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Accuracy of the neutron probe for measuring changes in soil water storage under potatoes

S. R. GAZE, M. A. STALHAM* AND E. J. ALLEN

Cambridge University Farm, Huntingdon Road, Girton, Cambridge, CB3 0LH, UK

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SUMMARY

The neutron probe (NP) is used widely to measure changes in soil water storage in research and more recently to aid irrigation scheduling. Its accuracy is rarely questioned and most of the relationships between soil water changes and productivity are based on its use. A field experiment was conducted at Cambridge University Farm in 1999 to address whether the NP could accurately measure changes in soil water content (SWC) under irrigation or substantial rain (> 10 mm). The experiment was a replicated split-plot design with four irrigation treatments allocated to the main plots, and surface profile (ridge, flat) and crop (potato *cv*. Saturna, bare soil) treatments allocated to the subplots. The mean results from four NP access tubes per plot installed to measure soil moisture deficit (SMD) across the row-width were analysed. The NP was inconsistent in measuring known irrigation or rainfall input. In relatively dry soil (SMD > 40 mm), the NP generally measured 93 to 110% of 18 mm of irrigation within 4 h of irrigation. The NP recorded much less water applied as irrigation in wetter soil, and often only 40 to 70% of the applied irrigation (18 or 36 mm) was measured. There were occasions when the NP did not measure all the water input even when the SMDs before irrigation were greater than the water subsequently applied. Some of the 'missing' water might be attributed to drainage, however, results from an additional experiment using an open-topped tank of soil showed that the NP was unable to detect all the water added to the soil, particularly where the water was largely confined close to the soil surface. Replicated measurements of the change in SMD in the field experiment were precise for a given event and treatment (mean S.E. = 1·3 mm) but were not accurate when compared against the input measured in rain gauges. It was concluded, that the NP could not be used reliably to measure changes in soil water storage after irrigation or substantial rain. For periods when there were minimal inputs of water, there was a closer correlation between changes in SMD measured by the NP and those predicted by a modified Penman–Monteith equation than after substantial inputs of water. However, for predicted changes in SMD of *c*. 20 mm, there was a range of *c*. ±5 mm in the changes in SMD measured by the neutron probe.

The value of the NP for monitoring SMDs where there is irrigation, or substantial rain, must be seriously doubted. Consequently, its limitations for scheduling irrigation, testing models or quantifying the effects of treatments on crop water use in potatoes must be appreciated, especially where the areal sampling limitations of single access tubes positioned only in the ridge centre have not been addressed.

INTRODUCTION

The neutron probe (NP) is used widely to measure changes in soil water storage in a range of soils and environments, and under a range of crops (Fernández *et al.* 2000). The changes in soil water storage derived from the NP measurements may be used, for example, in research to quantify treatment effects on crop water use and for testing soil water balance models, or commercially to schedule irrigation based on a predetermined allowable soil moisture deficit (SMD). The NP should ideally be calibrated for the soil under study, though the 'typical' calibration equations of Bell (1987) for sand, loam and clay are commonly used. If the NP is used to schedule irrigation in real time, a calibration for the field may not be available at the start of the season, and the operator has to use a standard or historic calibration line. This has the potential to introduce a systematic error in the resultant measurement of SMD, depending on the deviation of the standard calibration from the field-

* To whom all correspondence should be addressed. Email: m.stalham@farm.cam.ac.uk

specific calibration. For research purposes, changes in soil water storage can often be analysed retrospectively when a field-specific calibration becomes available. The changes in soil water storage derived from the NP measurements should then be accurate at any given location. The precision of the measurement will depend partly on the error associated with the calibration, on the spatial variability of the soil water balance in the field and on the random counting error of the NP.

In the past, measuring soil water content (SWC) using the NP has been the basis for many studies on water relations in potatoes (Siddig 1982; Prestt 1983; Ramadan 1986; Singh *et al.* 1993; Hamer *et al.* 1994; Bailey *et al.* 1996) and other crops (French *et al.* 1973*a*, *b*, *c*; Francis & Pidgeon 1982; Hall & Jones 1983; Brown & Biscoe 1985; Brown *et al.* 1987) and now the NP is being used to schedule irrigation in practice. Unpublished work at Cambridge University Farm (CUF) in potato agronomy experiments, however, showed that even when using a field-specific calibration, replicated measurements of SMDs using the NP at times deviated considerably from SMDs predicted using a soil water balance model based on Penman–Monteith estimates of evapotranspiration. Access tubes in these experiments were installed only in the centre of potato ridges, which is standard practice in most published reports of monitoring crop water use in potatoes using the NP (Martin *et al.* 1992; Singh *et al.* 1993) and in commercial irrigation scheduling in the UK. The difference between measured and modelled SMD was often > 20 mm, and the maximum difference recorded was 41 mm, with the measured SMDs tending to be greater than the modelled SMDs. The discrepancy was worrying and before seeking to modify the model it was decided to investigate the accuracy of the NP measurements.

This paper reports the results of a field experiment to test the accuracy of changes in soil water storage derived from NP measurements when compared with known amounts of irrigation or rainfall, and when compared with Penman–Monteith based estimates of evapotranspiration. Results are also presented from an additional experiment comparing known irrigation inputs and NP measurements in an open-topped tank of soil from which drainage could not occur.

MATERIALS AND METHODS

Field experiment

The experiment was carried out in 1999 at CUF. The soil in the field used for the experiment was a sandy loam over a gravelly loamy sand (Milton series; Anon. 1983). Mean volumetric stone content was 12% (range 8·4–16·7%) at 10 cm depth increasing to 25% (range 15·3–38·1%) at 40 cm depth, and then decreasing at subsequent depths.

The experiment was a split-plot design with four irrigation treatments allocated to the main plots, and surface profile (ridge, flat) and crop (potato *cv.* Saturna, bare soil) treatments allocated to the subplots, with three replicate blocks. The field was ploughed, sub-soiled, spring-tined then drawn into ridges in early April. On 15 April, the experimental area was power harrowed to give a flat soil surface. Ridges were then drawn up at 76 cm spacing in the appropriate plots using tractor-mounted ridging bodies. The tractor was driven the length of the experiment with each pass of the tractor, but the ridging bodies were lifted out of the soil when passing over the flat plots. The flat plots consequently had a wheeling between alternate rows. Cropped plots were hand-planted using dibbers with the cultivar Saturna on 16 April. Plots were eight rows wide (0·76 m row spacing) by 6 m length, with 2 m gaps between plots. Seed tubers (25–35 mm) were spaced 25 cm apart within the rows. Planting depth was 12 ($\pm$0·4 cm) in the ridges and 11 cm on the flat. Good weed control in the cropped plots was achieved by a combination of a pre-emergence herbicide (terbutryn + terbuthylazine and paraquat) supplemented by hand weeding as required through the season. In addition to the 'pre-emergence' herbicide, the bare plots also received two further applications of the same herbicides as the 'pre-emergence' application on 5 May and 1 July, supplemented by hand weeding throughout the season.

