
ENV 15
GPS

1 Abstract

Soil moisture content is measured with electromagnetic techniques that utilise the high permittivity of water in soil and avoid labour intensive site disturbance. The hydraprobe Data Acquisition System has been created by the University of Melbourne as an affordable user friendly measurement system. However the hydraprobe requires further development, the calibration equations provided by the manufacturer (sand, silt, clay) have been found inaccurate and individual site calibrations still need to be taken.

The effect of moisture content, temperature and soil type on the hydraprobe interpreted moisture content were investigated and while a generic equation was not determined, further work continuing the research started here may do so. The findings of this research support previous work that the temperature of the soil has an effect on the hydra soil moisture inference due to the manufacturer's inclusion of temperature in their dielectric constant adjustment.

Analysis of probe temperature variation confirmed that probe temperature is of negligible effect to the resultant hydra soil moisture reading. The effect of soil texture is apparent but more research needs to be conducted to accurately quantify this effect.

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2 Developing the HDAS

Soil moisture is important for optimum land management in regards to irrigation practices, planting crops, grazing and soil stability for machinery traffic. It is therefore important that it can be accurately and affordably measured (Kennedy 2001). Traditionally obtaining this sort of information would need to be done by gravimetric sampling (Gardner 1986), an accurate technique but time consuming, site disruptive and labour intensive. There are now new techniques that aim to overcome these problems and can collect data continuously storing it on site or transmitting to a base via radio or phone. (Seyfried 2004)

Soil moisture can be measured by remote sensing satellites which can produce large spatial scale of the surface; they are a rapid and useful soil moisture measurement approach with many applications. While in-situ sensors take a point measure at a depth dependent on installation and can be installed to take continuous readings or used manually for a one off reading. These soil moisture probes can be used to calibrate the large scale remote instruments. But first they too need to be calibrated

While there are many soil moisture sensors available there is the competing issue of accuracy and affordability as while TDR (time dependent reflectometry) sensors are fairly developed with the Topp equation they are costly to buy and difficult to use and here lies the need to further develop alternate means of determining soil moisture content that are just as accurate but more accessible. So ideally there will be one that is more affordable than other available options and ranks in the same accuracy standard as its leading competitors. The one which will be the focus of this paper is the Hydraprobe it is an affordable sensor and the purpose of this research is to enhance its accuracy.

Researchers at the University of Melbourne, Figure 1, have been working on developing a Hydraprobe Data Acquisition System (HDAS); a compact unit that incorporates the Hydraprobe sensor with an iPAQ to receive the data and plot it straight onto GIS software, Figure 2. This mechanism will be utilised in this research and the findings will contribute to its further development.

Figure 1Prof Walker and two versions of the developing HDAS

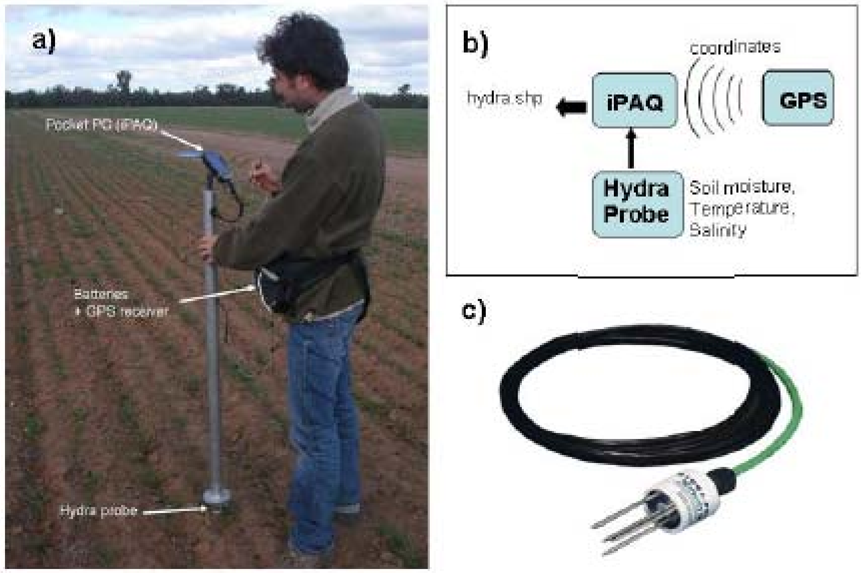

Figure 2. a The HDAS b. schematic of the HDAS c. the hydraprobe (Panciera et al 2006)

Minimal research into calibrating the hydraprobe has been done but what has been done has shown that the calibration equations provided by the manufacturer are insufficient and that site specific calibrations are required to improve accuracy. This is time consuming and if a general calibration equation is found for the Hydraprobe this will effectively be beneficial to all Hydraprobe users and those that will use the soil moisture readings eg land managers, farmers.

The aim of this investigation into developing the HDAS is to accurately calibrate the Hydraprobe for the 2006 NAFE farms ideally discovering one general equation that will suffice for all situations like the Topp equation for TDR.

This will be achieved by testing the probe against a variety of soils under a variety of conditions. Soils will be collected from Yanco and Coleambally in NSW the site of the 2006 National Airborne Field Experiment (NAFE) coordinated by Prof. Jeffrey Walker. The effect of soil temperature, probe temperature, moisture content and soil type will be analysed at the University of Melbourne Geomechanics lab and their relationship to the hydraprobe moisture content reading identified.

The results found will be directly applicable to the sampling sites and if a generic equation is not reached the results aim to be useful in the search for obtaining one.

3 Background

3.1 What is a Hydra Probe?

The Hydraprobe is a sensor that consists of a 4-cm diameter cylindrical head with four, 0.3-cm diameter tines, Figure 3, that protrude 5.8 cm and a thermistor in the head to measure temperature. (Seyfried in press)

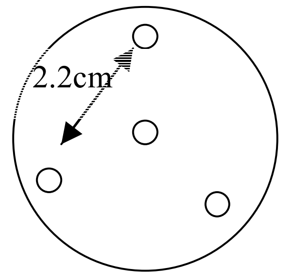

Figure 3. Arrangement of Tines at base of Hydra Probe

The hydraprobe is based on the same principles as those developed by Topp (1980) and determines soil moisture and salinity by making a high frequency (50MHz) complex dielectric constant measurement. The dielectric constant of a material under certain conditions is the extent to which it concentrates electrostatic lines of flux; it is the ratio of the amount of stored electrical energy when a potential is applied relative to the permittivity of a vacuum. The soil moisture measurements utilise the clear distinction between the dielectric properties of the water and soil particles; water having εr′ approx 80 and εr” approx 4, while dry soil has εr′ of 2-5 and εr” less than 0.05, εr′ and εr” being the real and imaginary components of the dielectric constant respectively.

Using a lower frequency than TDR sensors exposes the hydraprobe to greater interference from soil variability. The 50MHz signal is generated in the head of the sensor and transmitted via the tines. The raw signal output is four analogue dc voltages, the first three are used to determine the capacitive and conductive response (εr′ and εr”) and the fourth calculates temperature. The manufacturer supplies software which alleges to derive from these; temperature corrected εr ′and εr ″, soil water content, soil salinity, soil conductivity and temperature-corrected soil conductivity. (Seyfreid in press)
The manufacturer, Vitel, provides the option of programming the probe with one of three different equations to account for different soil textures, silt, clay and sand. Throughout this research the probes were set for silt; the recommendation of the manufacturer for when the soil type is unknown.

The manufacturer stated accuracy is:
Without knowledge of the soil type +/- 0.03 water fraction by volume (wfv) if know crudely sand, silt, clay then it is +/- 0.015-0.020 wfv with site specific calibrations reducing the error to +/- 0.005 wfv. They admit the remainder of the error is due to inaccuracies in the calibration process and the basic soil electrical properties measurement. They say that the real and imaginary parts of the dielectric constant will vary with temperature and that is why they have done a temperature correction using the measured soil temperature to calculate what the dielectric constants should be at 25^{o}C.
All soil measurement parameters (except temperature) are determined from the dielectric constant measurements. The temperature corrected dielectric constants are subject to uncertainty particularly at temperatures differing greatly from 25^{o}C due to the different temperature response of differing soil types.

3.2 Previous Research

The majority of research investigating the hydraprobe has been undertaken by Seyfried (2002, 2004, in press) and aside from the work currently being done by Panciera and Biasioni at the University of Melbourne for the NAFE campaigns little has been looked into for the hydraprobe.

The most developed and therefore most reliable of the electromagnetic methods is Time Domain Reflectometry (TDR) which operates by launching a fast rise voltage step along the transmission line or probe in the soil the pulse travels to the end of the probe and back where it is detected and analysed. The velocity of propagation of the pulse is related to the dielectric constant (Topp 2003). The TDR technique determines the dielectric constant of a medium from measurements of the propagation speed of an electromagnetic wave obtained from a pulse generator (Quinones et al 2003). Topp (1980) developed the empirical relationship between the dielectric constant of soil and soil moisture and since then the application of TDR has been widely accepted (Quinones, Ruelle & Nemeth 2003).
If the hydraprobe is to be as accepted as TDR it may need to follow a similar developmental path because as previously mentioned despite TDR being the best electronic technique (Seyfreid 2004) its very expensive and the level of ability required by the operator puts it beyond the means of the 'growers'/ users (Blonquist et al 2005) while the hydraprobe is easy to use and affordable. Despite commending the amount of research done on developing TDR within a variety of probe configurations Topp (2003) even called for further work to be done on capacitance devices and more affordable alternatives. Capacitance devices are designed to effectively make the soil of interest the primary dielectric material for a capacitor so that changes in soil moist result in changes in the circuit frequency (Seyfried 2004). Capacitance devices determine apparent capacitance of a probe placed in or near soil which changes depending on water content. Their low cost enhance their popularity (Western and Seyfried 2005). However despite receiving little independent evaluation the hydraprobe has more of direct comparison with TDR than capacitance resistors (Seyfried 2004) but although they both measure dielectric properties the hydraprobe has been found to report very different values, except for sand. The discrepancy between the two is due to soil dielectric properties as it has been found to be accurate in fluids (Seyfried 2004).

Seyfried (2004) investigated the three manufacturer-provided calibration equations, (sand, silt, and clay) against the Topp equation and found them to all be inadequate. This could be due to the dependence of ε_r'' and, to a lesser extent, ε_r' on frequency. The assumption, that $\varepsilon_r' >> \varepsilon_r''$ or $\tan \delta << 1$, is less applicable to Hydra Probe measurements ($f = 50$ MHz) than TDR ($f \approx 1000$ MHz) (Seyfried in press).
The work of Seyfried and Murdock (2002) found a linear response to temperature suggesting that the effect of soil temperature on the measured data may be substantial. They also found the sensors to have statistically significant but almost negligible temperature sensitivity. This will be looked into further in this research to determine if it is significant or not despite Seyfried (2004) stating that sensor specific calibrations are not necessary.

Past research has shown that the clay calibration fares worst with sand being best for soil moistures between 0-0.33 and silt for those greater than 0.33 (Seyfried and Murdock 2002). However soils with high clay content also tend to deviate from soil calibrations from the Topp equation using TDR (Or and Wraith, 1999, Evett, 2000) this could be due to ion exchange capacity and specific surface area varying considerably with clay mineralogy and affecting soil dielectric properties. There appears to be distinct instrument sensitivity to soil type explaining why those who use it currently perform individual soil calibrations beforehand. The effect of soil type will be explored in this research.

The method for this research will endeavour to utilise the successful techniques from the literature; the infiltration-addition method used in Seyfried (in press) as opposed to the mixed cells methods for investigating soil moisture; water added from the bottom of the cell and soil moisture determined from weighing.
The effect of temperature variation of the soil and of the probe, soil type and soil moisture content will be explored further using the NAFE 2006 farms as the sample study.

4 Methodology

4.1 Data Collection

Thirteen sampling site locations were chosen over six farms from the NAFE 2006 Yanco and Coleambally region to obtain the largest variation in soil types, see Appendix 10.1 Site Locations. The site locations at each farm were taken from opposing ends so as to cover maximum potential variation in soil type, detailed sampling location maps can be seen in appendix 10.2- 10.7.
In the field the samples were located with GPS navigation on the Yanco maps.

