COMPARING SOIL MOISTURE BY TDR AND NEUTRON PROBE AT 30CM DEPTH AND CROP YIELDS IN A MAIZE AND COWPEA AGRO-FORESTRY AND GRASS STRIP FARMING SYSTEM SEMI-ARID KENYA

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ABSTRACT
Time domain reflectometry (TDR) was compared with the neutron probe for determination of soil moisture at the top 30cm soil depth. The objective was to monitor water conservation and yield benefits obtained from hedgerows and grass strips on sloping areas. The yields from the control, mulched, mulched+hedgerow, hedgerow and grass strip treatments were compared with the moisture levels taken from the hedgerows and grass strips, 1m and 2m from structures respectively. The hedge and mulch had the highest moisture conservation benefits compared to 1 and 2m away positions. The soil moisture trends by the TDR were strikingly clearer compared to the neutron probe. For maize/Senna agro-forest system, the greatest yield benefits were in the 1st row of maize next to the hedgerow but were depressed in the middle of the alley. The 1st row of maize yield in the maize/grass strip system was depressed while those rows in the middle of grass strip had higher yields. For cowpea/Senna system, the first row of cowpea yield was depressed compared to the higher yields in the middle rows.

INTRODUCTION
Over the past, soil moisture measurements have been done using gravimetric methods and neutron probe with inevitable destruction of the soil. It has however become evident that the above methods cannot be applied especially where soil has to remain intact during the period of measurement. TDR has been found useful for this purpose and especially at the top 30cm depth where the neutron probe measures moisture inaccurately.

The surface soil moisture studies have become very crucial in agro-forestry systems because over 70% of tree roots and crop roots are found in the first 30cm soil depth (Ruhigwa et al., 1992; Toky and Bisht, 1992). The presence of fine roots in this 30cm depth show that competition for water and nutrients is inevitable (Johnson et al., 1988 and Toky and Bisht, 1992) and this may help explain yield distributions in relation to moisture within the agro-forestry alleys.

The neutron probe meter measures the volumetric moisture content of the soil indirectly at various depths of the soil profile, averaged for the volume of the soil from which neutrons are scattered. This is a non-destructive method, as it measures soil moisture availability without taking samples although access tubes have to be installed. The meter is a probe with a fast neutrons emitter and slow neutrons detector that senses the moisture content of the adjacent medium in terms of the detector count rates. Our probe
(Wallingford type I.H.III 1.85 GBq. AmBe, Abingdon, Oxford, England) was lowered inside an aluminium access tube of 4.15 cm internal diameter, 4.45 cm external diameter and 120 cm length, and the reading of the count rates is related to the required depth. Aluminium is preferred for use as access tubes because it is relatively transparent for neutrons (Raad, de, 1994). The fast neutrons will collide mostly with hydrogen nuclei present in the water molecules in the soil medium. After repeated collisions, the neutrons move at a lower speed and travel in a random direction. This way a cloud of thermal neutrons will exist around the source. Some of the thermal neutrons will find their way back to the source. A detector which is situated above the source will detect the number of backscattered neutrons, which will be a measure of the hydrogen nuclei in the soil and hence a way of measuring volumetric moisture. The count rate readings should be related to the total hydrogen content or moisture of the soil (Ibrahim, 1992). Some soil elements have also an unusually high absorption capacity for slow neutrons, such as cadmium, boron and chlorine and hence complicate the interpretation of soil moisture content (Van Bavel et al., 1963). Care has also to be taken as some hydrogen in the soil is bound in clay particles or in soil organic matter (Rawlins, 1976).

