

Y (2)

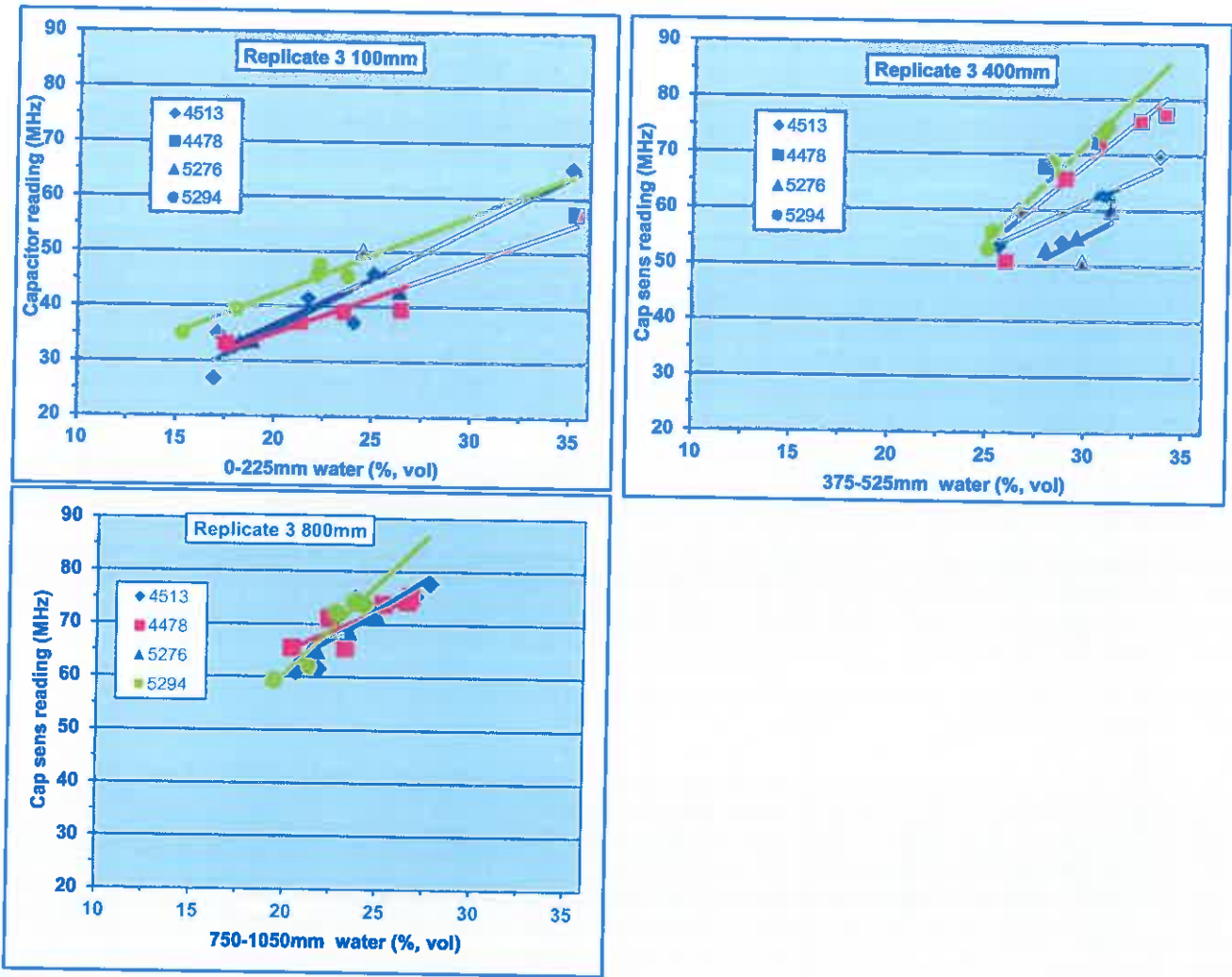


Figure 5.2-4: Selected calibration data for AquaCheck capacitance probes.

Table 5.2-8: Calibration equations for AquaCheck capacitance probe capacitors

Replicate/ Plot No.	Probe No.	Capacitor depth (mm)					
		100 mm	200 mm	300 mm	400 mm	600 mm	800 mm
1/4	2641	$y = 1.5685x + 18.412$ $R^2 = 0.9121$	$y = 0.684x + 41.079$ $R^2 = 0.7428$	$y = 1.4889x + 24.632$ $R^2 = 0.6357$	$y = 1.2013x + 33.48$ $R^2 = 0.6113$	$y = 0.6843x + 51.053$ $R^2 = 0.3395$	$y = 2.0702x + 23.583$ $R^2 = 0.9415$
1/7	2303	$y = 1.3728x + 21.231$ $R^2 = 0.9117$	$y = 0.7532x + 37.162$ $R^2 = 0.9825$	$y = 1.5665x + 27.715$ $R^2 = 0.9778$	$y = 2.052x + 16.584$ $R^2 = 0.8665$	$y = 3.8721x - 19.883$ $R^2 = 0.5924$	$y = 1.5801x + 32.668$ $R^2 = 0.5552$
1/16	4884	$y = 1.6305x + 17.234$ $R^2 = 0.486$	$y = 1.2523x + 30.835$ $R^2 = 0.5046$	$y = 1.7305x + 27.821$ $R^2 = 0.7037$	$y = 2.2859x + 13.974$ $R^2 = 0.7887$	$y = 2.5429x + 14.773$ $R^2 = 0.6644$	$y = 2.3407x + 11.762$ $R^2 = 0.3122$
1/19	2301	$y = 0.9367x + 21.999$ $R^2 = 0.9728$	$y = 0.9376x + 34.202$ $R^2 = 0.9957$	$y = 1.1203x + 33.356$ $R^2 = 0.9148$	$y = 1.9817x + 15.027$ $R^2 = 0.9538$	$y = 2.0423x + 17.651$ $R^2 = 0.8858$	$y = 0.785x + 49.645$ $R^2 = 0.8901$
2/29	5470	$y = 1.6974x + 9.6989$ $R^2 = 0.7735$	$y = 1.0829x + 30.141$ $R^2 = 0.4637$	$y = 1.0696x + 31.864$ $R^2 = 0.8002$	$y = 0.4776x + 46.13$ $R^2 = 0.1359$	$y = 2.0883x + 10.383$ $R^2 = 0.7887$	$y = 1.1471x + 36.628$ $R^2 = 0.8233$
2/34	5465	$y = 1.7134x + 13.941$ $R^2 = 0.6449$	$y = 1.1061x + 38.221$ $R^2 = 0.7273$	$y = 1.2644x + 34.39$ $R^2 = 0.498$	$y = 2.6867x - 7.9529$ $R^2 = 0.7506$	$y = 2.0002x + 11.724$ $R^2 = 0.8318$	$y = 3.0746x - 22.188$ $R^2 = 0.8121$
2/41	2370	$y = 1.0967x + 20.675$ $R^2 = 0.6738$	$y = 0.9686x + 33.558$ $R^2 = 0.4223$	$y = 0.7458x + 41.431$ $R^2 = 0.9657$	$y = 1.082x + 39.957$ $R^2 = 0.9506$	$y = 2.6856x - 4.5472$ $R^2 = 0.8092$	$y = 1.9628x + 17.889$ $R^2 = 0.8814$
2/46	2220	$y = 1.6082x + 15.525$ $R^2 = 0.2766$	$y = 1.5302x + 27.724$ $R^2 = 0.4906$	$y = 0.9377x + 30.179$ $R^2 = 0.0076$	$y = 1.6321x + 23.239$ $R^2 = 0.6136$	$y = 2.1514x + 12.639$ $R^2 = 0.987$	$y = 4.5027x - 55.697$ $R^2 = 0.9903$
3/49	4513	$y = 1.868x - 1.5713$ $R^2 = 0.9064$	$y = 1.0519x + 18.501$ $R^2 = 0.9743$	$y = 0.91x + 33.063$ $R^2 = 0.841$	$y = 1.6563x + 11.559$ $R^2 = 0.7115$	$y = 1.918x + 10.425$ $R^2 = 0.7841$	$y = 2.2367x + 16.873$ $R^2 = 0.749$
3/56	5276	$y = 1.6784x + 3.1637$ $R^2 = 0.7106$	$y = 1.8832x + 10.588$ $R^2 = 0.7045$	$y = -0.2371x + 63.698$ $R^2 = 0.0006$	$y = 1.9415x - 2.973$ $R^2 = 0.451$	$y = 0.2141x + 62.132$ $R^2 = 0.0194$	$y = 1.997x + 22.106$ $R^2 = 0.9827$
3/61	4478	$y = 1.3087x + 8.9288$ $R^2 = 0.9415$	$y = 1.145x + 28.047$ $R^2 = 0.7877$	$y = 1.3388x + 34.622$ $R^2 = 0.794$	$y = 2.9499x - 20.282$ $R^2 = 0.8346$	$y = 1.3382x + 30.474$ $R^2 = 0.8134$	$y = 1.5094x + 34.571$ $R^2 = 0.7269$
3/68	5294	$y = 1.4391x + 13.507$ $R^2 = 0.921$	$y = 1.5538x + 27.1$ $R^2 = 0.8921$	$y = 1.7719x + 20.739$ $R^2 = 0.8705$	$y = 3.4546x - 31.726$ $R^2 = 0.9669$	$y = 2.7694x - 14.508$ $R^2 = 0.9542$	$y = 3.4218x - 8.0542$ $R^2 = 0.9086$

Table 5.2-9: Statistical data for AquaCheck capacitance probe capacitor calibration

Replicate/Plot/ Depth (mm)	Probe No.	Calibration Equation ($Y = a + bX$) ¹	Valid X range	Degrees of freedom (n-2)	t test for regress coeff (b)	Variance explained (R ² , %)	Correlation coeff (r)
1/4/100	2641	$Y = 18.41223 + 1.56847X$	12.65 ≤ X ≤ 29.21	4	9.23***	91	0.9550**
1/7/100	2303	$Y = 21.23078 + 1.37284X$	11.63 ≤ X ≤ 30.03	2	7.36*	91	0.9548**
1/16/100	4884	$Y = 17.23383 + 1.63045X$	11.71 ≤ X ≤ 29.81	4	2.41NS	49	0.6971NS
1/19/100	2301	$Y = 121.99850 + 0.93666X$	11.71 ≤ X ≤ 30.39	2	12.60**	97	0.9863**
2/29/100	5470	$Y = 9.69889 + 1.69739X$	12.88 ≤ X ≤ 29.23	4	4.71**	77	0.8795**
2/34/100	5465	$Y = 14.25759 + 1.72549X$	13.48 ≤ X ≤ 30.23	4	3.32*	64	0.7994NS
2/41/100	2370	$Y = 20.67547 + 1.09671X$	11.71 ≤ X ≤ 28.75	2	3.00NS	67	0.8209NS
2/46/100	2220	$Y = 15.52485 + 1.60824X$	13.60 ≤ X ≤ 22.81	2	1.25NS	28	0.5259NS
3/49/100	4513	$Y = -1.57132 + 1.86799X$	16.93 ≤ X ≤ 35.11	4	8.26**	91	0.9520**
3/56/100	5276	$Y = 3.16366 + 1.67836X$	18.20 ≤ X ≤ 26.35	2	3.38NS	71	0.8430NS
3/61/100	4478	$Y = 8.92885 + 1.30868X$	17.46 ≤ X ≤ 35.28	4	14.00***	94	0.9703**
3/68/100	5294	$Y = 13.50686 + 1.43906X$	15.31 ≤ X ≤ 23.70	3	19.85***	92	0.9600**

¹Y = Capacitor reading (MHz); X = Volumetric soil water content; NS: Statistically not significant; * (p<0.05); ** (p<0.01); *** (p<0.001)

Routine measurement of SWC

Neutron water meter

2008/09: Temporal SWC (means of 3 replicates) for the various soil layers for treatment RTxF1xC1 (RT_F1C1) is shown as a function of rainfall events in Fig. 5.2-5. Unfortunately no NWM readings were taken during the period 23 December 2008 to 28 January 2009 to show SWC response to rainfall. Very uncharacteristically, SWC (even at the shallow depths) showed very little response to rainfall events. Only at 150 mm (0.15 m) depth during the period 28 January to 18 February 2009 was there some increase in SWC due to rainfall. Noticeable, however, is the gradual increase in SWC over time in the 900 mm (0.9 m) and 1200 mm (1.2 m) layers.

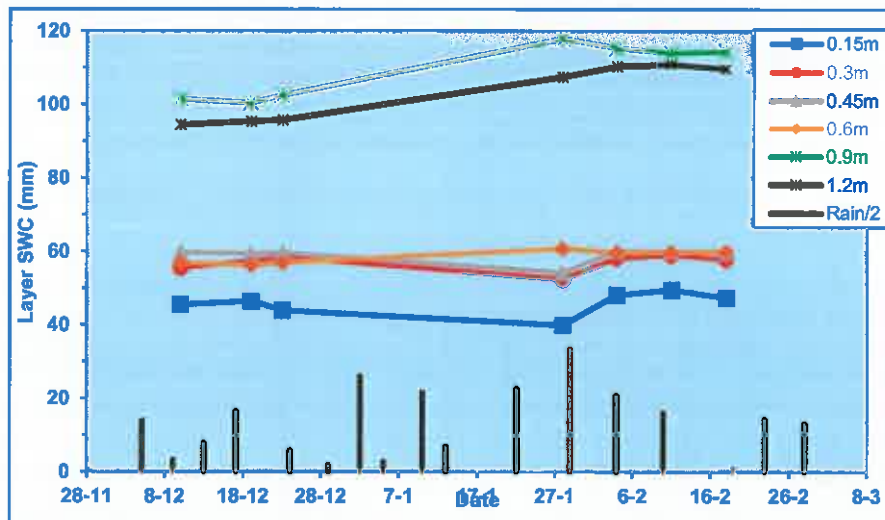


Figure 5.2-5: Temporal SWC with depth as a function of rainfall for RTxF1xC1.

Temporal SWC is shown in Fig. 5.2-6 for the 0-900 mm (0-0.9 m) soil profile as a function of various tillage, fertilizer and cropping treatments (*viz.* RT_F1C1, RT_F2C3, RT_F2C4, CT_F1C1, CT_F2C3 and CT_F2C4; means of 2 or 3 replicates). The RT treatments, especially RT_F1C1 and RT_F2C4, had higher SWC for the 0-0.9 m soil profile than the comparable CT treatments. Noticeable is the combined effect of fertilizer and cropping for a specific tillage treatment on SWC. For example, for RT the F1C1 combination (low fertilizer input and maize monocropping) resulted in much higher SWC than, say, F2C4. The latter treatment combination has a high fertilizer input and a higher cropping index (maize/legume intercropping). It would be expected that the higher fertilizer input would result in enhanced growth and, hence, higher water uptake and consequent lower SWC. On the other hand the intercrop system would also result in higher soil water extraction to give lower SWC. For all treatments, soil water content increased sharply

due to the rainfall events from 29 January 2009 onwards. No effect on SWC (i.e. decrease) due to crop water uptake is discernable from the SWC data. In Fig. 5.2-7 a comparison is made between RT and CT for the same fertilizer and cropping treatments for the 0-300 mm (0-0.3 m) soil profile. Much higher SWC was recorded for the former compared to the latter tillage treatment.

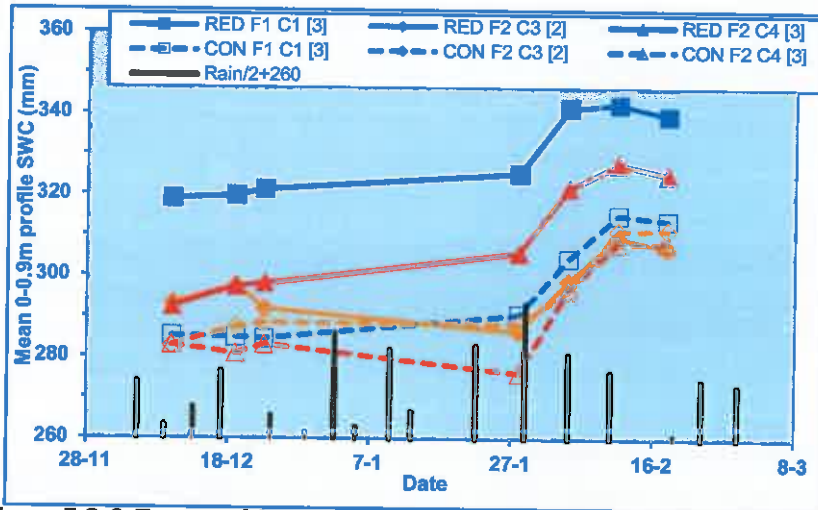


Figure 5.2-6: Temporal SWC as a function of rainfall for various treatments.

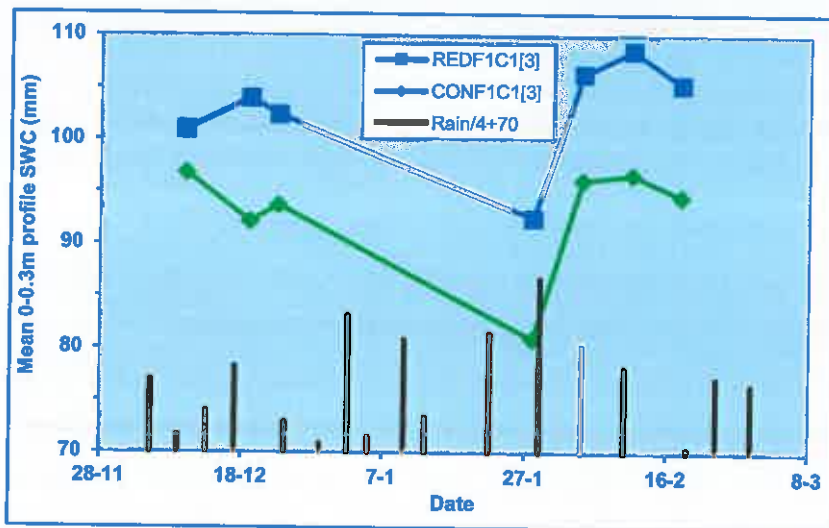


Figure 5.2-7: Temporal SWC as a function of rainfall for RT and CT.

Temporal SWC is plotted with depth for treatments RT_F1C1 (left) and CT_F1C1 (right) in Fig. 5.2-8. Noticeable for both tillage treatments is the increase in SWC in the deeper layers (i.e. 0.9 and 1.2 m) after 28 January 2009, probably due to a number of rainfall events since 22 January 2009 (see, for example, Fig. 5.2-5). In total 185 mm rain (data not presented) was recorded during this period. Also noticeable in both figures is the steep increase in SWC below 600 mm

(0.6 m) depth. This phenomenon could be due to an increase in clay content with depth (and consequent increase in water-holding capacity), as well as an absence of crop roots to extract water.

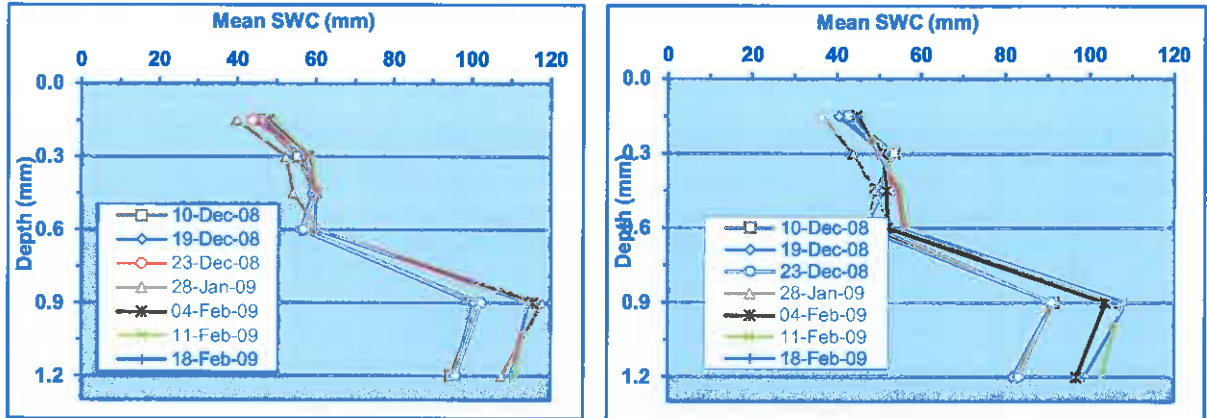


Figure 5.2-8: Temporal SWC with depth for RT_F1C1 (left) and CT_F1C1 (right).

2009/10: Fig. 5.2-9 shows means (of three replicates) of SWC for the 0-300 mm layer for RT_F1C1 vs. CT_F1C1 (left) and RT_F2C3 vs. CT_F2C3 (right) for 29 December 2009-10 February 2010. Noticeable is the higher soil water contents for the two cropping systems (F1C1 and F2C3) in the 0-300 mm layer under RT compared to CT tillage.

Temporal SWC is shown in Fig. 5.2-10 for the 0-0.9 m soil profile as a function of various tillage, fertilizer and cropping treatments (*viz.* RT_F1C1, RT_F2C3, RT_F2C4, CT_F1C1, CT_F2C3 and CT_F2C4; means of 2 or 3 replicates). The following observations are made:

- The RT treatments at all three fertilizer and cropping treatments (F1C1, F2C3, F2C4) had higher SWC for the 0-0.9 m soil profile than the comparable CT treatments.
- The combined fertilizer and cropping treatments also had an effect on SWC at both tillage treatments. For example, the F2C4 combination (high fertilizer input and intercropping of maize) resulted in lower SWC because of the expected enhanced growth and, hence, higher water uptake and consequent lower SWC.

Temporal SWC is plotted with depth for treatments RT_F1C1 (left) and CT_F1C1 (right) in Fig. 5.2-11. Noticeable for both tillage treatments is the increase in SWC in the deeper layers (i.e. 0.9 and 1.2 m). This phenomenon could be due to an increase in clay content (0-750 mm: 46%; >750 mm: 58%; data not included) with depth (and consequent increase in water-holding capacity), as well as an absence of crop roots to extract water.

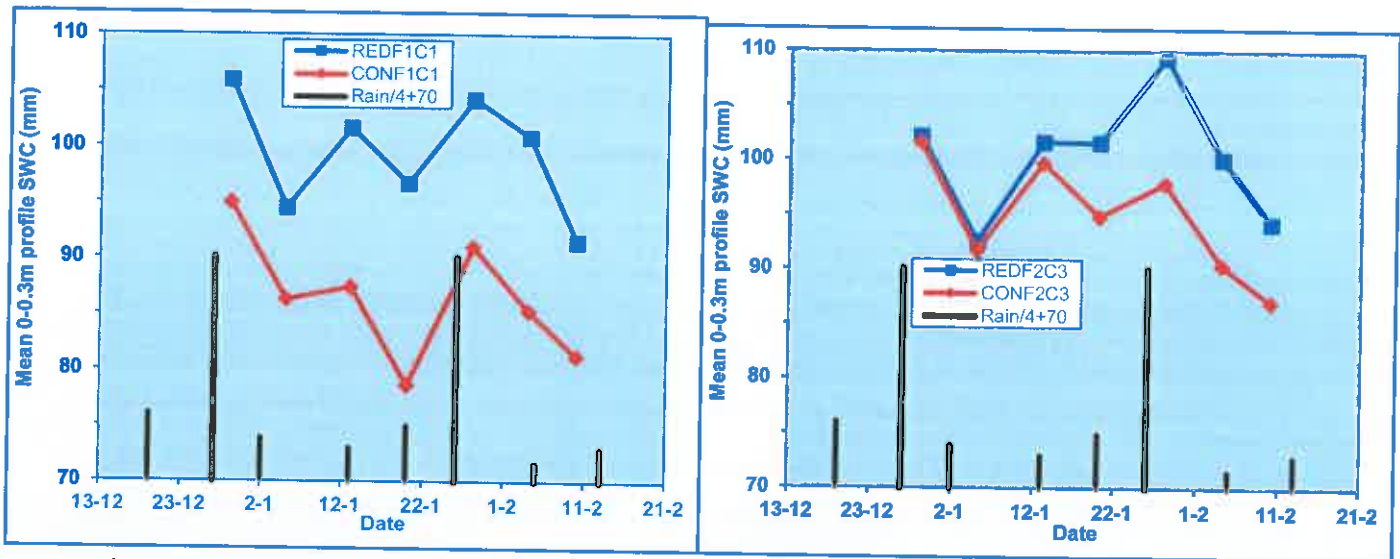


Figure 5.2-9: Temporal SWC in the 0-300 mm soil layer as a function of rainfall for RT and CT.

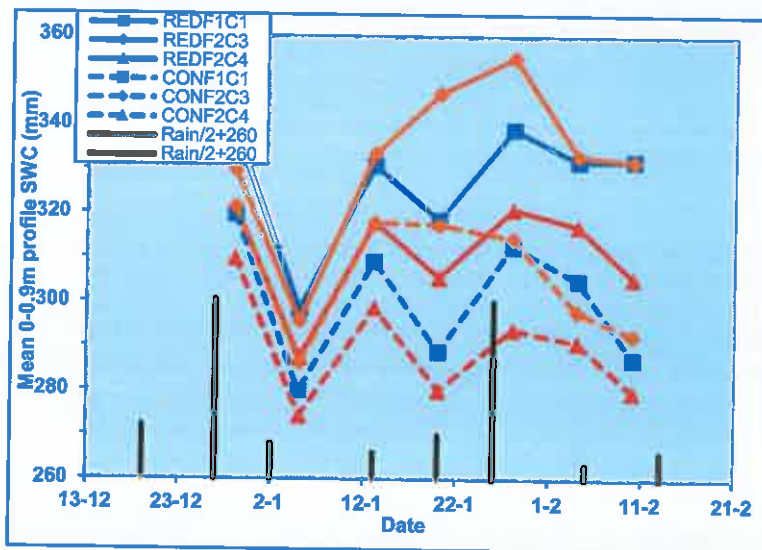


Figure 5.2-10: Temporal SWC as a function of rainfall, tillage and cropping systems.

