16.91	17.81
			Total[D]**:**	181.53	330.54	0.55	286.54	368.03	263.88	293.47	320.44	160.46	206.10	147.77	164.34	179.45
			Total-Cons[E]**:**	165.56	292.55	0.57	191.51	228.01	174.10	202.61	220.08	107.25	127.69	97.49	113.46	123.25

[A]Measurements made on in-tact soil as part of the field soil characterisation conducted at a location close to the soil moisture probe.

[B]The ratio of field:lab estimates of PAWC

[C]PAWC determined from lab analysis adjusted to a field equivalent based on the mean value of F:L (0.56).

[D]Total bucket size to 1 m depth assuming no constraints to crop growth and water uptake.

[E]Total bucket size to the depth at which ESP>15% (90 cm for the probe and 60 cm elsewhere) when obtained from the lab method (Figure 7a, b), but these are somewhat different to those obtained from the field-based characterisation (Figure 7c) which also suggests that the lab method is over-estimating the overall size of the bucket (see below). Indeed, the volumetric water contents at DUL/FC shown in Figure 6 are high, especially at sites JW-8 and JW-17, so much so that they suggest very little difference between FC and saturation and, as such, are difficult to believe; nonetheless, repeat analysis of theses samples has led to quite consistent results.

Note also that, because the soil samples used to generate Figure 6, 7 and the characterisation data shown in Table 1 were all collected from slightly different depth increments, to enable depth-based analysis and comparison across the available data, we fitted spline curves to the actual data (including bulk density) and used these to estimate values at 10 cm increments to a depth of 1 m.

Interpreting yield and moisture variation together

Assuming that the site used for in-field soil characterisation is a good facsimile for the actual probe location, the data in Figure 7 and Table 1 suggest that in this focus paddock, on average down the soil profile, the lab-based method of estimating plant available water capacity (PAWC) has over-estimated it by around a factor of 2 (1/0.56 = 1.8) compared to the site characterisation method based on measurement on intact soil. Accordingly, adjusted estimates of PAWC are also shown in Table 1. In addition, analysis of ESP suggests that throughout the paddock, subsoil levels of sodicity are such that they may present a significant constraint to crop growth (ESP > 15%) below 60 cm at all sampled sites except for the probe location where the constraint exists below 90 cm. This should be regarded as a potential constraint, the effects of which may be mitigated by seasonal conditions. Accordingly, Table 1 shows estimates of the total profile PAWC to an unconstrained depth (notionally 1m) and also to the depth at which ESP might be a problem (Total-Cons in Table 1). On average, the difference in adjusted PAWC between low (JW-4, JW-11) and high zone sites (JW-8, JW-15, JW-17; Figure 5) is 15 mm in the unconstrained case and 10 mm the constrained case.

He et al. (2022) have recently demonstrated the utility of yield maps for estimating within-field variation in PAWC. The difference in mean zone yields (Figure 4d) between the higher and lower yielding zones suggest that, on average, and excluding 2018 as an aberrant year, the low yielding zone achieves 80% of the yield achieved in the high yielding zone. This means that for a hypothetical season in which the higher yielding zone achieves 4 t/ha, the lower yielding zone could be expected to yield 3.2 t/ha. Sadras and Angus (2006) suggested that at maximum water use efficiency WUE, grain yields 22kg/ha/mm. Thus, a yield difference between the two zones of 800 kg/ha equates to a difference in crop water use of around 36 mm. Recognising that the soil 'bucket' can refill with water during the season due to rainfall, this is the same as the difference between the PAWC of the low and high yielding zones when the depth of sodicity is factored into the bucket size, and much less than the difference when it is not (Table 1). But in terms of the PAWC data adjusted to accommodate the difference between lab and field measurements, the zone difference on an unconstrained basis (~30 mm) is closer to the difference inferred by the yield than when the constraint is factored in (~21 mm; Table 1). These simple calculations therefore possibly infer that the main impact of the sodic subsoils in the low yielding zone are not so much in restricting crop water uptake later in the season, but more in regard to the impact of early season water-logging. Since subsoils in the higher yielding zone are also sodic, this interpretation makes sense – at least in respect of the relative performance of the two zones. Thus, the analysis could point towards the desirability of remedial drainage in the low-lying parts of the paddock and/or to a fertilizer management strategy in which the low-lying areas are managed on the basis that their yield potential is only 80% of that in the higher yielding areas. Addressing subsoil sodicity in the entire paddock may also improve performance in both zones.

Finally, it was noted at the beginning that gravimetric soil moisture is much easier to determine than volumetric; a farmer can easily determine gravimetric moisture content by drying samples in the kitchen oven at home. If, for example, Jordy Wilksch was to take a soil sample at location JW-8 (Figure 5) and determine the gravimetric moisture content at 20 cm depth to be 28% and 32% at 40 cm depth, he could use Figure 6c to interpret this as inferring that his bucket is about half full. If he also had access to the data in Table 1 and Figure 6d, he could further infer that this equated to around 185 mm of plant available water assuming that subsoil sodicity was not limiting, or 103 mm if it was. Again, using Sadras and Angus (2006), and assuming the above comment on water-logging has merit, this 185 mm could suggest a potential yield of 4.1 t/ha and so guide decision-making accordingly.

Conclusions

In this focus paddock, because the patterns of variation in yield are stable in time, zones derived from these do a good job of characterising the spatial variation in production potential can be described by the original zone maps. Whereas the effects of sodicity in restricting water uptake were previously assumed to be the main driver of between-zone differences, our assessments of PAWC and associated soil characterisation infer that the sodicity effect on water dynamics early in the growing season is the more likely major constraint to effective use of PAW by crops grown in this paddock. Accordingly, we would expect that, a basic level of soil characterisation (i.e profile inspection and determination of PAWC) with or without some simple assessment of gravimetric water content, which could easily be done by the farmer would allow the development of rules of thumb for estimating zonal yield potential during the growing season.

Acknowledgements

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