Irrigation treatments were scheduled using the CUF irrigation scheduling model (M. A. Stalham, unpublished data) and were: rain only (W1); 18 mm irrigation whenever the modelled SMD reached 40 mm (W2); 18 mm irrigation whenever the modelled SMD reached 20 mm (W3); 36 mm irrigation whenever the modelled SMD reached 20 mm (W4). For each irrigation application, mean irrigation amounts were estimated from 24 rain gauges per irrigation treatment, situated at ground level and not shielded by foliage. Irrigation was applied through an overhead boom (RST Irrigation) fitted with cone nozzles pointed vertically down. The boom was pulled through the experiment at a pre-set constant speed by a hose reel (Perrot SA, SH63/280). Irrigation amount was regulated by adjusting the speed at which the reel was wound (40 m/h for 18 mm irrigation, 20 m/h for 36 mm irrigation). There were slight variations in the measured mean application between irrigation events. For W2 and W3 over the season, the measured mean application for an irrigation ranged from 16·6–19·2 mm with an overall mean of 17·9 mm. For W4, the measured application ranged from 31·2–40·5 mm with an overall mean of 35·8 mm. The high intensity application rates (*c.* 720 mm/h) exceeded the infiltration rate of the soil and generated some overland flow so the plots were 'tied' with earth bunds to avoid overland flow between plots. The monthly totals of

Table 1. *Monthly rainfall and irrigation recorded for the four watering regimes (W1–W4) for the period between crop emergence and 4 October. Treatments W2–W4 received rain+irrigation for which only the applied irrigation is shown, the rain was the same as for W1*

	Rain	Irrigation		
Month	W1	W2	W3	W4
May*	46·2	0·0	18·0	36·0
June	98·8	17·6	33·6	73·5
July	28·6	72·8	92·0	183·8
August	97·4	17·5	17·5	33·4
September	77·0	0·0	16·6	31·2
October*	14·0	0·0	0·0	0·0
Total	362·0	107·9	177·7	357·9

* Rainfall included for only that part of the month for which the crop was between 50% emergence and the last NP reading.

irrigation and rainfall applied under the four watering regimes are shown in Table 1.

The NP measures SWC within a radius of 15 cm in wet soils to 30 cm in dry soils (Bell 1987). In order to ensure that the NP measurements represented the whole row-width, four access tubes for the NP were installed in each plot. The access tubes were sited between the fourth and fifth plant from the east end of the plot and were installed on 27 April in the bare treatments and on 17–19 May in the cropped treatments after emergence. The 45 mm (external diameter) aluminium tubes were gently hammered into 38 mm diameter holes, made using a corer attached to a percussion hammer (Atlas Copco), until the top of the tube was between 15 and 20 cm above the soil surface. In the ridge plots the tubes were installed in the ridge centre (RC); one-third of the distance between ridge centre and furrow centre (RF); two-thirds of the distance between ridge centre and furrow centre (FR); and in the furrow centre (FC, Fig. 1). In the flat plots, the tubes were installed in the equivalent positions to the ridge plot: the RC tube being in the row centre; the FC tube midway between rows; and the RF and FR tubes were one-third and two-thirds the distance respectively from the RC to the FC tube. The layout detailed in Fig. 1 was used so that all four tubes were not installed in the same ridge, which avoided excessive soil disturbance in the measurement zone. In total, 192 access tubes were installed in the experiment. A portable gantry spanning four rows was used which enabled the NP readings to be taken without damage to the soil surface or crop near the access tubes. Single readings of 16 s duration were taken at 10 cm intervals down the tubes to 100 cm depth relative to the top of the ridge in the ridge plots, or to the soil surface in the flat plots. A horizon-based integration was used to calculate the water content of the profile down to the maximum depth of measurement.

Calibration

At each measurement depth the NP gives a reading, which is referred to as the count rate, or more specifically the count rate in soil (r_s). The count rate in soil is usually normalized against a count rate in water (r_w) to give a count ratio (r_s/r_w), which accounts for instrument drift in count ratio over time (Bell 1987). A calibration line is required to convert the count ratio to the SWC. It has been written in the Institute of Hydrology handbook on NP practice that changes in SWC are easy to determine, since soil groupings

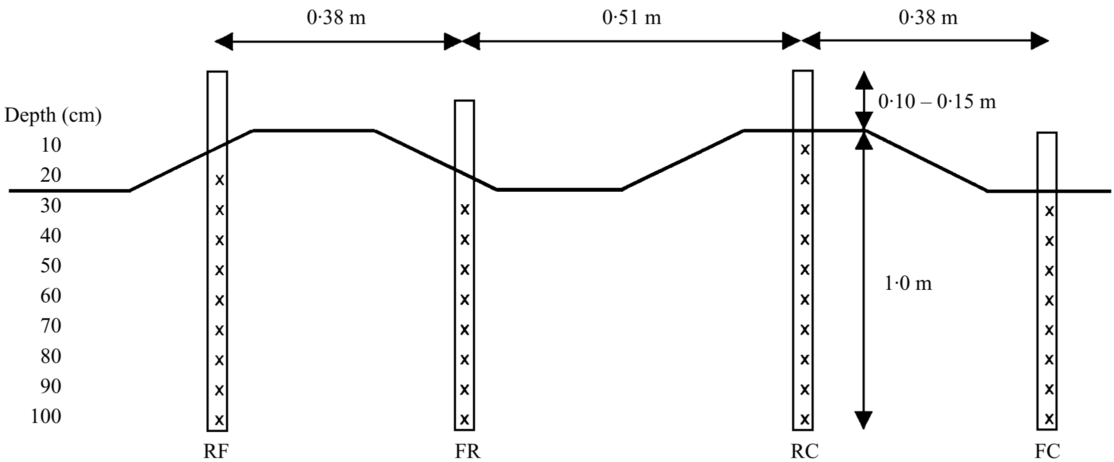

Fig. 1. Positions of the four neutron probe access tubes in each ridge plot.