Due to the heterogeneity of soils, it becomes very important for each soil type to have its own calibration curve (Ibrahim, 1992; Oteng'i, 1996). Differences in slope of calibration lines for the same soil type may also be due to soil compaction and dry bulk density (Greacen, 1981). Actually, the emission of neutrons from a spherical volume around the source influences the detector count rates (Van Bavel et al. 1963; Ibrahim, 1992). This is the sphere of importance (or influence) and is taken as the source of 95 % of reflected thermal neutrons, which means that if all soil and water outside it is removed, it will yield 95 % of the expected neutron flux from an infinite similar medium. As follows from the above, hydrogen content of the soil is the determining factor for the sphere of importance. The water in the soil closer to the source/detector has greater influence in the count rates than that further away.

According to Visvalingam and Tandy (1972) and Kristensen (1973) $\Theta_j = 100/(1.4+0.1*(\Theta_t))$ cm, where $\Theta_j =$ is the radius of sphere of importance and $\Theta_t$ is volumetric water content. Van Bavel et al. (1963) found from a comparable formula that data taken with a neutron probe at a depth of 20 cm and shallower were erroneous for all water contents below 35 %. The sphere of importance actually determines the depth at which measurements made could yield data with minimum error (Oteng'i, 1996). This sphere of importance is about 15 cm in wet soil and increases up to 50 cm in dry soils (Gardner et al., 1991).

TDR is also an indirect way of measuring the volumetric moisture content of the soil, particularly suited for the first top 30 cm where the neutron probe metre gives inaccurate moisture readings because of neutron escape into the air. The soil multimeter equipment (type FOM/Mts/92) of the Polish Easy Test TDR system had earlier been calibrated under the local field conditions and in the laboratory at Machakos (Gabreels and Vogtlander, 1993).

TDR is based on the measurement of the apparent dielectric constant, $K_a$, of the soil, which can be related to the soil water content and is defined as a measure of the degree of polarisation of a material. Soil is a composite of air, mineral and organic particles and water, which determine its electrical properties. The $K_a$ values for these components are $K_a = 1$ for air, $K_a = 2-7$ for mineral organic matter and $K_a = 80$ for water. Because of
the great difference in Ka for water compared to the other constituents, Ka for soil is highly dependent on the moisture content of the soil. Hence, a measurement of Ka for soil is a good measure of its volumetric water content. Because of the complex chemical structure of clay minerals, high clay content soils have high specific surface area. Since a few layers of water molecules around the soil particles are thought to have a restricted rotational freedom, the dielectric constant of these molecules are lower than that of bulk water. Organic matter in the soil has a further effect on the dielectric constant of the soil. This effect of organic matter content on the soil can be better understood by dividing the organic matter into dead and living portions. Young plant roots consist mainly of water. The TDR will interpret this fraction as soil moisture and hence overestimate soil moisture. The chemical nature of organic materials can lead to bonding of water on their surfaces. This has the effect of lowering the dielectric constant and hence the moisture content of the soil.

Temperature has also an effect on the dielectric constant of the soil. Normally Ka of soil solids and air are assumed to be temperature independent, but the dielectric constant of water decreases between about 20°C and 50°C (Gabreels and Vogtlander, 1993). Consequently, the dielectric constant of the measured soil is changing with temperature, depending on its water content and this was accounted for in the TDR formula.

**MATERIALS AND METHODS**

*Experimental site*
The on-station trials were conducted at ICRAF's Research Station at Machakos, situated 70km South East of Nairobi and lying between latitudes 1° 30' and 1° 35' South and longitudes 37° and 37° 15' East. It has an altitude of 1560 metres above sea level with the experimental plots established on 14% sloping land.

The site is semi-arid, receiving from between 310-370 mm for the short rains, occurring from mid-October until January, and 300-410 mm for the long rains, occurring from mid-March to July (Kinama et al., 2007). The soils are chromic luvisols (Kibe et al., 1981) and up to 150 cm deep. Due to low structural stability, the soils are prone to slaking, highly erodible and prone to surface capping by intense rainfall. This risk is enhanced by low sub soil permeability (Kiepe, 1995).