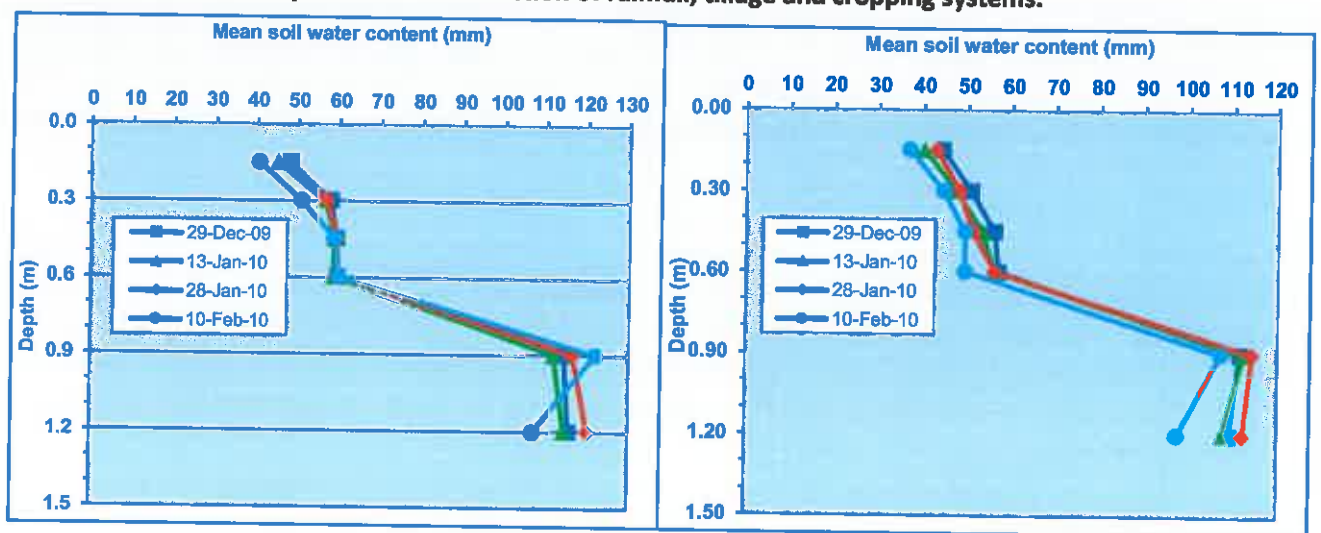


Figure 5.2-11: Temporal SWC with depth for RT_F1C1 (left) and CT_F1C1 (right).

2010/11: As an example, the effects of tillage on soil water content are shown in Fig. 5.2-12 ((Plot 1 (RT) and Plot 13 (CT); monocropped maize (F2C1)) for the 0-150 mm soil layer for the NWM measurements of 8 February-23 March 2011 (70-113 days after planting (DAP)). Excluding the data of 70 DAP, mean water storage in the 0-150 mm layer was 6.9 mm higher under RT than under CT. The effects of tillage on profile water content are depicted in Figure 14 for 8 February (70 DAP) and 9 March 2011 (99 DAP). The plotted values are the means of the three replicates with their standard error (SEM) values indicated (SEMs calculated according to Snedecor & Cochran, 1967). At both dates RT contributed to higher profile water storage than CT. The low SEMs indicate that the induced differences in profile water storage can be regarded as statistically significant.

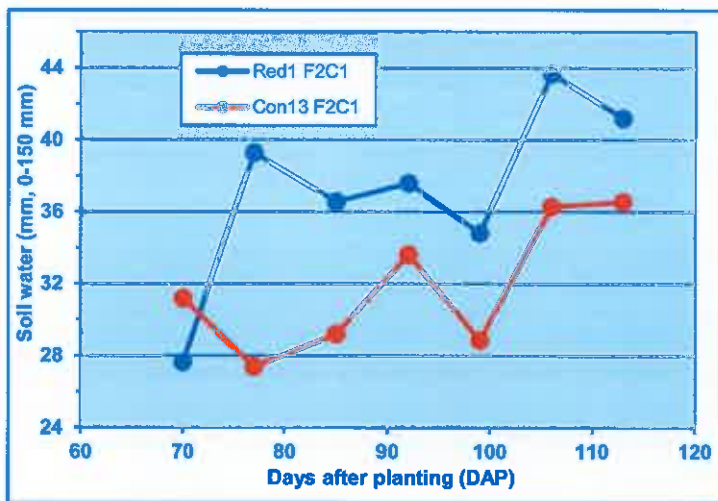


Figure 5.2-12: Tillage effects on temporal soil water contents.

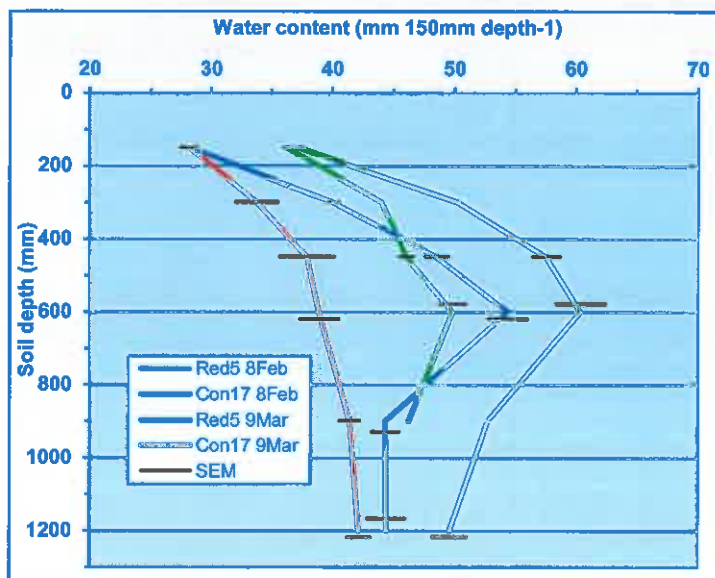


Figure 5.2-13: Tillage effects on profile soil water storage.

2011/12: As an example, the effects of tillage on soil water content as calculated from NWM measurements are shown in Fig. 5.2-14 for two depth increments, viz. 0-225 and 525-750 mm. For both depth increments, RT resulted in higher soil water contents over time compared to CT. Of significance is the fact that the beneficial effects of CA (residue retention, minimum tillage) on soil water content were evident to 750 mm depth. The effects of tillage and crop systems on profile water content are depicted in Fig. 5.2-15 for 23 February 2012. The figures show that profile water content is lower under CT than under RT, while water contents are lower under a high fertilizer x maize/legume intercrop system (F2C4) than under a low fertilizer x maize monocropping system (F1C1) because of a higher water uptake by two crops compared to a single maize stand.

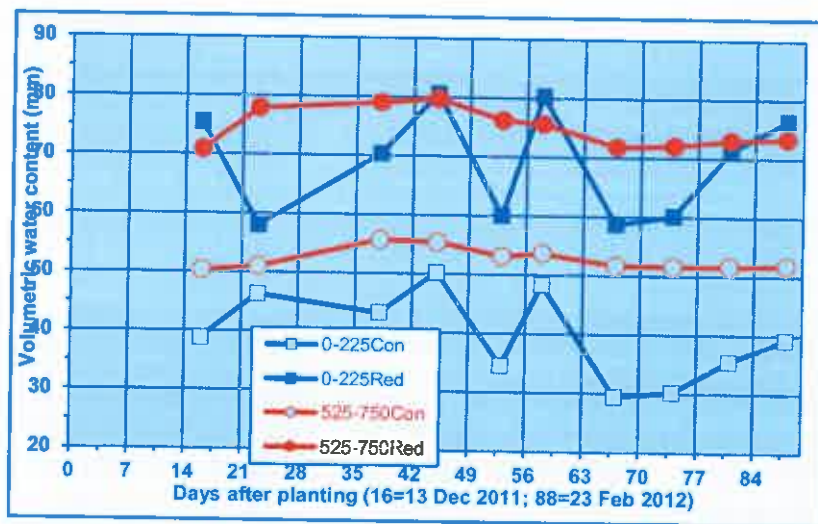


Figure 5.2-14: Tillage effects on NWM soil water contents.

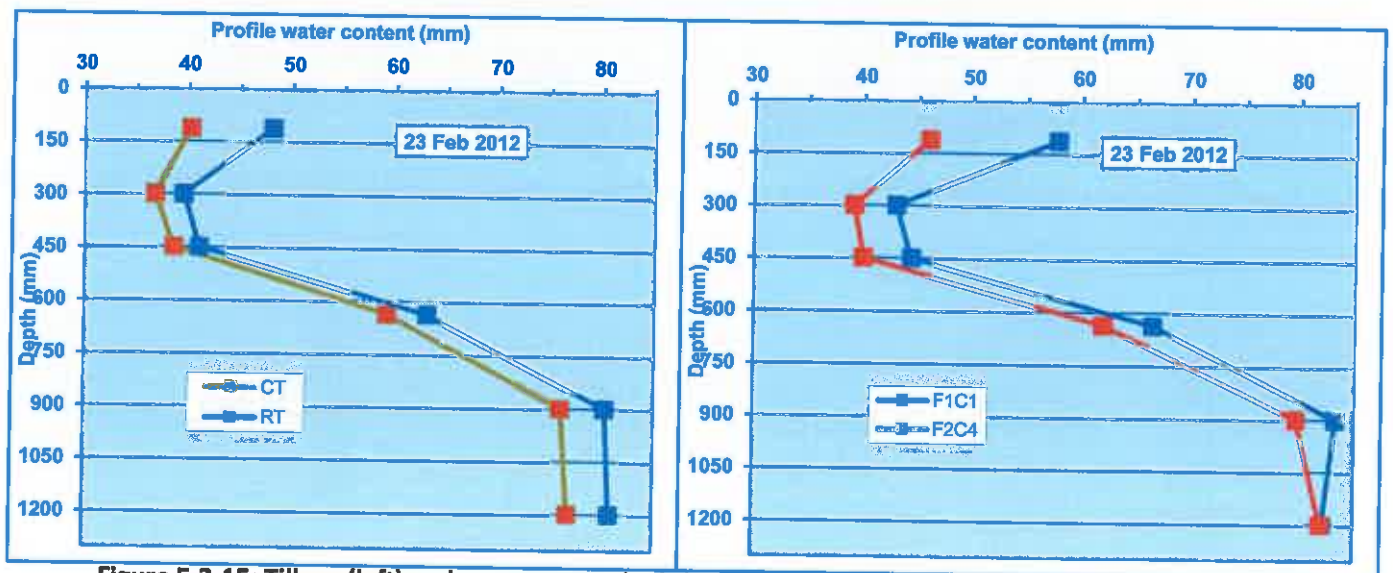


Figure 5.2-15: Tillage (left) and crop systems (right) effects on profile water contents.

2012/13: As an example, the effects of tillage on soil water content as calculated from NWM measurements are shown in Fig. 5.2-16 for Plots 49 (CT) and 61 (RT) for two depth increments, viz. 0-225 and 525-750 mm. For both depth increments, up till about 77 days after planting (DAP) no clear differences in soil water contents between RT and CT could be observed. After 77 DAP RT had higher soil water contents (solid symbols in figure) compared to CT at both depth increments. It is not clear why the beneficial effects of CA (residue retention, minimum tillage) on soil water content only manifested themselves later during the growing season. The effects of tillage and crop systems on profile water content are depicted in Fig. 5.2-17a and b, respectively, for 23 January and 6 March 2013. Unlike previous seasons (e.g. Swanepoel *et al.* 2012), no clear differences between tillage systems (Fig. 5.2-17a) could be observed. It would appear as if soil water contents were lower under a high fertilizer x maize/legume intercrop system (F2C4) compared to a low fertilizer x maize monocropping system (F1C1) (Fig. 5.2-17b) because of a higher water uptake by two crops compared to a single maize stand.

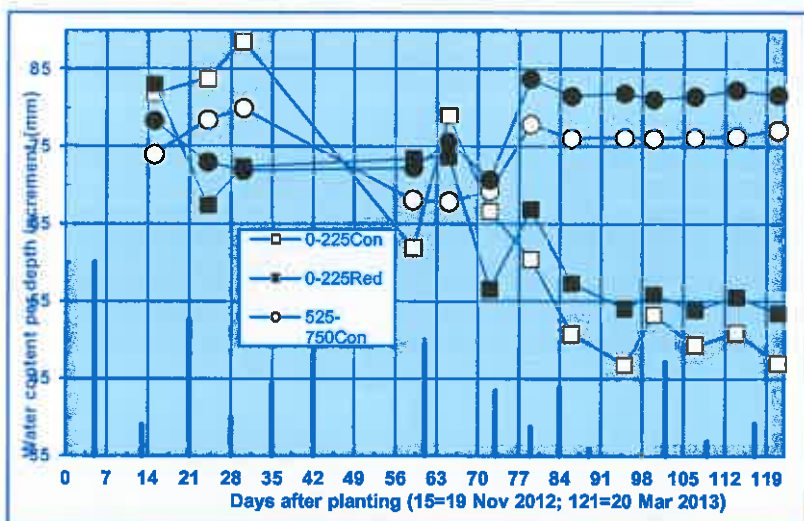


Figure 5.2-16: Tillage effects on NWM soil water contents.

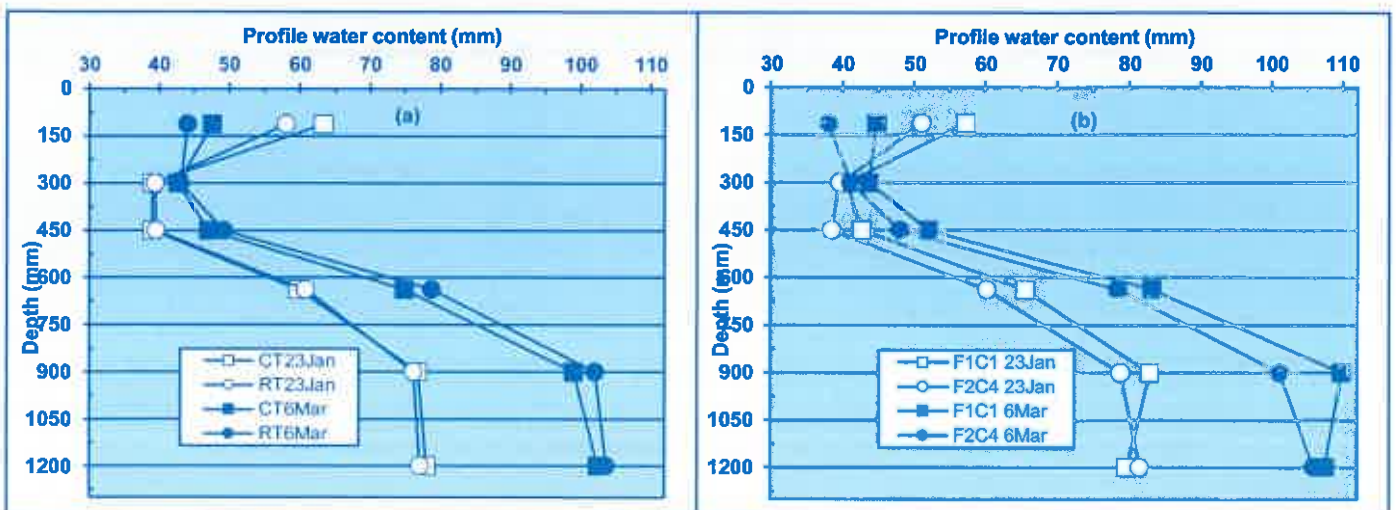


Figure 5.2-17: Tillage (a) and crop systems (b) effects on profile soil water contents.

Capacitance probes

2009/10: As the calibration of the capacitors for SWC was still incomplete at this point in time, capacitor readings on Plot 29 (Probe 5470) for the period 8 December 2009 to 2 February 2010 at 100, 400 and 800 mm depths are presented in Fig. 5.2-18 to show the performance of the capacitors as a function of soil water changes due to rainfall. The capacitor at 100 mm depth showed immediate response to rainfall events, followed by lesser response by the capacitor at 400 mm depth, while the capacitor at 800 mm depth responded only to large rainfall events.

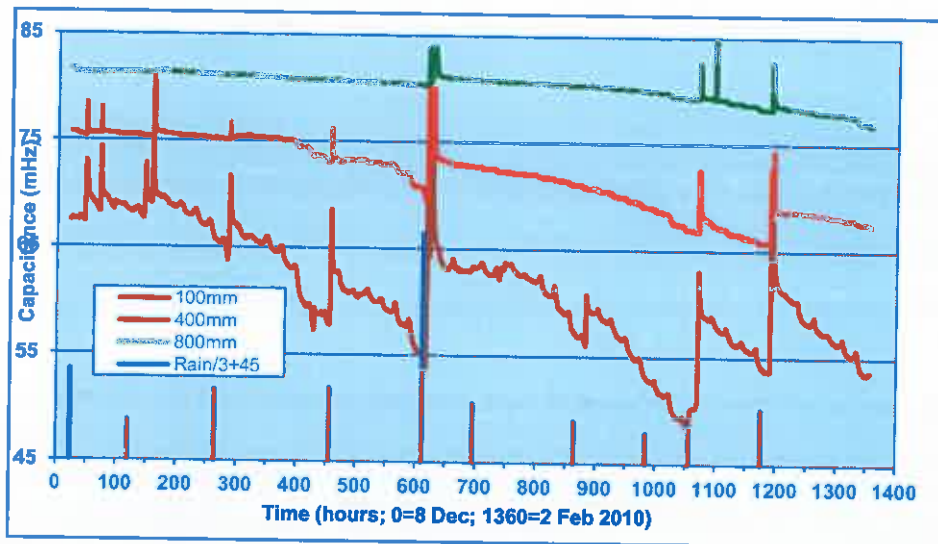


Figure 5.2-18: Capacitor response to rainfall events.

2010/11: As the calibration of the capacitors for SWC was still incomplete at this point in time, capacitor readings on Plot 49 (Probe 4513) for the period 06h00 25 January 2011 to 12h00 15 February 2011 at 100, 400 and 800 mm depths are presented in Fig. 5.2-19. The following observations can be made:

- The rainfall event (52 mm) at 29.5 hrs resulted in capacitor responses down to 800 mm depth, although only a minor response was noted at the latter depth.
- The rainfall event (17 mm) at 205 hrs resulted in capacitor responses only at 100 and 400 mm depths.
- In the absence of any rain after 205 hrs, capacitor readings show a gradual decrease, indicating a drying-out of the soil, particularly at 100 mm depth.

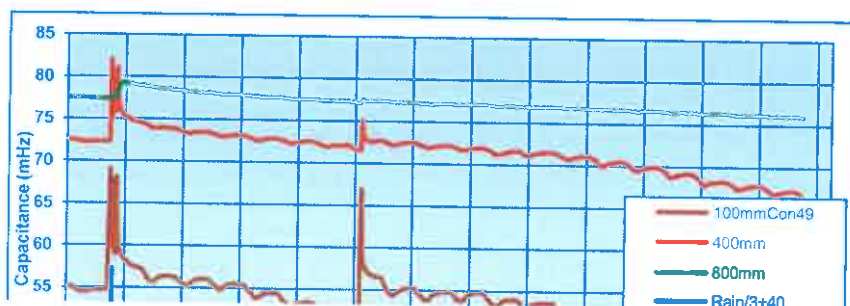


Figure 5.2-19: Capacitor response to rainfall events and drying out of soil.

2011/12: As an example, SWC calculated from capacitor calibration equations are shown in Figs. 5.2-20 and 21 for Plot 16 (Probe 4484, Treatment F1C3) and for Plot 61 (Probe 4478, Treatment F1C1) for the period 00h00 1 January 2012 to 11h00 24 January 2012 at 100, 400 and 600 mm (Plot 16) and 100, 400 and 800 mm (Plot 61) depths, respectively. The following observations can be made when comparing the two plots:

- The capacitors at 100 mm depth showed clear responses to rainfall events. The rainfall event (52 mm) at 29.5 hrs resulted in capacitor responses down to 800 mm depth, although only a minor response was noted at the latter depth.
- On Plot 16 the capacitor at 200 mm depth showed no response to rainfall events but rather displayed a drying out of the soil over time, while in contrast the capacitor on Plot 61 showed clear responses to rainfall events.
- Almost no changes in soil water content were displayed at either 600 or 800 mm depths.

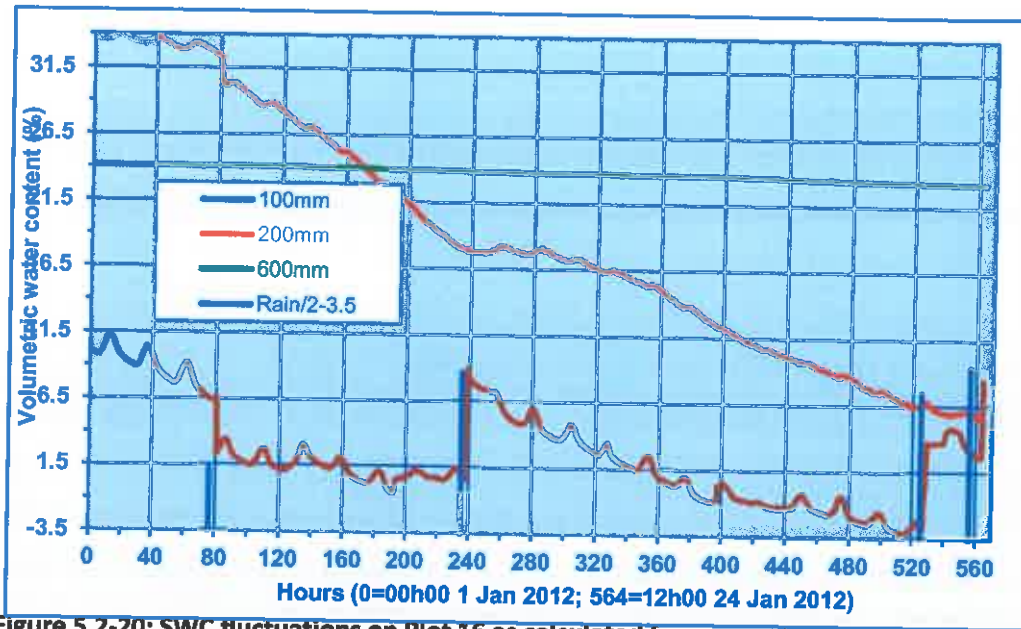


Figure 5.2-20: SWC fluctuations on Plot 16 as calculated from capacitor calibration data.

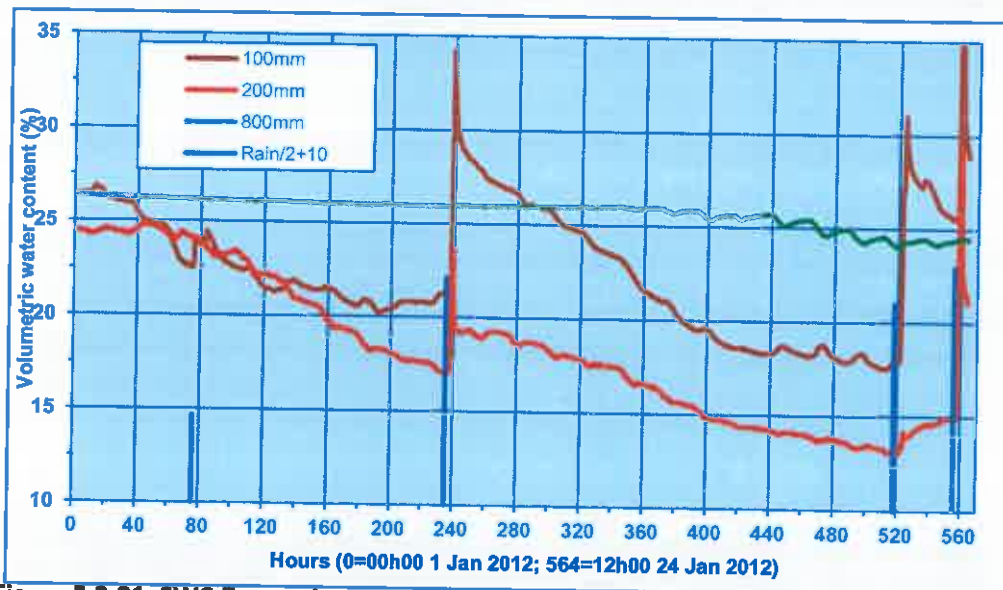


Figure 5.2-21: SWC fluctuations on Plot 61 as calculated from capacitor calibration data.

2012/13: In Figs. 5.2-22, 23, 24 and 25, SWC measured at 100, 200 and 800 mm depths with the capacitors are plotted for the period 00h00 12 January 2013 to 24h00 13 February 2013 for Plots 16 (CT), 49 (CT), 29 (RT) and 61 (RT), respectively. Due to very low rainfall during January 2013, irrigation was applied to the entire experiment. Plot 16 was irrigated on 11 January (30 mm), and plots 29, 49 and 61 were irrigated on 12 January (10 mm) and again on 15 January (30 mm).

In Figs. 5.2-21, 22, 23 and 24 rainfall and irrigation are depicted as vertical blue bars and expressed as numerical values ($\text{rain}/5 + 10$) of the Y-axis. For example, in Fig. 5.2-21 at time =178 hrs; rainfall = 19.04. To derive the real rainfall: $(19.04 - 10) \times 5 = 45.2$ mm.

The following observations can be made:

- Plot 16 (CT) (Fig. 5.2-22): The capacitors at both 10 and 20 mm depths showed responses to precipitations of 30, 45, 10 and 27 mm at 10, 178, 210 and 620 hrs, respectively. It is unclear why these capacitors showed no response to precipitations at 421 and 493 hrs, respectively. Notable is: (1) the much higher soil water content shown, as well as (2) no response to any precipitation, by the capacitor at 800 mm depth.
- Plot 49 (CT) (Fig. 5.2-23): The capacitors at both 10 and 20 mm depths only showed responses to precipitations of 45 and 27 mm at 188 and 600 hrs, respectively. The lack of capacitor response to other precipitations is not clear. Notable is the lower soil water content shown, as well as no response to any precipitation, by the capacitor at 800 mm.
- Plot 29 (RT) (Fig. 5.2-24): The capacitors at both 10 and 20 mm depths showed responses to precipitations of 30, 45, 25 and 27 mm at 66, 188, 405 and 600 hrs, respectively. Surprisingly (and unexpectedly), the capacitor at 800 mm depth showed a response to precipitation at 66, 188 and 600 hrs, respectively. Notable is the much higher soil water content shown by the capacitor at 800 mm depth, compared to the soil water contents at 100 and 200 mm depths, respectively.
- Plot 61 (RT) (Fig. 5.2-25): The capacitors at both 10 and 20 mm depths showed responses to precipitations of 10, 30, 45, 25 and 27 mm at 11, 83, 188, 405 and 600 hrs, respectively. Notable is the lack of response to any precipitation, by the capacitor at 800 mm depth.

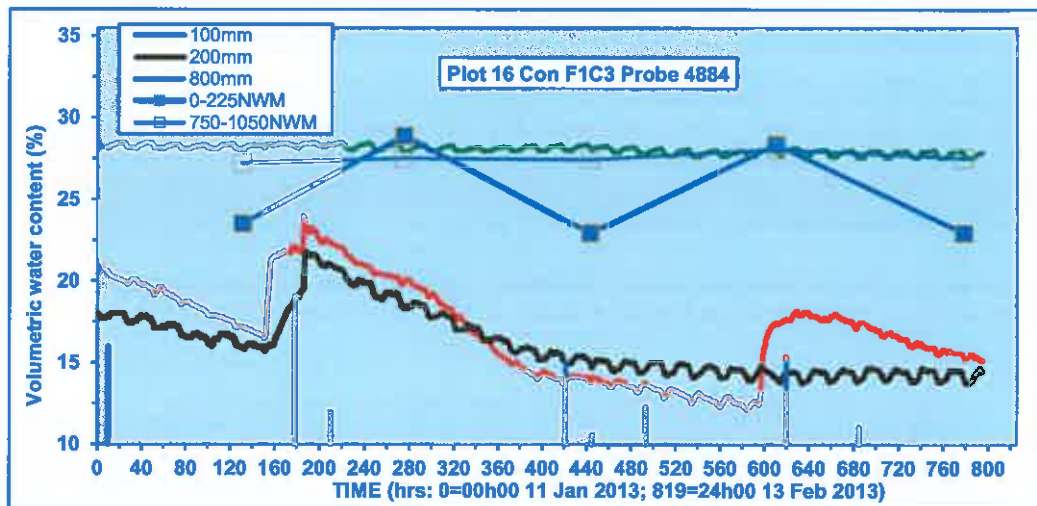


Figure 5.2-22: SWC fluctuations on Plot 16 as calculated from capacitor and NWM readings.