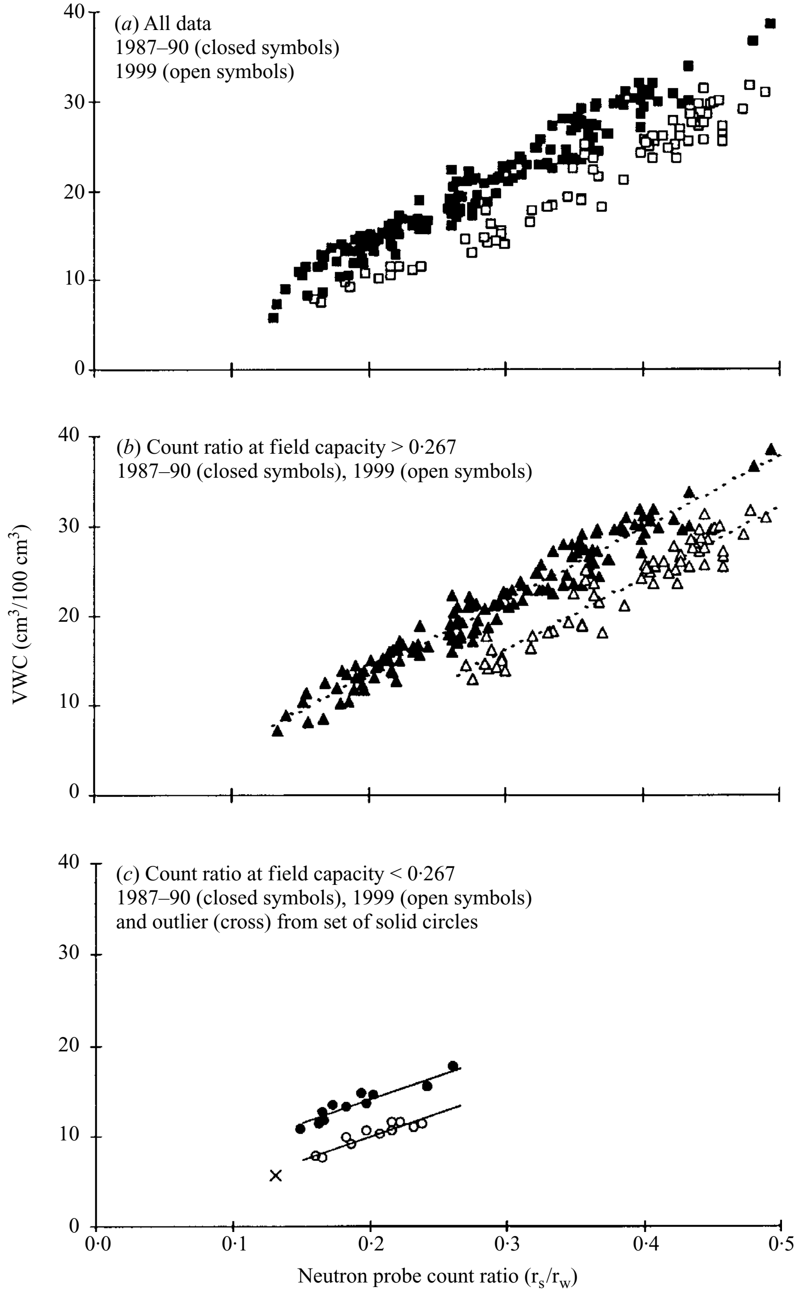

Fig. 2. Volumetric water content (VWC) of the soil measured in cores taken from around neutron probe access tubes and the associated count ratio recorded by the neutron probe. Data are for ⩾ 20 cm depth from fields at CUF. (*a*) all samples grouped by year of data set, (*b*) samples for which the count ratio at field capacity > 0·267, (*c*) samples for which the count ratio at field capacity < 0·267.

often have similar slopes to the calibration lines, but often widely differing intercepts (Bell 1987). Haverkamp *et al.* (1984) stated that the calibration component of error represented the major contribution to the total variance of an individual water measurement, and errors in calibration have been investigated far more often in the literature than any other source of error. McGowan & Williams (1980) stated that this emphasis may be misleading for water balance studies, where errors other than calibration are generally more important.

The calibration equations for the NP (IH II probe, Didcot Instrument Co., UK) were derived from field calibration data taken on 6–7 October 1999 from the bare soil treatments. These were compared with previous calibration data from similar soils at CUF over the period 1987–90. These calibrations differed from 1999 in that they were taken from cropped areas rather than bare soil. In 1987–89, the profiles were ridged, whilst in 1990 the crops were grown on the flat. In 1999, the calibrations were performed on both flat and ridge. Treatments were selected which had had different quantities of irrigation applied during the season in an attempt to obtain a large range in SWC at calibration. In 1987–90 the ranges in volumetric SWC were 1·0–12·4 $cm^3/100\ cm^3$ (10 cm depth) and 5·7–38·5 $cm^3/100\ cm^3$ (depths ⩾ 20 cm), whilst heavy rainfall during September prior to the calibration meant that most of the horizons in 1999 had returned to field capacity (ranges 15·5–34·3 $cm^3/100\ cm^3$ at 10 cm depth, 7·5–38·9 $cm^3/100\ cm^3$ at depths ⩾ 20 cm).

Four soil cores were taken at each depth for each tube. Prior to disturbing the soil profile, a single 64 s count was taken at each depth to be calibrated. In 1987–90, the cores were 70 mm diameter, 50 mm length, and in 1999 were 74 mm diameter, 80 mm length. Cores were obtained by carefully excavating around the access tube using a spade and builder's trowel to a depth of 25 mm (1987–90) or 40 mm (1999) above the centre of the appropriate depth. The steel coring rings (1987–90) or aluminium irrigation pipe (1999) were then pushed into the soil using the flat surface of a small builder's or plasterer's trowel until flush with the soil surface. A hammer or mallet was used where resistance was high. The cores were then dug out, the soil trimmed flush with the edge of the sampling ring and the soil transferred immediately to a sealed plastic bag to prevent any change in water content. The four cores were taken annularly around the access tube, *c.* 5–10 mm from the wall of the tube. Care was taken to ensure that the sample rings retained their circular shape to prevent changes in the volume of soil sampled. Cores were taken at 10 cm increments from 10 cm down to 60 cm in all years. Samples were taken back to the laboratory and the volumetric SWC and dry bulk density determined on the whole soil sample by drying in an oven at 105 °C for 24 h. Cores which were incomplete at the time of sampling (e.g., some soil was lost during trimming or transfer) were included for SWC, but not bulk density, determination. The average bulk density of the intact soil cores for that depth was used to calculate the volumetric SWC from the gravimetric SWC.

For ⩾ 20 cm depth, visual inspection of the 1999 data suggested they were best described by a split line with a break point at a count ratio of *c.* 0·25 (Fig. 2*a*). A Genstat program (Payne *et al.* 1993) to fit a split line to the 1999 data calculated the break point to be at a count ratio of 0·267. However, the program did not test if the split line was a significantly better fit than a single straight line. To enable comparison, the two parts of the split line were considered as two separate lines and the regression of two lines through the 1999 data, separated according to count ratio at field capacity, was compared with a single line through all the 1999 data. In running the comparison, equal weighting was given to the residuals of the deviations from the fitted lines to account for the two lines distinguished by count ratio not individually covering the same range in count ratios as a single line through all the data. The analysis indicated a significant improvement using the two lines as opposed to one line fitted through all the data.

Table 2. *Calibration equations used to convert neutron probe readings to volumetric water content (θ_v, %) derived from field calibration data at CUF. r_s is the count in soil; r_w is the count in water. For ⩾ 20 cm depths, the equation used depends on the count ratio (r_s/r_w) at field capacity*

Profile/Depth	Ratio of r_s/r_w at field capacity	Equation
Ridge		
10 cm	All values	$\theta_v = 45.97\frac{r_s}{r_w} - 1{\cdot}17$
⩾ 20 cm	⩾ 0·267	$\theta_v = 81{\cdot}55\frac{r_s}{r_w} - 8{\cdot}48$
⩾ 20 cm	< 0·267	$\theta_v = 52{\cdot}89\frac{r_s}{r_w} - 0{\cdot}69$
Flat		
10 cm	All values	$\theta_v = 53{\cdot}71\frac{r_s}{r_w} - 0{\cdot}47$
⩾ 20 cm	⩾ 0·267	$\theta_v = 81{\cdot}55\frac{r_s}{r_w} - 8{\cdot}48$
⩾ 20 cm	0·267	$\theta_v = 52{\cdot}89\frac{r_s}{r_w} - 0{\cdot}69$

As can be seen from the equations in Table 2, the slope was considerably shallower for data with field capacity r_s/r_w ratios < 0·267 than for count ratios ⩾ 0·267. Further work to identify whether there was some mechanistic reason for such a split in the data revealed that separating calibrations by bulk density classes did not alter the overall relationship between SWC and r_s/r_w at depths below 20 cm. Introducing soil texture using the classes of Bell (1987) as a parameter proved equally unsuccessful in trying to establish separate calibration lines, since most of the calibration data were taken from loamy textures as there were few clay horizons above 60 cm. The soil texture of the different horizons around each access tube was not recorded in 1999, but clay was not encountered when digging pits at the end of the season. On visual inspection during calibration there was, however, a band of sand at 40–50 cm which mostly produced r_s/r_w readings < 0·267. Nevertheless, the slope of the calibration from these data was considerably shallower than the sand calibrations of Bell (1987) or Gaze (1996).