*Field design*
The experimental plots were on land that had been under alley cropping, with hand hoe cultivation, and long term runoff/soil erosion monitoring since the establishment of the hedgerows in 1988. The Grass strips (*Panicum maximum*) were established earlier, in 1984. The plant rows, the grass strips and the *Senna siamea* hedgerows were contour planted in about E/W directions. The experiments covered in this paper were for the short rains of 94/95 and the long rains of 1995 when TDR measurements took place out of six seasons of experimentation. During the short rains drought tolerant and high yielding cowpeas (*Vignia unguiculata, cv. K80*) were planted while maize (*Zea mays, cv. Katumani composite B*) was planted during the long rains. *Senna siamea*, a non-nodulating leguminous tree, was chosen because it was among the few multi-purpose trees/shrubs considered suitable for the area as contour hedgerows barriers. The tree species is drought tolerant and suited to the local semi-arid conditions (Rao and Westley, 1989). Its mulch is suitable for erosion control purposes because of the high amounts of tannin in the mulch (Kiepe, 1995).
Senna siamea loppings obtained from the hedgerows were used as mulch. The hedgerows were cut to a height of 25 cm two weeks before the onset of the rains and spread uniformly on the soil surface. No external source of mulch was provided in the experimental plots.

The study consisted of five treatments with no replicates. The plots measured 10 m width x 40 m downslope and the sampling procedure was replicated. This means that sampling points were replicated in each plot. The following treatments were used:

- **Treatment 1.** Maize or cowpeas control (C)
- **Treatment 2.** Maize or cowpeas + *Senna siamea* mulch (M)
- **Treatment 3.** Maize or cowpeas + *Senna siamea* hedgerow + mulch (H+M)
- **Treatment 4.** Maize or cowpeas + *Senna siamea* hedgerow with no mulch (H)
- **Treatment 5.** Maize or cowpeas + grass strip with no mulch (G)

There were four rows of maize in the alleys formed by the *Senna siamea* hedgerows. These hedgerows were 4 metres apart and within row and plant distance was 25 cm. The closest maize row to these hedgerows was 50 cm. The spacing of the maize that was completely added to the hedges was 27 cm by 100 cm, which gave a population of 37,037 plants/hectare. The G treatment had a population of 33,333 maize plants/hectare because the seven grass strips occupied an area of 70 m². The cowpeas between the hedgerows were planted at a spacing of 20 cm by 60 cm, not completely added to the hedges, which gave a plant density of 75,000 plants per hectare in the H+M and H-M plots and a plant density of 83,333 plants ha⁻¹ in the C and M plots. The G plot had a plant population of 72,917 plants ha⁻¹ as 70 m² was taken up by the grass strips. The distance from the hedgerow to the first row of cowpeas was 50 cm. There were six rows of cowpeas in the alleys of the agroforestry plots. The distances from the grass strip to the first row of maize and cowpea were 50 cm respectively.

No mulch was applied in the C plot. The second plot had its mulch obtained from the fourth, hedged, plot that had no mulch, while the third plot had mulch from its own hedgerows. The fifth plot had grass strips forming the alley and had no mulch. It had ten rows of cowpea and five rows of maize. The grass strips were cut two weeks before planting and at harvest. No fertilizer was used during the six seasons of measurement. Analysis of variance was used to assess the moisture differences among different points of measurement.