Figure 4.a The ring. b. hammering the ring into ground c. Collecting soil sample for gravimetric analysis

A measurement ring of dimensions; diameter 67.2mm and depth of 52.1mm was used as a constant volume to obtain soil samples. When a suitable site was chosen/ located the

ring, Figure 4, was placed on the ground covered with the wooden plank and hammered into the soil. When completely filled with dirt the surrounding soil was removed, Figure 4c, so that the ring could be removed without any loss of soil. The contents of the ring were then bagged up securely to avoid any change in moisture content and labelled to be taken back to the lab.
The Hydraprobe readings were taken in close proximity to the soil sample, Figure 5, and three to five readings were taken at each sample location in order to get an average reading before the soil was removed and before the ring was put in the ground to avoid interference from the metal ring or disruption in the soils natural state.

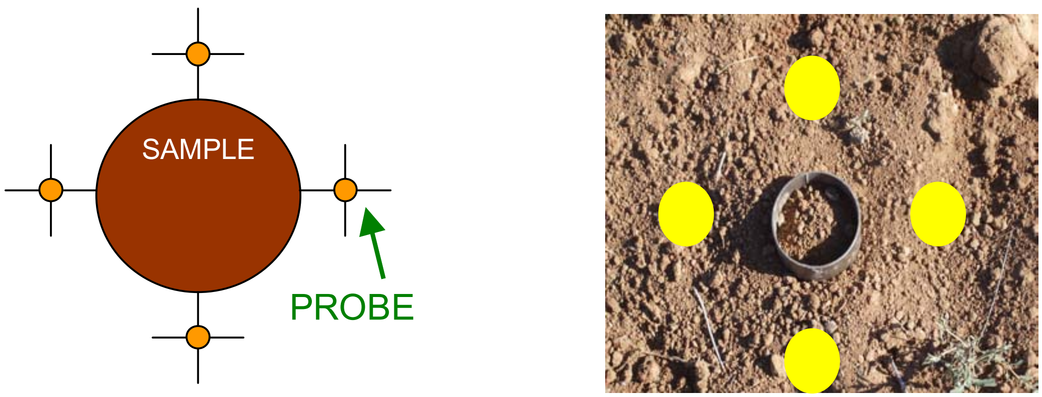

Figure 5 a. Sample and hydraprobe measurement relative locations as recommended by Danielle Biasioni 2005 b.As done in the field

Recorded at each site via arcpad Figure 6, was site ID, hydraprobe reading of moisture content, temperature and the four voltages, salinity is also recorded but was not required for the scope of this research.

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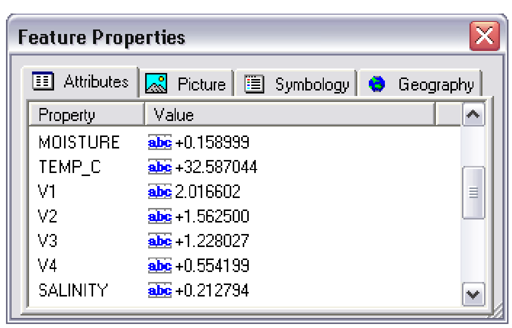

Figure 6 An example of a hydraprobe reading in arcpad

Upon immediate return to the lab all samples are oven dried at 105°C and the wet weight and dry weight are used to calculate the bulk density of the soil in the field, Equation 1.

Equation 1 Bulk density = mass of solids / total volume

$$\rho_b = M_s / (V_s + V_w + V_a)$$

4.2 The Dry Down Curves and Infiltration-addition method

The dried soil samples are saturated by putting them into PVC pipe containers with pin holes on the outside, Figure 7, and to ensure no entrapment of air bubbles and a thorough saturation, the top holes are covered with tape and the pipe placed in a bucket of water and the soil saturated from below, Figure 7b. It is left for a minimum of 24hours to allow complete saturation. Before this the volume of dry soil in the cylinder is noted, Equation 2.

Equation 2. Volume of a cylinder

$$V = \pi r^2 h.$$

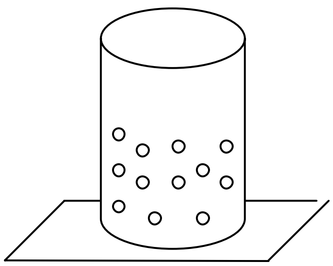

Figure 7 a. PVC pipe container

b. saturating in bucket

Weights of all containers, wires, sensors, dry samples and wet samples are to be taken before commencement. Upon saturation a probe in then inserted into the container, excess water drained off and the samples are put in the oven at 45°C, along with the probes, which are safe as long as the oven temperature does not exceed 45°C (Figure 8a). This prevents disruption to the soil from constant probe insertion.

Figure 8 a. drying samples with probes in oven

b. lab reading

Readings were taken in the lab twice daily until the soil dried to obtain sufficient data to plot drying curves. The sample and their pipe were taken from the oven for as little time possible to weigh the sample and then plug into the iPAQ and power the sensor, Figure 8b, to note hydraprobe measurements.

4.3 Texture Analysis

To assess the actual variation in collected soil samples a basic texture analysis was performed. A pinch of each soil was wetted and rubbed between the fingers of an experienced lab technician and based on the feel of the soil classified as predominantly sand, silt or clay. Using the soil texture triangle, Figure 9, the percentage distribution of sand and clay were estimated. The intention was for samples to be sent away to the CSIRO for proper classification but unfortunately this was unfeasible at the time but is recommended if further research is to follow on from this report.

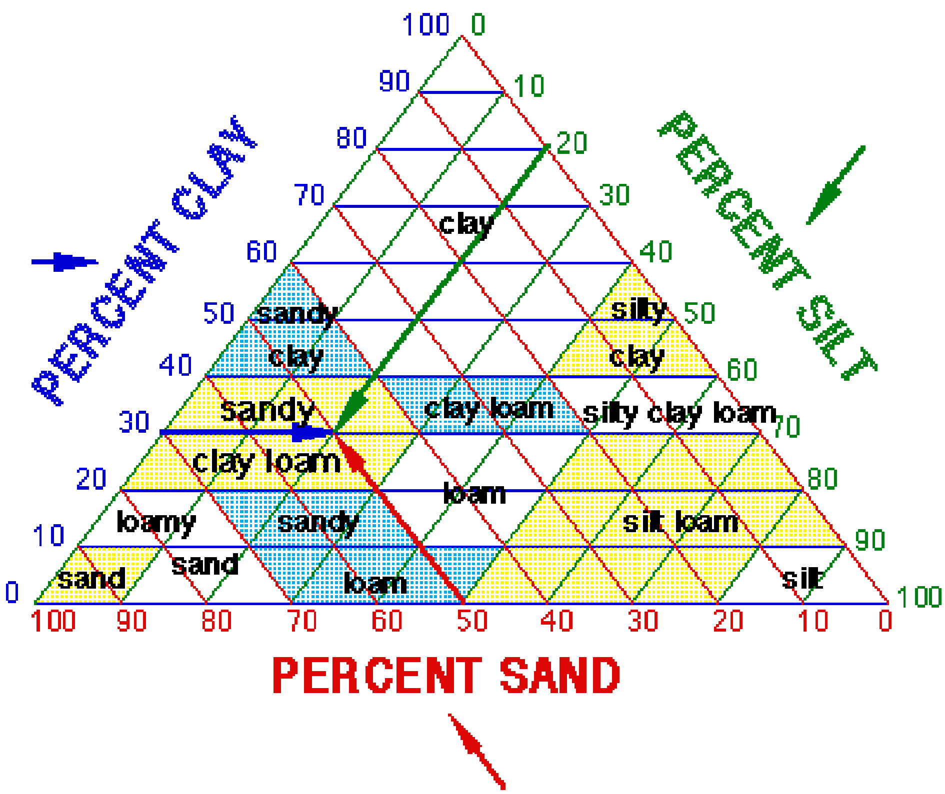

Figure 9 USDA soil texture triangle

4.4 Temperature Testing

Probe Temperature Variations

In order to assess whether variations in the temperature of the probe have an effect on the hydraprobe determined moisture content the probe is to be heated in the oven from ambient temperature to 45°C, taken out at regular intervals to read a sample of water, soil and air, all kept at ambient temperature.

Just the one probe was used and measurements were taken in succession, air soil water and always the same order with a quick wipe in between sample so not to cross contaminate any of the soil into the water jar. The temperature of the probe was recorded as the value given from the hydraprobe reading.

Material temperature variations

Nine samples were involved; a dry, normal and nearly saturated sand sample (regular sand obtained from the soils lab), a dry, normal and nearly saturated soil sample (Y9A) and cold, ambient and warm water. The probe was maintained at ambient room temperature.

The soils and sand were heated in the oven from ambient temperature up to 45°C and to prevent any change in actual moisture content all holes on the container were electric taped over with the top opening covered down with tin foil. While heating in the oven samples were taken out one by one every 5-10minutes to take a reading, the tin foil was removed in order to insert the probe but great care was taken that this was for as short a time as possible to prevent any possible evaporation. However the probes were left in the sample long enough for the temperature reading of the probe to reflect the increase in temperature of the sample.

4.5 Data Analysis

Plots of gravimetrically determined soil moisture vs. the hydraprobe inferred soil moisture are to be made for each farm from the dry down data. Trend lines are to be fit to the curves obtaining a succession of a equations of the form: $\vartheta_v = a\ \vartheta_{HP}^2 + b\ \vartheta_{HP} + c$; where a, b, c will be computer generated coefficients, ϑ_v is the gravimetric water content and ϑ_{HP} the hydraprobe read water content at 45°C. Each coefficient is to then be plotted against soil type (%clay) in order to assess the effect of soil type on the dry down curve coefficients.

The temperature variation data is to be included by plotting the hydraprobe soil moisture reading at variable soil temperatures against the soil moisture content reading at 45°C for the soil moisture content that is held constant as described above in section 4.4 Material temperature variations.

From these a generic equation incorporating the two effects can be culminated in the form $\vartheta_{HP}^{45} = T_{soil} * \vartheta_{HP}^{t} * d + e$, where d and e are possibly factors of the soil texture and T_{soil} is the temperature of the soil.

5 Results and Discussion

Gravimetric analysis of the samples determined the bulk densities, Table 1.
The sample Y2B1 will not be further used as it was inhabited by bull ants and the density will not be reflective of the area, Y2B2 was taken near by and will be used for Y2B.
Two samples were taken at Y2C, Y7A, Y7B and Y10B to check the accuracy and consistency of the sampling technique. The maximum resultant variation in moisture content is 0.01, at Y10B and the others only having 0.01-0.06 variation and this would be due to human imperfections in obtaining a precise volume.

Data was collected over two expeditions. The majority were collected on the first trip in August, (Y2, Y7, Y10 and Y12) and the remainder later in the September trip (Y1 and Y9). The conditions were different, the first was a frosty day and those farms visited in the morning were covered in frost and samples were taken at sites of minimal frost and vegetation cover. In September the conditions were very hot and dry.