In order to test whether the 1987–90 data could also be grouped by their count ratios at field capacity, NP measurements from earlier in the season were used to determine the count ratio at field capacity. In 1987–90, for soils with count ratio at field capacity $> 0{\cdot}267$, the count ratio at calibration ranged from 0·13–0·5, which was greater than in 1999 (Fig. 2*b*). For soils with count ratio at field capacity $< 0{\cdot}267$, the range in count ratios at the time of calibration was similar for the 1987–90 and 1999 groups (Fig. 2*c*), and the SWCs were low.

The 1987–90 and 1999 calibration data for each group were best described statistically by parallel lines, as opposed to separate lines with different gradients. Parallel lines fitted to data with a count ratio at field capacity $> 0{\cdot}267$ accounted for 94·1% of the variance about the lines (Fig. 2*b*). Parallel lines fitted to data with a count ratio at field capacity $< 0{\cdot}267$ accounted for 93·4% of the variance about the lines (Fig. 2*c*). It was, therefore, concluded that for measuring changes in SWC the data were consistent between 1999 and previous years, but the absolute SWCs predicted by the calibration equations were significantly different between 1987–90 and 1999.

The 1999 data were offset from previous years. The 1999 data were taken from bare soils whereas the 1987–90 data were obtained from cropped soil. All calibration data was taken towards the end of the season. The cropped soil may have had different bulk density from the bare soil, which might have affected the calibration though no effect of bulk density on the calibration was found within the bare soil data from 1999. The time in the season at which sampling for calibration occurs might affect the calibration if there are substantial changes in soil structure through the season but this was considered unlikely to be important for the soils sampled at CUF. The organic matter in the 1999 field was 7% and from fields in 1987–90 ranged from *c.* 4–7%. The differences in organic matter were small in relation to those required to have a significant effect on calibration of the NP (Visvalingham & Tandy 1972). It was not possible, therefore, to identify why the 1999 data were offset from those of previous years.

For a given measurement point $\geqslant 20$ cm depth, the count ratio of the NP when the soil was at field capacity determined the gradient of the calibration equation used. Since all our work with the NP involves quantifying changes in SWC (e.g. change from field capacity to produce an SMD) a single set of calibration equations was used based on the 1999 data (Table 2). For the 10 cm depth, separate calibrations were derived for flat and ridge surface profiles (Table 2), using data from all available years (1987–90 and 1999). Since the different access tubes in the ridge treatments had different depths of soil surrounding them relative to the top of the ridge, different calibration were used for each access tube in the surface profiles. The RC tube used the ridge 10 cm calibration at 10 cm depth and the > 20 cm calibration at all depths at or below 20 cm (Fig. 2; Table 2). The RF tube did not have a 10 cm reading taken, and at 20 cm used the 10 cm ridge calibration. The FR and FC tubes did not have readings taken at 10 or 20 cm, and at 30 cm used the 10 cm flat calibration. Any effect of potato tubers on the calibration has been assumed to affect only the intercept of the calibration, if it has any measurable effect at all (MacKerron & Jefferies 1987). The consistency of the gradient between years gave some confidence in the calibration of the NP at CUF for measuring changes in water stored in the soil profile. This is consistent with the claim that the NP provides accurate measurements of changes in water content (Bell 1987).

In this paper, results are based on the mean of the four access tubes per plot to give the mean soil water status measured across the row-width. Results from individual access tube positions are not reported here. Positive values of change in water storage indicate the profile got drier over the period in question; negative values indicate the profile got wetter over the period. Soil moisture deficits are changes in SWC relative to field capacity. The term 'field capacity' can be defined as the water retained by a thoroughly wetted soil after free drainage (with no drying through evaporation or plant water use). As a practical guideline, soil is considered to be at field capacity after 2 days of drainage from the thoroughly wet state. Drainage rates, however, vary considerably between soil types and there is no critical physical definition of 'field capacity' (Marshall & Holmes 1988). At the time of the first NP readings (25 May) the soil profile was not considered to be at field capacity because there would have been some drying of the upper profile through crop water use and evaporation from the soil surface. The first occasion when it was considered that the soil profile in all treatments would have fully wetted and had two days to drain was for readings taken on 8–9 June. These readings were therefore taken as 'field capacity'. As the season progressed, it became evident that there was further drainage from the lower profile (60–100 cm depths) after 8–9 June amounting to 5–10 mm. Consequently at the end of the season the 'field capacity' point was set retrospectively to give the best estimate of the water content at which there was negligible subsequent drainage and there had been no drying of the profile through root water uptake. The dates of returning to field capacity below 60 cm ranged from 15–23 June. Retrospective fitting of the field capacity, in this experiment, reduced SMDs over the whole profile by 5–10 mm compared with the initial field capacity values used.

The data illustrate that it can be difficult to set the field capacity of a soil profile with confidence from NP measurements early in the season. This is a problem if the instrument is to be used for scheduling irrigation for a crop since the measurement of SMD may not be reliable (irrespective of any other problems associated with access tube location and replication). Accurate setting of field capacity is not critical for measuring changes in soil water storage from one reading to the next, and such measurements of changes in SWC are useful for research purposes, but accurate irrigation scheduling requires the combination of field capacity and changes in soil water storage. If the NP is to be used as a real time scheduling tool, where the objective is to maintain the soil wetter than some predetermined limiting SMD, it is necessary to be able to determine field capacity accurately as near to the start of the season as possible.

Differences in SWC or SMD between treatments were considered statistically significant when the probability of the differences occurring by chance was less than 0·05 (i.e. $P < 0{\cdot}05$). An indication of the error associated with the data is shown by the standard error (S.E.). On occasions only a subset of the data were analysed (e.g. data were not available from all NP access tubes on all occasions). Consequently, error bars for some of the data presented graphically may not all have the same number of degrees of freedom. However, for consistency it has been decided to use S.E.S throughout the paper, rather than a mixture of S.E.S and least significant differences.

From 25 May until 23 June, all access tubes were monitored weekly. After 23 June, weekly monitoring continued for the cropped plots and the bare plots were only monitored occasionally. Changes in water storage in the soil profile measured with the NP were compared with either predicted evapotranspiration (ET) or known rain or irrigation inputs. For ET, changes in water storage measured between successive readings when there was < 5 mm rain and irrigation between readings were compared with the ET predicted by the CUF irrigation scheduling model. For rainfall, changes in water storage measured between successive readings were compared with rainfall recorded in a tipping-bucket raingauge < 100 m from the experiment (after accounting for potential evaporative losses from the crop and soil) for those occasions where the net input (rainfall – potential evaporation) was smaller than the measured SMD before rain. For irrigation, additional NP readings were taken immediately before and 2–4 h after irrigation for three applications to W2 (24 June, 15 and 21 July), and to W3 and W4 (28 May, 21 June and 12 July). No correction was made for evaporative loss from plants or soil during the period (3–6 h) between pre- and post-irrigation measurements when calculating water capture. For W2, changes in water storage beneath cropped and bare soil were recorded. For W3 and W4, measurements were only taken from the cropped treatments other than on one separate occasion (30 July) when frequent measurements of the changes in SWC following irrigation were made on two bare soil plots in W4.