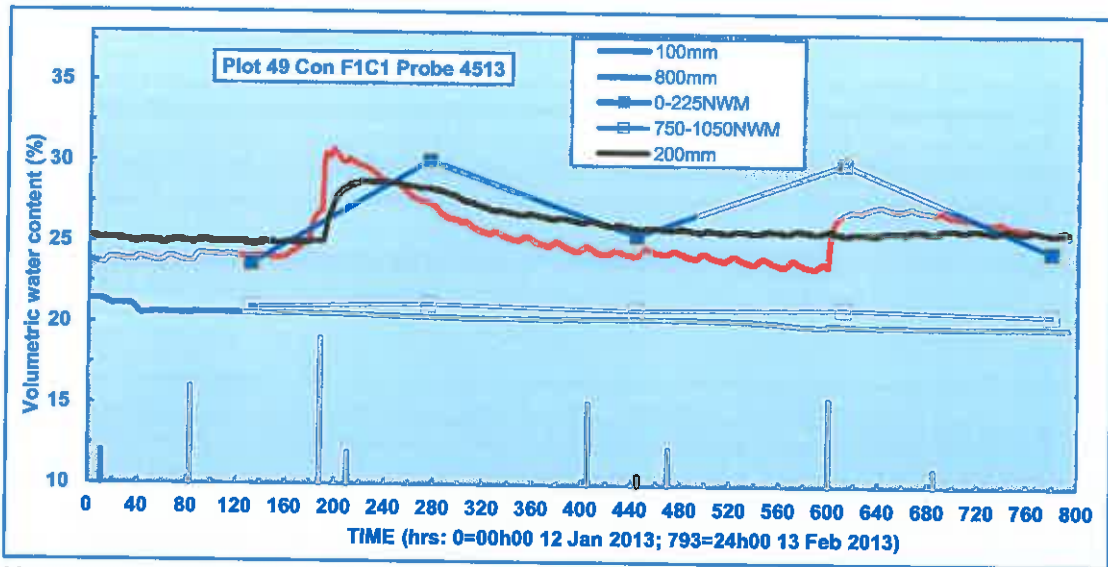


Figure 5.2-23: SWC fluctuations on Plot 49 as calculated from capacitor and NWM readings.

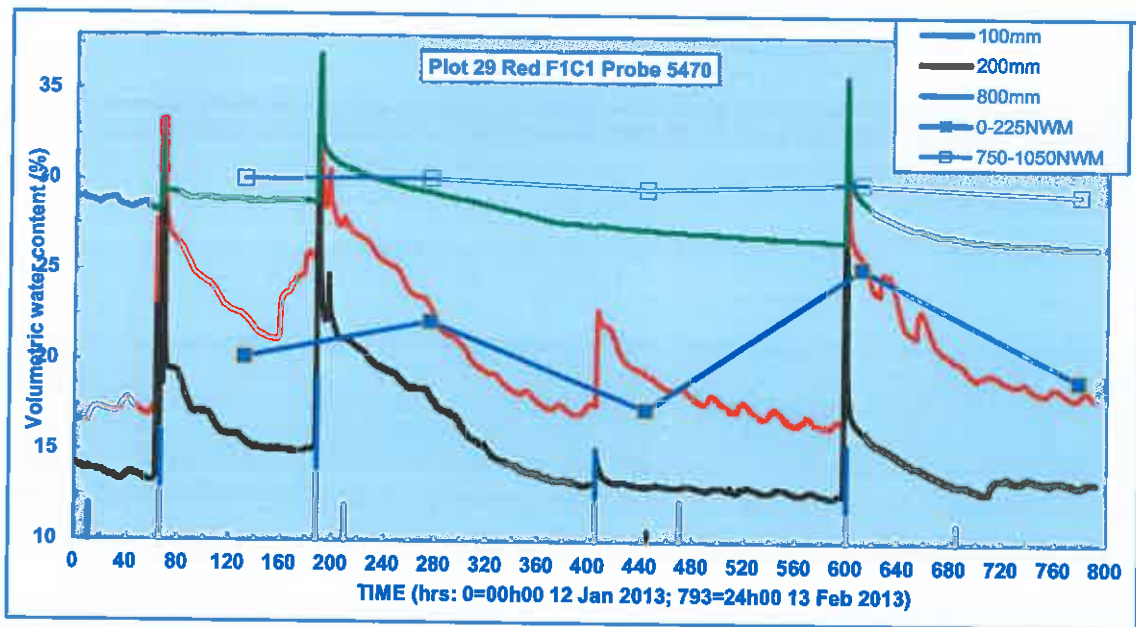


Figure 5.2-24: SWC fluctuations on Plot 29 as calculated from capacitor and NWM readings.

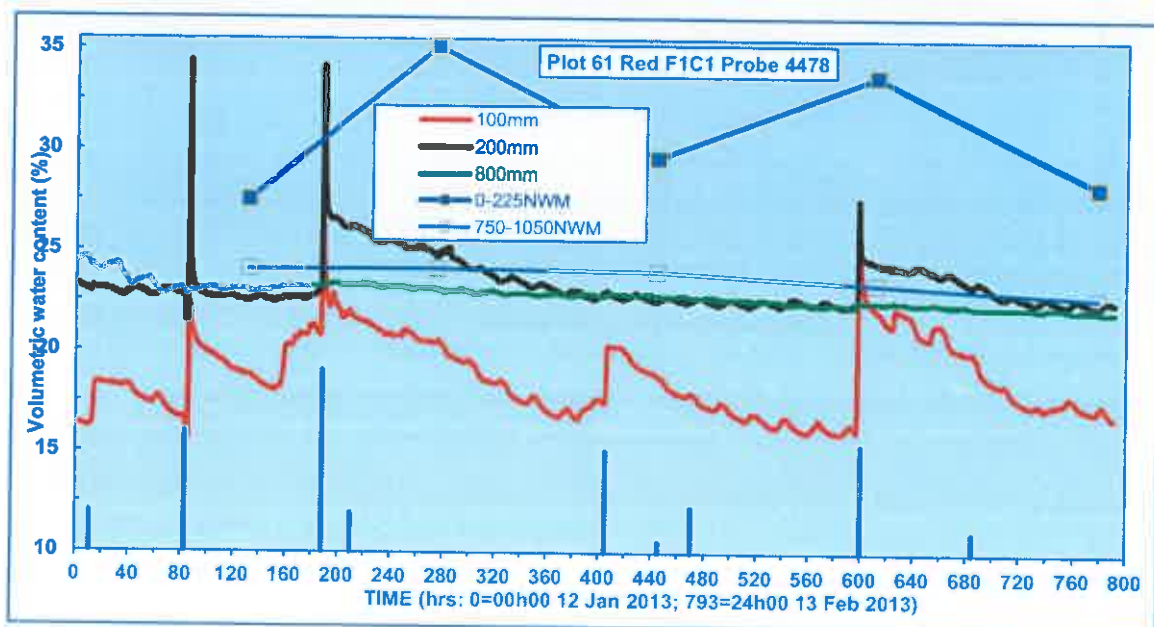


Figure 5.2-25: SWC on Plot 61 as calculated from capacitor and NWM readings.

Comparison of capacitance probe and NWM soil water outputs:

2011/12: A preliminary comparison of capacitance probe and NWM calculated soil water values is given in Fig. 5.2-26 for Plot 61 (Probe 4478). The capacitor soil water contents at 100, 200 and 800 mm can be compared with NWM values at 0-225, 225-375 and 750-1050 mm depths, respectively. Apart from a good agreement at 800/750-1050 mm, there is almost no agreement at the shallower depths. Notable, however, is the similarity in values after rainfall events, i.e. at 240 and 560 hrs.

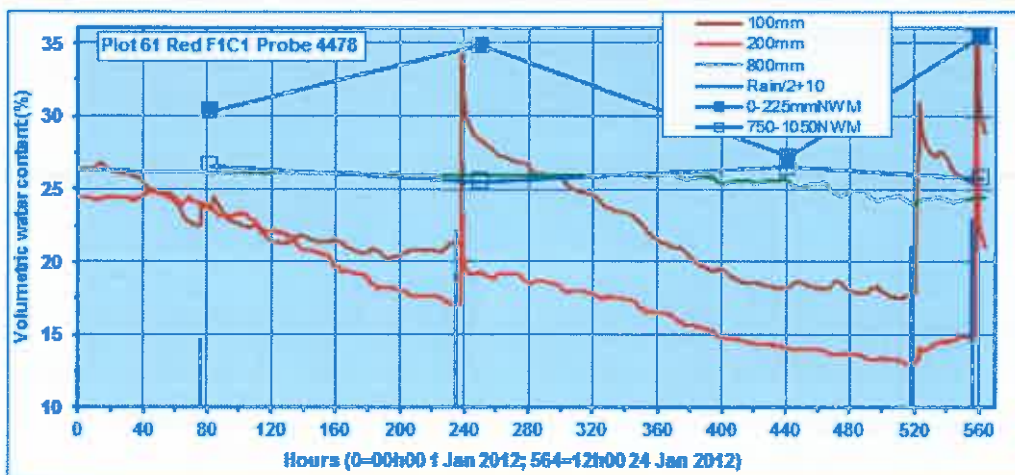


Figure 5.2-26: Comparison of capacitance capacitor and NWM soil water contents.

2012/13: A comparison of capacitance probe vs. NWM soil water values is given in Figs. 5.2-22, 23, 24 and 25 for the period 00h00 12 January 2013 to 24h00 13 February 2013 for Plots 16 (CT), 49 (CT), 29 (RT) and 61 (RT), respectively. The capacitor soil water contents at 100, 200 and 800 mm can be compared with the NWM water contents measured at five dates (plotted as open and solid symbol lines) for the 0-225 mm and 750-1050 mm depth intervals, respectively. The following observations can be made:

- Plot 16 (CT): Large differences in temporal soil water contents are observed when comparing capacitor soil water values at 100 and 200 mm depth with NWM values of the 0-225 mm depth increment. Very similar soil water content values were obtained for the two instrument types at 800 mm and 750-1050 mm depth increments, respectively.
- Plot 49 (CT): Very similar soil water contents were calculated at all the depths of measurement when comparing the two types of instruments.
- Plot 29 (RT): Capacitor soil water values at 100 mm depth compared well with NWM values of the 0-225 mm depth increment (a mean of 20.7% soil water can be calculated for both instrument types over the time period of 131-792 hrs). Apart from unexplainable peaks in the capacitor soil water values at 800 mm depth, similar values were obtained for both types of instruments (mean values of 28.1% and 29.8% can be calculated for capacitor and NWM data over the time period of 131-792 hrs).
- Plot 61 (RT): Large differences in temporal soil water contents are observed when comparing capacitor soil water values at 100 and 200 mm depths with NWM values of the 0-225 mm depth increment. Very similar soil water content values were obtained for the two instrument types at 800 mm and 750-1050 mm depth increments, respectively.

Conclusions and Recommendations

Field calibration of NWMs:

- All the statistical parameters, i.e. the t-test values for the regression coefficients, R^2 values, and correlation coefficients (r) tested significant to highly significant, indicating that the NWMs were successfully calibrated.
- For all replicates (blocks) the best calibration results were obtained for the 0-225 and 225-375 mm depth increments. The poorer calibration results for the deeper soil layers were probably caused by others factors such as the presence of Fe and Mn concretions. Comparing replicates, the poorest calibration results were obtained for replicate 1, probably for the same reasons.

Field calibration of capacitance probes:

- In general the results of the statistical parameters, i.e. the t-test values for the regression coefficients, R^2 values, and correlation coefficients (r) varied from non-significant to highly significant.
- However, the inconsistency in the calibration data is unexplainable. There was a tendency that poorer calibrations were obtained for the deeper (400, 600 and 800 mm) capacitors. This phenomenon cannot be explained at this point in time.
- All capacitors per probe displayed different calibration equations. The implication is that there is no “universal” calibration per probe – capacitors need to be calibrated individually.
- When calibrations per replicate (block) were compared for the four calibration plots, large variations in capacitor readings were found at the same soil water contents. While the capacitors at 100 mm show similarity in slopes, there was almost no agreement among capacitors at 400 and 800 mm, with the latter being the worst.

Routine measurement of SWC: Neutron water meter results:

- For three out of the four seasons, seasonal SWC was affected by tillage.
- The combination of fertilizer and cropping systems also affected SWC.
- Profile soil water storage was affected by tillage and cropping system.

Routine measurement of SWC: Capacitance probe results:

- The capacitor at 100 mm depth showed immediate response to rainfall events, followed by lesser response by the deeper capacitors, while the capacitor at 800 mm depth responded only to large rainfall events.
- In general, almost no changes in soil water content were displayed at either 600 or 800 mm depth, although a gradual drying out of the soil profile at these depths could be noticed.
- Because of the ease of obtaining field readings (by means of a data logger), as well as the advantage of obtaining continuous SWC values, the capacitance probes could be considered for measuring SWC instead of a NWM.

Comparison of capacitance probe and NWM output:

- In general, large differences in temporal soil water contents were observed when comparing capacitor soil water values at the shallower depths (e.g. 100 and 200 mm depth) with NWM values of the 0-225 mm depth increment. However, the agreement tended to be inconsistent, by also displaying similar SWC data for the two instruments.

- Very similar soil water content values were obtained for the two instrument types at 800 mm and 750-1050 mm depth increments, respectively.
- The lack of agreement between the two types of soil water instruments needs further investigation.

Other recommendations that could be considered are:

- Relationships between soil temperature and water content vs. yield components and microbiological findings should be investigated.
- Results should be evaluated in terms of potential scientific articles that can be written.

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5.3 Soil Physical Properties: Soil water II

Soil properties and elements other than hydrogen that can affect the field calibration of a neutron water meter²

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Abstract

A neutron water meter (NWM) operates on the principle that emitted high energy neutrons are thermalised by elastic collisions with atomic nuclei present in soil, such as that of the hydrogen (H) atom. Thermalised neutrons, however, are affected by other nuclear-matter interactions such as their capture by soil elements and properties, thereby decreasing the counts and leading to an underestimation of soil water content (SWC). The objective of this preliminary study was to determine which soil and concretion properties and elements (apart from H) would have a neutron capture effect during the field calibration of a NWM, and whether statistical relationships could be established. Soil and concretion samples from the field calibration of a NWM were analysed for a number of properties and elements. Linear regression analyses revealed that, apart from volumetric SWC, soil and concretion (Cl, K, Fe, ECe) properties were correlated with NWM count ratio. A multiple regression equation containing SWC, soil K and ECe, as well as concretion Fe, explains 87% of the variation in NWM count ratio. It is recommended that the present study be followed up with additional observations to establish a more rigorous multiple regression equation that contains SWC and other soil and concretion parameters.

² Accepted with minor changes for publication as a research note in *South African Journal of Plant and Soil* (publication date to be confirmed).

A neutron water meter contains a radioactive source such as americium-beryllium [$^{9}\text{Be}(\alpha, n)^{12}\text{C}$] that emits high energy (5.05 MeV) neutrons. The latter are slowed, lose energy and are changed in direction by elastic collisions with atomic nuclei present in soil, such as that of the hydrogen (H) atom. These so-called thermalised neutrons are detected by the BF_3 counter in the NWM probe and consequently registered as a count. In general, most of the H in soil is associated with water (and to lesser degree with organic matter). The calibration of a NWM is accomplished by obtaining a relationship between probe counts (expressed as a ratio) and simultaneously measured gravimetric SWC.

The thermalised neutrons, however, are affected by other nuclear-matter interactions such as their capture by soil elements like boron (B), cadmium (Cd), chlorine (Cl), iron (Fe), potassium (K) and lithium, thereby decreasing the counts and leading to an underestimation of SWC by the calibration curve (Gardner, 1986). The magnitude of capturing depends on the nuclear cross-section of an element measured in "barns". The capture cross-sections for Cl, Fe and K, for example, are 34, 2.53 and 2.07 barns, respectively (Gardner, 1986), while manganese (Mn) has a barn value of 13.2 (De Juren & Chin, 1955). Visvalingam & Tandy (1972) reported that in a field calibration of a NWM, 9% of the neutron activity was reduced by a Fe content of 7% by weight. Grismer *et al.* (1995) found no significant correlation between count ratio and saturation extract Cl concentrations ranging from 355-3550 mg Cl/L and concluded that no adjustments to the NWM calibration equations were necessary to reflect Cl interference. A review by Visvalingam & Tandy (1972) mentions that: (1) a Cl concentration of about 7400 mg Cl/kg soil can produce an underestimation of 10% in SWC values; (2) soil K and magnesium can absorb neutrons to cause an underestimation of SWC; and (3) a soil Fe content of about 7% can reduce neutron activity by 9% at every SWC value. Including soil E_c as a parameter, Al-Ain *et al.* (2009) found a slight improvement in the prediction capability of the NWM calibration equation.

It is well known that variations in soil bulk density also have an effect on probe count vs. SWC and should be compensated for during the calibration process (Marais & De V Smit, 1962; Lal, 1974). Water content values for stony or concretion-rich soils, both on a mass and volume basis, can be grossly misleading. The problem arises from the fact that the concretions can occupy a substantial volume in the soil and contribute appreciably to the mass (and consequently the soil bulk density) without making a commensurate contribution to the porosity or water storage capacity of the soil (Gardner, 1986). It is, therefore, imperative to adjust bulk density and SWC values as a function of concretion content (Klute, 1986).

The present study was conducted on a clay soil that contained varying amounts of >2 mm concretions (probably Fe and manganese hydroxy-oxides) with depth. Taking into account the latter phenomenon, the following objectives were formulated for this study: (1) to determine which soil and concretion properties and elements (other than H) would have a neutron capture/absorbing effect during the field calibration of the NWM, and (2) to establish the statistical relationships between these parameters and NWM count ratios.

A medium-term dryland field trial with various crops was conducted north of Pretoria at the Zeekoegat Experimental Farm (25° 36' 55" S, 28° 18' 56" E) of the Agricultural Research Council to quantify the effects of conservation agriculture practices on soil and crop properties. The experimental soil was classified (based on a field survey and soil analyses) as a deep (120 cm) Shortlands form (Zebediela family) (Soil Classification Working Group, 1991). Salient soil features include clay texture (A and B horizons: 40% and 55% clay, respectively), luvisc eutrophic B horizon with a cation exchange capacity of 12 cmol_c/kg and concretions occurring in both the A and B horizons.

A standard procedure (Gardner, 1986) was used for installing thin-wall (1.6 mm) aluminium access tubes (inner diameter: 40 mm) to a depth of 1350 mm on the plant rows of 12 plots per replicate. Installation holes were drilled with a soil auger having a diameter slightly less than the access tubes. The procedure as described by Gardner (1986) was used to calibrate a Geoquip Waterman Model 2000 NWM making use of measurements on 12 plots (four per replicate) at depths of 150, 300, 450, 600, 900 and 1200 mm. Standard counts were used to convert probe readings to count ratios. Simultaneously, soil samples were augered within a radius of ca. 300 mm (Williamson & Turner, 1980) from the access tube at depth intervals of 0-225, 225-375, 375-525, 525-750, 750-1050 and 1050-1350 mm, and SWC was determined gravimetrically. The calibration procedure was repeated six times to obtain data over a wide range of SWCs. For the purpose of this study, data from three calibration measurements was selected, representing low, medium and high SWC regimes. The assumption was made that the calibration was based primarily on H from soil water because: (1) gravimetric SWC was determined at 105 °C (thereby excluding structural H in the clay minerals), and (2) mean soil organic matter (SOM) was only 2.5% and 1.9% in the A and B horizons, respectively (data not included). According to Visvalingam & Tandy (1972), the contribution of H by SOM contents of up to 5-10% is negligible.

Soil bulk densities were determined (Blake & Hartge, 1986) in duplicate in the centre of the same depth intervals used for the gravimetric SWC determination. Concretion masses and volumes

per individual soil core were also determined in order to adjust bulk densities to a <2 mm soil fraction as recommended by Gardner (1986) and Klute (1986). Volumetric SWC was calculated by multiplying gravimetric values with the adjusted bulk density values. Soil and concretion properties and elements were determined on the soil samples from the calibration plots used for gravimetric soil water determination. These samples were composited per replicate and depth increment (depth increments were combined into 0-375, 375-525 and 525-1050 mm; the 1050-1350 mm interval was excluded) and composite sub-samples taken. The samples were sieved and the masses of the fractions >2 mm (concretions) and <2 mm (soil) determined. Sub-samples of the concretions were ground and powdered to <0.5 mm diameter. Table 5.3-1 indicates the properties and elements that were included in the study, as well as their methods of determination. Soil and concretion analysis values were adjusted prior to statistical analysis according to the mass of concretions present per depth increment. The dataset comprised 21 sets of values on which simple linear regression analyses (Gomez & Gomez, 1984) were performed in order to determine the relationships between NWM count ratio, soil and concretion properties and elements. The regression coefficient "b" was tested with the Student's t distribution, while the linear correlation coefficient "r" was tested against tabular r values (Snedecor & Cochran, 1967). The r value is indicative of the closeness of fit between the estimated regression line and the observed points. Stepwise multiple regression analyses (SAS Institute Inc., 1999) were also performed on the dataset with the dependent variable (Y) taken as the NWM count ratio vs. the independent variables (X) being the properties and elements.

Table 5.3-1: Extraction and measurement methods

Sample type	Property/element analysed	Analysis method
Neutron water meter (Waterman Model 2000)	Thermalised neutrons	Count ratio (Gardner, 1986)
Soil + Concretions	Volumetric SWC	Gravimetric (Gardner, 1986)
Soil + Concretions	Bulk density	Core method (Blake & Hartge, 1986)
Soil (<2 mm) and Concretions (>2 mm)	Clay and silt	Pipette (Gee & Bauder, 1986)
	Chloride (Cl)	Extraction: Saturation extract (The Non-Affiliated Soil Analysis Work Committee (NASAWC), 1990) Measurement: Liquid chromatography (Tabatabai & Frankenberger, 1996)
	Electrical conductivity (EC _e)	Extraction: Saturation extract (The NASAWC, 1990) Measurement: Conductivity-Cell (Rhoades, 1996)
	Potassium (K)	Extraction: Acid digestion (EPA 3050B, 1996) Measurement: ICP-MS (Parviz <i>et al.</i> , 1996)
Concretions (>2 mm)	Iron (Fe)	Extraction: Dithionite-citrate-bicarbonate (The NASAWC, 1990) Measurement: ICP-MS (Parviz <i>et al.</i> , 1996)
	Manganese (Mn)	Extraction: Dithionite-citrate-bicarbonate (The NASAWC, 1990) Measurement: ICP-MS (Parviz <i>et al.</i> , 1996)

The statistical tests on the linear regression and regression coefficients for the relationships of NWM count ratio vs. soil and concretion properties and elements (Table 5.3-2) reveal the following:

- Linear regression coefficients: The linear response of NWM count ratios to individual variables in their respective ranges was not significant at the 5% level of significance (t test).
- Correlation coefficients (r): The statistically significant positive relationship of NWM count ratio vs. volumetric SWC is in accordance with the theory of neutron scattering by H atoms (Gardner, 1986).
- A statistically significant negative relationship of NWM count ratio vs. adjusted soil Cl was observed. This is in agreement with the findings of Visvalingam & Tandy (1972) and Gardner (1986) that Cl can capture thermalised neutrons, leading to an underestimation of SWC.
- A negative relationship for NWM count ratio vs. soil K was measured. Although this trend was not statistically significant, the finding is in agreement with the findings of Visvalingam & Tandy (1972) and Gardner (1986).

- Statistically negative relationships for NWM count ratio vs. soil and concrete E_c were observed, which means that as E_c increases, the count ratio decreases, thereby enhancing the underestimation of SWC. Both Al-Ain *et al.* (2009) and Phillips (2010) reported effects of E_c on the NWM calibration equation.
- The presence of concrete Fe did not exhibit the expected negative relationship for NWM count ratio vs. Fe (i.e. the capturing of thermalised neutrons) as reported in the literature (Gardner, 1986). According to Visvalingam & Tandy (1972), the reduction in neutron activity was caused by a Fe content of 7%. In the present study the maximum Fe content was 4.9% (data not included).
- The presence of concrete Mn did not exhibit the expected negative relationship for NWM count ratio vs. Mn. With its relatively large barn value of 13.2, neutron capturing was anticipated.

Table 5.3-2: Statistical relationships of count ratio vs. soil and concrete properties

Description (Y vs X)	Calibration Equation (Y = a + bX)	Valid X range	Degrees of freedom (n-2)	t test for regress coeff ² (b)	Variance explained (R ² , %)	Correlation coeff (r)
CR ¹ vs Volum SWC	Y = 0.14787 + 0.06667X	17.21 ≤ X ≤ 34.90	19	-0.96NS ³	55	0.7397**
CR vs Clay content	Y = 1.72301 + 0.00637X	30.0 ≤ X ≤ 59.0	19	0.21NS	2	0.1549NS
CR vs Clay+silt	Y = 1.67095 + 0.00550X	46.4 ≤ X ≤ 77.0	19	0.19NS	2	0.1416NS
CR vs Soil Cl	Y = 2.31188 - 0.07966X	1.91 ≤ X ≤ 10.23	19	-0.70NS	29	-0.5359*
CR vs Soil K	Y = 2.78742 - 0.00033X	1761 ≤ X ≤ 2788	19	-0.34NS	7	-0.2587NS
CR vs Soil E _c	Y = 3.42765 - 0.02019X	55 ≤ X ≤ 91	19	-0.92NS	46	-0.6767**
CR vs Concrete Cl	Y = 1.90350 + 0.21202X	0.06 ≤ X ≤ 1.09	19	0.25NS	3	0.1752NS
CR vs Concrete K	Y = 1.72999 + 0.00076X	58.7 ≤ X ≤ 651.4	19	0.54NS	17	0.4110NS
CR vs Concrete Fe	Y = 1.84122 + 0.00001X	2842 ≤ X ≤ 48940	19	0.39NS	9	0.2972NS
CR vs Concrete Mn	Y = 1.88207 + 0.00010X	42.5 ≤ X ≤ 2416.4	19	0.32NS	6	0.2408NS
CR vs Concrete E _c	Y = 3.28579 - 0.03418X	27 ≤ X ≤ 46	19	-0.71NS	30	-0.5447*

¹ count ratio

² regression coefficient

³ statistically not significant

* statistically significant at the 5% level of significance

** statistically significant at the 1% level of significance

The sequence of variables in Table 5.3-3 reflects the stepwise entering of variables into the multiple regression equation. Although the four variables in the equation highly significantly ($p < 0.0001$) explain 86.9% of the variation in NWM count ratio, volumetric SWC and soil E_c

account for most of the explained variation. All four variables positively or negatively affect the NWM count ratio (Visvalingam & Tandy, 1972; Gardner, 1986; Al-Ain *et al.*, 2009; Phillips, 2010).