Table 1 Field data; Sample Bulk Densities and measured soil moistures

Sample	bulk density	Gravimetric SM	Hydraprobe SM	Predominant soil type
Y2A	1.5843	0.072777	0.067525	Silt
Y2B1	0.9687	0.072667	0.093625	Silt
Y2B2	1.4297	0.168949		Clay
Y2C1	1.3330	0.103124	0.086206	Silt
Y2C2	1.3491	0.102572		Silt
Y7A1	1.5980	0.144175	0.143338	Clay
Y7A2	1.5200	0.141692		Clay
Y7B1	1.6584	0.099096	0.164497	Silt
Y7B2	1.5002	0.093799		Silt
Y10A	1.1742	0.096889	0.130815	Silt
Y10B1	1.5600	0.177060	0.188954	Clay
Y10B2	1.4462	0.187985		Clay
Y10C	1.5397	0.195434	0.167313	Clay
Y12X	1.3574	0.151293	0.177881	Clay
Y12Y	1.0660	0.242168	0.238784	Clay
Y1A	1.4281	0.009386	0.000000	Silt
Y9A	0.9825	0.135920	0.154932	Clay
Y9B	1.3625	0.062195	0.051428	Silt

Interestingly the sites with the greatest difference between the gravimetrically determined soil moisture and the hydraprobe inferred soil moisture content are all predominantly silt. Supporting the notion that soil type effects the resultant hydraprobe reading, however the hydraprobe used in this experimentation was set to the manufacturers ‘silt’ soil type so following their theories it should be the silt that is more correlated not the clay justifying that investigations need to be done in rectifying the manufacturers calibrations. The overall correlation for all the above samples is shown below in Figure 10. It is very near to a one to one linear relationship but there are a couple of outliers as just discussed that warrant further investigation.

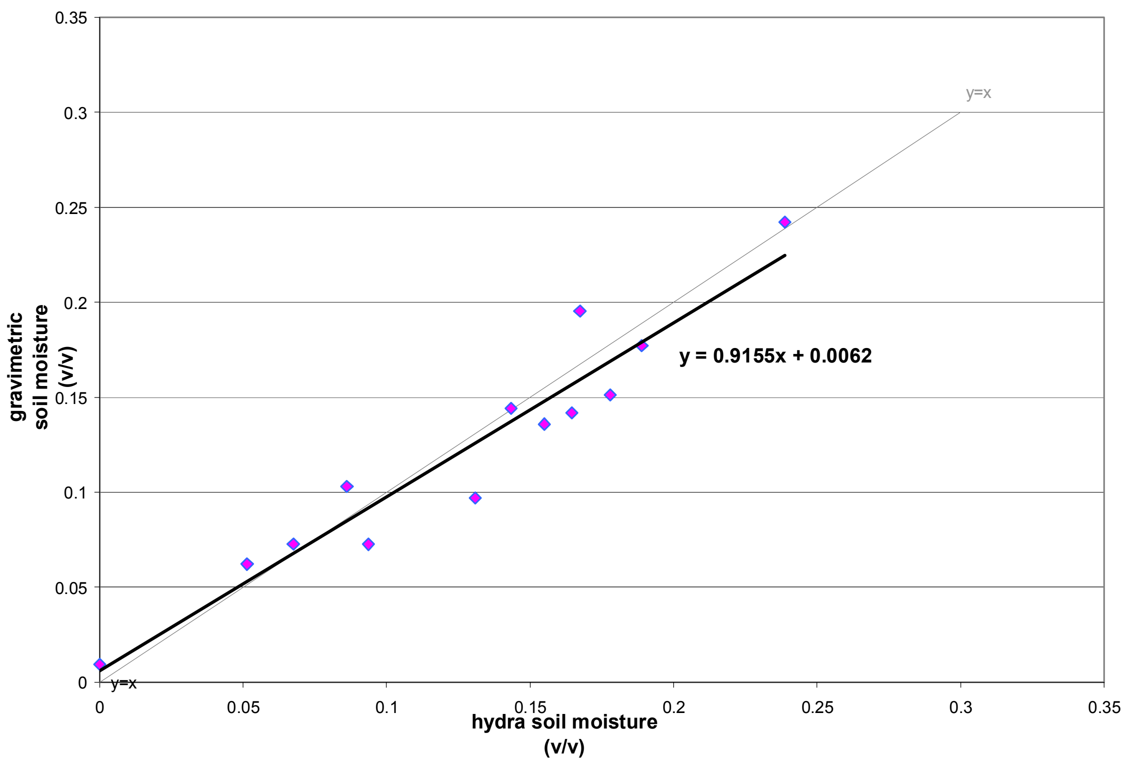

Figure 10 Relationship between hydraprobe soil moisture reading and the gravimetrically measured soil moisture content for the field site samples

5.1 Effect of Moisture Content

The dry down curves for the hydraprobe measured soil moisture content vs. gravimetrically determined soil moisture of each of the farms at 45°C are shown below, Figure 11- Figure 16. The values for the entire sample dry down measurements can be accessed in the accompanying file drying.xls.

Due to laboratory difficulties the first few measurements from the first batch have been omitted for their inaccuracy. Furthermore some of the initial weights from the second batch were lost and there arose the difficulty of determining specific bulk densities for the soils compacted in the pipe containers. Ideally, they were to be compacted to replicate field conditions and if this was done accurately, then the field determined bulk density would be appropriate. However this is hard to guarantee and it was decided that new bulk densities needed to be determined. It was assumed that the final soil weight, after the week of being oven dried at 45°C was the dry weight. To further dry the soil at 105°C to obtain the absolute dry weight would first require the removal of the probe as it can not be heated above 45°C, this would not have been practically manageable the already nearly dry soil was all stuck to the probe and it would have been impossible not to incur losses. So while the final dry weight from the 45°C oven may still have a gram of water in it, it was found that this was more accurate than approximating the dry weight from the field determined bulk density and even for those samples were the initial dry weight data was available in some cases the dry weight after heating at 45°C was less. Appendix 10.8 shows this analysis.

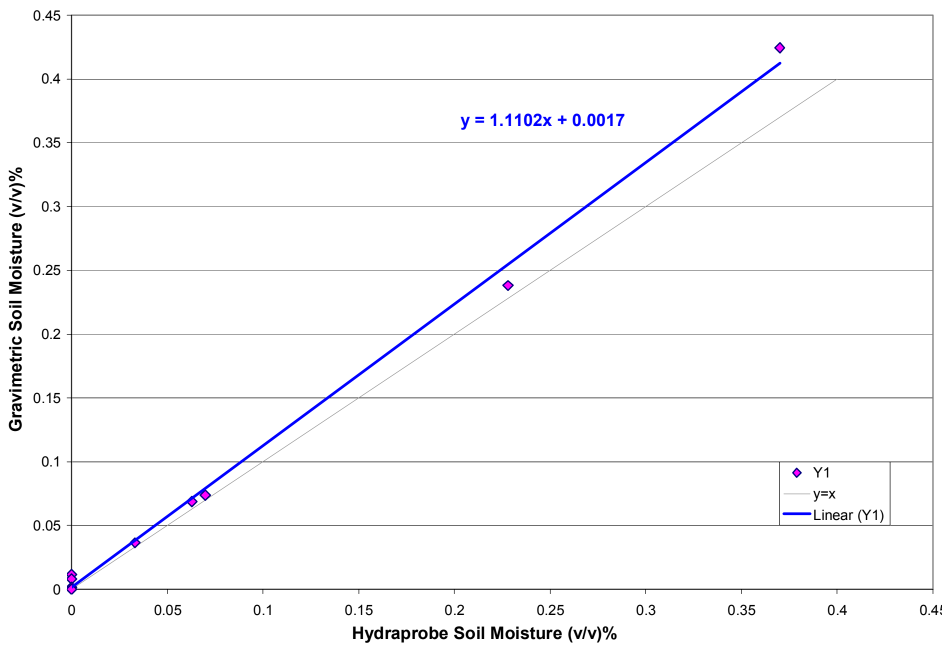

Figure 11 Dry down Curve for farm Y1

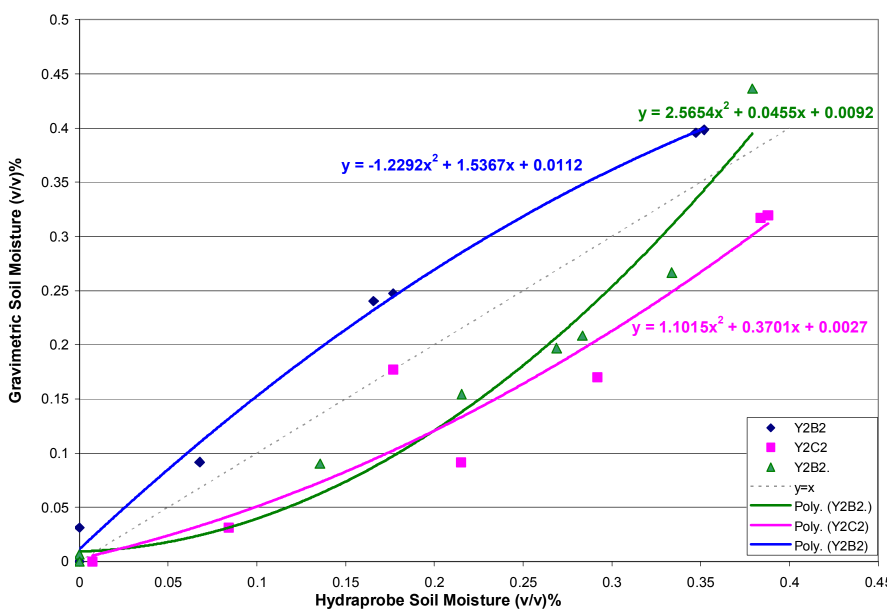

Figure 12 Dry Down Curve for farm Y2

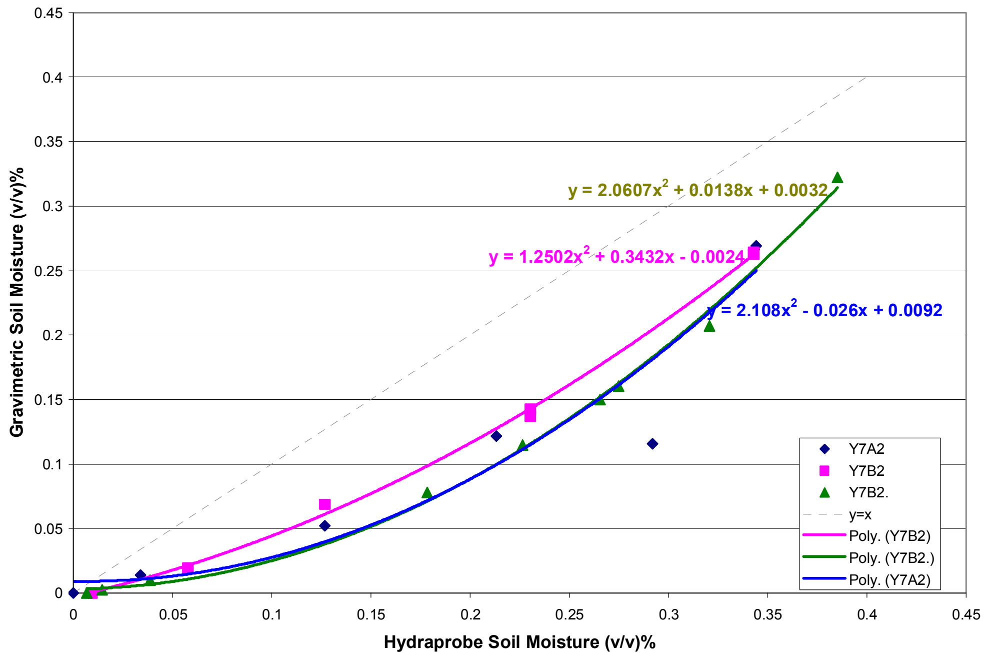

Figure 13 Dry down Curve for farm Y7

So it looks like Y7 is of a fairly uniform soil type...