Meteorological data were recorded using a Delta-T weather station (Delta-T Devices, Burwell, Cambridge) located at one end of the experiment. Rainfall, wind speed, global radiation, relative humidity, air temperature and soil temperature at 10 cm were measured at 5-min intervals, and the hourly average (or total where relevant, e.g. rainfall) recorded. It is widely accepted that the empirical, physically based Penman–Monteith estimates of ET, when adjusted for the effects of leaf area index and canopy height on surface roughness and bulk stomatal (canopy) resistance, are accurate across a wide range of climates and locations when compared with lysimeter data (Allen *et al.* 1989). Potential evaporation was calculated from the recorded meteorological data using the Penman–Monteith equation (Monteith 1965, 1981) modified using the standard reference crop parameters for grass (Smith 1992). Actual potato ET was predicted from the reference potential evaporation using an aerodynamic canopy resistance (Thom & Oliver 1977) based on crop height (maximum 0·80 m) and using a stomatal conductance of 50 s/m (Monteith 1986; Bailey & Spackman 1996) in the surface resistance function of Grant (1975). Further adjustments to the predicted actual ET accounted for the proportion of green ground cover and the effect of limited water supply on ET based on experimental data from CUF (M. A. Stalham, unpublished data). The water balance of the soil was modelled following a capacity-based approach where soils wetter than field capacity drained to field capacity within 1 day (the minimum time-step) irrespective of soil type, and subsequent drying of the profile was through ET.

Soil tank experiment

An additional experiment to test the ability of the NP to measure water input to soil in a closed system was carried out in April 2000. An open-topped fibreglass tank, 75 cm wide by 65 cm long by 55 cm deep, with a single access tube situated in its centre, was packed with topsoil from a field adjacent to that used for the field experiment. The soil was at field capacity in the field (26·8 $cm^3/100\ cm^3$), but during digging and transfer, the soil may have dried slightly. The texture of the soil in the tank was similar to that of the surface (0–30 cm) horizons of the field experiment, but during transfer of the soil the structure and hence hydraulic characteristics may have altered from those of the soil in the field experiment. In the absence of a specific calibration for the neutron probe in the tank, the calibration equations used were the same as for the flat profile treatments in the field experiment.

The soil level initially was 2 cm below the top of the tank to facilitate application of water and to contain any water that ponded on the soil surface within the tank. Measurements of SWC were made with the NP at 10, 20, 30 and 40 cm depths. Owing to the probe source/detector geometry and the position of the bung in the base of the access tube, a reading at 50 cm could not be taken, but the reading of SWC at 40 cm was used to calculate the SWC at depths from 35 to 53 cm instead of 35 to 45 cm. Layer integration was used to calculate the SWC over the depth of the tank. Duplicate 16 s counts were taken in order to reduce the random count error, and an initial reading was taken prior to applying water. Water was applied in 20 mm depth increments using a watering can with rose attachment. Six applications were made over a period of 2 h 45 min, with the shortest interval between applications being 10 min and the longest 72 min. During periods when measurements were not being taken frequently, or irrigation was being applied, the soil surface was covered with polythene sheeting to prevent evaporation.

RESULTS

Irrigation – field experiment

Visual observations indicated that there was considerable overland flow during irrigation, but it was assumed that by using the mean of four measurement locations that spanned the row-width there was no net run-on or run-off within the measurement area, which was tie-bunded to prevent water escaping overland outside the boundaries of the plot.

Under bare soil in the W2 treatments, there was no significant difference between ridge and flat profiles in recovery of applied input. An average of 8·9 mm of the 18 mm irrigation applied was measured by the NP within 4 h of irrigation (Fig. 3*a*). In the cropped treatments in W2 and W3 receiving irrigation applications of *c.* 18 mm, 100% recovery was generally achieved where the measured initial SMD was ⩾ 40 mm (Fig. 3*a*). There was no significant difference between ridge and flat treatments in recovery of applied water, except for the W2 application on 24 June. On this occasion, despite initial SMDs of nearly 40 mm in the cropped ridge and flat treatments, only 69% of the input was measured under the ridge compared with 110% under the flat. For initial SMDs between 20 and 40 mm, the amount of input recorded by the NP decreased with wetter initial SMDs (Fig. 3*a*). These wetter measurements were from the W3 treatments. For the cropped W4 treatment, where the irrigation applied was greater than the initial SMD, 100% recovery was never achieved (Fig. 3*b*). Also, on all three monitored irrigations in W4 there was significantly less water recovered within 4 h of irrigation under the ridge profiles than under the flat.

The discrepancy between known input and that recorded by the NP was often greater under ridges than under flat, but this was not consistent. There were occasions, even within the same treatment, when measured capture was significantly smaller under ridges than under flat, and other occasions where there were no differences in measured capture between ridge and flat.

For a given treatment and irrigation date, the

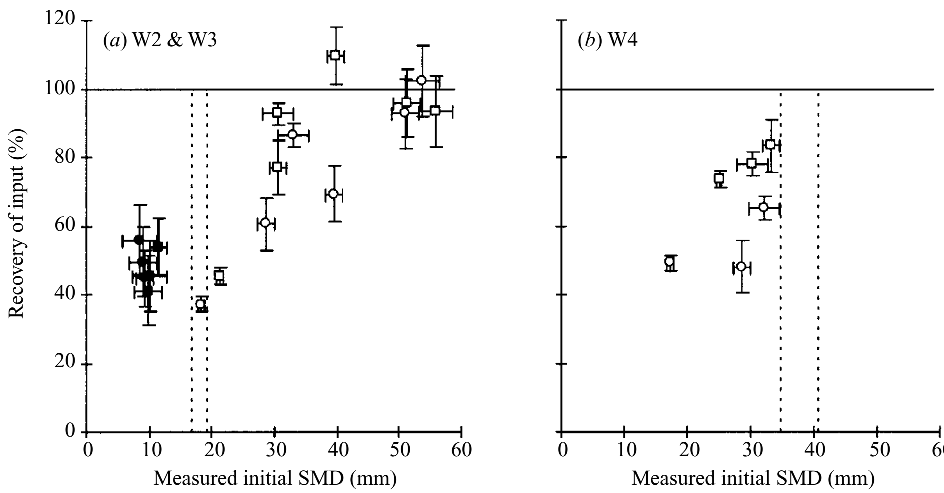

Fig. 3. Percentage recovery of applied irrigation (measured change in soil moisture deficit (SMD)/irrigation applied * 100) plotted against the measured SMD immediately before applying irrigation. A single data point in the figure represents the mean of all (12) access tubes in a given treatment for that irrigation. (*a*) W2 and W3, (*b*) W4. Cropped flat (□); cropped ridge (○); bare flat (■); bare ridge (●); shaded data are for 24 June (see text). Error bars indicate ±1 S.E. (W2 = 6 D.F., W3 and W4 = 4 D.F.). Dotted lines indicate range of irrigation amounts applied (mm).