Table 5.3-3: Statistical data for multiple regression analysis

Variables in equation	Total variance explained (R ² , %)	Regression coefficient	F value	Probability (p)
Volumetric SWC	54.7	0.06264	22.9	0.0001
Soil E _c	82.4	-0.01412	42.1	<0.0001
Concretion Fe	84.4	0.00001	30.6	<0.0001
Soil K	86.9	0.00030	26.5	<0.0001

The results of this preliminary study confirm that soil and concretion properties and elements (other than H) could have a neutron capture/absorbing effect during the field calibration of a NWM, and that statistical relationships between these parameters and NWM count ratios could be established. Apart from SWC, the inclusion of E_c in the calibration equation should be considered. It is recommended that the present study be followed up with additional observations to establish a rigorous multiple regression equation that not only contains SWC, but also other soil and concretion parameters.

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5.4 Soil Physical Properties: Soil Temperature

The effects of CA and conventional agricultural practices on soil temperature

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Introduction

In the present study the medium-term effects of CA and conventional cultivation practices on temporal soil temperature fluctuations, as well as soil profile temperature at specific points in time, were evaluated over a period of four experimental seasons, *viz.* 2009/10 to 2012/13. The results from individual seasons will be presented and discussed.

Materials and Methods

Laboratory calibration of capacitance probe thermistors

AquaCheck BASIC 0.8 capacitance probes that were used in the trial have capacitors (water content) and thermistors (temperature) at 100, 200 300, 400, 600 and 800 mm depth intervals, offer continuous readings at 30 minute intervals of the mentioned properties, and incorporate a data storage facility. Prior to field installation, temperature calibrations of the thermistors were performed for all probes during October and November 2009. A 100 mm diameter PVC pipe was cut to a length of 900 mm and capped on the one end with silicon sealant. The pipe was fitted with two hoses (one at the bottom and one at the top), one of which was connected to a Julabo heater and pump, and the other to serve as a discharge into a 16 L urn. The pump was mounted on the urn in order to circulate the water through the system. A thermometer was placed in the Julabo, as well as in the PVC pipe to monitor temperature. A batch of three capacitance probes was placed in the PVC pipe for each calibration run (Plate 5.4-1). Ice was placed in the urn to lower the water temperature to about 8 °C. Thereafter the temperature was increased in increments of 10 °C to 40 °C. Each temperature setting was maintained for at least 1 hour to obtain temperature equilibration with the time and temperature recorded. After each calibration run, the data was captured by a hand-held logger and transferred to a computer with the aid of Cropgraph software. Thermistor output is in degrees Celsius. Statistical analysis entailed a simple linear regression analysis of the data in order to determine the relationship between measured temperature and temperature readings of the thermistors at each of the six positions of each probe. The regression coefficient "b" was tested with the Student's t distribution, while the linear correlation coefficient "r" was tested against tabular r values (Gomez & Gomez, 1984).

Field installation of capacitance probes

Commencing in December 2009, probe installation was done annually at about 2 weeks after planting (first week of December) on 18 selected plots on the plant row of the main crop (Table 5.4-1; Appendix 5.2). A specially designed hand auger was used to bore holes to a depth of 900 mm on the plant row of the main crop on the selected plots. Water was used during the augering process to ease the extraction of the soil. Using the extracted soil, a slurry was prepared and poured into the hole before the probes were inserted to ensure a good contact between the soil and the probes. All capacitance probes were removed annually before the onset of the next growing season to facilitate tillage and planting operations.



Plate 5.4-1: Thermistor calibration set-up.

Table 5.4-2: Capacitance probe installation data

Plot No.	4	5	7	16	17	19	29	34	35
Probe No. ¹	2641	2417*	2214 ² 2303 ^{3#}	4521 ⁴ 4884 ⁵	4504	2137 ² 2301 ³	5470	4510 ⁴ 5465 ⁵	4480*
Plot No.	41	46	47	49	56	60	61	68	72
Probe No.	2370	2220	2395	4513	5276	4475	4478	5294	5302

¹ Probe Nos. with no superscripts installed 2009/10-2012/13; ² Installation 2009/10-2011/12;

³ Installation 2012/13; ⁴ Installation 2009/10; ⁵ Installation 2010/11-2012/13

* No data generated in 2011/12 because of faulty probe or flat batteries

No data generated in 2012/13 because of faulty probe

Routine measurement of soil temperature

Capacitor and thermistor data were periodically captured from the 18 installed capacitance probes (Table 5.4-1; Appendix 5.2) with a hand-held data logger, transferred to a computer using Cropgraph software and subjected to quality control before converting thermistor temperature readings to calculated temperatures with the acquired calibration equations. In this report the measurements from four growing seasons, *viz.* 2009/10 to 2012/13, will be presented and discussed.

Results and Discussion

Laboratory calibration of capacitance probe thermistors

The calibration results for the thermistors are presented in Table 5.4-2. As an example of the statistical tests of the calibration data, those for probe no. 2641 are given in Table 5.4-3, while the estimated regression lines and the observed data are plotted in Fig. 5.4-1. An evaluation of the thermistor temperature calibration equations (Table 5.4-2) reveals that:

- Slope values are almost equal to 1 to yield a relationship close to 1:1 for measured vs. recorded temperature.
- Intercept values are extremely variable, ranging from -1.127 to +2.75, translating to recorded temperatures being adjusted downwards or upwards.
- There is no similarity in measured vs. recorded temperature among any of the six thermistors on any individual probe. This means that every thermistor needs to be individually calibrated for correct soil temperature values to be calculated.

The statistical test data (Table 5.4-3, Fig. 5.4-1) reveals the following:

- The t-test values for the regression coefficients (Table 5.4-3) indicate that the linear response of thermistor temperature to changes in measured temperature is highly significant.
- The R^2 values indicate that 99% of the variation in the dependent variable (Y) is accounted for by the respective linear functions.
- Highly significant correlation coefficients (r) were calculated for all linear relationships.
- Graphical displays of the relationships in Fig. 5.4-1 show excellent "closeness of fit" (indicated by magnitude of the r values) between the estimated regression lines and the observed points.

Table 5.4-3: Capacitance probes: Thermistor calibration equations

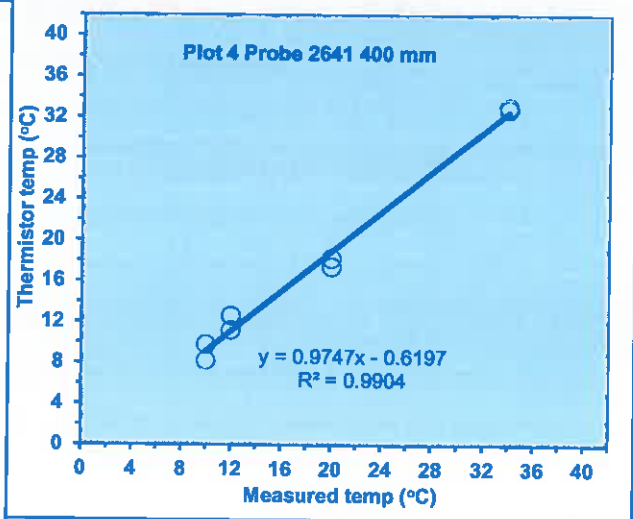
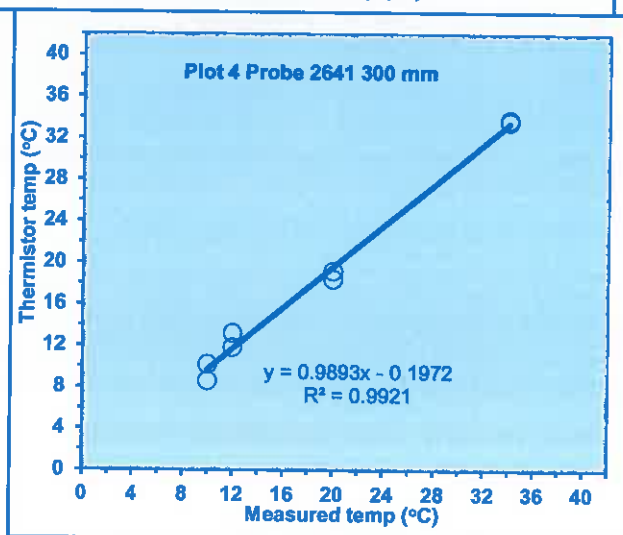
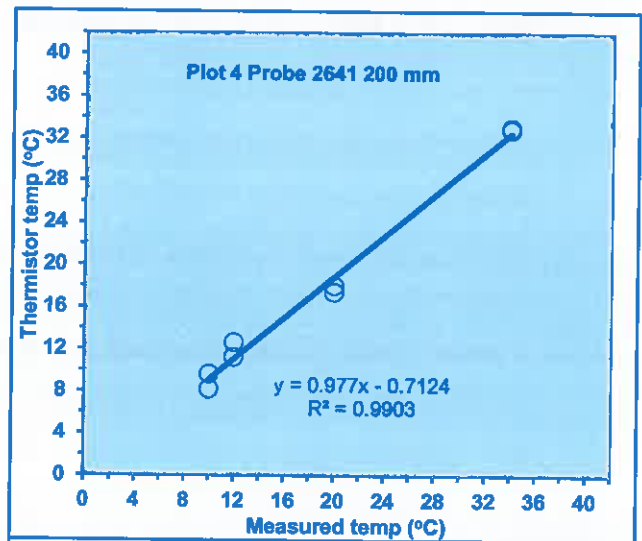
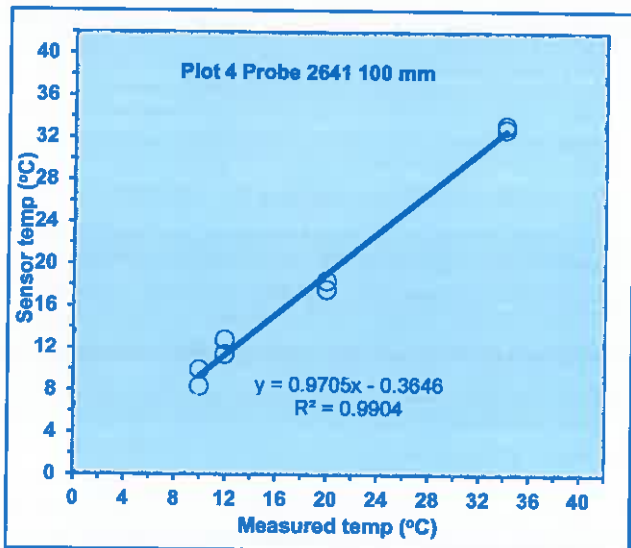
Plot No.	Probe No.	Depth (mm)					
		100	200	300	400	600	800
4	2641	$Y=0.9705X-0.3646$ $R^2 = 0.9904$	$Y=0.9770X-0.7174$ $R^2 = 0.9903$	$Y=9893X-0.1972$ $R^2 = 0.9921$	$Y=0.9747X-0.6197$ $R^2 = 0.9904$	$Y=0.9843X-2.0511$ $R^2 = 0.9890$	$Y=1.0118X-1.8242$ $R^2 = 0.9887$
5	2417	$Y=1.0243X-0.0699$ $R^2 = 0.9913$	$Y=1.0280X+0.3888$ $R^2 = 0.9909$	$Y=1.0054X-0.0381$ $R^2 = 0.9907$	$Y=1.0041X+0.1916$ $R^2 = 0.9900$	$Y=1.0208X-0.2733$ $R^2 = 0.9902$	$Y=1.0264X-0.3756$ $R^2 = 0.9889$
7	2214	$Y=0.9931X-0.5487$ $R^2 = 0.9459$	$Y=0.9906X-0.5147$ $R^2 = 0.9459$	$Y=0.9819X+1.6946$ $R^2 = 0.9967$	$Y=0.9963X+0.7413$ $R^2 = 0.9972$	$Y=0.9908X+0.9211$ $R^2 = 0.9970$	$Y=0.9741X+0.8443$ $R^2 = 0.9973$
16	4521	$Y=0.9983X-0.5228$ $R^2 = 0.9976$	$Y=1.0002X-0.7833$ $R^2 = 0.9976$	$Y=1.0053X-0.4566$ $R^2 = 0.9971$	$Y=1.0035X-0.6961$ $R^2 = 0.9973$	$Y=1.0041X-0.8292$ $R^2 = 0.9974$	$Y=1.0112X-0.8435$ $R^2 = 0.9980$
17	4504	$Y=0.9836X-0.0416$ $R^2 = 0.9976$	$Y=0.9990X-0.5781$ $R^2 = 0.9972$	$Y=1.0024X-0.352$ $R^2 = 0.9972$	$Y=1.0021X-0.2465$ $R^2 = 0.9978$	$Y=1.0044X-0.5763$ $R^2 = 0.9975$	$Y=1.0044X-0.5763$ $R^2 = 0.9975$
19	2137	$Y=0.9440X+2.85$ $R^2 = 0.9928$	$Y=0.9610X+2.00$ $R^2 = 0.9942$	$Y=0.9450X+2.60$ $R^2 = 0.9934$	$Y=0.9630X+2.20$ $R^2 = 0.9940$	$Y=0.9470X+2.45$ $R^2 = 0.9944$	$Y=0.9530X+1.70$ $R^2 = 0.9955$
29	5470	$Y=0.9456X+1.1641$ $R^2 = 0.9901$	$Y=0.9401X+1.1614$ $R^2 = 0.9898$	$0.9462X+1.2317$ $R^2 = 0.9907$	$Y=0.9471X+1.012$ $R^2 = 0.9911$	$Y=0.9394X+1.5178$ $R^2 = 0.9861$	$Y=0.9531X+1.1429$ $R^2 = 0.9922$
34	4510	$Y=0.9460X+0.40$ $R^2 = 0.9906$	$Y=0.9520X+0.20$ $R^2 = 0.9929$	$Y=0.957X+0.20$ $R^2 = 0.9934$	$Y=0.952X+0.25$ $R^2 = 0.994$	$Y=0.953X+3E-14$ $R^2 = 0.9943$	$Y=0.977X-0.40$ $R^2 = 0.9957$
35	4480	$Y=0.9690-0.35$ $R^2 = 0.9939$	$Y=0.9740X-0.055$ $R^2 = 0.9933$	$Y=0.973X-0.85$ $R^2 = 0.9933$	$Y=0.9840X-0.85$ $R^2 = 0.9947$	$Y=0.983X-0.85$ $R^2 = 0.9958$	$0.9990X-1.15$ $R^2 = 0.9976$

Table 5.4-2 (continued)

Plot No.	Probe No.	Depth (mm)				Y=0.927X+1.90 R ² = 0.9902	Y=0.9410X+1.55 R ² = 0.9891	Y=0.9800X+0.50 R ² = 0.9937
		100	200	300	400			
41	2370	Y=0.9150X+2.65 R ² = 0.9853	Y=0.9170X+2.65 R ² = 0.9870	Y=0.922X+2.20 R ² = 0.9898	Y=0.927X+1.90 R ² = 0.9902	Y=0.9410X+1.55 R ² = 0.9891	Y=0.9800X+0.50 R ² = 0.9937	
46	2220	Y=0.946X+3.20 R ² = 0.9924	Y=0.9630+2.35 R ² = 0.9937	Y=0.9560X+2.20 R ² = 0.9939	Y=0.9420+2.10 R ² = 0.9943	Y=0.9370X+1.85 R ² = 0.9953	Y=0.9420X+2.30 R ² = 0.9943	
47	2395	Y=0.9687X+1.5699 R ² = 0.9895	Y=0.9745X+1.5522 R ² = 0.9878	Y=0.9861X+1.7169 R ² = 0.9851	Y=1.0031X+0.1366 R ² = 0.9918	Y=0.9852X+0.7350 R ² = 0.9927	Y=0.973X+1.3157 R ² = 0.9897	
49	4513	Y=0.9340X+0.15 R ² = 0.9908	Y=0.9400X+0.10 R ² = 0.9924	Y=0.9340X+0.15 R ² = 0.9908	Y=0.9340X+0.15 R ² = 0.9908	Y=0.9400X+0.05 R ² = 0.9925	Y=0.9500X-0.25 R ² = 0.9940	
56	5276	Y=0.9886X-0.7010 R ² = 0.9951	Y=1.0037X-1.1088 R ² = 0.9957	Y=0.10030X-1.1270 R ² = 0.9960	Y=0.10030X-1.1270 R ² = 0.9960	Y=1.0181X-0.5347 R ² = 0.9951	Y=0.9979X-0.7911 R ² = 0.9953	
60	4475	Y=0.9611X+0.1237 R ² = 0.9984	Y=0.9610X+0.1237 R ² = 0.9984	Y=0.9610X+0.1237 R ² = 0.9984	Y=0.969X+0.0972 R ² = 0.9981	Y=0.9849X+0.3923 R ² = 0.9961	Y=0.9892X-0.4464 R ² = 0.9958	
61	4478	Y=0.9170X+0.9375 R ² = 0.9939	Y=0.9230X+0.8269 R ² = 0.9934	Y=0.9366X+0.2836 R ² = 0.9941	Y=0.9351X+0.3613 R ² = 0.9947	Y=0.9575X-0.1313 R ² = 0.9940	Y=0.9833X-0.6764 R ² = 0.9950	
68	5294	Y=0.883X+1.95 R ² = 0.9911	Y=0.899X+1.30 R ² = 0.9921	Y=0.9000X+1.50 R ² = 0.9920	Y=0.9040X+1.45 R ² = 0.9924	Y=0.915X+1.55 R ² = 0.9936	Y=0.9310X+1.00 R ² = 0.9954	
72	5302	Y=0.8720X+2.55 R ² = 0.9655	Y=0.8730X+2.55 R ² = 0.9657	Y=0.8720X+2.45 R ² = 0.9654	Y=0.8730X +2.55 R ² = 0.9657	Y=0.8810X+2.75 R ² = 0.9652	Y=0.889X+2.65 R ² = 0.9665	

Table 5.4-4: Statistical data for relationships between soil properties (2010/11)

Depth (mm)	Calibration Equation (Y = a + bX) ¹	Valid X range	Degrees of freedom (n-2)	t test for regress coeff (b)	Variance explained (R ² , %)	Correlation coeff (r)
100	Y = -0.36461 + 0.97051X	10<=X<=34	6	15.44***	99	0.9952**
200	Y = -0.71236 + 0.97697X	10<=X<=34	6	15.50***	99	0.9951**
300	Y = -0.19719 + 0.98933X	10<=X<=34	6	16.10***	99	0.9961**
400	Y = -0.611966 + 0.97472X	10<=X<=34	6	15.48***	99	0.9952**
600	Y = -2.05112 + 0.98427X	10<=X<=34	6	15.28***	99	0.9945**
800	Y = -1.82416 + 1.01180X	10<=X<=34	6	15.49***	99	0.9944**



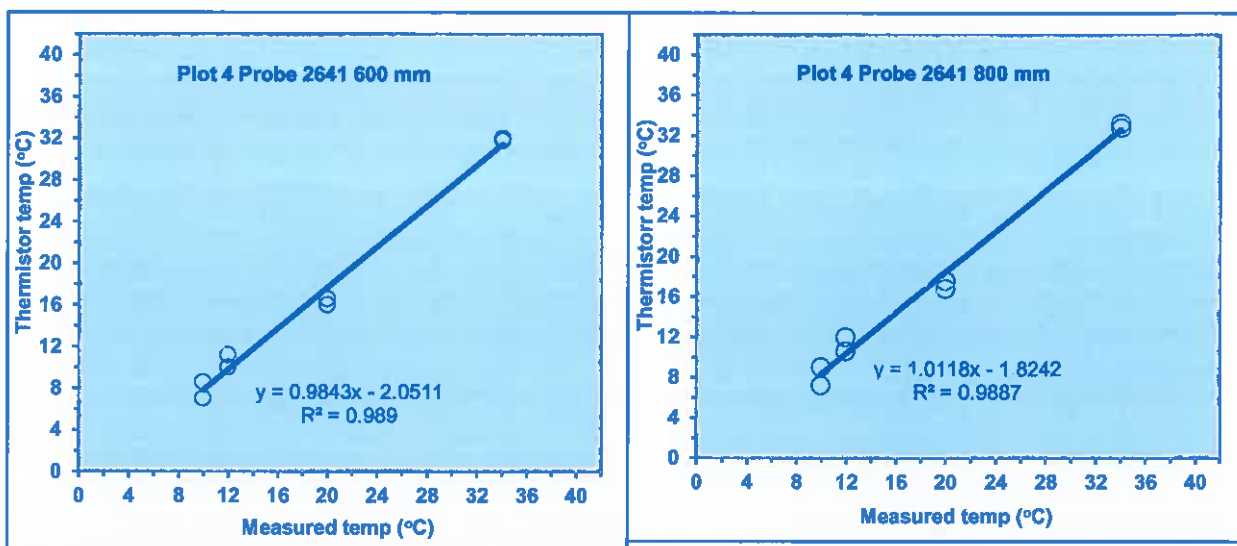


Figure 5.4-1: Capacitance probe no. 2641: Thermistor calibration graphs for six depths.

Routine measurement of soil temperature

2009/10: The presentation and discussion of the soil temperature data displayed in Figs. 5.4-2 and 5.4-3 serve as an example of data recorded on the 18 plots where capacitance probes were installed. In Fig. 5.4-2, hourly soil temperatures at 100 and 400 mm depths (Plot 29; RT; Treatment F1C1; Probe 5470) are plotted against air temperature for the period 8 December 2009 (Time=0 hrs) to 2 February 2010 (Time=1360 hrs). The following observations can be made:

- Soil temperatures at 100 mm depth closely follow air temperature fluctuations, although at smaller amplitudes.
- Diurnal fluctuations of soil temperatures at 400 mm depth are at a magnitude of about 1 °C, compared to about 14 °C at 100 mm depth.
- Diurnal soil temperature fluctuations at 400 mm depth display a lag of about 13 hrs, compared to air temperature.
- Soil temperature fluctuations at 400 mm depth follow a longer (3-5 days) time trend.

In Fig. 5.4-3, hourly soil temperatures at 100 mm depth under RT (Plot 34; Treatment F1C4; Probe 4510) are compared with those under CT (Plot 41; Treatment F1C1; Probe 2370) for the period 24 December 2009 (Time=391 hrs) to 2 February 2010 (Time=1360 hrs). Soil temperatures under RT are about 3-5 °C lower than under CT.

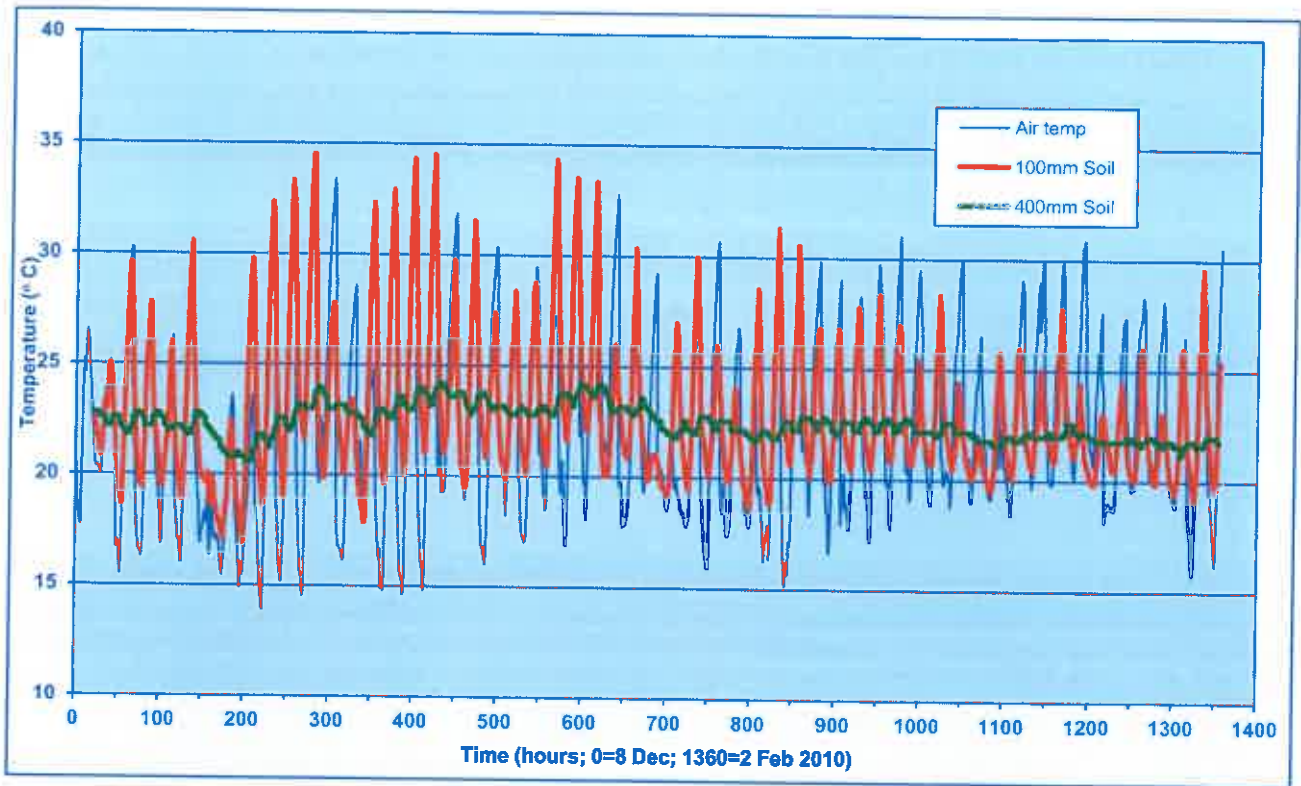


Figure 5.4-2: Hourly soil vs. air temperatures.