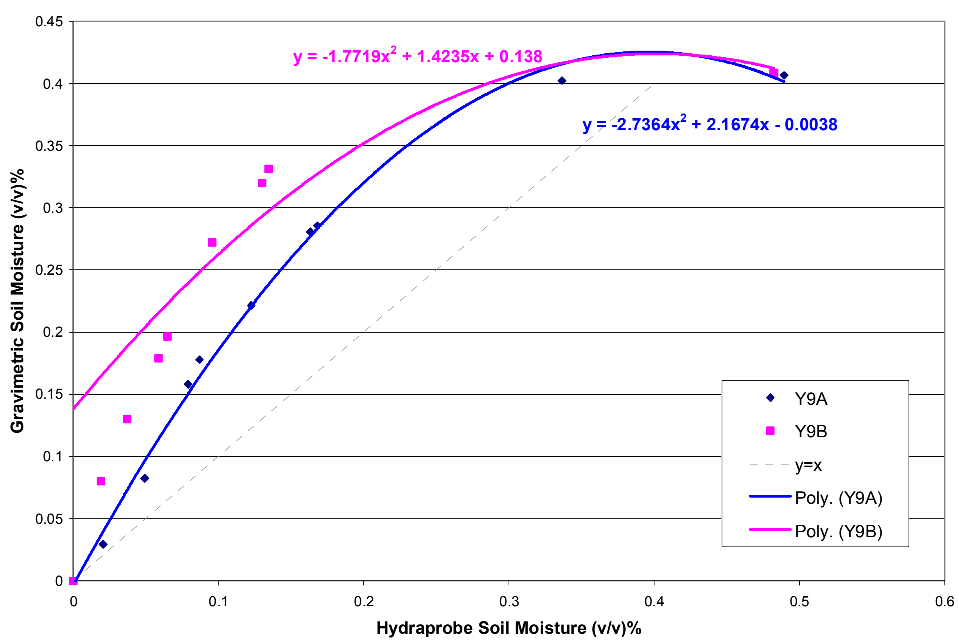

Figure 14 Dry down curve for Y9

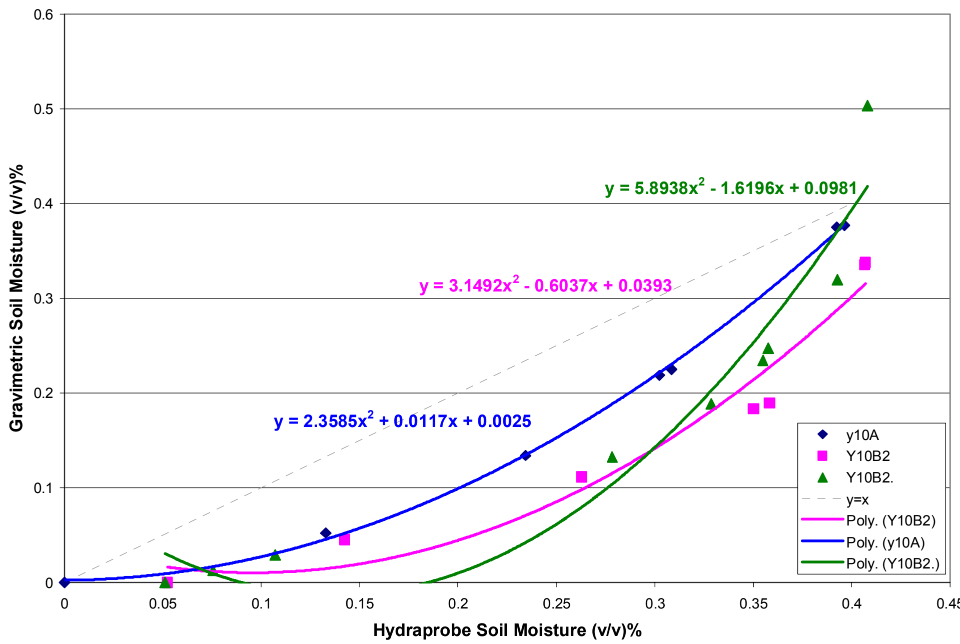

Figure 15 Dry down curve for farm Y10

Despite the wacky graphs the data points are all in similar alignment

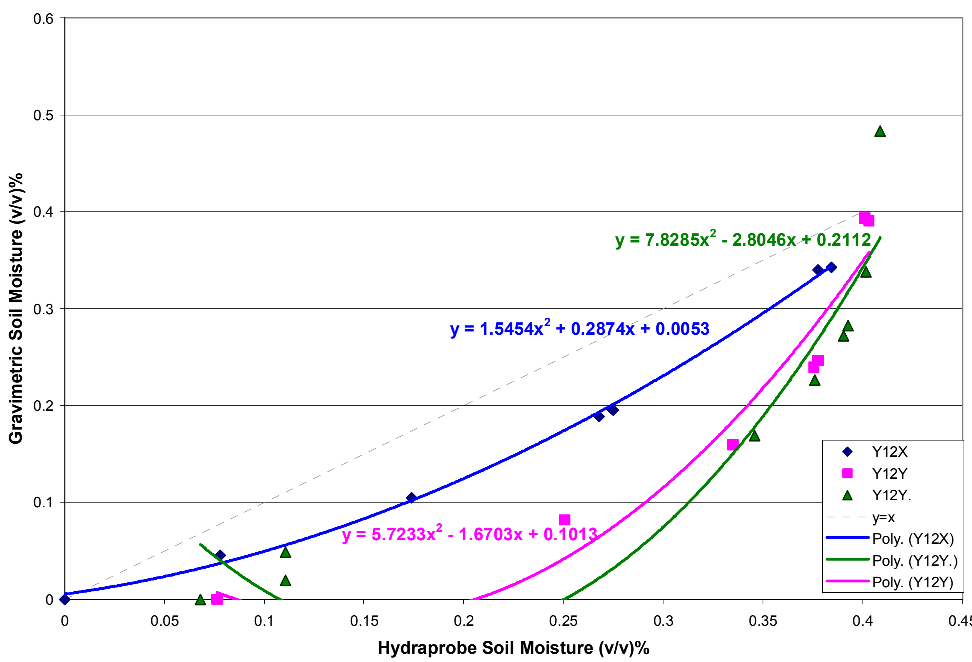

Figure 16 Dry down curve for farm Y12

Figure 11 Dry down Curve for farm Y1 is the only sandy soil curve and the only linear relationship formed from the samples and their dry down curves. The remaining are all fit with second order polynomials. The majority of the soils appear to have dried down consistently with other samples taken from the same farm a variation shown on Y2 where Y2B and its repeat appear to be mirrored opposite over the y=x line; yet it was the same sample analysed twice so somehow this has to be a lab error as opposed to a gross discrepancy in the soil itself.

The equations for all of the above trend lines can be summarised as shown in Table 2 below. Where the equations are of the form $\vartheta_v = a\ \vartheta_{HP}^2 + b\ \vartheta_{HP} + c$.

Table 2. Polynomial co-efficients

SITE	a	b	C
Y1	0	1.102	0.0017
Y2B2	-1.2292	1.5367	0.0112
Y2B2	2.5654	0.0455	0.0092
Y2C2	1.1015	0.3701	0.0027
Y7B2	1.2502	0.3432	0.0024
Y7B2	2.0607	0.0138	0.0032
Y7A2	2.108	-0.026	0.0092
Y9B	-1.7719	1.4235	0.138
Y9A	-2.7364	2.1674	-0.0038
Y10A	2.3585	0.0117	0.0025
Y10B2	3.1492	-0.6037	0.0393
Y10B2	5.8938	-1.6196	0.0981
Y12X	1.5454	0.2874	0.0053
Y12Y	7.8285	-2.8046	0.2112
Y12Y	5.7233	-1.6703	0.1013

Each of the coefficients was plotted against the soil type to distinguish if soil type plays a part in determining coefficients. Soil type is distinguished 1=sand, 2=silt and 3=clay.

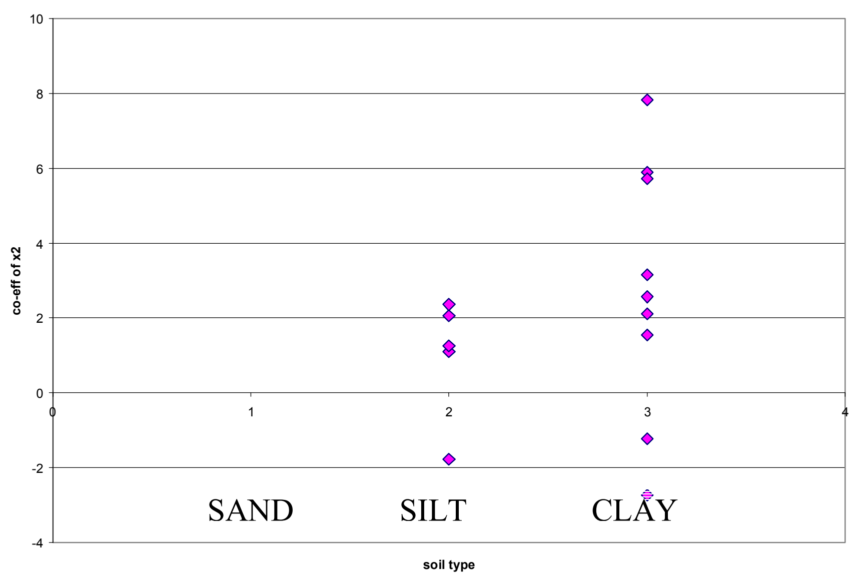

Figure 17 The coefficient ‘a’ vs. soil type

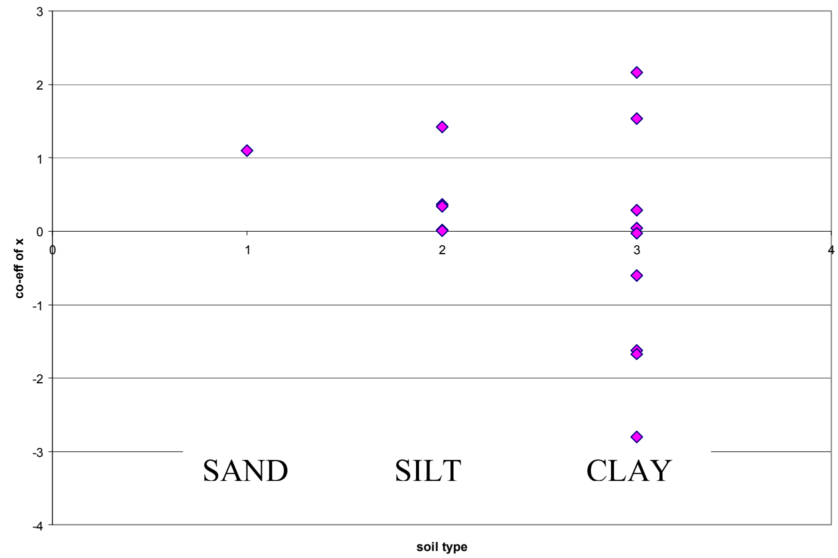

Figure 18 The coefficient b vs. soil type

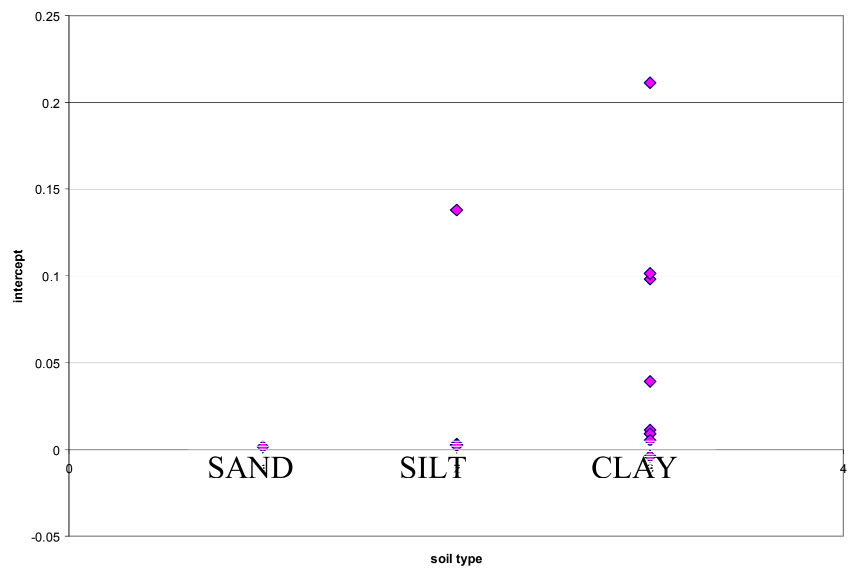

Figure 19 The intercept ‘c’ vs. soil type

Clay appears the least conforming soil type, having the largest range of coefficient values. This supports previous research that clay is the most difficult to determine for. However in this instance a larger number of soils were clay therefore more tests need to be done on sand and silt in order to determine the actual relationship.