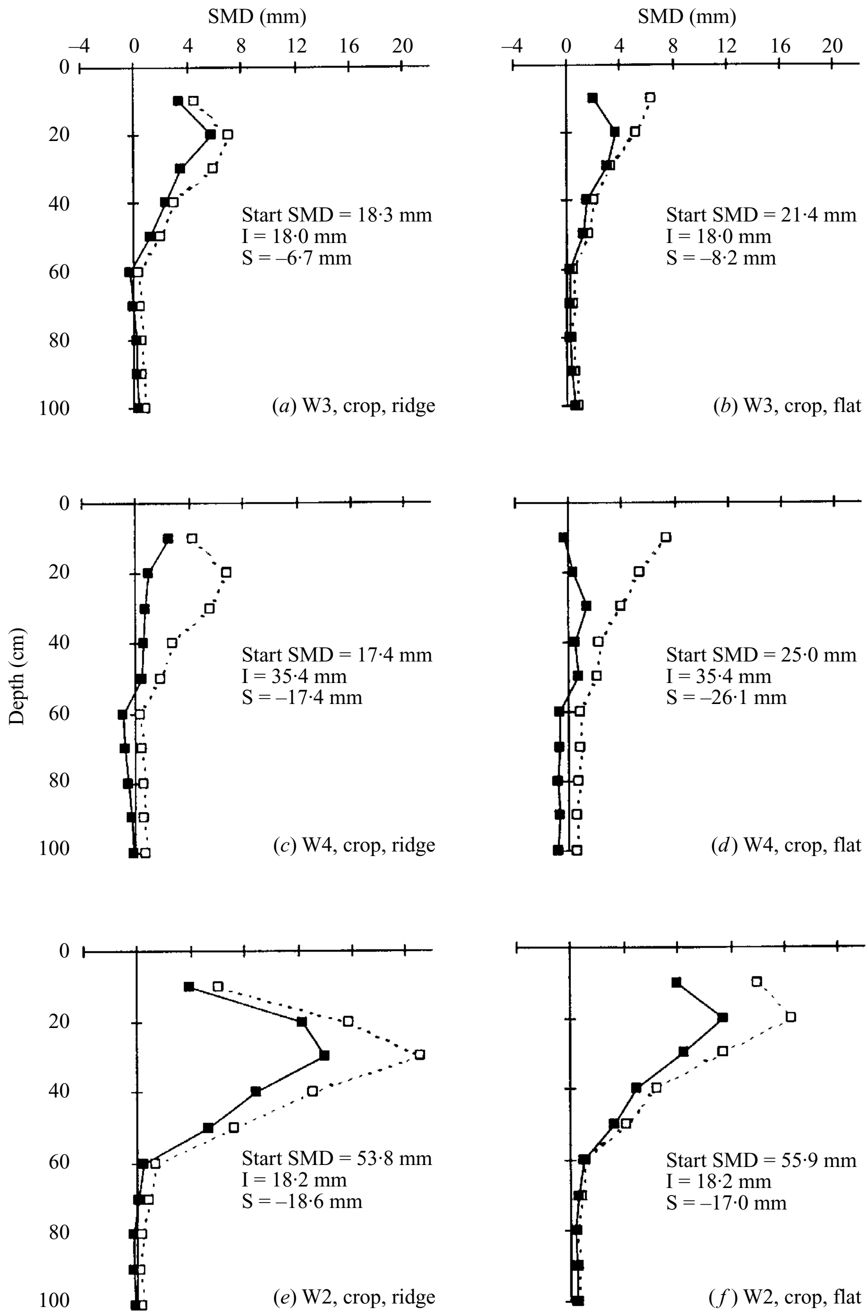

Fig. 4. Soil moisture deficits (SMD) down the soil profile measured before (□) and < 4 h after (■) selected irrigations. Start SMD = total SMD measured in the profile before irrigation; I = amount of irrigation applied as recorded in rain gauges; S = measured change in SMD before and after irrigation. (*a–d*) Irrigation applied 28 May to soils with small initial SMDs; (*e–f*) Irrigation applied 21 July to soils with large initial SMDs.

standard error of the measured change in SMD before and after irrigation was small (mean S.E. = 1·3 mm), but between treatments and irrigation dates the irrigation input measured by the NP ranged from 37 to 110%. The replicated measurements using the NP were, therefore, precise for a given event and

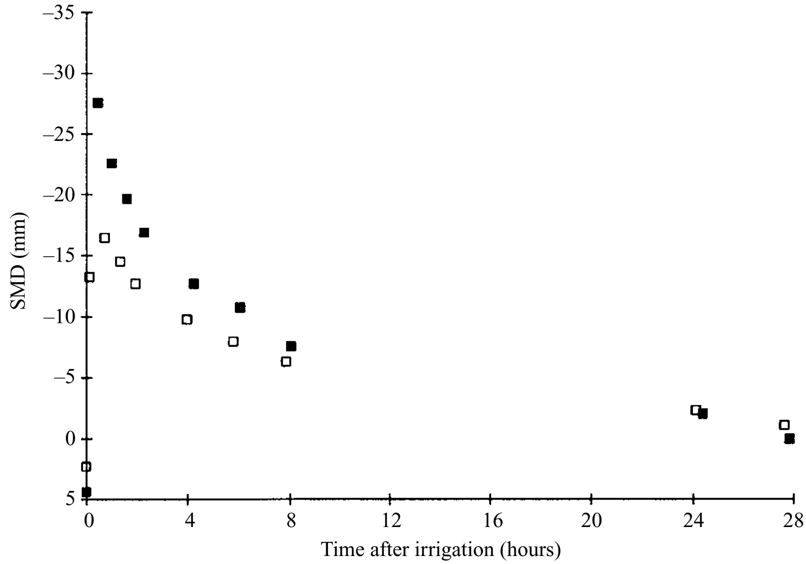

Fig. 5. Total soil moisture deficits (SMD) measured immediately before and then following 34·3 mm irrigation to a bare flat (■) and bare ridge (□) plot. Each point is the mean SMD from four access tubes.

treatment, but were not accurate when compared with the input measured in rain gauges.

Soil moisture deficits at individual depths down the soil profiles under cropped treatments before and after irrigation are shown in Fig. 4 for selected irrigations. Similar data were obtained from other irrigations, but are not shown. The change in SMD at depths ⩾ 60 cm in all treatments was numerically small and in most cases not statistically significant. There was no consistency between the amount of irrigation measured by the NP and the size of the changes in SMD at the base of the profile. For example, in Fig. 4*a*, *b* only half the irrigation was measured under the ridge and flat profiles, but there was very little change in SMD at depth under either profile; in Fig. 4*c*, *d* there was considerably less capture under ridge than under flat but the change in SMD at depth was numerically smaller under ridge than under flat; in Fig. 4*e*, *f* the capture recorded by the NP was close to the irrigation amount in the rain gauges but the changes in SMD at depth were similar to those in Fig. 4*a*, *b* where capture was much poorer.

The possibility that some of the irrigation may have drained from some profiles before the post-irrigation measurement was investigated by taking frequent measurements of the soil water storage over a period of 28 h, following 34 mm of irrigation to a bare ridge and a bare flat plot (Fig. 5). Both plots were close to field capacity (2–4 mm total SMD) at the start of irrigation. In the flat plot, maximum capture was 32 mm 30 min after irrigation, close to the amount applied (Fig. 5). Soil water content then decreased at an exponential rate until 28 h after irrigation when the plot had returned to field capacity. Two hours 15 min after irrigation only 21 mm of the 34 mm applied was measured by the NP. In the ridge plot, the maximum capture was only 19 mm 45 min after irrigation. At the time of the first reading (10 min after irrigation), there was still considerable water ponded in the furrows, but all the water had infiltrated by the time of the second reading, 45 min after irrigation. As in the flat plot, the SWC subsequently decreased at an exponential rate, and 28 h after irrigation the soil had returned to field capacity.

The timing of movement of water down the profile is crucial in understanding whether the NP was capable of detecting all of the water present following irrigation. Figure 6 presents data to show the profile SMDs under both ridge and flat profiles in the RC and FC access tube positions. Under ridges, at the RC position water had not penetrated beyond 90 cm 12 min after irrigation, and at the FC position had not yet reached the deepest measurement point 16 min after irrigation (Fig. 6*a*, *b*). In the flat plots, the water had not reached 80 cm by 30–34 min after irrigation at either RC or FC position (Fig. 6*c*, *d*). The RF and FR positions showed patterns of wetting intermediate between RC and FC positions where the profile was ridged, and all positions on flat profiles behaved similarly. Therefore, the irrigation water was either in the soil within the measurement zone of the NP or sitting on the soil surface, since it did not move laterally out of the plot. As time progressed after the irrigation, the deeper profiles got wetter at all depths, before draining back to field capacity *c*. 28 h after irrigation.