**Neutron probe measurements**

In each plot, six aluminium access tubes were installed at the selected sampling points, using the special corers that ensured that there was minimum soil compaction and disturbance. In order to protect soil and water from entering the access tubes, rubber bungs were inserted into each of the probe tubes before, and immediately after taking measurements. In the C and M plots, the first 3 access tubes were placed 10 m (downslope) from the top of the plots and about 4 m from the edge of the right side of the plots. Two others were placed at 1 m apart within the plant rows and one tube between the rows downslope at 1 m from the first two access tubes. The second 3 access tubes were placed 25 m downslope from the top of the plot in a similar manner as the first ones, but this time two of the access tubes were placed within the rows at 1 m apart and the third was placed 1 m upslope between rows (fig. 1). These access tubes in the C and M plots above were assumed to represent the sloping plot conditions. In the H+M...
and H plots, however, the access tubes were placed within the 4th and 7th hedgerows, 1 m from these hedgerows and 2 m from the same hedgerows respectively. These access tubes at 1 m and 2 m from the hedgerow were placed at the centre of the 1st and 2nd row of maize upslope and downslope in the 3rd and 7th alley respectively. For the cowpea, however, these last two pairs of access tubes were placed between the 1st and 2nd cowpea row at 10 cm downslope from the second row and between the 2nd and 3rd cowpea row at 20 cm downslope in the 3rd and 7th alleys respectively. These access tubes were assumed to represent the H+M and H conditions. In the G plot, the access tubes were placed in the 3rd and 5th grass strips, as well as 1 and 2 m from these grass strips respectively (fig. 1). The access tube positions with respect to both maize and cowpea plant rows were as described for the H+M and H plots above, but this was done in the second and fifth alley respectively (fig. 1).

In each plot, the sampling points were in similar positions on the slope. The moisture content levels were taken at 0-30 cm depth at an interval of one week, from one week before planting throughout the growing period until harvest.

The neutron detector attached to the probe was lowered into the access tube. The count rates in the 30 cm depth each plot were recorded for conversion into volumetric moisture contents, using the appropriate derived calibration equations, for analysis during calibration period.

**TDR measurements**

The TDR system was calibrated both in the field and laboratory conditions for ICRAF field station at Machakos (Gabreels and Vogtlander, 1993). The calibration showed that the results for the two methods were positively correlated \( r^2 = 0.94 \). Therefore, to use the TDR system a calibration is necessary for each specific soil and site. The formula derived for use in the Machakos lixols was of the form: 

\[
\Theta_{\text{grav}} = 1.2* \Theta_{\text{PET}} - 3.4
\]

where \( \Theta_{\text{grav}} \) = the gravimetric determined volumetric soil moisture content, \( \Theta_{\text{PET}} \) = the Polish Easy Test TDR soil moisture content reading.

The TDR equipment measures the dielectric constant of the soil and relates this directly to the soil moisture content. It also measures soil salinity and temperature if needed. For sensor installation, a small hole, 2.5 cm diameter, was made in the soil at an angle of 45°, taking care that the remainder of the soil remained undisturbed. This small hole was made using a thin iron bar, 2.5 cm diameter and length 1 m, which was driven about 37.5 cm at 45°C into the soil using a wooden hammer supported by a wooden right angled block. It was in this soil hole that the two 10 cm long TDR probe needles, measuring 2 mm diameter and separated by a distance of 16 mm, were inserted in such a manner that they remained in contact with the soil at a depth of 30 cm perpendicular to the soil surface during measurement. The TDR probe needles are supported by a 2 cm outer diameter plastic PVC pipe. A cable of 5 m connects the sensors via the plastic pipe to the TDR meter (fig. 2). As the probe needles were placed in the pre-augured hole and made contact with the soil, the TDR screen displayed the volumetric moisture content, temperature and salinity at 30 cm depth respectively. Every sampling point had one hole made from where measurements could be taken. Five TDR readings were taken by having five insertions at every sampling point and their mean taken for use in the formula derived during the calibration.
The TDR readings were taken within 20 seconds when the TDR was set on mineral mode. It was by this formula that correct volumetric moisture contents were obtained. In each plot three measuring points, were used which were replicated once. These were near (30-40cm) the same positions where the access tubes had been installed (fig. 1).

RESULTS AND DISCUSSIONS
The seasonal moisture distribution in the top 30 cm depth of the soil as measured by the TDR for the short rains 94/95 and the long rains 1995 are presented and discussed.