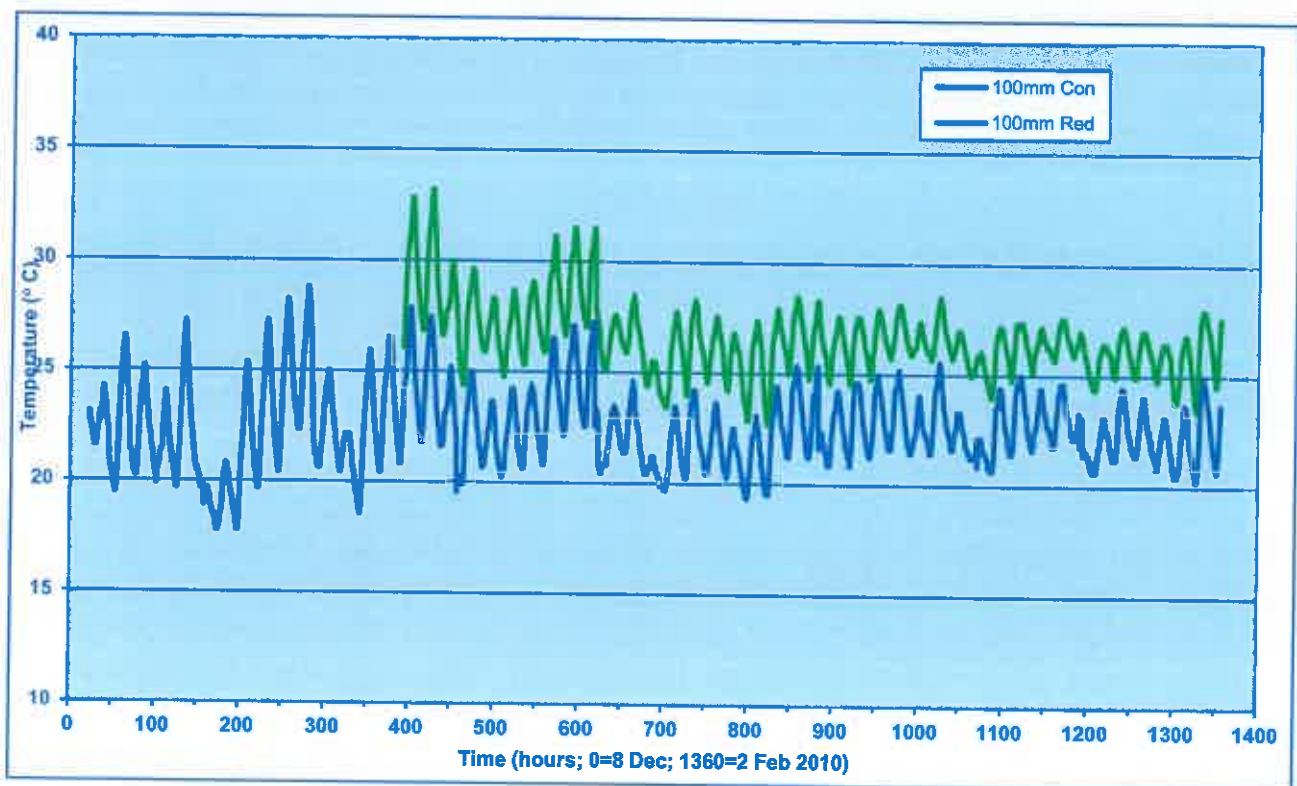


Figure 5.4-3: Comparison of soil temperatures under reduced and conventional tillage.

2010/11: As an example of the effects of air temperature on soil temperature, hourly soil temperatures at 100 and 400 mm depths (Plot 61; RT; Treatment F1C1; Probe 4478) are plotted against air temperature for the period 06h00 25 January 2011 to 12h00 15 February 2011 in Fig. 5.4-4. The following observations can be made:

- Soil temperatures at 100 mm depth closely follow air temperature fluctuations, although at a lag (about 3 hrs) and at smaller amplitudes.
- Diurnal fluctuations of soil temperatures at 400 mm depth are at a magnitude of about 0.4 °C, compared to about 7 °C at 100 mm depth.
- Diurnal soil temperature fluctuations at 400 mm depth display a lag of about 10 hrs, compared to air temperature.
- Soil temperature fluctuations at 400 mm depth follow a longer (about 7 days) time trend.

In Fig. 5.4-5, hourly soil temperatures at 100 mm depth under RT (Plot 61; Treatment F1C1; Probe 4478) are compared with those under CT (Plot 49; Treatment F1C1; Probe 2370) for the period 06h00 25 January 2011 to 12h00 15 February 2011. In Fig. 5.4-6, accumulated Celsius-hours at 100 mm depth are plotted for the two tillage practices. The following observations can be made:

- Maximum and minimum soil temperature values are higher under CT than under RT.
- Accumulated soil temperature values are higher under CT than under RT.

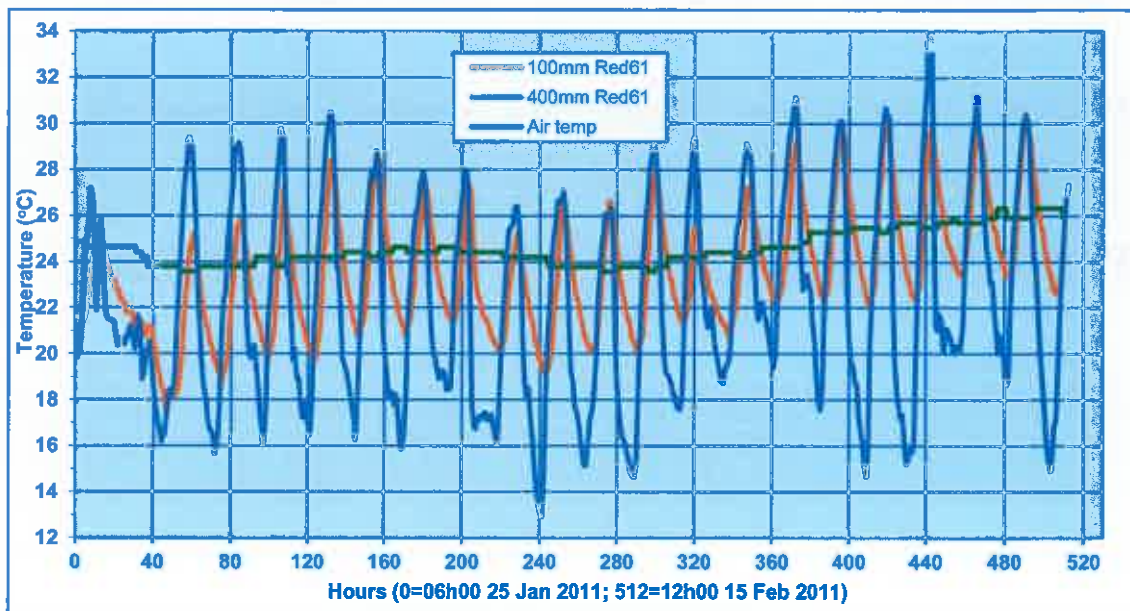


Figure 5.4-4: Hourly soil vs. air temperatures.

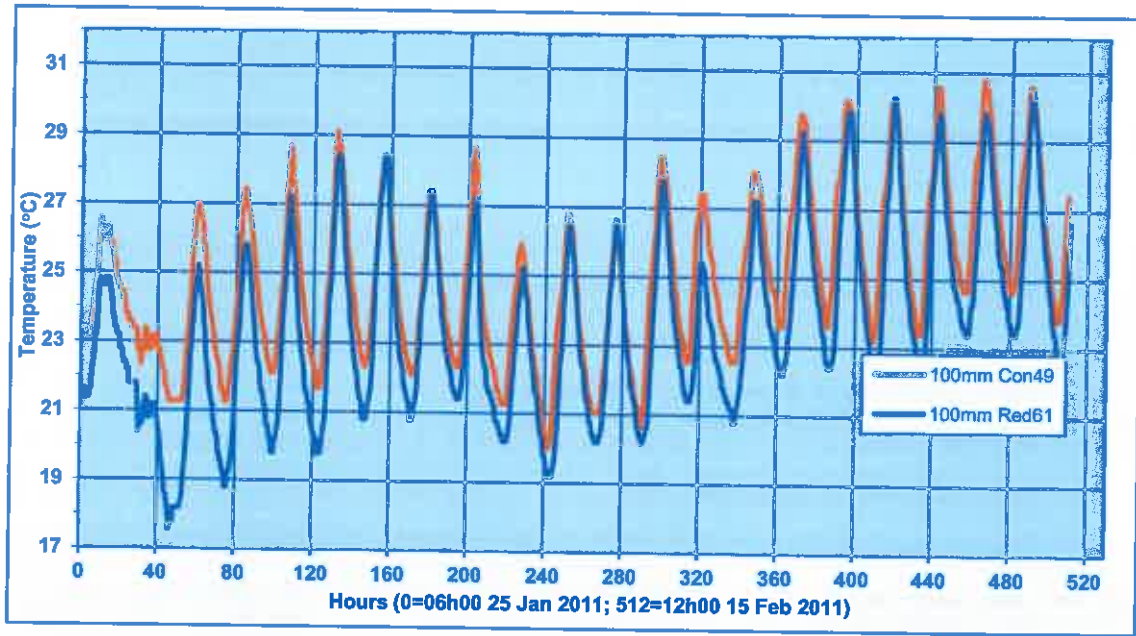


Figure 5.4-5: Comparison of soil temperatures under reduced and conventional tillage.

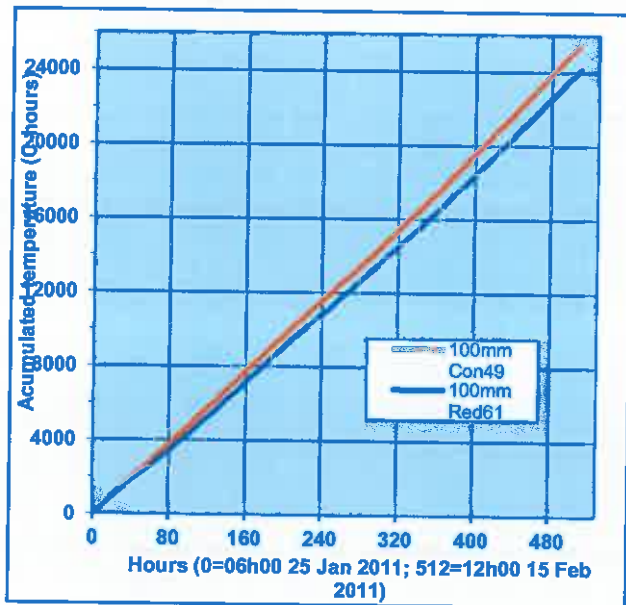


Figure 5.4-6: Accumulated Celsius-hours at 100 mm depth for reduced vs. conventional tillage.

2011/12: As an example of the effects of air temperature on soil temperature, hourly soil temperatures at 100 and 400 mm depths (Plot 29; RT; Treatment F1C1; Probe 5470) are plotted against air temperature for the period 00h00 1 January 2012 to 11h00 24 January 2012 in Fig. 5.4-7. The following observations can be made:

- Soil temperatures at 100 mm depth closely follow air temperature fluctuations, although at a lag (about 1.5 hrs) and at smaller amplitudes;
- Diurnal fluctuations of soil temperatures at 400 mm depth are at a magnitude of about 0.4 °C, compared to about 8 °C at 100 mm depth;
- Diurnal soil temperature fluctuations at 400 mm depth display a lag of about 15-16 hrs, compared to air temperature;
- Soil temperature fluctuations at 400 mm depth also follow a clear and longer (about 6-7 days) time trend.

in Fig. 5.4-8, hourly soil temperatures at 100 mm depth under RT (Plot 61; Treatment F1C1; Probe 4478) are compared with those under CT (Plot 41; Treatment F1C1; Probe 2370) for the period 00h00 1 January 2012 to 11h00 24 January 2012. Maximum and minimum soil temperatures are higher under CT than under RT.

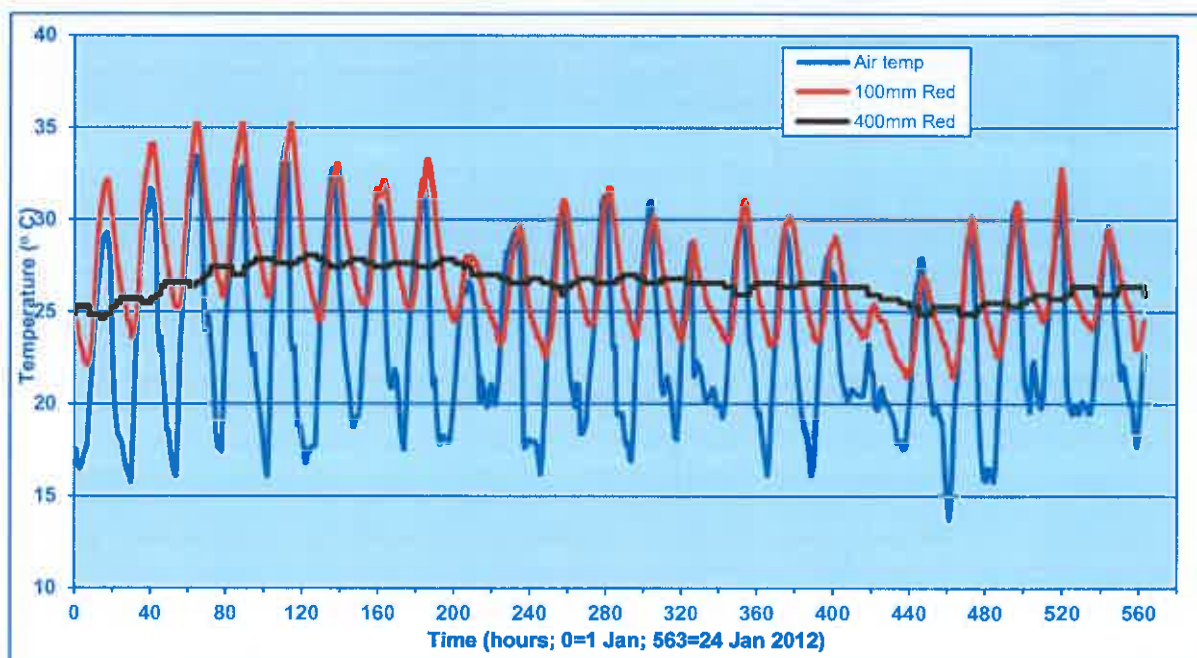


Figure 5.4-7: Hourly soil vs. air temperatures.

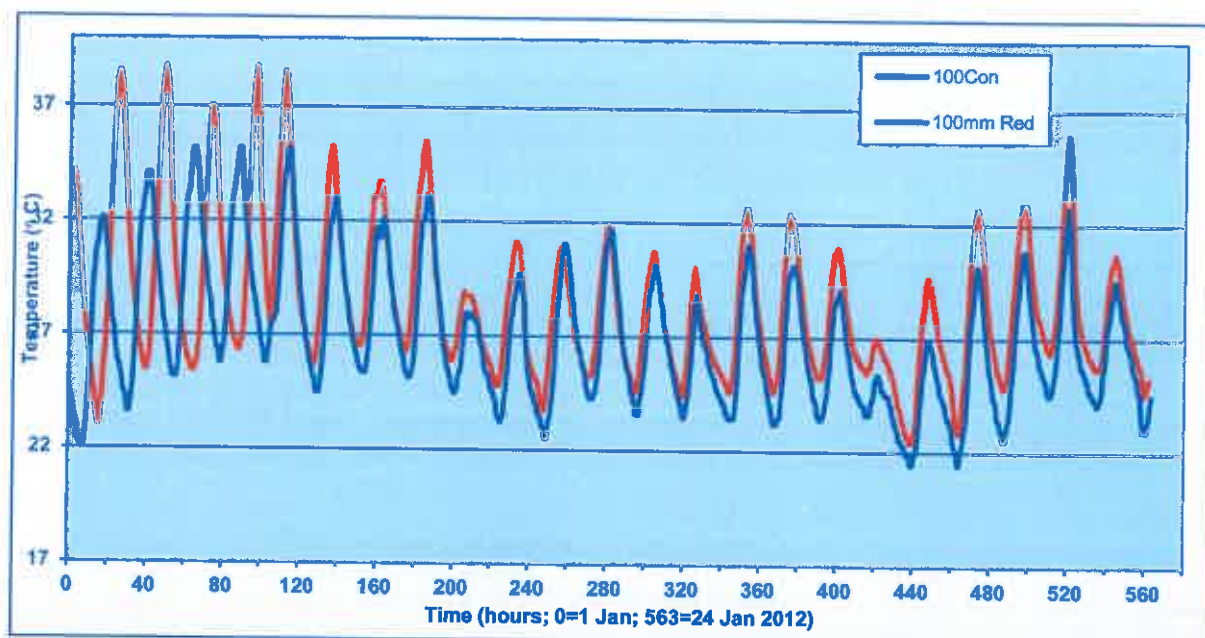


Figure 5.4-8: Comparison of soil temperatures under reduced and conventional tillage.

2012/13: As an example of the effects of air temperature on soil temperature, hourly soil temperatures at 100 and 400 mm depths (Plot 29; RT; Treatment F1C1; Probe 5470) are plotted against air temperature for the period 00h00 12 January 2013 to 24h00 13 February 2013 in Fig. 5.4-9. The following observations can be made:

- Soil temperatures at 100 mm depth closely follow air temperature fluctuations, although at a lag (about 2.5 hrs) and at smaller amplitudes.
- Diurnal fluctuations of soil temperatures at 400 mm depth have a mean amplitude of about 0.5 °C, compared to about 8 °C at 100 mm depth.
- Diurnal soil temperature fluctuations at 400 mm depth display a lag of about 14-16 hrs, compared to air temperature.
- Apart from small diurnal fluctuations, soil temperature fluctuations at 400 mm depth also follow a longer (about 4-6 days) time trend.

In Fig. 5.4-10, hourly soil temperatures at 100 mm depth under RT (Plot 29; Treatment F1C1; Probe 5470) are compared with those under CT (Plot 16; Treatment F1C3; Probe 4884) for the period 00h00 12 January 2013 to 24h00 13 February 2013. The following observation can be made:

- Maximum and minimum soil temperature values under CT are 4-5 °C and 0.4-1.1 °C, respectively, higher than under RT.

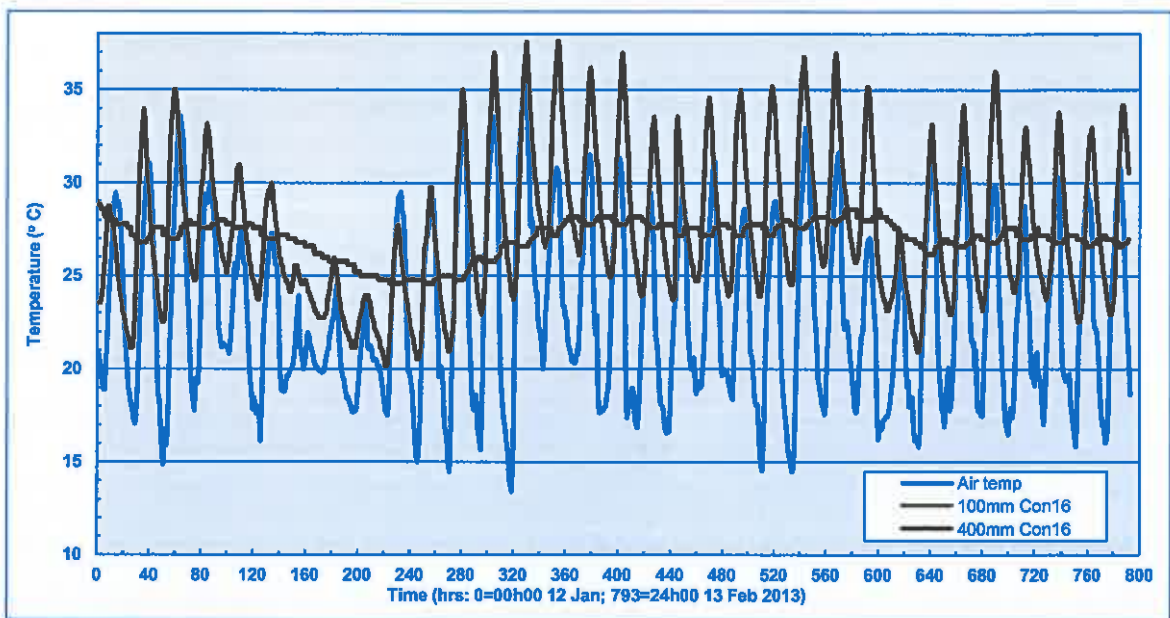


Figure 5.4-9: Hourly soil vs. air temperatures.

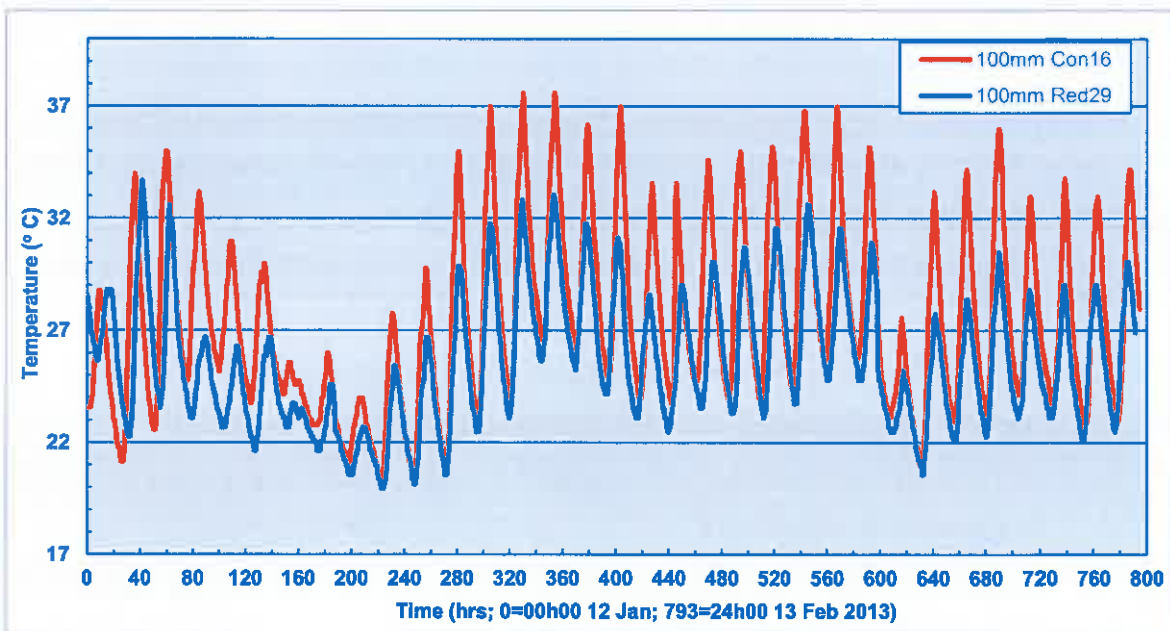


Figure 5.4-10: Comparison of soil temperatures under reduced and conventional tillage.

Conclusions and Recommendations

The calibration results for the thermistors reveal that:

- Slope values are almost equal to 1 to yield a relationship close to 1:1 for measured vs. recorded temperature.

- Intercept values are extremely variable, ranging from -1.127 to +2.75, translating to recorded temperatures being adjusted downwards or upwards.
- The statistical test data reveals highly significant t-test, R^2 and r values for all the linear relationships.
- The thermistors need to be calibrated. It was found that there was no similarity in readings of thermistors embedded on the same capacitance probe. Likewise there was no similarity in output of the thermistors when probes were compared.

From the routine measurement of soil temperature with the thermistors it can be concluded that:

- The thermistors proved to be very sensitive to changes in soil temperature, particularly in the shallow soil layers.
- The effect of air temperature and soil depth, respectively, on diurnal soil temperature changes could be quantified.
- The effects of different tillage treatments on diurnal soil temperature changes could be quantified.

It is recommended that because of the ease of obtaining field readings (by means of a data logger), as well as the advantage of obtaining continuous soil temperature values, the capacitance probes with their embedded thermistors could be considered to quantify soil temperature as a function of various soil treatments. Furthermore, soil temperature data can be used to elucidate its effects on soil biological and chemical processes and dynamics.

References

- Gomez KA, Gomez AA. 1984. Regression and correlation analysis. pp. 357-423. In: KA Gomez, AA Gomez (eds.). *Statistical Procedures for Agricultural Research*. Second Edition, John Wiley & Sons, New York, USA.

5.5 Soil Physical Properties: Soil Penetration Resistance

Interpretation of soil penetration resistance assessments under various cultivation practices: A case study³

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Introduction

Conservation agriculture (CA) is widely viewed as an ideal system for sustainable crop production intensification that improves soil physical, chemical and biological properties, while at the same time reducing input costs, soil erosion and water pollution. It also optimises yields and thereby contributes to food security. However, CA has sometimes been criticised for not living up to these claims. Some critics say that CA is not as economical as it has been advocated to be, that the yields are not optimal, that weeds pose a serious problem, and that topsoil compaction in the absence of tillage seems to be a major challenge. During a recent visit to South Africa, the South American CA activist and researcher, Dr Rolf Derpsch, shared some interesting experiences on CA. During two dialogue sessions with farmers and advisors in the summer grain areas, it was evident that the challenges of implementing CA under certain conditions in South Africa seemed to be insurmountable to some farmers and researchers. Dr Derpsch was unmoving in his convictions. He recurrently emphasised that if there was a problem with CA, then it was probably not done correctly, and referred to numerous studies to support his claims. CA is not just minimum or reduced tillage, he said, it also involves crop diversity (including multi-cropping) and permanent organic soil cover. Farmers who only use a no-till planter to save costs will not experience the full advantages of CA unless they also incorporate the other factors mentioned above.

Practising and adapting CA within the realities of an existing farming system requires a continuous learning process. There are many factors influencing this process, such as economic realities, market forces, preferred crops, access to cover crops, different soils and different climates. What might work on one farm might not work on another. However, the positive outcomes of persevering with this process are substantial. By increasing the soil organic matter,

³ Prepared to submit to *SA Grain*.

Presented as an oral paper at the Combined Congress in Grahamstown, January 2014.

soil properties like structure, nutrient cycling and water-holding capacity improve. Practising CA can cut down cost and reduce the use of pesticides and fossil fuels, which is highly beneficial to farmers. With the relentless pressure on water resources, as well as the reduction in soil quality and climate change, more and more farmers will soon have no choice but to practise CA.

On-station research trial to quantify the effects of CA

To evaluate the effect of CA on soil and plant properties, the ARC ran an on-station, dryland field trial from 2007 to 2013. The trial was conducted just north of Pretoria at Zeekoegat, Roodeplaat, on a Hutton soil form with a clayey texture (51% clay). An iron-manganese oxide concretion layer occurs at varying depths of 300-1000 mm throughout the trial area. The area receives an annual rainfall of 704 mm. The trial has been designed to compare conventional farming practices (ploughing and monoculture) with various CA practices (reduced tillage, permanent soil cover and diversified cropping systems). The trial was statistically laid out in a randomised complete block design, with tillage as the main factor. Other treatments included cropping systems (maize monoculture, maize/cowpea rotation, maize/soybean rotation, maize/cowpea intercropping, maize/oats intercropping and maize/vetch intercropping), as well as fertilizer application (optimal and low fertilizer level). In terms of tillage, the soil was prepared as follows: conventionally tilled plots were ploughed with a mouldboard plough, disked and then a tine implement was used to draw furrows for planting; whilst on the reduced tillage plots, only furrows were drawn for planting. In the first 3 years of the trial these furrows were made by hoes, but due to the time-consuming nature of this practice a tractor was used in the last 3 years. Planting was done by hand with a specialised no-till planter.

What we expected to see was a steady improvement in maize yield under reduced tillage systems, and especially in a dry season, we were expecting to measure higher maize grain yields under CA systems, as a result of improved soil health. Initially our results surprised us when we found that right from the start the grain yield under reduced tillage was higher than that under conventional tillage. In the third season, which was characterised by a poor rainfall distribution, the yield declined, but still reduced tillage outperformed conventional tillage (Fig. 5.5-1). During the last three seasons, however, the yields were significantly lower. Rainfall was low or poorly distributed throughout the season, which partly explains the low yield and biomass. What was particularly surprising was that yield and biomass under reduced tillage performed worse than under conventional tillage.