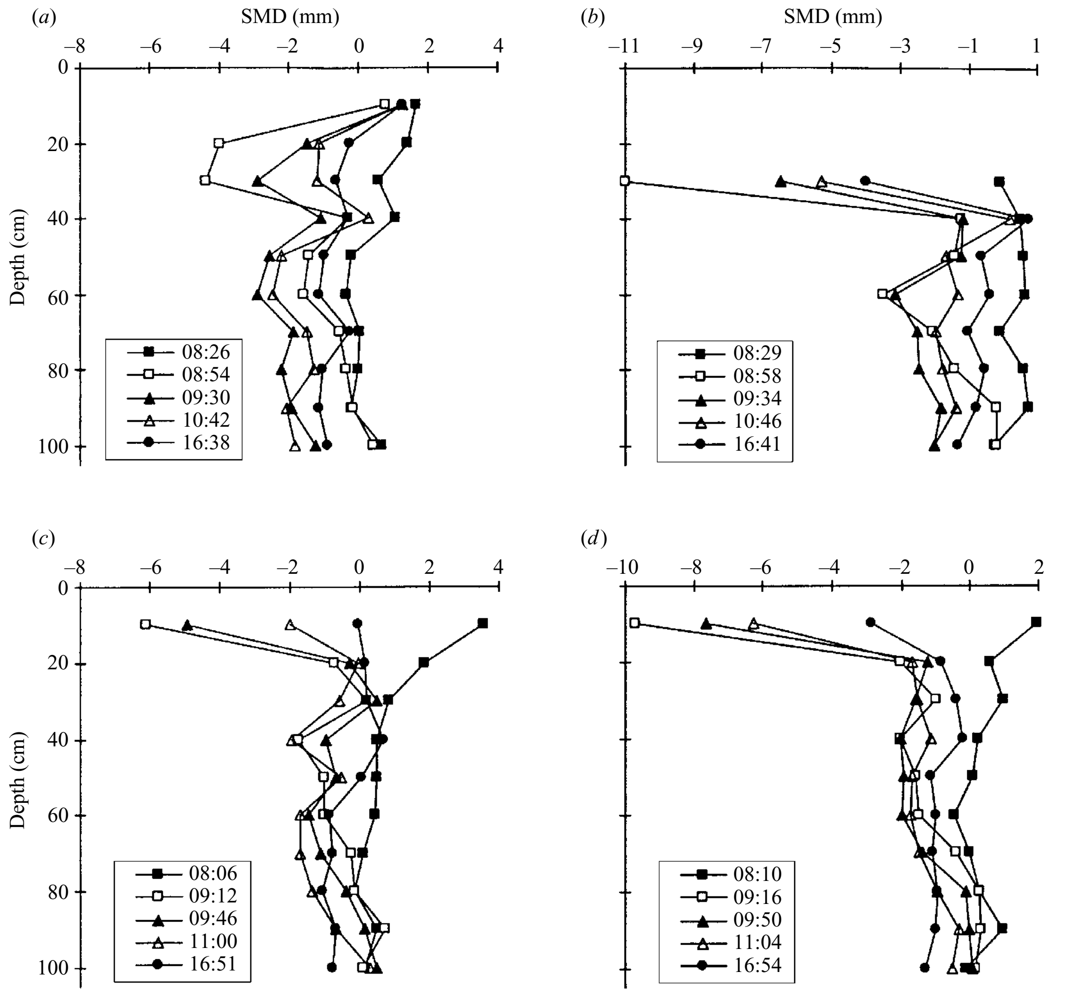

Fig. 6. Soil moisture deficits (SMD) in bare plots down the profile prior to and at four intervals after irrigation. Irrigation (34·3 mm) was applied at 08:42. (*a*) ridge RC position; (*b*) ridge FC position; (*c*) flat RC position; (*d*) flat FC position.

Irrigation – soil tank experiment

Table 3 shows the cumulative change in SWC measured using the NP following successive applications of irrigation to soil in the open-topped tank. The first 20 mm of water applied caused a measured increase in SWC of only 13 mm after 26 min. A little water (0·4 mm) reached 40 cm almost immediately after irrigation, suggesting that water may have run down the outside of the tube which was not as tight a fit in the soil as the tubes in the field experiment. Just prior to the third application, the NP had detected only 20 mm of the 40 mm applied, but the change in water content was confined mainly to the 0–15 cm (11·4 mm) and 15–25 cm (6·6 mm) layers at this stage. The SWC at 30 and 40 cm began to increase rapidly 50 min after the first irrigation, by which time a total of 60 mm had been applied, and infiltration became slower for subsequent irrigations. Seventy minutes after applying the third 20 mm, the NP recorded a total change of 62 mm for a total application of 60 mm. The 50 min taken for water to move through the soil to 40 cm in the tank was slower than that recorded in the field using the NP where water appeared to reach at least 80 cm within 30 min of 34 mm of irrigation to soil at field capacity (Fig. 6*c*, *d*).

During the course of measurement some soil slumping occurred in the soil tank. The soil settled by *c*. 4 cm. Using the equation of Vachaud *et al.* (1977) it was estimated that the bulk density would have increased from 1·2 to 1·3 g/cm^3 by settling, which would have reduced the final apparent SWC by *c*. 3 mm over the depth of soil measured, increasing the

Table 3. *Irrigation amount to soil in an open-topped tank and resultant change in water storage recorded by the neutron probe in a single access tube placed in the centre of the tank. A negative value indicates a recorded increase in water storage relative to the start of the experiment*

	Irrigation (mm)		Measured change in water stored (mm)		
Date and time	Application	Total	0–25 cm	25–53 cm	Total
07/04/00 09:35	20	20			
07/04/00 09:40			−8·3	−0·4	−8·7
07/04/00 09:44			−10·2	−1·0	−11·2
07/04/00 09:51			−11·6	−1·1	−12·7
07/04/00 10:00	20	40			
07/04/00 10:05			−16·4	−1·0	−17·5
07/04/00 10:08			−18·0	−1·5	−19·5
07/04/00 10:10	20	60			
07/04/00 10:22			−32·8	−15·8	−48·7
07/04/00 10:26			−31·8	−20·9	−52·7
07/04/00 11:20			−19·1	−42·7	−61·7
07/04/00 11:22	20	80			
07/04/00 11:30			−22·9	−47·0	−69·9
07/04/00 11:35			−21·6	−54·5	−76·1
07/04/00 11:44			−21·0	−61·6	−82·5
07/04/00 11:46	20	100			
07/04/00 11:56			−28·9	−68·0	−96·8
07/04/00 12:05			−28·0	−67·7	−95·7
07/04/00 12:17			−30·4	−67·2	−97·6
07/04/00 12:19	20	120			
07/04/00 12:33			−39·7	−67·8	−107·4
07/04/00 12:51			−40·3	−68·2	−108·5
07/04/00 13:02			−38·7	−67·5	−106·2
07/04/00 14:11			−38·7	−69·1	−107·8
07/04/00 17:25			−37·6	−68·8	−106·4

total amount measured in the soil to 111 mm compared with 120 mm applied. In order to estimate the effects of the soil slumping on the surface reading of the NP (which would have been 6 cm from the surface rather than 10 cm), 4 cm of soil at field capacity was placed on the existing soil surface in the tank, and another measurement taken. This increased the SWC measured using the NP by 6 mm. A further 10 mm of water was applied which ponded on the surface, only gradually infiltrating the newly applied soil layer. After *c*. 6 h, the SWC had increased by just 2 mm in response to the further rewetting, and water was still ponded on the soil surface. It was observed that the soil was saturated with water at this point. As a check, using the field capacity of 28·8 $cm^3/100\ cm^3$, the amount of water contained in the soil prior to irrigation was *c*. 147 mm. For a dry bulk density of 1·3 g/cm^3, one would expect a saturated water content of *c*. 50% volumetric, or 275 mm. The difference between theoretical saturation and field capacity was 128 mm, and since 120 mm of irrigation was applied this gave confidence to the visual impression that the soil had reached saturation in the tank.