Soil water content at 20-30cm depth by the TDR for the 94/95 short rains
A comparison of the C and M plots showed that the two treatments had relatively similar soil moisture levels at the top 30 cm, with the M values slightly lower on average. Soil moisture for the C plot was as high as 0.28 cm$^3$cm$^{-3}$ (fig. 3). Comparing the moisture levels in the H+M plot showed that there was more moisture concentrated beneath the hedgerows than at 1 and 2 m from the hedgerow (fig. 4). This was due to the barrier effect in the plot of holding runoff water and allowing it to infiltrate more beneath the hedgerow. This led to a decreasing moisture trend in the 1 and 2 m positions from the hedgerow barrier. There was also more moisture concentrated beneath the hedgerow in the (H) plot than at 1 and 2 m from the hedgerow barrier (fig. 5) for the same reasons as explained for the H+M plot. The same trend of holding more water at the grass strip barrier than at 1 and 2 m from the barrier into the alley was as well portrayed (fig. 6).

A comparison was made of soil moisture measurements at the 20-30 cm soil depth at three measuring points, throughout the season, using TDR (figs. 3, 4, 5 and 6) and neutron probe metre method as shown in seasons results in figures (7, 8, 9, 10 and 11). The results showed that the C and M plots had similar and very close moisture values by both instruments (figs. 3, 7 and 8). This must be due to the uniformity of soil moisture at the measuring points in C and M plots. For the H+M plot, the soil moisture values by the TDR were clear cut, as and showed a decrease from H1+M > H2+M and > H3+M (fig. 4). The picture shown by the neutron probe metre for the same measuring points, though in trends relatively similar to the ones by TDR, was not so clear-cut among the points of measurement but had a wider scatter of the moisture levels (fig. 9). For the H plot, there was a similar trend of moisture level distribution at H1, H2 and H3 as in H+M plot throughout the season as well as a decreasing trend in moisture levels from H1> H2 and > H3 particularly clearly for the TDR (fig. 10). For the G plot, a similar trend in moisture levels distribution was noted as in the AF plots in the G1, G2-and G3 positions and over the season (fig. 6).

The probe metre values were however somewhat lower than the TDR values, particularly at the G1 positions during the wetter part of the season (figs. 6 and 11). Compared to the probe metre the results showed that the TDR portrayed a better and clearer cut picture of the soil moisture levels and distribution at the hedgerows/grass strips and at 1 and 2 m away from them. The explanation for this is that the neutron probe metre has some of its neutrons escaping into the air, which could not be detected by the neutron detector and hence resulting in lower than the usual count rate ratios with consequent low moisture content. The drier the soil, the larger the percentage error. This is because the sphere of importance that backscatters the neutrons is larger in a dryer soil. This does not happen with the TDR, which directly monitors soil moisture content at the surface depths where it is mounted. The moisture values by the neutron probe were also lower than the moisture values by the TDR, an indication that indeed the TDR
values were more accurate than the neutron metre. The moisture levels as measured by the TDR in the C and M were rather close even though there was mulch application in the M plot. The mulch rates were rather low and may not have been effective enough in holding water for infiltration to show differences in moisture levels.

For the Neutron Probe, there were significant differences at points of measurement within treatments at \( P<0.05 \), LSD = 0.007, CV =36.8, LSD = 0.012, CV =51.2\% in 94/95 and 1995 seasons respectively. For the TDR there were also significant differences among points of measurement in 94/95 and 1995 seasons at \( P=0.05 \), LSD = 0.4 CV= 20.69 and LSD 0.35 and CV = 21.14\% respectively.

Soil water content at 20-30cm depth by the TDR long rains 1995

A comparison of C and M plots show that they had relatively similar moisture levels (fig. 12) as found in 94/95 season. A comparison of the moisture levels inside the hedgerow, 1 and 2 m from the hedgerow showed that there was more moisture inside the hedgerow in (H+M) than at 1 and 2 m away into the alley (fig. 13). This was as earlier mentioned due to moisture accumulation and infiltration at the hedgerow barrier. A similar pattern of moisture distribution was also portrayed in the H and G plots, also explained as for H+M plot above (figs. 14 and 15).