Rocco’s calibration results from the NAFE ’05 data, Figure 20, found there to be a linear relationship for sand which is supported by the only sandy soil from this research data set, Figure 11.

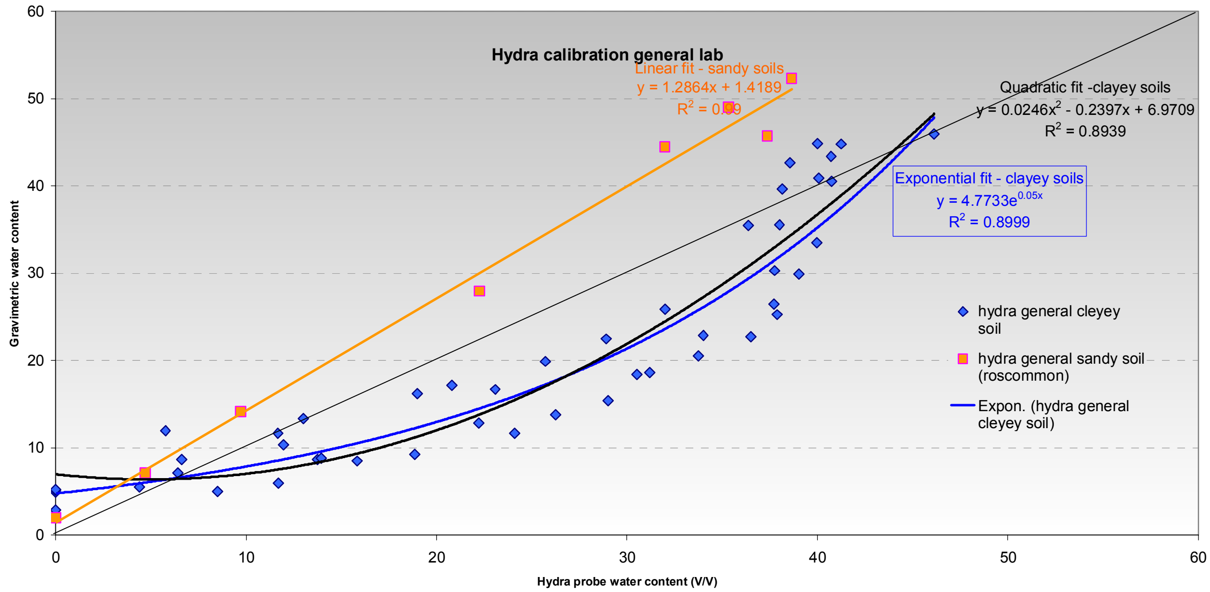

Figure 20 General Hydraprobe calibration for clayey soils and sandy soils from NAFE'05 (Rocco's?)

5.2 Temperature Analysis

Probe temperature variations

The small effect of probe temperature on the hydraprobe moisture content reading shown in Figure 21 can be explained by the manufacturer's calibrations adjusting for temperature. This is seen by looking at the separate voltages of the four channels. Figure 23 shows the obvious relationship between the temperature and the voltage of the fourth prong whereas Figure 22 shows that for air and water temperature has no effect at all on the remaining three prongs and no noticeable effect of soil.

Therefore if a probe was to heat up during the day whilst being driven between sites in the back of a car it will be of no detriment to the hydraprobe readings.

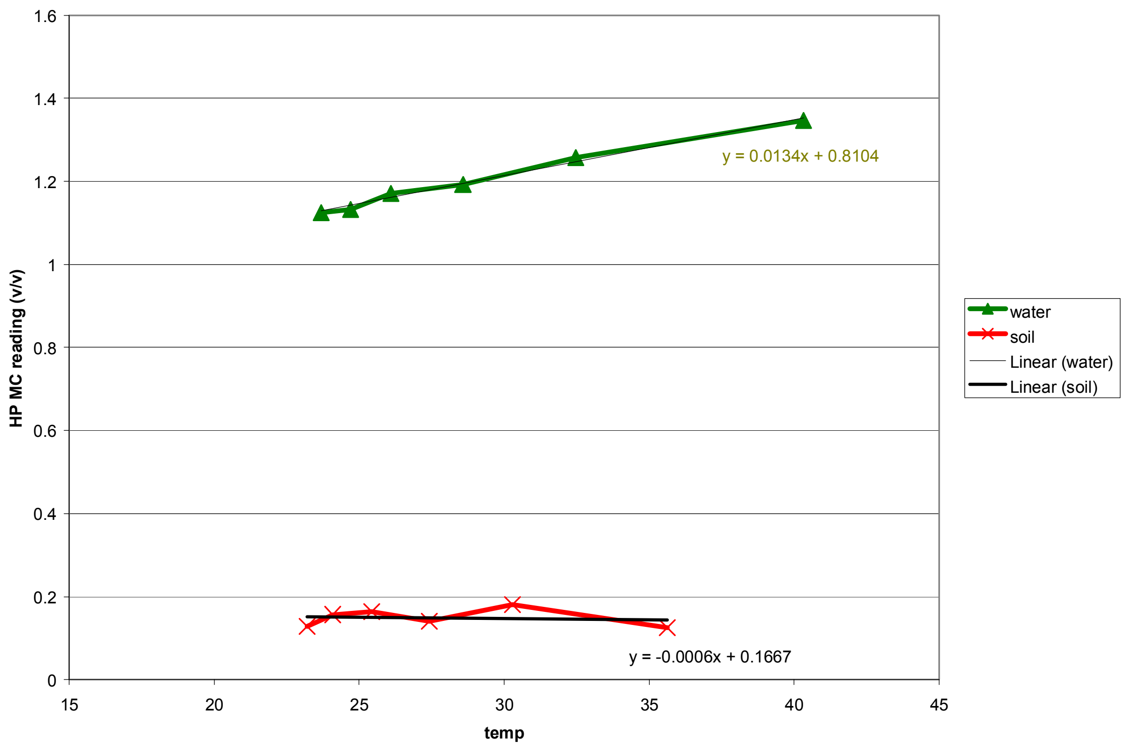

Figure 21 Effect of probe temperature variation on the moisture content reading in soil and water

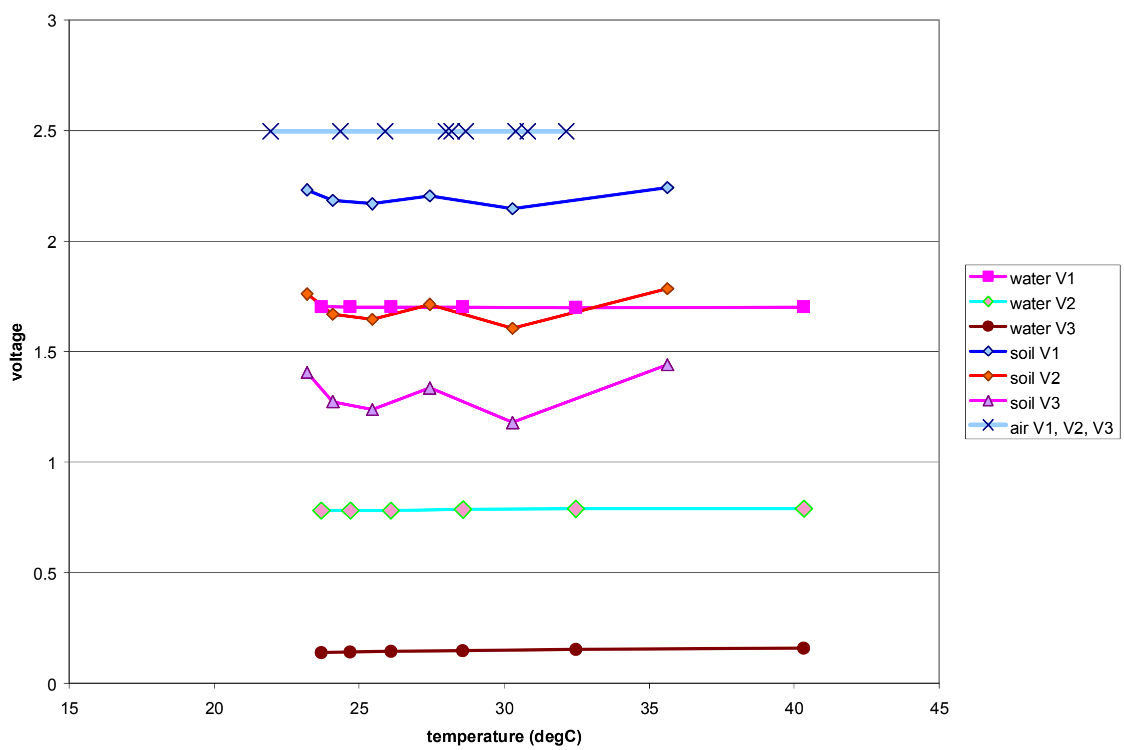

Figure 22 The effect on the 3 voltages read in soil, water and air by changing probe temperature

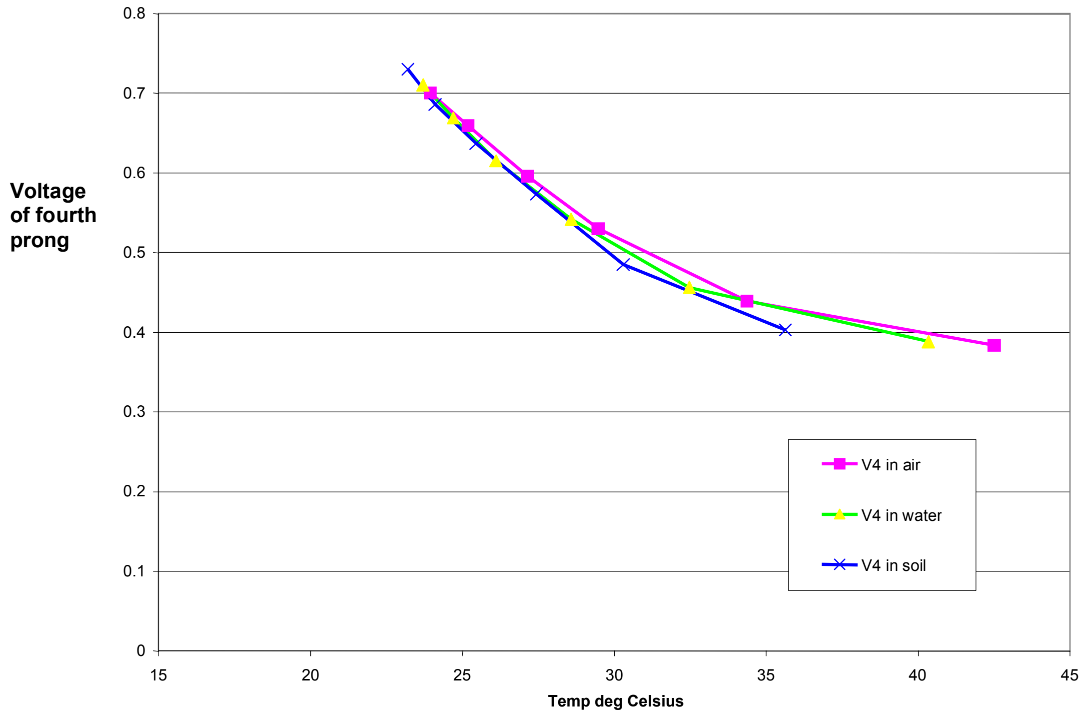

Figure 23 The effect of temperature on the voltage of the fourth tine.

Material temperature variations

The temperature of the material appears to have an effect on the hydraprobe moisture content reading, Figure 24. Closer examination of the actual voltage readings shows that for the water sample the temperature has no effect on the three main prongs, Figure 26, and therefore the resultant difference in moisture content is due to the manufacturer's correction factor. However there does appear to be a relationship between the temperature of the soil or sand and the voltages of the three prongs, Figure 25 and Figure 26 and this is more evident in the wetter soil samples. This could be due to the relative difference in dielectric properties between the soil and its water constituents being picked up more sensitively by the hydraprobes reading of the dielectric constant as there is no effect when just in water.