The ARC research team scrutinised all the data to come up with an explanation. We measured soil water content, and as expected, the soil water was consistently higher under reduced tillage compared to conventional ploughed soils. As far as soil water-holding capacity was concerned, CA had the desired impact. The soil organic matter also increased under reduced tillage, and we were able to measure a steady increase in organic carbon under reduced tillage soil while organic C in conventionally tilled soils remained constant. So here too, CA had the desired positive effects. When we compared grain yield with weed occurrence, we found that the weeds under reduced tillage and or conventional tillage had no significant effect on the maize grain yield. It was only in the last season that we identified soil compaction as a possible cause of declining yields.

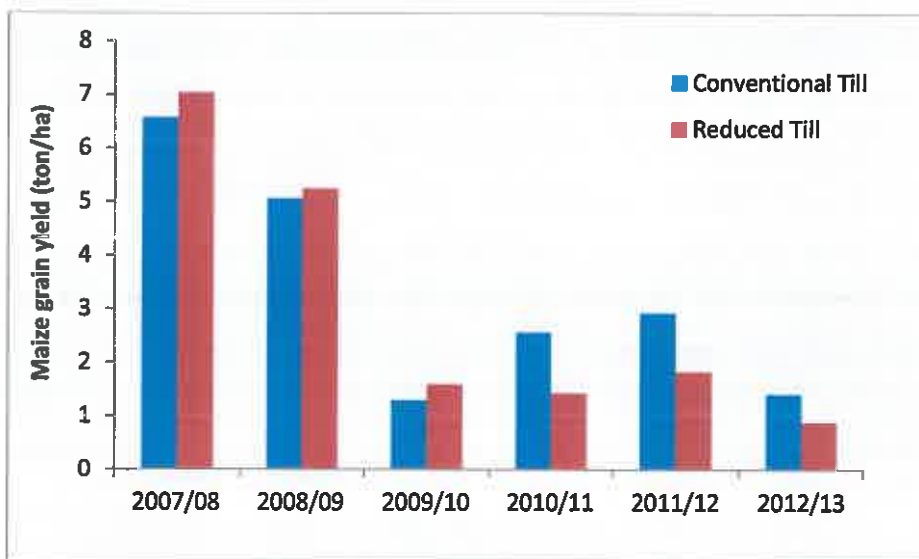


Figure 5.5-1: Maize grain yield production in ton/ha under conventional and reduced tillage during the six trial seasons at Zeekoegat, Pretoria.

Measuring soil compaction

To determine soil compaction, soil penetration resistance is often measured as an indicator thereof, and confirmed with additional data such as soil bulk density and root distribution. High soil resistance could indicate soil compaction, but in the case of rocky soil or the presence of concretions, high resistance values only indicate obstructions for the penetrometer's rod, which might influence the accuracy of the measurements. In our case, we were only able to collect soil penetration resistance values, using a Geotron penetrometer (Plate 5.5-1). Soil penetration resistance was measured on 24 selected plots (12 with reduced tillage and 12 conventionally tilled) with six measurements per plot. Prior to the measurements the soil was saturated with

water and left to drain to field capacity. Readings were taken every 10 mm up to a depth of 800 mm where possible, and the penetrometer was set at a maximum pressure of 4000 kPa. The average of the six measurements per plot was determined and the data from all plots was statistically analysed.



Plate 5.5-2: Measuring soil penetration resistance with a penetrometer, as indicator of soil compaction. The tyre was used to help wet the soil in preparation for sampling.

Results

According to literature, increasing soil resistance correlates with a decrease in root length. Root growth is seriously affected from 1200 kPa and virtually ceases by 2000-2500 kPa. However, since there is a direct correlation with the increase in soil resistance and decrease in root elongation, roots growing in soils with a higher penetration resistance could be compromised enough to affect the growth of the plant overall. In our trial, soil penetration resistance values were relatively high and already approaching 2000 kPa at 300 mm soil depth, possibly due to the presence of concretions (Fig. 5.5-2). The data that we were interested in was the topsoil penetration resistance values, and in the absence of plant root data or soil bulk density, we used comparative methods to evaluate the soil resistance under reduced tillage compared to

conventional tillage. Values for reduced and conventionally tilled soil were similar up to 50 mm, when a clear increase in resistance was measured under reduced tilled soils. Significant differences were measured between 110-170 mm and again at 310-350 mm (Fig. 5.5-3). This was the first indication that soil compaction could be a possible cause of the poor maize yields under reduced tillage. Compaction probably set in over the last three experimental years, which coincided with the switch from manual field preparation to using a tractor, however, not in a controlled traffic system.

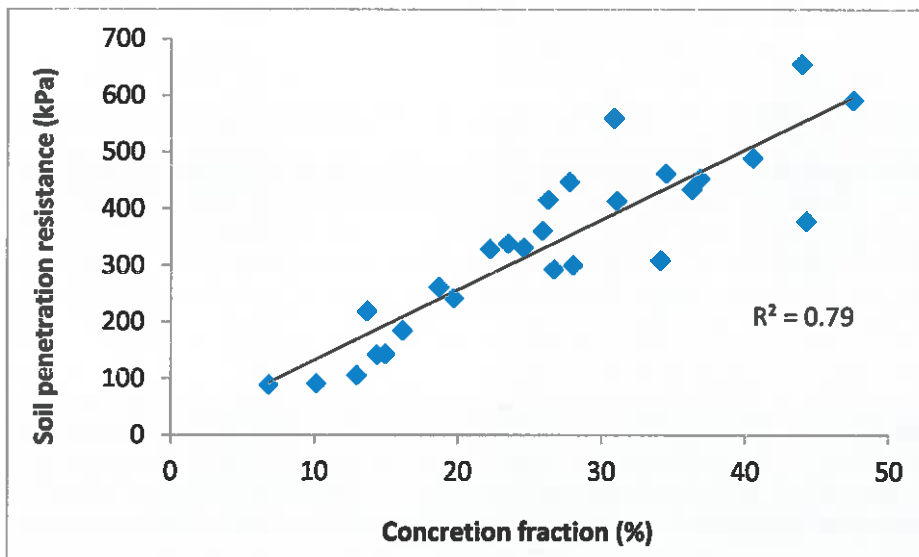


Figure 5.5-3: Correlation between soil penetration resistance and concretion fractions.

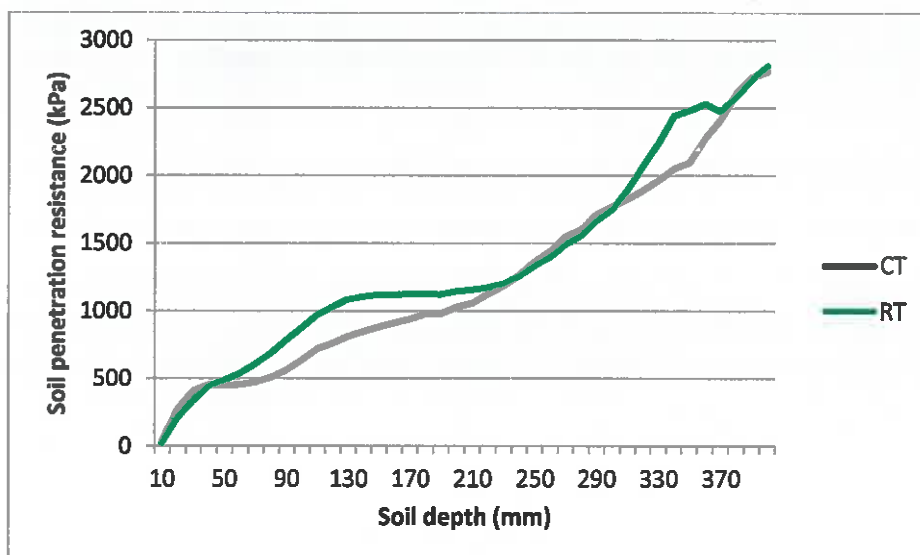


Figure 5.5-4: Soil penetration resistance values from RT and CT, at the Zeekoegat field trial.

Discussion and Conclusion

So where does this leave us in terms of CA? Do these results indicate that CA does not work? No, absolutely not. Our results stress the importance of practising CA in an adaptive manner, a trial-and-error approach continuously working to adapt the CA principles to the local socio-economic and biophysical constraints. Soil compaction is definitely a potential problem, especially during the transformation period, although not everyone agrees on how to address this problem. It is also true that there is no absolute right or wrong, just different solutions in different situations. Farmers on sandy soils will tell you that no-till does not work well in their situation and that they need to do some (deep) tillage every year, as their sandy soil is naturally very prone to compaction. An example where reduced tillage is practised successfully to alleviate compaction in very sandy soils is the so-called 'rip-on-the-row' system on the water table sandy soils in the northwestern Free State. The situation on clayey soils is very different, and compaction could take longer to show an effect; in this situation it is currently common practice to do some form of soil tillage every 3 years, depending on the soil type and management practices. Alternatively, Dr Derpsch reckons that it is possible to practise CA successfully in any situation, even on very sandy soils, but the answer is in applying all the elements of the system with *quality*. During his dialogue sessions in South Africa, Dr Derpsch mentioned that controlled traffic systems are ideal to prevent compaction, but acknowledged that it is usually quite difficult to do it correctly. He emphasised the importance of reducing traffic in the fields, using smaller implements and reducing tyre pressure (<0.6 bars). Implementing the three CA principles of permanent organic soil cover, diversified cropping systems (including cover crops and crop rotations) and minimum mechanical soil disturbance with *quality* is essential to improve and maintain soil health and to prevent compaction over the long term. If the soil is already compacted, one could alternatively consider growing annual cover crops with deep tap-roots, like radish or rapeseed, or a permanent ley crop system for a period of around 5 years, to recuperate the soil. Crops with tap-roots have all the right characteristics to penetrate compacted soils compared to fibrous-rooted species, and could help to alleviate compaction through "biological tillage".

Finally, it is clear that farmers, researchers and other practitioners should apply appropriate methods to evaluate compaction or other restrictive layers in the soil. Soil penetration resistance can be used successfully in certain conditions, but should preferably be supported with additional data such as soil bulk density and root distribution. The latter is an excellent

practical indicator and farmers are encouraged to do routine root evaluations in the soil profile during the growing season.

5.6 Agronomic Aspects: Weeds

Temporal variation in weed occurrence and biomass under conservation agriculture and conventional tillage practices at Zeekoegat, Gauteng, South Africa⁴

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Abstract

Conservation agriculture (CA) is advocated as a management system for sustainable productivity, while preserving the environment at the same time. CA has many advantages, but weed management is regarded as one of its biggest challenges. This study reports on the temporal variation in weed occurrence and biomass under conservation and conventional farming practices. A split-plot randomised complete block design with three replicates was employed, including tillage as the main plot factor (reduced tillage [RT] and conventional tillage [CT]), and treatment (a combination of cropping systems and fertilizer levels) as the sub-plot factor. Only cultivation year ($F(2,48) = 9.12, p < 0.001$) and the cultivation year and tillage interaction ($F(2,48) = 22.41, p < 0.001$) significantly affected weed biomass. Weed biomass and species diversity increased under RT from cultivation year 3 to 5. Under CT weed biomass had a slight downward trend and species composition was similar across the three years with two dominant weeds representing between 87.2 and 75.1% of total weed biomass. The results suggest that tillage practices can affect both the biomass and diversity of weeds. It is therefore important that practitioners understand such variation and apply weed management practices accordingly.

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Introduction

In recent years, conservation agriculture (CA) has gained momentum as a more sustainable alternative agricultural management system to conventional agricultural practices (Hobbs *et al.*, 2008; Wall, 2008). This is especially true in areas where conventional agricultural practices are difficult and costly to implement. For example, it is estimated that 30-35% of the world's population do not have access to high input technologies associated with modern farming practice (Pretty, 1999). Despite the great successes achieved in the adoption of CA practices, weed management under CA remains one of the biggest challenges (Rockström & Steiner, 2003; Hobbs *et al.*, 2008; Giller *et al.*, 2009).

Weed biomass, density, composition and temporal variation are closely associated with management practices, especially tillage (Teasdale *et al.*, 1991). For example, conventional tillage practices may effectively control weeds by burial (Froud-Williams *et al.*, 1984; Hobbs *et al.*, 2008; Wall, 2008), or stimulate weed germination by raising soil temperature (Froud-Williams *et al.*, 1984; Teasdale *et al.*, 1991; Murphy *et al.*, 2006). Alternatively, minimal or reduced tillage can shift weed composition from broadleaf to grass species (Swanton *et al.*, 1999) or perennial weeds (Vogel, 1995), or increase weed species diversity when specific habitats for certain weeds was created (Murphy *et al.*, 2006). Mulch or soil cover may reduce or inhibit weed germination through the release of allelopathic compounds (Christoffoleti *et al.*, 2007) or smothering of weeds (Teasdale *et al.*, 1991; Thierfelder & Wall, 2010). Furthermore, weeds can be influenced by location, year, nitrogen management (Swanton *et al.*, 1999), timing of cultivation, rainfall (Teasdale *et al.*, 1991), crop residue management, crop rotations, harvest procedures and other aspects of the production system (Wall, 2008).

Conventional tillage practices have many advantages, such as preparation of the seedbed, uniform placement of seeds, temporary relief from compaction and effective removal of all weeds prior to planting (Hobbs *et al.*, 2008). On the other hand, reduced tillage lessens the use of fossil fuels, decreases runoff and erosion, thereby conserving soil organic matter (SOM), and preventing soil physical degradation (Hobbs *et al.*, 2008; Wall, 2008). All three of the CA principles are intended to increase SOM, which, in turn, results in improved physical, chemical and biological properties of the soil that are associated with practising CA (Bot & Benites, 2005). High input cost, decrease in soil productivity and depletion of SOM could motivate a farmer to change from conventional agriculture to CA. However, this change could also present new challenges regarding weed management (Rockström & Steiner, 2003; Murphy *et al.*, 2006).

It is therefore important to understand not only the effect of agricultural practices on weed dynamics, but also the temporal variation expected under different agricultural practices. This study reports on the effect of conservation and conventional agricultural practices on weed abundance and biomass as well as the temporal variation in weed species composition in a long-term field trial at Zeekoegat, Gauteng, South Africa.

Materials and Methods

Experimental site

An on-station field trial was conducted at Zeekoegat, north of Pretoria (25° 36' 55" S, 28° 18' 56" E), in Gauteng Province, South Africa. The soil form is Shortlands with a clayey texture. An iron-manganese oxide concretion layer occurs at varying depths of 500-1000 mm throughout the trial area. The mean daily minimum and maximum temperatures are 10.8 °C and 27.1 °C, respectively, and the mean long-term rainfall for the area is 704 mm/year (AgroClimatology Staff, 2006). An automatic rain gauge (Texas 525 TE) was installed adjacent to the field trial, providing site specific rainfall measurements for the duration of the trial (Table 5.6-1).

Table 5.6-1: Site-specific rainfall data for Zeekoegat experimental farm for the period 2009-2012 indicating rainfall as corresponding with planting dates and weed sampling

	Planting start date	Weed sampling start date	Rainfall for period between planting and sampling (mm)	Total rainfall for season* (mm)
Season* 3 2009/10	18 Nov 2009	13 Jan 2010	294.2	1316.7
Season* 4 2010/11	29 Nov 2010	25 Jan 2011	544	1010.8
Season* 5 2011/12	29 Nov 2011	10 Jan 2012	200.1	571.5

* Season started in June and ended in May

Trial layout

The trial was laid out as a split-plot randomised complete block design replicated three times. Each replicate was split into two tillage systems (whole plots) and then each whole plot (reduced tillage [RT] and conventional tillage [CT]) was further subdivided into six treatments (three cropping systems x two fertilizer levels), giving a total of 36 plots. The cropping systems were: maize monoculture (MM), maize/soybean rotation (MS) and maize/cowpea intercropping (MC). Fertilizer was applied at a high level according to the fertilizer application guidelines, and at a

low level, which was 50% of the high application. Plot dimensions were 7.2 m x 8 m with 0.9 m planting rows. The maize (*Zea mays*, cultivar 6P/110 from Pannar) in the MC treatment was planted in 1.8 m tramline rows to accommodate the intercropping of cowpea (*Vigna unguiculata*, mixed variety) between maize rows.

Land preparation and weed management

At the onset of each season, all crop residues from the previous season were flattened and slashed. The CT plots were ploughed with a mouldboard plough and then disked with a disk harrow. Furrows were drawn with a four tine cultivator frame on both CT and RT plots.

Weed control consisted of a combination of chemical treatment and manual weeding. During November, just before planting, Roundup® (glyphosate) and DualGold® (S-metolachlor) were applied equally across the trial by using a tractor and sprayer. Crops were planted after significant rainfall, usually by the end of November or early December. After crop emergence, manual weeding was done two to three times during the season, by using hand hoes to remove weeds between the crops. Weeds were sampled before the first manual weeding in January of each year. Ideally no weeds should occur on a research trial. However, due to the nature of the sampling (chemical weed control interfered with biological samples), and due to the planting time (weed populations established during December vacation time when there was no labour available for manual weeding), some weeds did occur. This situation is representative of most small to medium scale farming practices, where either labour manual weeding or funding for chemical treatments is limiting and weeds remain a challenge.

Data collection

The Zeekoegat trial was designed to quantify effects of CA on soil and plant properties. Since weed evaluation was not originally included in the aim of the trial, weed data was initially opportunistically collected. However, in the third trial season (2009/10) the obvious difference between weed composition under reduced and conventional tillage systems served as a motivation to start thorough weed data collection. Weed samples were thus collected in January 2010 (third cultivation year (yr 3)), January 2011 (yr 4) and January 2012 (yr 5).

Two destructive weed sub-samples of 1 m² each were combined to represent each plot. To eliminate biased sampling, the sub-samples were taken at fixed points. In each, individual weeds were removed at ground level (above-ground biomass) after which they were oven dried at 40 °C and weighed. The weights of two dominant weeds, large apple thorn (*Datura ferox*) and

purple nutsedge (*Cyperus rotundus*), were measured separately, to calculate their relative abundance. Other weeds, which included flax-leaf fleabane (*Conyza bonariensis*), khaki weed (*Tagetes minuta*), khaki bur weed (*Alternanthera pungens*), common blackjack (*Bidens pilosa*), narrow-leaved ribwort (*Plantago lanceolata*), and devil's thorn (*Tribulus terrestris*) were grouped in a separate class 'Other'. The focus was initially only on large apple thorn and purple nutsedge as they were the obviously dominant weeds. By the fifth cultivation year, other weeds were also becoming dominant, albeit in the RT plots (such as flax-leaf fleabane and khaki weed), but since these species were not included from the start, they were not specified at the end.

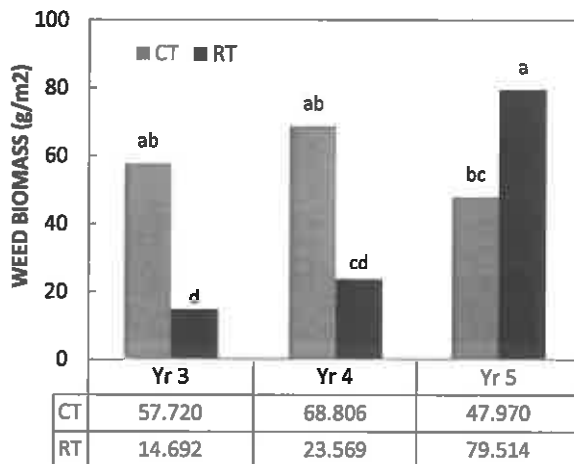
Statistical analyses

Weed biomass data was subjected to analysis of variance, using a split-plot model. Tillage was the whole-plot factor, subdivided into six treatments (three cropping systems x two fertilizer levels), with cultivation year as the repeated variable. Cluster analysis (vertical hierarchical tree plot) was used to statistically analyse data on weed biomass using STATISTICA 6.1 (StatSoft Inc. Tulsa, OK, USA). A dendrogram was constructed with Ward's clustering algorithm, and the Euclidean distance measured, i.e. the geometric distance between variables in a multidimensional space. Analysis of variance was done with statistical package R (R Development Core Team, 2012).

Results and Discussion

Weed biomass

Weed biomass was significantly affected by cultivation year ($F(2,48) = 9.12, p < 0.001$), as well as the cultivation year and tillage interaction ($F(2,48) = 22.41, p < 0.001$). No other main effects or interactions were significant. Weed biomass under RT systems was low in the third cultivation year (weed biomass for cultivation year 1 and 2 was not determined), but increased significantly by the end of the fifth cultivation year (Fig. 5.6-1). Under CT, however, weed biomass was initially high, but it stayed more constant, even decreasing overall (Fig. 5.6-1). The results suggest that a temporal variation can be expected; with an increase in weed biomass under RT practices while under CT practices weed biomass was more stable.



* Significant differences are indicated by different letters (a, b, c and d)

Figure 5.6-1: Effect of tillage practice (CT = conventional tillage; RT = reduced tillage) and cultivation year on weed biomass (g/m²) at the Zeekoegat field trial, 2009-2012.

The significant interaction between tillage and the cultivation year is confirmed in the cluster analysis (Fig. 5.6-2). Cluster analysis assigns treatments into groups, thus clustering similar treatments together. Three distinctive clusters were identified, with a RT-only cluster on the left (exclusively from cultivation year 3 and 4), a CT-only cluster on the right (mainly from year 3 and 5), and thirdly, a mixed cluster (consisting of both CT and RT) closely linked to the CT-only cluster. It is interesting to note that the RT treatments included in the mixed cluster are all from cultivation yr 5, where the biomass was, contrary to previous cultivation years, exceptionally high. The dendrogram successfully illustrated the shift in weed biomass dynamics under CT and RT from the third to the fifth cultivation year.

The results concur with other authors (Teasdale *et al.*, 1991; Vogel, 1995; Mashingaidze *et al.*, 2012) who also recorded increased weed biomass with cultivation time under RT practices. Furthermore, the temporal variation in weed biomass under different tillage practices concur with Swanton *et al.* (1999) who reported that weed biomass varied between tillage practice and cultivation year. In conventionally tilled soils, this can be explained by the increase in environmental variables, such as temperature and moisture, as a result of tillage. Increased environmental variables could lead to more favourable conditions in certain years, and this in turn could lead to a large year-to-year variation in weed density (Clements *et al.*, 1996). Additionally, tillage could increase the soil temperature and stimulate weed germination (Froud-Williams *et al.*, 1984). Weed biomass in tilled soils is thus a function of burial depth, periodicity of emergence and climatic conditions such as rainfall and temperature (Froud-Williams *et al.*,

1984; Teasdale *et al.*, 1991; Mashingaidze *et al.*, 2012). In contrast, under reduced tillage soils, weed seeds are often buried shallower, which might lead to more weed germination. Weed germination under RT systems would more likely be linked to rainfall than temperature, as is the case in CT (Froud-Williams *et al.*, 1984). Thus, weed biomass, emergence or diversity might be increased or decreased in both tillage systems, but for different reasons. It is therefore possible to see large year-to-year fluctuations between RT and CT as the specific weed seed bank changes, or certain climatic factors favour one or the other system (Menalled *et al.*, 2001; Murphy *et al.*, 2006).

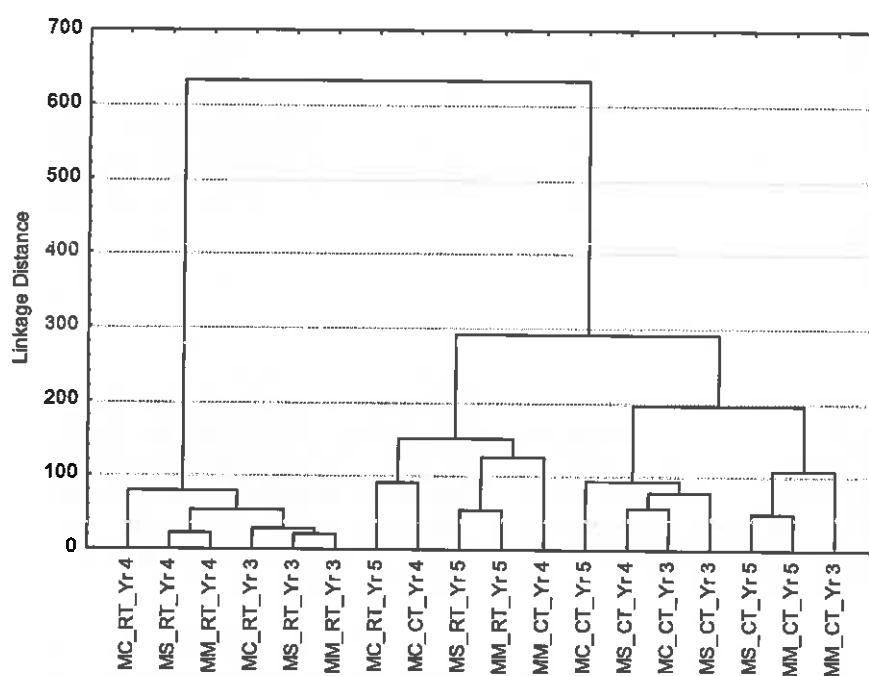


Figure 5.6-2: Dendrogram illustrating the clustering of weed biomass under CT and RT from the third to the fifth cultivation year.

Weed diversity

The visual effect of tillage on weed occurrence was very clear (Plate 5.6-1). The CT system was annually dominated by the two pioneer weed species, i.e. large apple thorn and purple nutsedge, which when combined, contributed to 87.2% (yr 3), 75.1% (yr 4) and 78.5% (yr 5) of the total weed biomass (Fig. 5.6-3). This can be explained by the succession of a plant community that must start anew each year after ploughing, resulting in pioneer plants germinating first, thus dominating weed composition. However, under RT systems, there was a temporal increase in weed diversity (Fig. 5.6-3) largely due to the successional trajectory of the weed community (Murphy *et al.*, 2006). Weed communities are indicative of ecological succession, and since a

reduction in soil tillage leads to a reduction in agro-ecosystem disturbance, the associated change in weeds can be measured accordingly (Clements *et al.*, 1996). Under RT the dominant weeds (large apple thorn and purple nutsedge) actually declined in biomass (34.8% [yr 3], 28.3% [yr 4], 13.4% [yr 5]; Fig. 5.6-3). The decrease in pioneer weed species under RT coincided with an increase in other weeds, such as flax-leaf fleabane, khaki weed, khaki bur weed, common blackjack and devil's thorn.