A comparison of the TDR (figs. 12, 13, 14 and 15) and neutron probe (figs. 16, 17, 18, 19 and 20) methods for soil moisture measurement at 20-30 cm depth was made. The results show that both the TDR and neutron probe metre show a rather similar trend of moisture levels throughout the season for the C and M plots (figs. 12, 16 and 17) with minor variations as was the case in 94/95 season. These variations could be due to differences arising from soil heterogeneity in the plots. It is an indication that more sampling points would have increased the accuracy but this is also caused by the non-suitability of neutron probe measurements near the surface. For the H+M plot, the picture on moisture levels is clearer with the TDR than with the neutron probe metre, with the moisture levels on average decreasing with increasing distance to the centre of the alley (fig. 13 and 18). There was also a tendency for the TDR to show higher moisture values, with higher absolute differences when the soils were wet than when they were dry. This was most likely because of neutrons escaping into the air (which as a percentage should be higher in dry soil) which could therefore not be detected by the neutron probe detector, resulting in rather lower moisture content obtained by the by the probe metre. For the H plot, the picture on moisture distribution is again clearer by the TDR than by the probe metre, with decrease in moisture levels at H1 >H2 and >H3 actually only visible for TDR observation. This must be due to actual sampling differences over depth. The range of moisture levels by both instruments was, however, rather similar, with TDR showing a more clear pattern of moisture distribution than the probe (figs.14 and 19). As in the H+M and H plots, the G plot had similar moisture pattern distribution by both the TDR and the probe metre over the season. Only the TDR showed a clear-cut picture of moisture levels as G1 >G2 >G3 respectively, with higher absolute moisture levels by the TDR than by the probe metre, especially during wet periods at the G1 position (fig. 15 and 20). This was partly due to runoff water accumulation at the grass strip compared to the positions G2 and G3 in the alley. Why this is at least relatively again not shown by the neutron metre is not immediately clear. Possible reasons may be differences in sample volume, that is much larger for the neutron probe, which also samples therefore another horizon of the soil. This introduces
biases. Actual differences between measuring points due to local effects may be involved as well.

A comparison of the TDR and neutron probe methods for soil moisture measurement at 30 cm depth during both seasons has shown that the TDR was more reliable than the neutron probe meter. In cases where high accuracy soil moisture is needed with minimum soil disturbance in the 30 cm topsoil layer, TDR though also expensive, is recommended for use.

Cowpea yield results for the short rains of 94/95 and maize yield results for the long rains of 1995.

The results for the short rains (549mm) of 94/95 show that the rows of cowpea in the C and M plots had on average higher yields than those in the H+M, H and G plots respectively. The rows of cowpea near the hedgerows and grass strips were slightly lower compared to the rows in the middle rows of the alley. For the G plot however, the rows in the middle of alley had distinct better yields than those near the grass strip. This suggests that the moisture concentration at the hedgerow and shading was not favourable to cowpea growth as those in the middle rows had better yields and less moisture (Figs 3, 4 and 5). However, the depressed yields near the grass strip were contrary to the moisture concentrations beneath the grass strip (Fig 5). This was due to severe competition for nutrients, light and water between the grass and cowpea even when the rainfall was far above mean average.