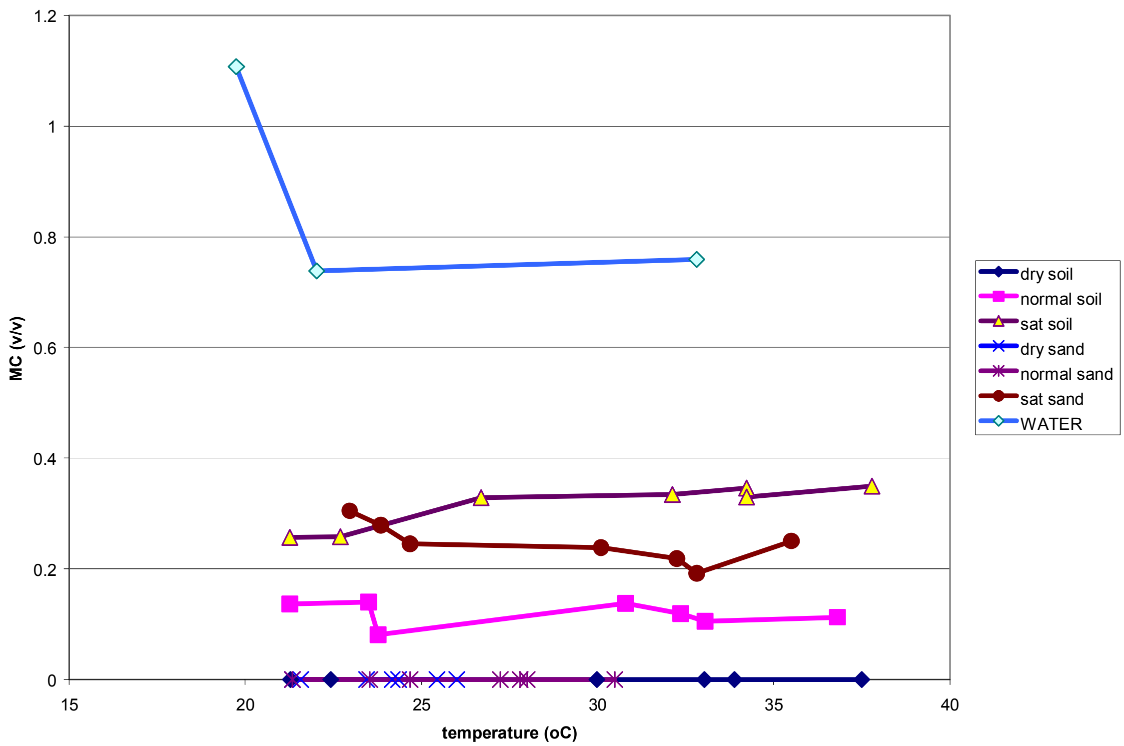

Figure 24 The effect of the temperature of a material on the hydraprobe moisture content reading

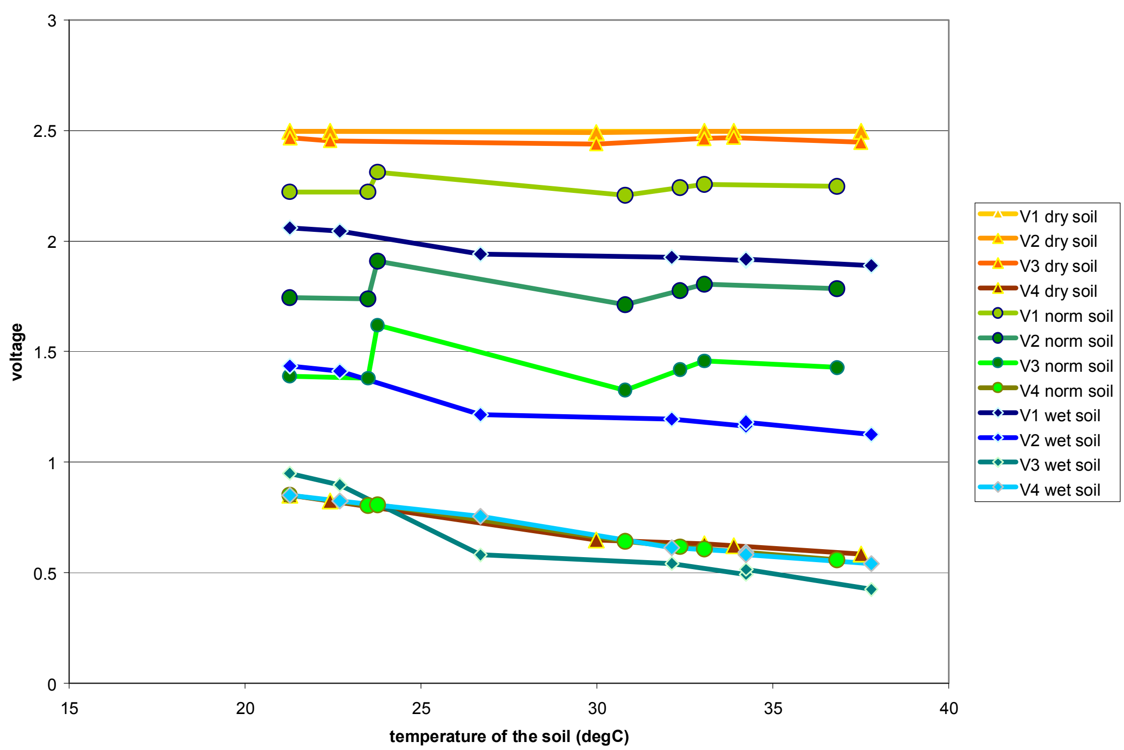

Figure 25 The effect of varying the temperature of the soil on the voltages of the 3 main prongs

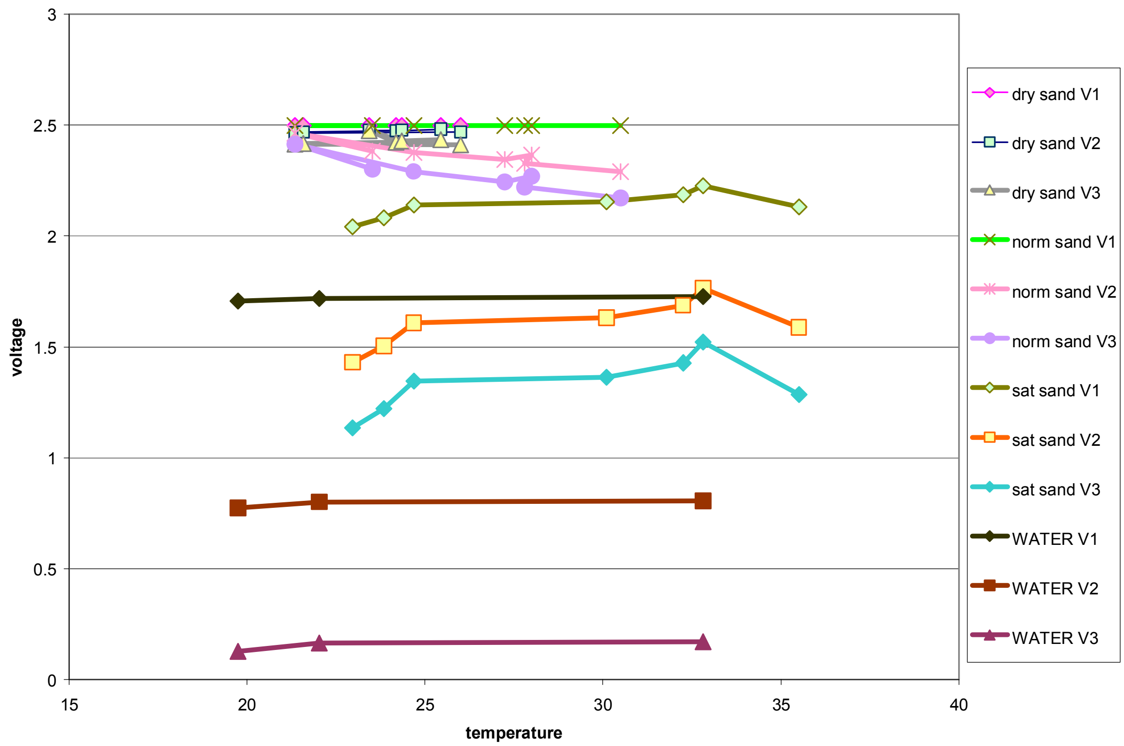

Figure 26 Temperature of sand and water vs. voltage of three main prongs

Figure 24 is extrapolated out to include the hydraprobe soil moisture content reading for the materials at 45°C.

The desired outcome was a curve for ϑ_{HP}^{45} vs. ϑ_{HP}^{t} possibly of the form:

$\vartheta_{HP}^{45} = T_{soil} * \vartheta_{HP}^{t} * d + e$

Where d and e are factors of the soil texture and T_{soil} is the temperature of the soil.

6 Conclusions

The findings support the theories that the temperature of the material has an affect on the hydraprobe inference of soil moisture content and that the effect of variations in temperature of the probe is negligible. Also following Seyfrieds findings that it is the dielectric properties of the soil that cause the discrepancies as there was no significant variation in measurements taken in water or air.

These results were also in line with Rocco's hydra calibration graph for soil texture; a linear relationship for sand and curvilinear for clay.

Further work needs to be done in concocting a universal general equation for the hydraprobe and the following recommendations are made for the continuation of this research.

7 Recommendations

- Soil classification to be undertaken by the CSIRO for a more accurate determination of the relative sand/ clay percentages. Providing more detailed texture graphs for more insight rather than just basic classifications of sand silt and clay.
- A broader cross section of soil types to complement the data obtained here. A common sand perhaps.
- As mentioned in the current manual in very saline soils measurement accuracy of a number of parameters can be degraded. In very saline soils the imaginary dielectric constant exceeds the real dielectric constant by a factor greater than two, which degrades the accuracy of the real dielectric constant. Thus further research should investigate the effect of the soil salinity on the dielectric properties.
- If anyone is to continue this research the author strongly recommends overestimating the expected lab time!

8 Acknowledgements

The author wishes to thank Associate Professor Jeffrey Walker for his patience and continual advice, Christoph Rüdiger for helping from the other side of the globe, Rocco Panciera, Olivier Merlin & Rodger Young for their technical assistance, Tony Lowe for his company and assistance in the lonely labs, Chris Pellizzoni for accompaniment into the field and the class of 421327 for enduring the late nights and caffeine addictions