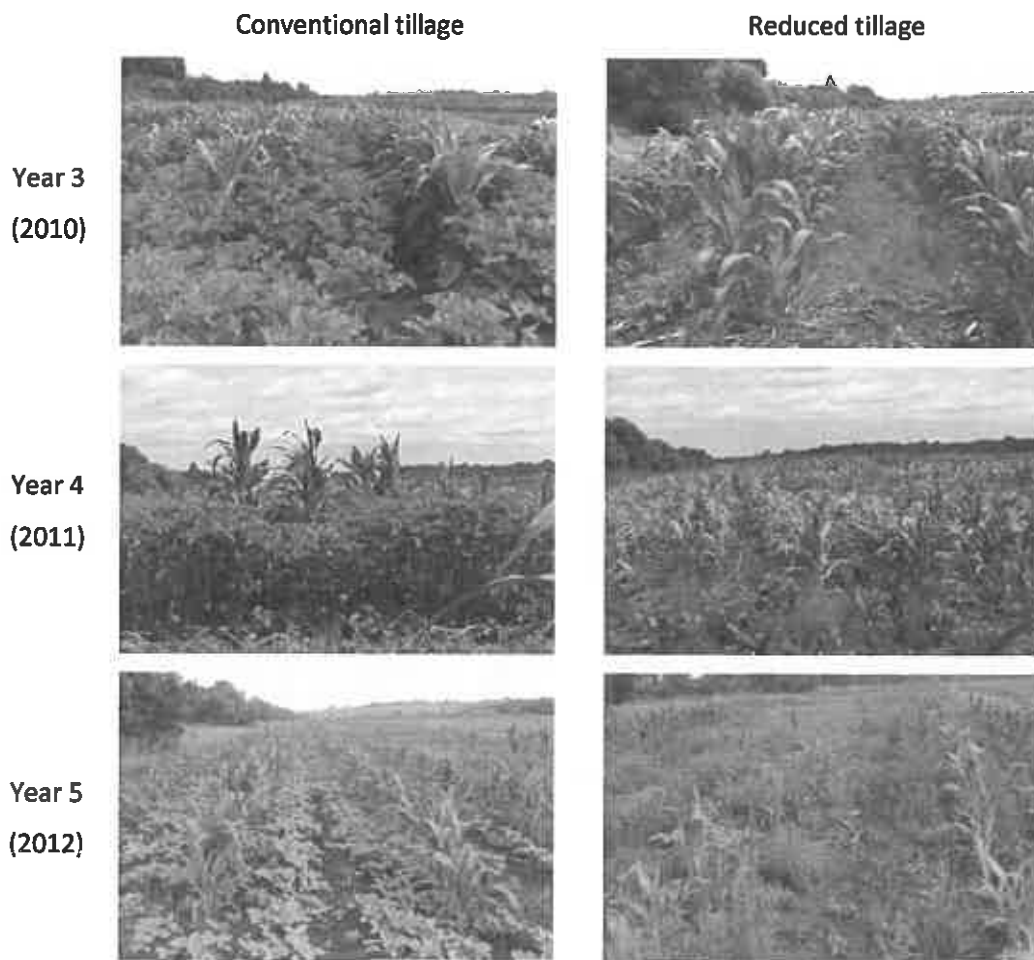


Plate 5.6-3: Weed infestation under conventional tilled soils (left) and reduced tilled soils (right) for the three cultivation years (2010, 2011 and 2012).

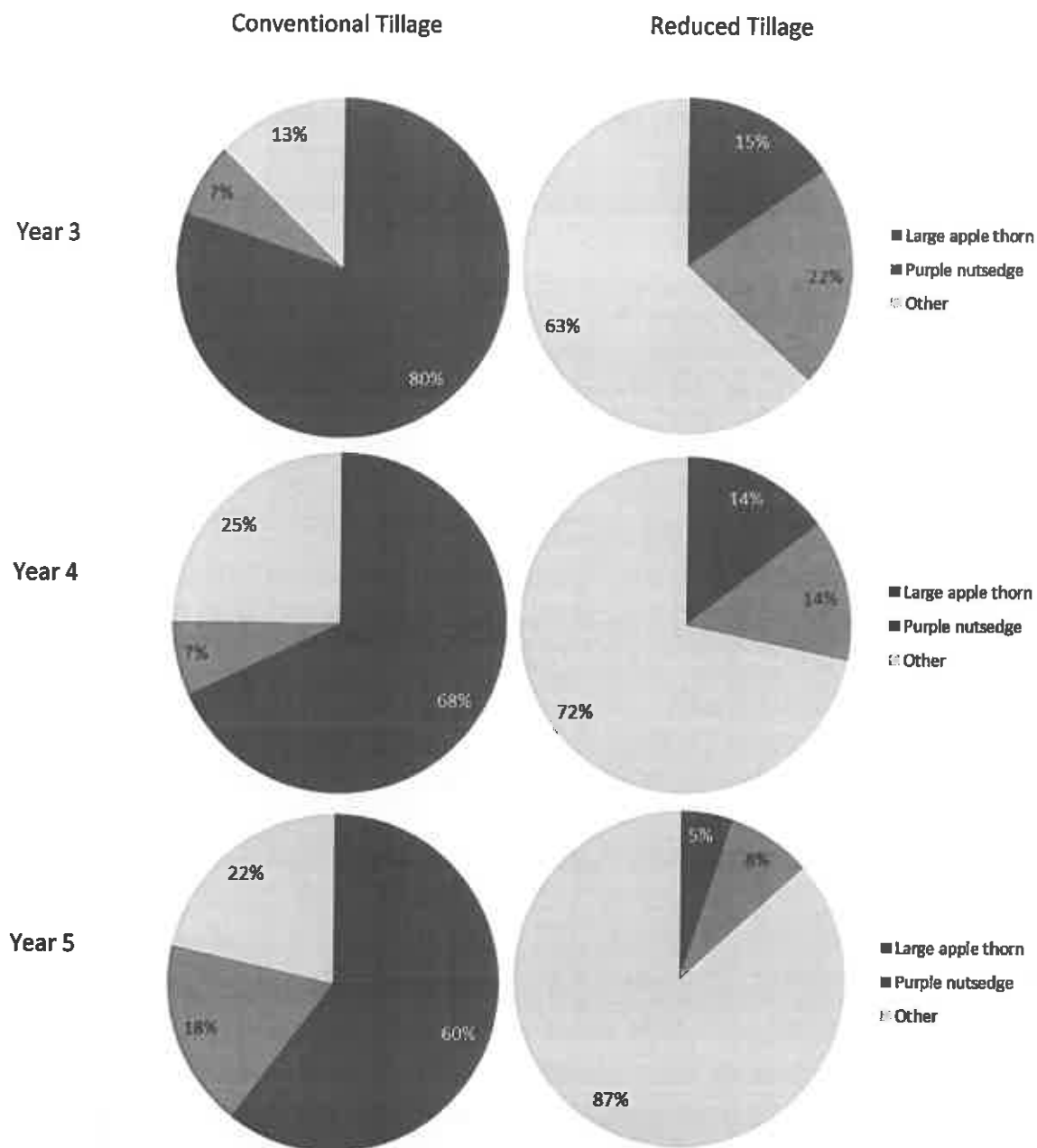


Figure 5.6-4: Temporal variation of weed species composition (% of biomass), under CT (left) and RT (right) practices, for a long-term trial at Zeekoegat.

Crop performance

The impact of increased weed diversity on crop performance could be negative or neutral depending on the farming system (Murphy *et al.*, 2006; Giller *et al.*, 2009). In this study, no significant impact of weed diversity or weed biomass was found on maize grain yield production (Fig. 5.6-4). This result concurs with a study done by Murphy *et al.* (2006), where increased weed species composition under commercial no-till systems did not result in significant crop losses. However, in smallholder CA systems increased weed biomass and diversity could lead to an increase in the amount of labour required for weeding, or alternatively requires increased use

of herbicides (Giller *et al.*, 2009), which can be a major limitation in implementation of CA on smallholder farms.

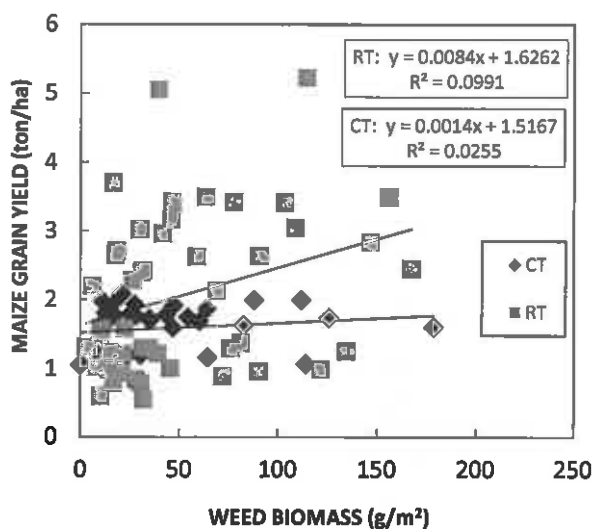


Figure 5.6-5: Effect of weed biomass on maize grain yield under CT and RT practices, for a long-term trial at Zeekoegat.

Conclusion and Management Implications

After five cultivation years of CA practices, a measurable shift in weed biomass and species composition was observed. Cover crops and crop rotation did not have an effect on weed biomass, possibly due to low biomass from previous years that led to ineffective soil cover and weed management. Tillage and cultivation year, however, did have an effect, and while weed biomass was initially low under RT in cultivation yr 3, it had increased considerably by yr 5, possibly due to a build-up of the seed bank. Species composition also changed; pioneer weeds made up a decreasing fraction of the weeds under RT, while under CT, more than three quarters of the weed biomass consisted of the two main pioneer weeds. The results confirm that weed dynamics under RT can be inconsistent, and that the increase in weed species diversity complicates weed management programmes. Adaptable weed management (where continued monitoring of a system should influence the decision-making process and can be changed as needed depending available resources) or integrated weed management (combination of biological, chemical and mechanical weed management) should be practised for effective weed control. Such weed control programmes can include crop rotation and application of mulch (Teasdale *et al.*, 1991; Swanton & Murphy, 1996). Cover crops or mulch only suppress weeds

effectively when the cover is adequate, and should cover at least 30% of the soil surface (CTIC, 1999).

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5.7 Nematodes⁵

M Marais and A Swart

Nematology Unit, Biosystematics Programme, ARC-PPRI

Background

The Nematology Unit joined the Zeekoegat research team during the 2008/09 season, with the main purpose to monitor, over an extended term the succession of nematode trophic levels, genera and species in some of the reduced tillage and conventional tillage treatments of the trial. In this we were trying to gain a better understanding of the effect of tillage on nematodes under South African conditions. It is known that long-term cycles of land use can have influence on the structure of nematode communities.

Materials and Methods

The nematode samples were each year collected from end of January to beginning of February depending on when the trial was planted. Two or three maize plants in the key treatment plots of Block B were sampled. Each sample was placed in a labelled plastic bag, transported to the laboratory and stored at 12 °C. Each sample was thoroughly mixed from which a 250 cm³ soil sub-sample was collected. Nematodes were extracted according to the sieving-centrifugation-sugar-flotation method (Kleynhans, 1997). The roots were rinsed and cut in smaller pieces (\pm 20 mm), the material (20 g) was shredded in a food blender, washed through 1000 μ m, 150 μ m, 45 μ m and 38 μ m aperture sieves. The residue of the last three sieves was transferred to 100 ml centrifuge tubes and the nematodes extracted according to the centrifugation-sugar-flotation method. The population numbers of the plant-parasitic nematodes were determined by withdrawing a sub-sample into a De Grisse counting dish, identifying the nematodes to genus level and counting the number of specimens of each genus with a Laboratory DC Counter. For quick identification to species level, the nematodes were mounted on temporary slides and identified with a research microscope by relevant experts (Table 5.7-1) in the ARC-PPRI Nematology Unit. The plant parasitic nematodes found at the trial site over the course of the trial are given in Table 5.7-2. The population numbers of the other groups of free-living nematodes as defined by Yeates *et al.* (1993) were also determined using the same method and during the same time as that of the plant-parasitic component. The effects of the different

⁵ Funded through the "Biosystematics of important nematodes (J13001)" project of ARC-PPRI

treatments on the nematode population had not been evaluated. Current work suggests that the relative abundance of fungivorous and bacterivorous nematodes is sensitive to management changes and may be a good indicator of underlying changes in the composition of the nematode fauna, therefore the population numbers of the different free-living nematodes were also determined since the 2009/10 season (see Appendix 2).

Table 5.7-1: Relevant experts in the ARC-PPRI Nematology Unit

	Family	Subfamily	Genus
Dr Mariette Marais (Nematology project leader)	Trichodoridae		
	Belonolaimidae		
	Dolichodoridae		
	Heteroderidae	Meloidogyninae	
	Hoplolaimidae		<i>Helicotylenchus</i>
Dr Antoinette Swart	Anguinidae;		
	Longidoridae		
	Aphelenchoididae		
	Heteroderidae	Heteroderinae	
Dr Esther van den Berg	Cricematidae		
	Pratylenchidae		
	Tylenchulidae		
	Hoplolaimidae		

Results and Discussion

The classification followed in the report is a synthesis of those employed by Maggenti *et al.* (1988) and Hunt *et al.* (2005) for Tylenchina; Hunt (1993) for Longidoridae and Decraemer (1995) and Duarte *et al.* (2010) for the Trichodoridae. To compensate for the effect of the feeding behaviour of the different nematodes, the results of the nematodes extracted from the roots and soil were combined and are given in Appendix 2.

Table 5.7-2: Incidence of herbivores observed in soil and roots in key plots in Block B

Nematodes	Common name	2008/09		2009/10		2010/11		2011/12		2012/13	
		Roots	Soil	Roots	Soil	Roots	Soil	Roots	Soil	Roots	Soil
BELONOLAIMIDAE											
<i>Tylenchothynchus brevilineatus</i> Williams, 1960	Stunt nematodes	6*	31	17	33	17	33	-	25	-	33
<i>Tylenchothynchus</i> spp. (immature)		-	19	-	-	-	-	-	-	8	25
<i>Geocenamus brevidens</i> (Allen, 1955) Brzeski, 1991		-	6	-	-	-	-	-	-	-	-
PRATYLENCHIDAE											
<i>Pratylenchus brachyurus</i> (Godfrey, 1929) Filip'ev & Schuurmans Stekhoven, 1941	Lesion nematodes	50	44	17	83	8	-	8	8	-	-
<i>Pratylenchus penetrans</i> (Cobb, 1917) Filip'ev & Schuurmans Stekhoven, 1941		75	63	-	-	-	-	-	-	-	-
<i>Pratylenchus zeae</i> Graham, 1951		25	31	100	83	100	100	82	82	100	100
HETERODERIDAE											
<i>Meloidogyne</i> spp. (immature)	Root-knot nematodes	-	-	-	-	-	17	8	-	17	17
<i>Meloidogyne javanica</i> (Treub, 1885) Chitwood, 1949		-	-	2	33	-	-	-	-	-	-
HOPLALAIMIDAE											
<i>Helicotylenchus</i> spp. (immature)	Spiral nematodes	-	-	-	-	17	25	-	33	-	-
<i>Helicotylenchus digonicus</i> Perry in Perry, Darling & Thorne, 1959		-	13	-	-	-	-	-	-	-	-
<i>Helicotylenchus dthystera</i> (Cobb, 1893) Sher, 1961		31	63	-	25	-	-	-	-	9	25
<i>Scutellonema brachyurus</i> (Steiner, 1938) Andrásy, 1958		100	100	92	83	75	100	17	100	3	83
<i>Rotylenchulus parvus</i> (Williams, 1960) Sher, 1961				92	92	92	100	50	83	75	92
CRICONEMATIDAE											
<i>Criconemoides sphaeroccephalus</i> Taylor, 1936	Ring nematodes	-	19	0	25	8	33	-	42	8	8
<i>Criconemoides xenoplax</i> Raski, 1952		-	13	-	-	-	-	-	-	-	-
<i>Hemicyclophora typica</i> de Man, 1921	Sheath nematodes	6	6	-	-	-	-	-	-	-	-
TRICHODORIDAE											
<i>Nanidorus minor</i> (Colbran, 1965) Siddiqi, 1974 = <i>Paratrichodorus minor</i> (Colbran, 1956) Siddiqi, 1974	Stubby root nematodes	-	81	42	58	-	92	-	58	-	67
LONGIDORIDAE											
<i>Longidorus pisi</i> Edward, Misra & Singh, 1964	Needle nematodes	-	-	-	-	-	8	-	-	-	33

* Incidence

Plant-parasitic nematodes

All the plant-parasitic nematodes (herbivores) that have been found at the trial site (Table 5.7-2) have previously been reported in association with maize or soybeans in South Africa (Kleynhans *et al.*, 1996; South African Plant-Parasitic Nematode Survey database). One hundred and sixteen plant-parasitic nematodes species belonging to 24 genera are reported associated with maize in South Africa (Kleynhans *et al.*, 1996; South African Plant-Parasitic Nematode Survey database).

Nematode communities in crop soils are highly variable in their composition and the feeding of plant-parasitic nematodes on plant tissue, their interaction with fungi and bacteria or their transmission of viruses can significantly influence the plant growth and reduce crop yields. The genus *Tylenchorhynchus* is found throughout South Africa associated with a large variety of crop plants (SAPPNS database). The genus is primarily considered ectoparasites that feed along the root surface penetrating epidermal cells of roots and root hairs. Occasionally they do feed as endoparasites, usually confined to the outer cortical layers of the root (O'Bannon *et al.*, 1991). *Tylenchorhynchus brevilineatus* one of the most common of the so called stunt nematodes was found during all five planting seasons. *Geocenamus brevidens* another stunt nematode found in all nine provinces in South Africa was only observed during the 2008/09 season (Kleynhans *et al.*, 1996).

In a questionnaire survey South African nematologists regarded *Pratylenchus* as the second most economically important genus after *Meloidogyne* in South Africa (Keetch, 1989). *Pratylenchus* spp. are considered important in agriculture not only because of their very wide host range, which include some weeds, but also because of their distribution in almost every temperate and tropical environment (Davis & MacGuidwin, 2000; Ntidi *et al.*, 2012). *Pratylenchus brachyurus*, *Pratylenchus penetrans* and *Pratylenchus zaeae* were the most common endoparasites found at the trial site (Table 5.7-2). These nematodes are common in maize fields and are often associated with poor growth (McDonald & Nicol, 2005). In Zimbabwe, Martin *et al.* (1975) found that a good host plant such as maize will permit an increase in the *Pratylenchus brachyurus* population which alone could produce a yield loss of approximately 25%. *Meloidogyne javanica* is one of four *Meloidogyne* species reported from maize in South Africa (Kleynhans *et al.*, 1996; South African Plant-Parasitic Nematode Survey database). Maize is regarded as a good host to root-knot nematodes. An interesting phenomenon is that the typical

galls formed by root-knot nematode infestation may be absent and therefore maize has often been considered a poor host of *Meloidogyne* species (McDonald & Nicol, 2005).

The semi-endoparasitic genera *Helicotylenchus* and *Rotylenchulus* and ectoparasitic genus *Scutellonema* are common in South African soils (Kleynhans *et al.*, 1996). High population numbers were recorded for these genera at Zeekoegat. The same trend of high population numbers was also found in tillage trials in the Eastern Cape Province and KwaZulu-Natal (Marais & Swart, 2007; Lamprecht *et al.*, 2010). According to Windham (1998) the threshold density for *Helicotylenchus dihystera* on maize in field microplots was found to be more than 2 individuals per g. Maize plants that are attacked by spiral nematodes may have numerous small light to dark brown lesions on their roots (Taylor, 1961). The high incidence of *Rotylenchulus parvus* supports previous findings that maize is a good host of this nematode (Van den Berg, 1978; De Waele & Jordaan, 1988). Maize is an excellent host for *Criconemoides* spp. or ring nematodes and although huge increases in nematode numbers on maize have been observed over a growing season, it has been difficult to establish pathogenicity of these nematodes on maize (Windham, 1998). *Nanidorus minor* or stubby root nematodes is among the most common ectoparasites associated with maize in South Africa (De Waele & Jordaan, 1988) and this nematode is also considered an important parasite of maize in the United States of America (Windham, 1998; Jackson, 2005). Please note that due to taxonomic changes, the stubby root nematode *Paratrichodorus minor* is now known as *Nanidorus minor* (Duarte *et al.*, 2010). An interesting phenomenon that was observed during the 2012/13 season was that males of *N. minor* were observed for the first time in the trial. *Nanidorus minor* males are extremely rare and were reported for the first time in South Africa from the Hermanus and the Douglas areas in the Western Cape and Northern Cape Provinces, respectively (Decraemer, 1995; Marais & Botha-Greeff, 1997). The ARC-Roodeplaat experiment farm of is one of the localities in South Africa from where *N. minor* males were reported (National Collection of Nematode database).

Plant-parasitic nematode population numbers

Of concern is the high population numbers of herbivores compared to that of the free-living nematodes in all the treatments during the different growing seasons. This can be explained by the fact that increased management levels not only causes a decrease in nematode diversity but also an increase in specific plant-feeding nematodes associated with crops (see section on comparison of incidence of the different trophic levels). The population numbers of the herbivores continued to slowly increase in the successive plantings seasons (Fig. 5.7-1). During the 2012/13 season we reported that the population number of herbivores was higher than in

the 2011/12 season except for treatments RT 27 and RT 29 (Fig. 5.7-1 and Appendix 2) (Marais & Swart, 2012; 2013). In the 2012/13 planting season the highest number of nematodes in all the sampled treatments was the 8825 herbivores observed in the RT 34 sample (Appendix 2 Table N1). This was the second year that the highest number of herbivores was observed in plot RT 34 and constitutes the second highest number of herbivores observed at the Roodeplaat CA trial (Table 5.7-3) (Marais & Swart, 2009; 2010; 2011; 2012; 2013). In all the planting seasons the incidence of lesion nematodes (*Pratylenchus* spp.) were the highest as shown in Appendix 2 Fig. N1.

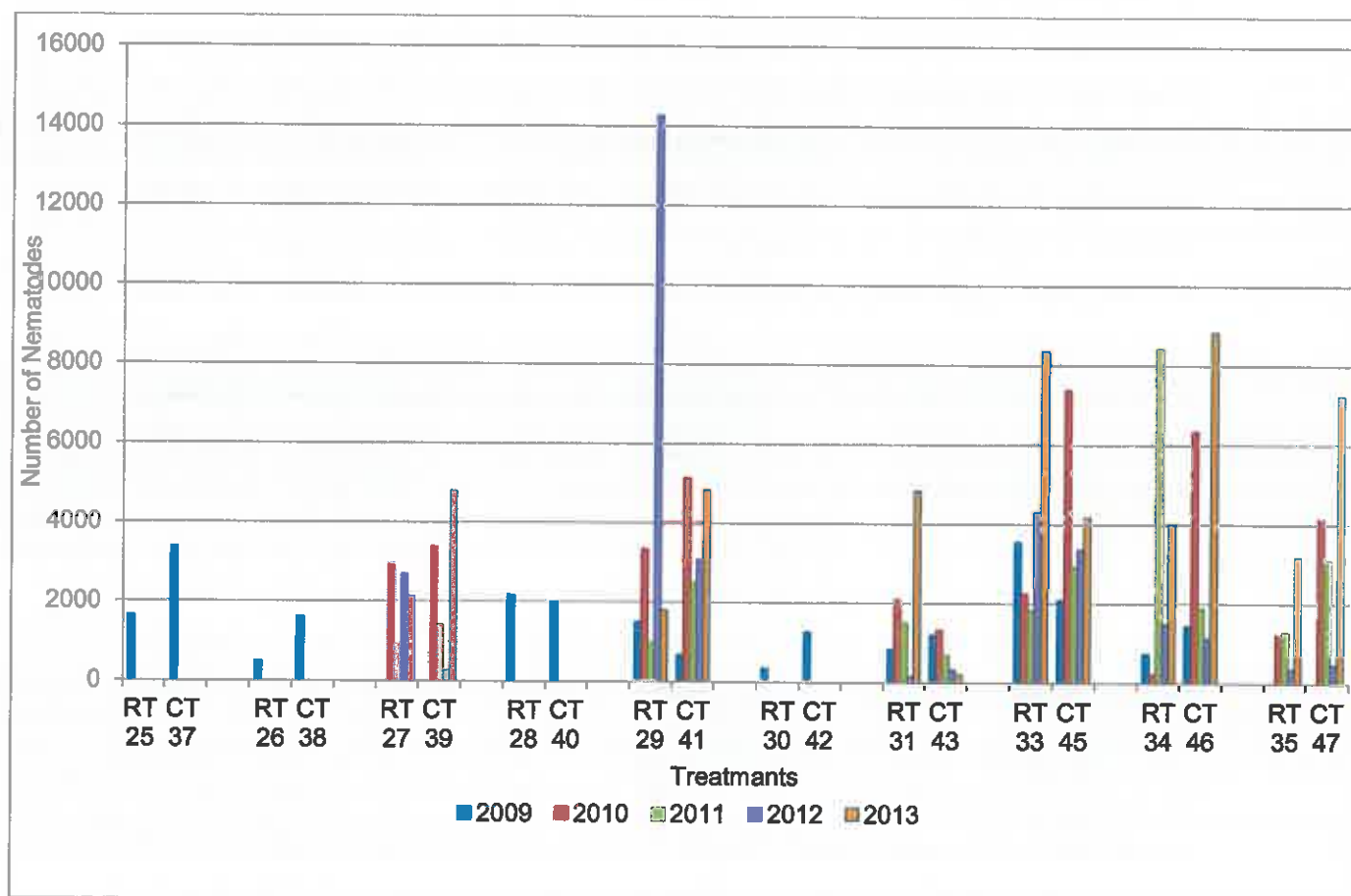


Figure 5.7-1: Population number of herbivores over the different planting seasons.

Table 5.7-3: Highest population numbers of herbivores reported (2009-2013)

	Treatment Number	Reporting Year	Number of Herbivores	% Herbivores	Crop System
Reduced Tillage	35	2013	7210	96	Maize + Soybean
Conventional Tillage	45	2010	7375	78	Maize Monoculture
Reduced Tillage	33	2013	8320	86	Maize Monoculture
Reduced Tillage	34	2011	8420	98	Maize/Legume intercropping
Reduced Tillage	34	2013	8825	88	Maize/Legume intercropping
Reduced Tillage	29	2012	14255	97	Maize Monoculture

Free-living nematodes

Conventionally, all nematodes that are not animal parasites are called free-living, including the herbivores or plant parasitic nematodes (Poinar, 1983). However, in this discussion the term free-living will be used in a more restricted sense to refer only to non-plant-parasitic terrestrial nematodes. Free-living nematodes are an integral part of the interlocking chain of nutrient conversions. They function in the recycling of carbon-containing substances, mineral nutrients and nitrogenous components. Likewise they control explosions of micro-flora and micro-fauna and maintain the balance of life forms that constitute the delicate balance of nature. Viglierchio (1991) duly emphasised the fact that although free-living nematodes are considered benign by mankind, they constitute one of the vital components in the preservation of the balance of life processes of our world.