The results for the long rains (255mm) of 1995 show that the maize rows in the C and +M plots had on average higher yields than those in the H+M, H-M and G-M plots. This was due to the absence of competition for water, light and nutrients by maize and senna in the C and +M plots. The rows of maize near the hedgerows had higher yields than those in the middle rows possibly because of moisture concentrations at the hedgerows (figs 13 and 14) and improved soil temperature at these points (Kinama, 1997). The yields in the middle rows were depressed because of competition for water and other resources from sena roots extension in middle of alley Umaya 1991, Mungai et al. 1996b). The rows of maize near the grass strip were equally depressed as those of cowpea in the short rains of 94/95 despite the concentration of moisture for similar reasons (fig. 15). However, the maize yields were higher in the middle rows of G plot possibly because the grass roots had not spread to middle rows to compete with maize for growth resources. There were higher maize and cowpea yields with increase in rainfall amounts but the yield depressions within alleys of agroforestry systems and near grass strip systems remained (Kinama, 1997). These are some of the limitations for agroforestry systems in semi-arid areas.

CONCLUSION

A comparison of TDR and neutron probe methods for soil moisture measurement at 30cm depth during both seasons has shown that the TDR was more accurate and more reliable than the neutron probe meter. The surface soil moisture trend corresponds quite well with the maize row yields except for the grass strip plot were yield depressions occurred near the grass strip. The cowpea yields appeared to be better were moisture was correspondingly lower particularly for grass strip plot but less clear in agroforestry plots. It can hence be concluded that panicum grass strips exert a lot of competition for water and other growth resources with the associated crop and though adopted by the farmers
may not be appropriate for the area. Higher moisture concentrations in agroforestry plots favoured higher maize yields while for cowpea this did not favour higher cowpea yields. For these yield per row comparisons TDR was particularly useful as it pinpointed accurately the actual moisture situations in studying yield differences in agroforestry and grass strip alleys. Lower yields in the middle rows of maize in AF plots were in areas with lower moisture concentrations due to competition for water and nutrients by the senna with maize. The middle rows of cowpea in particularly grass stripped plot had higher yields than those near the grass strip. However, TDR is recommended for high accuracy soil moisture determination with minimum surface soil disturbance, particularly high value export horticultural produce, which can off set initial instrument cost.

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REFERENCES


Fig. 1. Field layout of runoff plots showing neutron probe tube measuring points

KEY:  C - Control; M - Mulch; H+M - Hedge + Mulch; H - Hedge; G-M - Grass strip

- Neutron probe tube measuring points
Fig 2: The TDR metre box and the sensor stick
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Fig 6. Comparison of soil moisture by TDR (20-30cm depth) in the grass strip, 1m from grass strip and 2m from grass strip for the G plot, short rains of 94/95.

Fig 6. Comparison of soil moisture by TDR (20-30cm depth) in the grass strip, 1m from grass strip and 2m from grass strip for the G plot, short rains of 94/95.
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Fig 9. Comparison of soil moisture by neutron probe (0–30 cm) depth at hedge, 1m and 2m from hedge, H+M plot for the short rains of 94/95

Volumetric water content (cm$^3$ cm$^{-3}$)

Time in weeks

Fig 9. Comparison of soil moisture by neutron probe (0–30 cm) depth at hedge, 1m and 2m from hedge, H+M plot for the short rains of 94/95
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Volumetric water content ($cm^3/cm^3$)

Time in weeks

- G1-M
- G2-M
- G3-M

Fig 11. Comparison of soil moisture by neutron probe (0-30cm) depth at the grass strip, 1m and 2m from grass strip, G plot for the short rains of 94/95
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Volumetric water content (cm$^3$ cm$^{-3}$)

Time in weeks

- H1+M
- H2+M
- H3+M

Fig 13. Comparison of soil moisture by the TDR (20-30cm) depth in the hedge 1m from hedge, 2m from hedge in the H+M plot for the long rains of 1995
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Fig 14. Comparison of soil moisture by the TDR (20-30cm) depth in the hedge, 1m from hedge, 2m from hedge in the H plot for the long rains of 1995
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Volumetric water content (cm$^3$ cm$^{-3}$)

Time in weeks

- H1+M
- H2+M
- H3+M

Fig 18. Comparison of soil moisture changes in the hedge, 1 m from hedge and 2 m from hedge, by neutron probe (0-30 cm depth). H+M plot, long rains of 1995.
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