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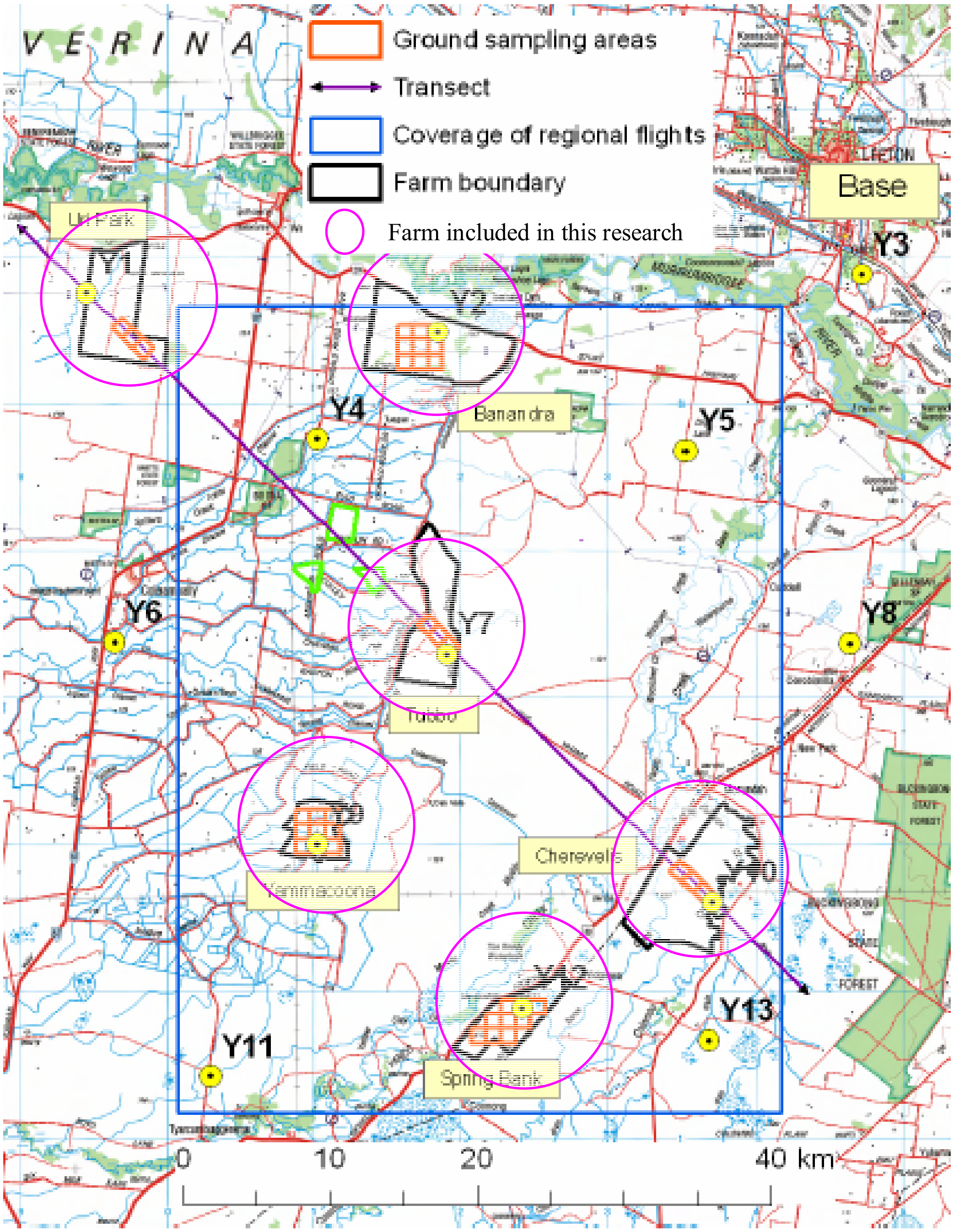
10 Appendices