Free-living nematodes are common in natural veld and some species are particularly common in cultivated fields in South Africa. These include members of the Rhabditida, Cephalobida, Panagrolaimida, Tylenchida, Dorylaimida, Enoplida, Aerolaimida, Triplonchida and Mononchida (Heyns, 1971). For the agriculturalist, free-living soil-inhabiting nematodes, or soil nematodes for short, are of particular interest. They are small, generally between 0.3-5.0 mm long and can be abundant (in their millions) but also diverse (commonly more than 30 taxa) in all soils (Yeates, 1979). As nematodes feed on a wide variety of soil organisms and are dependent on the continuity of soil water films for movement, their activities are largely controlled by the biological and physical conditions of the soil. Although the body form of soil nematodes is basically the same in all stages, their greatest apparent morphological diversity can be seen in the head and mouth structures, which are closely related to their feeding habits. In many studies on the relationship between nematode community structure and various agricultural practices the trophic groups are reduced to five main groups: bacterivores, fungivore, herbivores (plant-parasitic nematodes), omnivores and predators. Given this range of feeding types, the soil

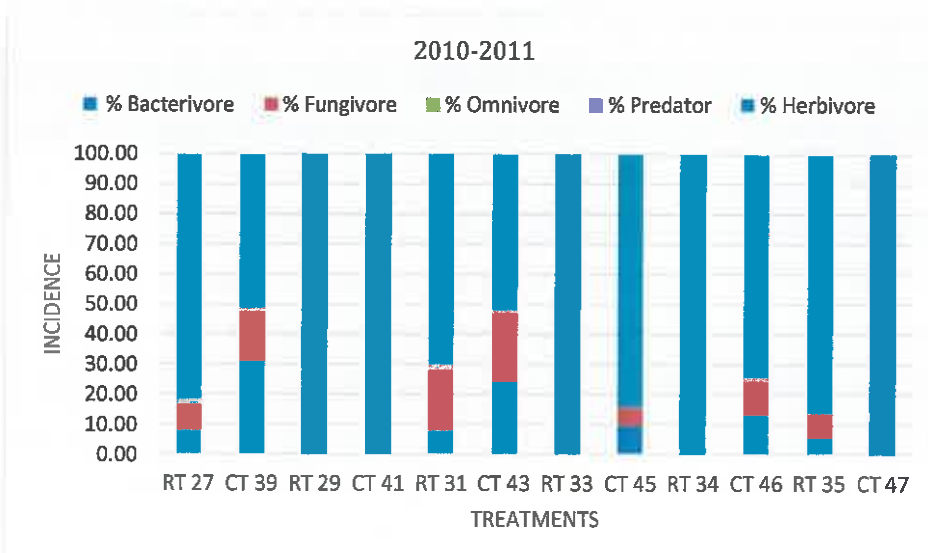
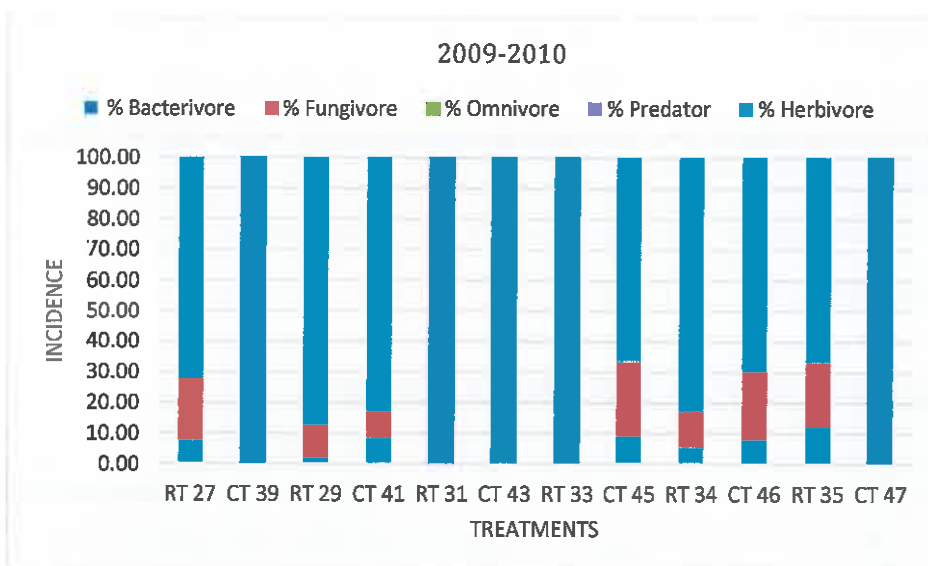
nematode fauna interacts with many other groups of soil organisms and therefore play a critical role in controlling the mineralisation of nutrients for plant growth. In soil, nematodes, collembolans and mites are three groups of mesofauna considered as important biological indicators. Of the three groups, nematodes may be the most suitable for environmental diagnosis based on the community structure analysis, especially as more information exists on their taxonomy and feeding roles (Gupta & Yeates, 1997) than for other mesofauna. Routine analysis of the nematode fauna provides a rapid assessment of responses to management activity and environmental stress. It provides decision-making criteria for conservation and remediation and a thorough understanding of nematodes in these processes is also a key to understanding the relationships between plant and soil nematode communities.

As nematodes are aquatic animals, they must be able to move freely through water films to feed and complete their life cycles. Thus in agro-ecosystems soil texture, soil moisture and the availability of suitable foods are critical in determining the diversity of the nematode fauna (Yeates & Bongers, 1999). Not only the climate-driven annual cycles of agriculture, but also longer term cycles of land use influence the proportions of various nematode taxa which make up the nematode fauna at a particular time (Yeates & Bongers, 1999).

The decrease in diversity of nematode fauna with increasing level of management reflects not only physical disturbance and change in quality of organic matter being returned to the soil, but also possible increases in specific herbivorous nematodes associated with crops (Yeates & Bongers, 1999). Generally, soils with annual arable crops contain fewer nematode species, whereas up to 154 species have been recorded in grasslands (Hodda & Wanless, 1994; Marais *et al.*, 2013). In a Dutch study (Bouwman & Zwart, 1994), arable fields receiving lower agro-chemical and tillage inputs ("integrated management") consistently had increased total nematode biomass. The greatest increase was in herbivores, but omnivores/predators were also always greater under integrated management. While the numbers of fungivores were lower, bacterivores comprised the dominant feeding group at 40-69%. Hendrix (1999) showed that no-till management favours foodwebs dominated by fungi and fungivores and high numbers of earthworms. In contrast, foodwebs in ploughed soils show greater importance of bacteria and bacterivores, which colonise buried residues. As a consequence of these altered biotic communities, residue decomposition, organic matter mineralisation and nutrient release rates tend to be higher in ploughed than in no-till soils.

Comparison of incidence of the different trophic levels

Except during the 2011/12 season (Fig. 5.7-2) in two reduced tillage plots (RT 31 and RT 35) the incidence of herbivores were always higher than that of the bacterivores, fungivores, omnivores and predators. The incidence of bacterivores in comparison to that of the fungivores were not constant. During the 2009/10 season the incidence of bacterivores was mostly higher than that of the fungivores in both the reduced tillage (RT) and conventional tillage (CT) plots. In the following three planting seasons the incidence of fungivores was generally higher than that of the bacterivores in both the reduced tillage and conventional tillage plots.



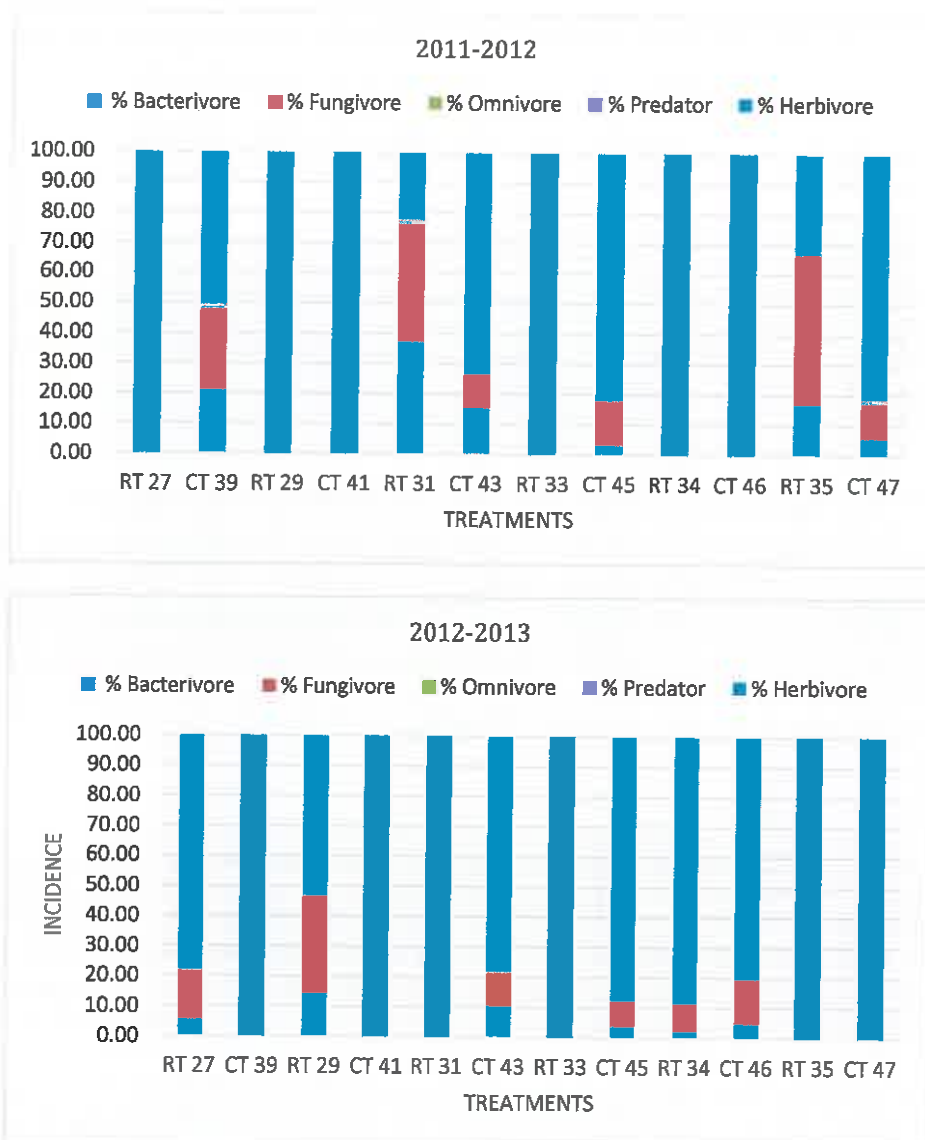


Figure 5.7-2: Incidence of different trophic levels in seasons 2009/10 to 2012/13.

Tillage

In South Africa very little is known about the impact of conservation tillage on nematode populations (Lamprecht *et al.*, 2007; 2008; Marais *et al.*, 2009). The data available in the international literature on the impact of tillage on nematode populations are inconsistent (Barker & Koenig, 1998; Mendoza *et al.*, 2008). It appears that tillage can increase, decrease or have no effect on the population size of nematodes depending on the nematode species. For example, according to Overhoff & Rossner (1990) there was significant higher infestation of *Pratylenchus* spp. under no-till compared to mouldboard ploughing, but Caveness (1974; 1979) and Alby *et al.* (1983) reported more *Pratylenchus* in tilled fields and Gallaher *et al.* (1988) reported that in a field experiment over four growing seasons *P. brachyurus* were not affected

by tillage. But in both Nebraska and Illinois reduced tillage, minimal or no-till in maize production are considered as risk factors in managing plant-parasitic nematodes (Jackson, 2005; Niblack, 2007).

The same trend of inconsistency was observed in the key plots monitored during the trial. One year the herbivores may be more numerous in the conventional tillage plots compared to the reduced tillage plot and the next year just the opposite may occur. If the population numbers herbivores in plots 29 and 41 are compared during the 2010/11 season with the same plots during the 2011/12 season (Fig. 5.7-3), it was noticed that the higher populations were observed in the conventionally tilled plot but in the following season exactly the opposite were true.

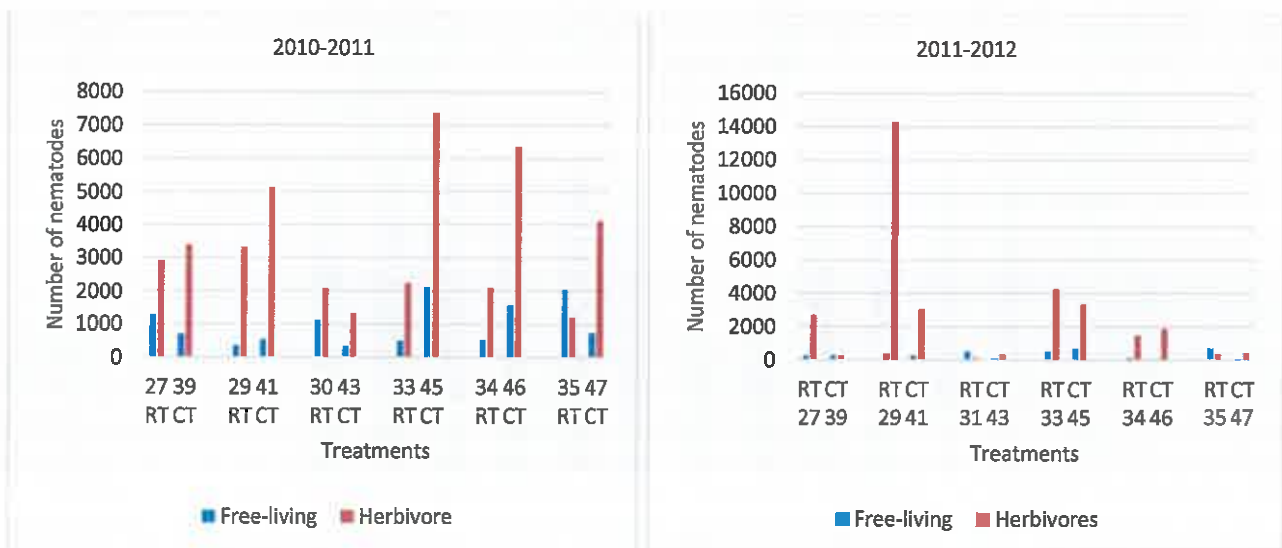


Figure 5.7-3: Number of free-living and herbivores in key plots (Block B).

Conclusions

- The information obtained during this trial is extremely valuable in gaining knowledge about the effect of tillage on soil nematodes.
- One of the most important observations is that it takes far longer to observe a definite trend, probably because there are so many factors that influence soil borne organisms.
- The activity and diversity of microbes, as reported in section 5.8, have never been reflected in the number of especially bacterial feeding nematodes, perhaps because these nematodes do not recognise these microbes as a source of food. Moreover, we do know that bacterivores is not only specific in the trophic level but may also be species specific in choosing their food source.

- Herbivores extracted from the soil and roots were *C. sphaerocephalus*, *C. xenoplax*, *H. digonicus*, *H. dihystra*, *H. typica*, *G. brevidens*, *L. pisi*, *M. javanica*, *N. minor*, *P. brachyurus*, *P. penetrans*, *P. zaeae*, *R. parvus*, *S. brachyurus* and *T. brevilineatus*. All the herbivores were also previously reported from maize in South Africa.
- Of these, *S. brachyurus*, *P. zaeae* and *R. parvus* were predominant. The plant-parasitic nematodes or herbivores found during trial will act in a complex, the genera *Criconemoides*, *Hemicycliophora*, *Scutellonema*, *Tylenchorhynchus* and *Nanidorus* as ectoparasites, *Pratylenchus* and *Meloidogyne* as endoparasites and *Helicotylenchus* and *Rotylenchulus* as semi-endoparasites.

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5.8 Soil Fauna: Soil Microbiology

Soil microbial population dynamics in the Zeekoegat CA trial

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ARC-PPRI

Introduction

Since soil biological properties, i.e. soil microorganisms, play integral roles in nutrient cycling, organic matter decomposition and soil sustainability, they can be engaged as important indicators of soil quality. An increasing demand exists to quantify the impact of various agricultural management practices on the physical, chemical and biological properties of soil (Pankhurst & Lynch, 1995). This is essential to ensure that recommended practices sustain soil health/quality and maximize profitability to farmers. While agricultural practices such as tillage, cropping sequence, fertilisation inputs, and irrigation are known to have significant effects on the physical and chemical properties, less is known of the associated changes in the biological properties of the soil (Dick, 1994). Microbial community biodiversity is an integral part of soil quality and crucial to maintain ecosystem function. It is therefore important to study communities rather than species (Degens & Harris, 1997; Degens *et al.*, 2000). Baseline data on the impact of agricultural management practices on soil microbial populations is rarely available for South African agricultural soils. Monitoring the effect of management practices on microbial diversity and activities in soil will also enable researchers to develop biological indicators or markers for sustainable crop production.

A wide range of microbiological and molecular techniques are available to study soil microbial populations. The selected methods/marker used should nevertheless be both cost-effective and useful/valuable. One such marker is the determination of functional profiles, used to measure the biological status of soil microbial populations, since it relates to the actual or potential activities of organisms that contribute to ecosystem dynamics. Biogeochemical cycling of nutrients such as carbon, nitrogen, and phosphorus, is a fundamental soil function and it is therefore of great interest to assess the relative activity of soil microbial communities. In this context, microbial community level physiological profiles (CLPP) and enzymatic activity assays are often analysed to determine the functional diversity of soil microbial populations. In both types of analyses, the ability of soil microbial populations to utilise a specific substrate is measured. Substrate availability is the main factor that influences both size and activity of microbial communities. The catabolic diversity of bacterial communities can be determined

based on sole-carbon substrate utilisation, using the Biolog[®] system. Biolog microplates were originally designed to identify gram-positive (GP/GP2) and gram-negative (GN/GN2) bacterial isolates and contained 95 different carbon substrates and a low concentration of proprietary growth medium. The Biolog EcoPlate, on the other hand, was created more specifically for microbial ecological studies and community analyses. EcoPlates were designed to contain more carbon substrate replicates than Biolog GN MicroPlates. The Biolog EcoPlate contains 31 of the most useful carbon sources for soil microbial community analyses. Utilisation of the carbon sources will give a characteristic reaction pattern to soil microbial communities called a metabolic fingerprint, from which community level physiological profiles (CLPP) are generated. Diversity indices based on richness and evenness can then be calculated with this data (Garland & Mills, 1991). This method has been used as an indication of soil quality under different land-use and management practices. Microbial communities were distinguished based on soil type, plant species, disturbance, tillage practices and cropping sequences (Zak *et al.*, 1994).

Enzymatic activity in the soil environment is a major fundamental factor to soil microbial activity in general (Garcia *et al.*, 2002). β -glucosidase, urease, acid phosphatase, and alkaline phosphatase activities were assayed because of their vital role in soil microbial activity and organic C, N and P mineralisation (Dick, 1997; Deng & Tabatabai, 1997). Although both acid and alkaline phosphatase are found in soils, acid phosphatase has been detected in animal, microbial and plant cells, whereas alkaline phosphatase has been detected only in microorganisms and animals (Alef *et al.*, 1995). Both these enzymes play important roles in plant nutrition since their activity is higher in the rhizosphere than in bulk soil. Due to the influence of pH, temperature, organic matter (OC) content, and soil water on microbial enzymatic activity, they are considered early indicators of ecosystem stress and can be biological indicators of soil degradation, rather than slowly changing soil properties such as OC.

Cropping systems that return crop residues to the field, significantly increase the activity of a wide range of soil enzymes over unamended soil, due to stimulation of microbial activity (Frey *et al.*, 1999). Over time, crop rotation also provides greater plant diversity than monoculture systems, with a positive effect on soil enzyme activities (Bolton *et al.*, 1985). Stimulation of microorganisms in the rhizosphere and improved physical condition of soils in crop rotations has been observed particularly when rotations contained legume species. The objective of this study is to determine the effect of various CA facets, especially fertilizer levels, tillage practices, and cropping systems on soil microbial dynamics over five years.

Materials and Methods

Data generated from composite soil samples randomly collected annually within 36 key plots during January 2009 to January 2013 (eight weeks after planting) was organised and subjected to various statistical analyses. Data was generated from soil samples collected from three cropping systems, i.e. maize monoculture (MM), maize/soybean rotation (MS), maize/legume intercropping (ML), at two fertilizer levels, i.e. low (FL) and high (FH), under two tillage practices, i.e. conventional tillage (CT) and reduced tillage (RT), for analyses of microbial functional diversity and enzyme activities (refer to progress reports 2009-2013 for detailed materials and methods). The functional diversity of the soil microbial populations was determined using the amount and equitability of carbon substrates metabolised as indicators of richness and evenness, respectively (Garland & Mills, 1991).

Data on soil microbial diversity indices and enzymatic activity were subjected to non-parametric statistical analyses using STATISTICA 6.1 (StatSoft inc. Tulsa, OK, USA). Dendrograms were constructed with Ward's clustering algorithm, and the Euclidean distance measure, i.e. the geometric distance between variables in a multidimensional space. Homogenous grouping with Fisher Least Significant Difference (LSD), considered to be a less conservative post hoc test than the Tukey Honest Significant Difference (HSD), was calculated at $p < 0.05$. Soil microbial biodiversity was determined using the Shannon-Weaver diversity index and Evenness Index, indicating species richness (number of active microbial species) and abundance (how "close in numbers"/"equally abundant" the different microbial species are in a soil microbial community), respectively (Magurran, 1988).

Results and Discussion

Soil microbial diversity

The mechanism of colour development in Biolog EcoPlates™ is related to differences in carbon source utilisation which, in turn, appears to relate to the number of microorganisms able to utilise the substrates within the wells of the EcoPlate as a sole carbon source (Garland & Mills, 1991). The results of this research also confirms findings by Garland & Mills (1991) that the direct incubation of environmental samples in Biolog plates produced patterns of metabolic response useful in the characterisation of soil microbial communities.

Cropping systems and tillage practices greatly influenced soil microbial carbon source utilisation and thus soil microbial richness and abundance as illustrated in Table 5.8-1 by the Shannon-Weaver and Evenness Indices, respectively (see also Appendix 3.1). The impact of cropping

systems on soil microbial richness, i.e. the number of active microbial species, is clearly demonstrated with the significant increase in microbial species in maize monoculture (MM) and maize/soybean rotation (MS) treatments under CT from the 2009/10 to the 2012/13 planting seasons. The composition of root exudates is greatly influenced by planted crops. This difference in root exudate composition between crops could thus contribute to the difference in physiological (carbon source utilisation) profiles of soil bacterial populations. The released root exudates attract microbial populations that are especially well adapted to utilise the specific compounds, thus influencing microbial richness and abundance. The impact of tillage on microbial richness is illustrated by the significant difference between maize/legume intercropping (ML) under CT and RT during the 2009/10 planting season. According to Table 5.8-1, cropping systems under CT seemingly exhibited the lowest species richness and abundance, whereas the contrary was true for cropping systems under RT.

Table 5.8-1: Comparison of soil microbial diversity dynamics under various agricultural practices during January 2010 and 2013

Sample Name	Shannon-Weaver	Sample Name	Evenness
FH-MS_CT-10	2.127 a	FL-ML_RT-13	0.698 a
FL-MS_CT-10	2.143 ab	FL-MM_CT-10	0.724 ab
FL-MS_RT-10	2.173 abc	FH-ML_CT-10	0.741 abc
FL-ML_CT-10	2.217 abc	FL-ML_CT-10	0.748 abc
FL-MM_CT-10	2.279 abcd	FH-MM_RT-10	0.748 abc
FH-MS_RT-10	2.308 abcde	FH-ML_CT-13	0.755 abcd
FL-ML_RT-13	2.309 abcde	FL-MS_RT-10	0.768 abcde
FH-ML_CT-10	2.314 abcde	FH-MS_RT-10	0.768 abcde
FL-MM_RT-10	2.336 abcdef	FH-MS_CT-13	0.770 abcde
FH-ML_CT-13	2.356 abcdef	FH-MM_CT-10	0.807 bcdef
FH-MS_CT-13	2.404 abcdef	FH-MM_CT-13	0.811 bcdef
FL-ML_CT-13	2.428 abcdefg	FL-MM_CT-13	0.813 bcdef
FL-MS_RT-13	2.432 abcdefg	FH-ML_RT-10	0.817 bcdef
FH-MM_RT-10	2.436 abcdefg	FL-MS_RT-13	0.818 bcdef
FH-ML_RT-10	2.462 abcdefgh	FL-ML_CT-13	0.819 bcdef
FH-MM_CT-13	2.496 bcdefgh	FH-MS_CT-10	0.825 cdef
FL-MS_CT-13	2.515 cdefgh	FL-MS_CT-10	0.825 cdef
FH-ML_RT-13	2.606 defgh	FL-MM_RT-10	0.825 cdef
FL-MM_CT-13	2.652 efgh	FH-ML_RT-13	0.828 cdef
FH-MM_CT-10	2.655 efgh	FL-ML_RT-10	0.833 cdef
FL-ML_RT-10	2.658 efgh	FL-MS_CT-13	0.850 def
FH-MM_RT-13	2.692 fgh	FH-MS_RT-13	0.858 ef
FL-MM_RT-13	2.786 gh	FH-MM_RT-13	0.861 ef
FH-MS_RT-13	2.814 h	FL-MM_RT-13	0.868 f

* Means within a row followed by the same letter do not differ significantly ($p > 0.05$)

The influence of cropping systems and/or tillage practices on soil microbial diversity can be better illustrated with the use of dendograms (Fig. 5.8-1). Cluster analysis was performed to assign treatments into groups, so that treatments in the same cluster are more similar to each other than to treatments in other clusters.

A clear distinction in soil microbial species richness could be observed in treatments subjected to CT during the 2009/10 season (Fig. 5.8-1a – red block) and species richness in treatments subjected to RT during the 2012/13 season (Fig. 5.8-1a – blue block), with significant increases in species richness from 2009/10 to 2012/13 in MM and MS treatments under RT. It is interesting to note that species richness in treatments subjected to CT at 2012/13 season, were more closely related to species richness in treatments subjected to CT during the 2009/10 season. Microbial species abundance was altered from the 2009/10 season (Fig. 5.8-1b – red block) to the 2012/13 season (Fig. 5.8-1b – blue block) due to different agricultural practices. The most “equally abundant” species within a soil microbial community was found in MM and MS treatments under RT (Table 5.8-1 – Evenness index), with a significant change in microbial abundance in MM treatments under RT over time. This means less variation in microbial populations between species, thus, less dominance, and higher diversity.

Close examination of the overall average species richness from the 2008/09 to 2012/13 seasons revealed the impact of various agricultural practice combinations on active soil microbial species (Fig. 5.8-2a – blue bars). Investigation of average species richness under low (FL) and high (FH) fertilizer levels (Fig. 5.8-2a – red bars) revealed more active microbial species under high fertilizer levels under RT, compared to CT. The influence of cropping systems (Fig. 5.8-2b – blue bars) revealed a wide variation in active microbial species, depending on the present crop. The highest overall average species richness was observed in ML under RT. This could be attributed to the effect of crop diversification, resulting in more diverse root exudates being released into the soil, attracting a wider number of active microbial species with the special ability to utilise these specific compounds. The average species richness was the lowest in the same treatment subjected to CT (Fig. 5.8-2b – red bars), clearly demonstrating the detrimental effect of soil disturbance on the number of active microbial species.

The Evenness index (Fig. 5.8-3) is used as an indication of how abundant microbial species are within a soil microbial community, i.e. how close in “numbers” / “equally distributed” each microbial species are within a soil microbial community. If abundances / quantities of different species in a community are measured, it will invariably be found that some species are rare, whereas others are more abundant / dominant. The variation in microbial abundance due to different agricultural practice combinations is clearly demonstrated in Fig. 5.8-3a (blue bars). The levels of fertilizer did not exert a significant effect on microbial abundance (Fig. 5.8-3a – red bars). As suspected, soil microbial species were not equally abundant in the different cropping systems (MM, MS, ML) under CT, due to the frequent soil disturbance disrupting microbial species development (Fig. 5.8-3b – blue bars). Reduced tillage, on the other hand, demonstrated a significant difference in species abundance between MM and MS (Fig. 5.8-3b), with a slightly higher species abundance under RT, compared to CT (Fig. 5.8-3b – red bars).