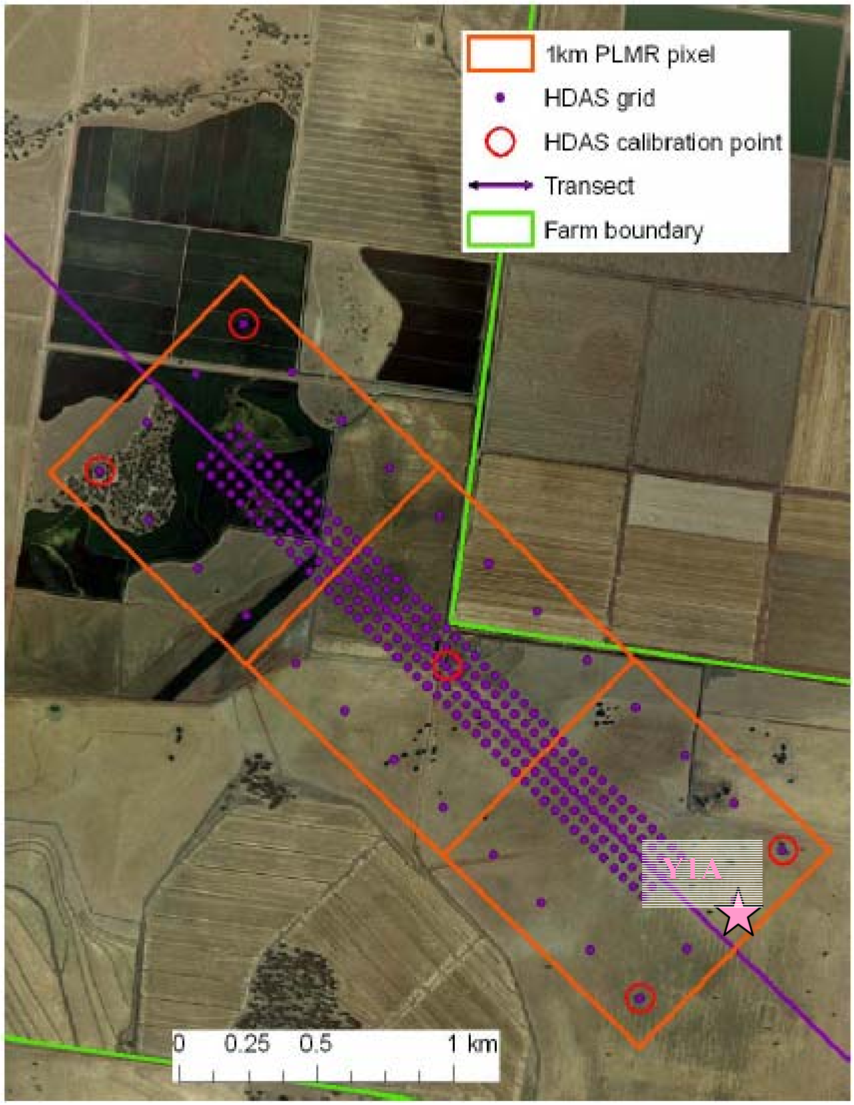
10.1 Site Locations

Map of the NAFE 2006 region, Yanco - Coleambally NSW and the selected farms



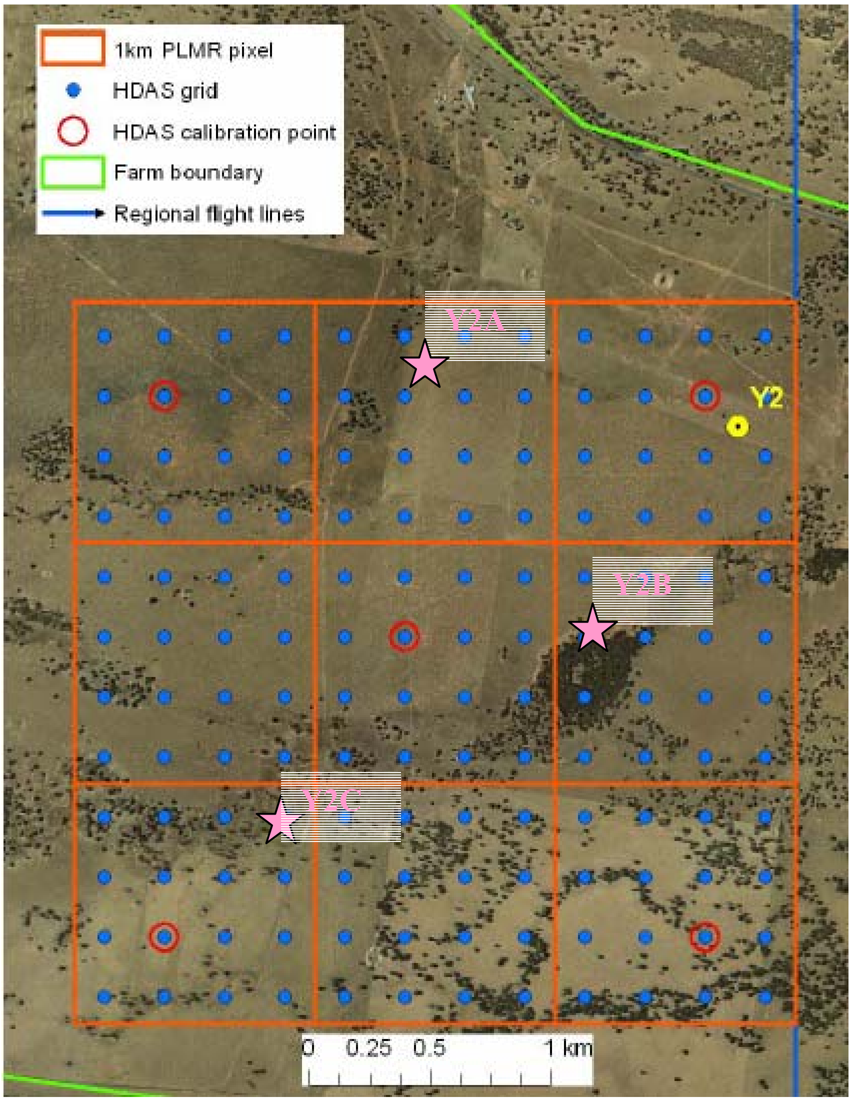
10.2 Y1

The Location of the sampling sites of farm Y1



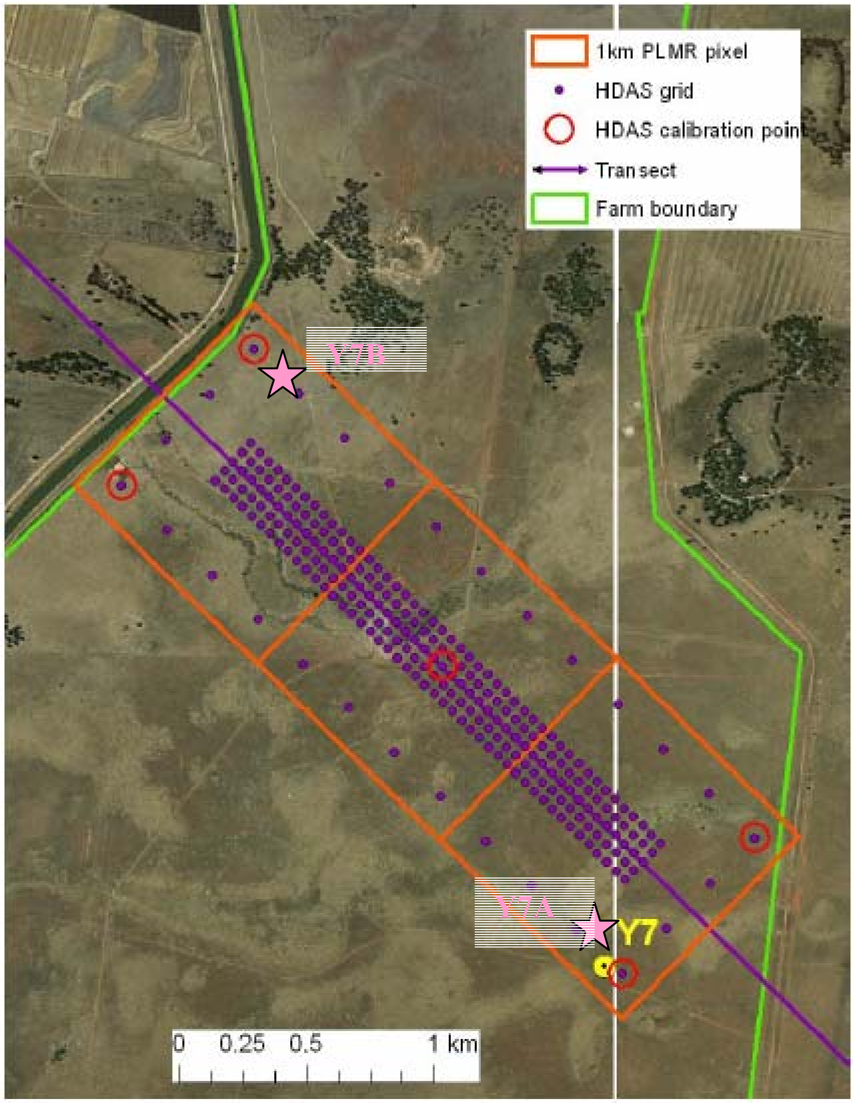
10.3 Y2

The Location of the sampling sites of farm Y2



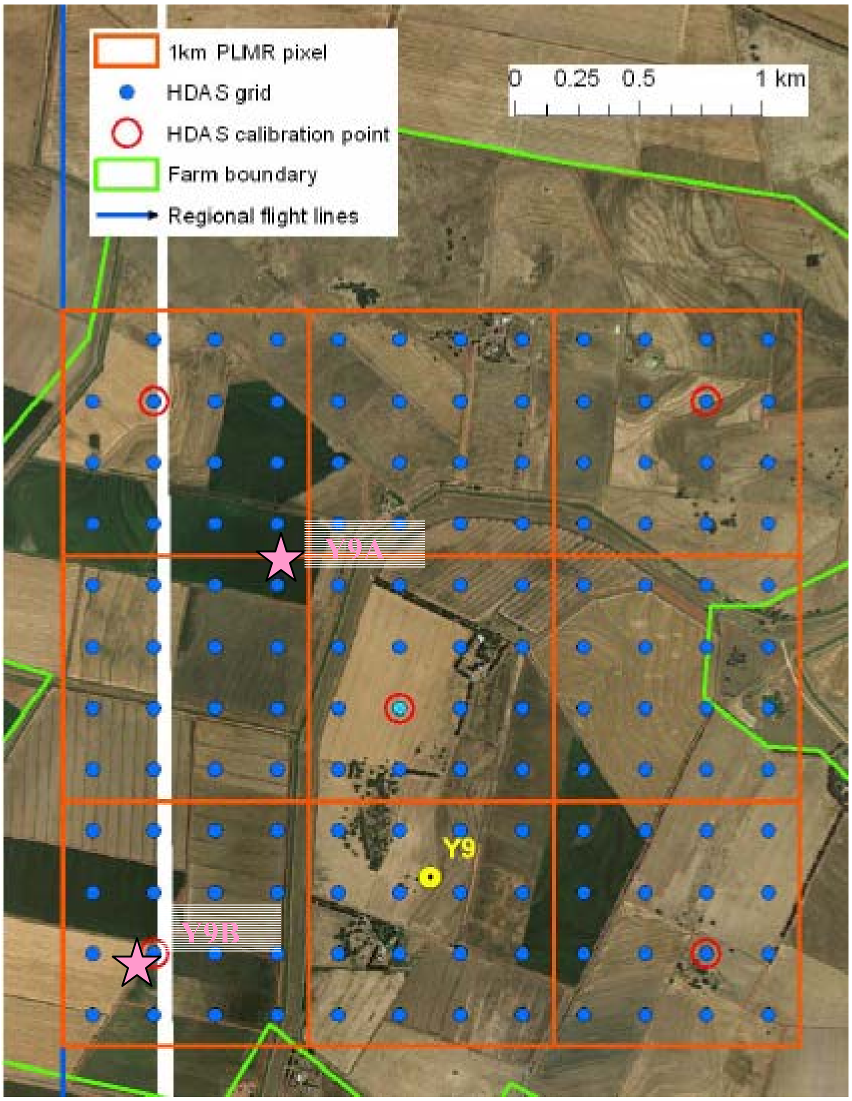
10.4 Y7

The Location of the sampling sites of farm Y7



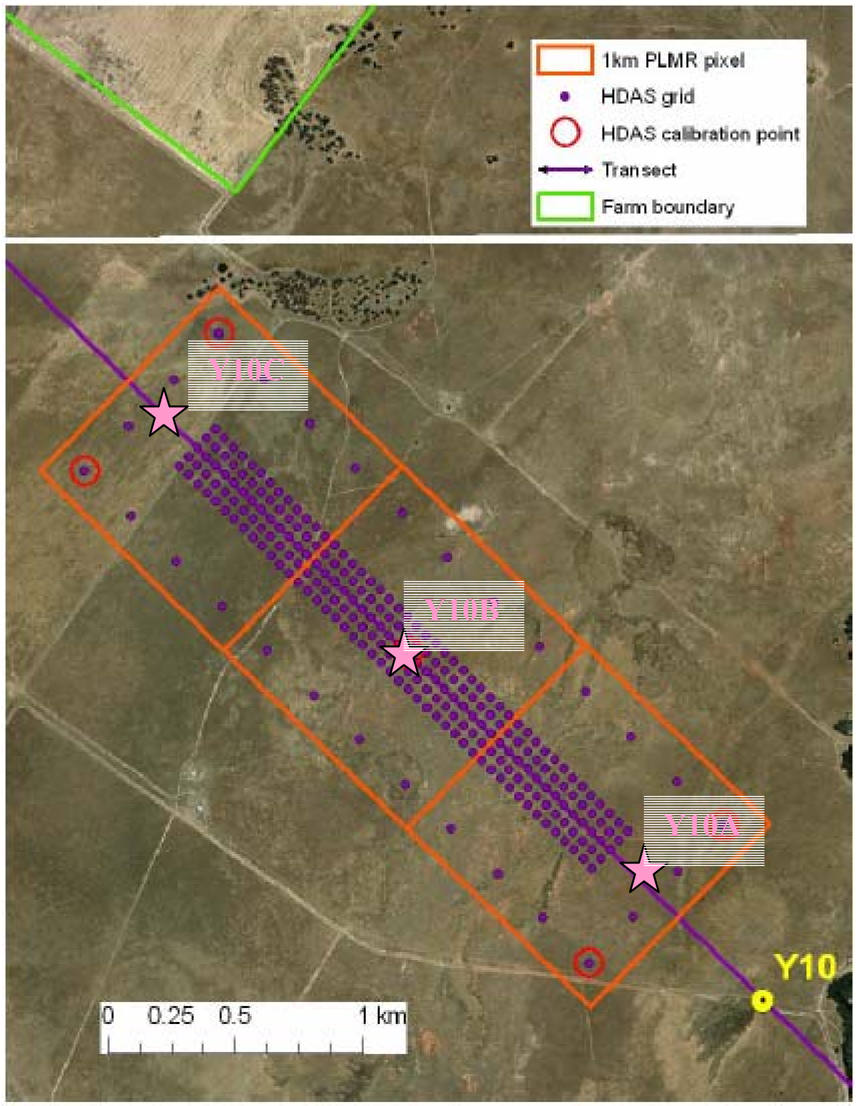
10.5 Y9

The Location of the sampling sites of farm Y9



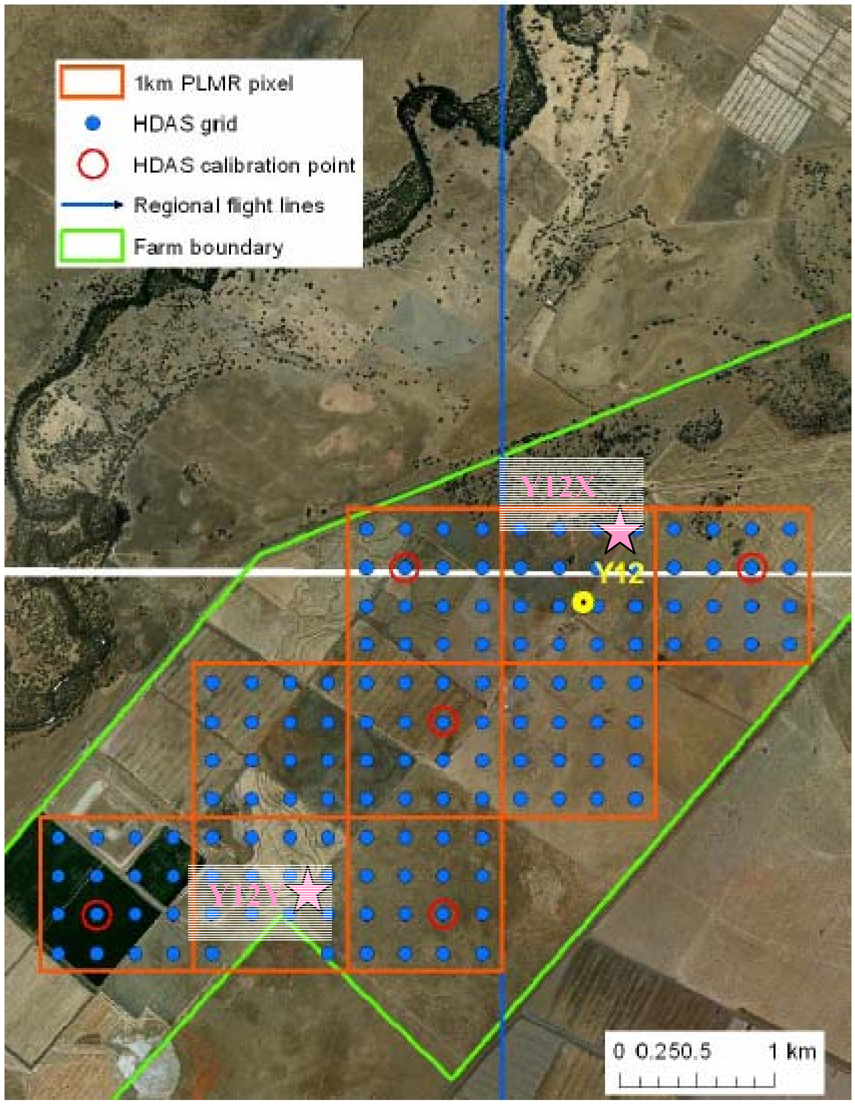
10.6 Y10

The Location of the sampling sites of farm Y10



10.7 Y12

The Location of the sampling sites of farm Y12



10.8 Bulk Densities for drying

Investigating the variation in resultant soil moisture content from the different possible dry weights…

SITE	vol of soil (cm3)	bulk density from field	lab measured Ms before saturating	calc Mw from lab measured Ms	approx calc Ms	approx calc Mw	Ms from being dried at 45C	Mw from being Ms at 45C	bulk density of pipe @45	SM from approx	SM from lab	SM from 45	% error in approx vs. lab	% error in approx vs. 45	% error in 45 vs. lab
y2b2	155.61	1.42972	199.14	70.81	222.47	47.477	182.52	87.43	1.17297	0.3051	0.5084	0.56187	20.33	25.68	5.35
Y2c2	156.02	1.34911	185.83	73	210.49	48.339	188.41	70.42	1.20759	0.3098	0.53	0.451346	22.02	14.15	7.86
Y7A2	153.94	1.52005	194.25	70.58	233.99	30.836	196.13	68.7	1.27408	0.2003	0.5523	0.446281	35.20	24.60	10.60
y7b2	178.73	1.50018	222.72	74.56	268.12	29.156	224.24	73.04	1.25465	0.1631	0.5022	0.408667	33.91	24.55	9.35
y10a	147.69	1.1742	153.35	79.89	173.42	59.822	156.29	76.95	1.05823	0.4051	0.6117	0.521024	20.67	11.60	9.07
y10b2	174.77	1.44622	184.22	90.24	252.76	21.705	190.92	83.54	1.09241	0.1242	0.7084	0.478	58.42	35.38	23.04
y12x	173.10	1.35739	185.61	83.01	234.97	33.652	184.66	83.96	1.06676	0.1944	0.6071	0.485028	41.27	29.06	12.20
y12y	151.86	1.066	152.55	93.87	161.88	84.541	160.36	86.06	1.056	0.5567	0.656	0.566721	9.92	1.00	8.92
Y1A	143.32	1.42807	189.86	61.65	204.66	46.846	187.36	64.15	1.30733	0.3269	0.4637	0.447614	13.68	12.07	1.61
y9a	157.48	0.98246	-		154.72	43.751	120.84	77.63	0.76733	0.2778		0.492951		21.51	
y9b	171.23	1.36252	217.26	75.21	233.3	59.168	208.28	84.19	1.21639	0.3456	0.3711	0.491682	6.88	14.61	12.06
y10b2	143.73	1.44622	-		207.87	21.532	150.56	80.28	1.04751	0.1498		0.55854			
y7b2	171.23	1.50018	-		256.87	3.696	196.03	66.08	1.14484	0.0216		0.385917			
y2b2	156.44	1.42972	-		223.66	45.386	199.6	70.97	1.2759	0.2901		0.45366			
y12y	164.77	1.066	-		175.65	58.454	147.49	88.1	0.89512	0.3548		0.534681			