Rainfall

There was acceptable correlation between input after accounting for evapotranspiration (rain – potential evapotranspiration) and the measured change in SMD for those occasions when the initial SMD indicated there was sufficient capacity in the soil to retain the rain (Fig. 7). However, as with the irrigation input, there were occasions when the change in storage recorded by the NP following rain was less than the 1:1 line (Fig. 7).

Drying

There were no significant differences in measured water use between flat and ridge profiles during drying periods, so the mean data are presented in Fig. 8. The comparison between measured and modelled changes in SMD was close to the 1:1 line indicating the model and the NP returned similar changes when inputs were minimal. Absolute deviations from the 1:1 line were greater for larger changes in SMD and were *c*. ± 5 mm for changes in SMD of *c*. 20 mm. Nevertheless, the NP measured changes in soil water

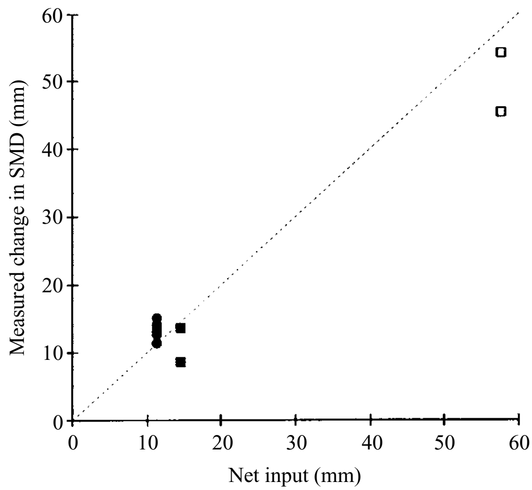

Fig. 7. Measured change in soil moisture deficit (SMD) compared with the net input (rain – potential evaporation) for occasions when the net input was ⩽ SMD before rain. 28–29 Jun (■), 3–10 Aug (□), 14–21 Sept (●). 1:1 relationship (broken line).

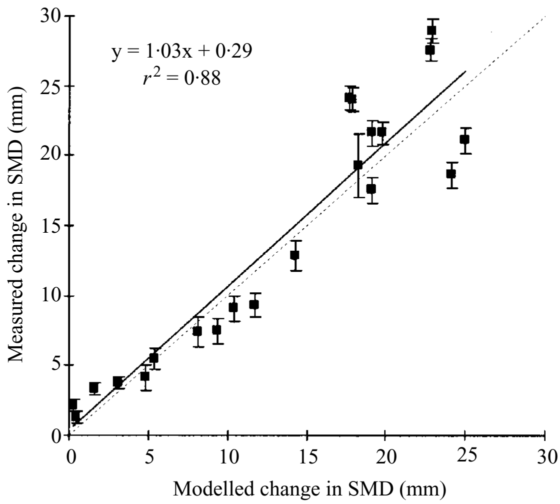

Fig. 8. Comparison of measured and modelled changes in soil moisture deficit (SMD) for periods when inputs were < 5 mm. Regression equation is for the fitted line (solid line), 1:1 relationship (broken line), error bars are ±1 S.E. (range in D.F. = 6–12).

storage under drying conditions more closely and consistently than it measured water inputs.

DISCUSSION

The NP has been used widely to measure changes in SWC and thereby SMD, but the accuracy of the data depends on a number of factors which can all contribute to error. These include calibration, installation, location and the setting of field capacity when working with relative changes in SWC, i.e. SMDs. In addition to all these factors, since potatoes are grown on widely spaced rows which considerably exceed the sphere of resolution of the NP in wet soil, areal sampling needs to be more extensive if an average SMD for the entire row width is to be estimated. The combined effect of these factors can lead to considerable error in the estimate of SMD, and thereby inaccurate scheduling of irrigation.

Discrepancies between irrigation or rainfall input recorded in rain gauges and the change in soil water storage recorded by the NP have been noted previously in the literature. The discrepancies have generally been attributed to either surface run-off (Hebblethwaite & McGowan 1977; Jefferies *et al.* 1991; Gaze *et al.* 1997), or drainage beyond the measurement zone (Singh *et al.* 1993). Similar explanations have been offered where rain gauge readings were greater than measured changes in soil water storage using time domain reflectometry (TDR; Olesen *et al.* 2000). These explanations assume that the NP (or other measurement device) recorded accurately the changes in soil water storage within its measurement zone, and the measurement zone adequately represents the row width of the crop.

For most irrigations in the field experiment the NP did not measure all of the water applied, even though measurements were taken within 2–4 h of irrigation. Where the irrigation applied was greater than the initial SMD, some drainage might have been expected (e.g. bare soil W2, and cropped W4). In the bare soil treatments, changes in SWC pre- and post-irrigation were monitored on three separate occasions. Averaged over these three events, irrigation was applied when the mean SMD measured immediately before irrigation was only 9·7 mm, which was close to the 8·9 mm increase in SWC recorded by the NP following an average of 18·3 mm of irrigation (Table 4). Similarly, for the three monitored irrigations to flat cropped W4 and for one of the monitored irrigations to the ridge cropped W4, the change in soil water storage recorded by the NP was within 2·5 mm of the SMD recorded immediately before irrigation. The amount of input not measured by the NP in these situations, therefore, approximated what might have been expected to drain. This, however, may be simply fortuitous in view of the other results. The timing of the drainage is crucial, since post-irrigation monitoring was *c.* 2–4 h after irrigation application.

For two other monitored irrigations to ridge cropped W4, the change in soil water storage recorded by the NP was substantially less than the SMD recorded before irrigation. There were also occasions when initial SMDs measured in cropped W2 and W3 indicated sufficient capacity to retain all the irrigation applied, but the change in soil water storage recorded

Table 4. *Change in soil moisture deficit (SMD) measured by the neutron probe before and after irrigation compared with the SMD measured immediately before irrigation (initial SMD), for those treatments where the initial SMD was less than the irrigation amount*

Date	Treatment	Irrigation amount (mm)	Initial SMD (mm)	Change in SMD (mm)
24 June	W2 bare ridge	17·6	9·3	−7·9
	W2 bare flat	17·6	11·4	−9·5
	S.E. (6 D.F.)	1·99	1·31	1·44
15 July	W2 bare ridge	19·0	8·9	−9·4
	W2 bare flat	19·0	9·9	−7·8
	S.E. (6 D.F.)	1·71	2·16	1·84
21 July	W2 bare ridge	18·2	8·5	−10·2
	W2 bare flat	18·2	10·0	−8·3
	S.E. (6 D.F.)	0·86	2·72	1·88
28 May	W4 crop ridge	35·4	17·4	−17·4
	W4 crop flat	35·4	25·0	−26·1
	S.E. (4 D.F.)	4·22	0·54	0·64
21 June	W4 crop ridge	37·0	28·7	−17·8
	W4 crop flat	37·0	33·3	−30·8
	S.E. (4 D.F.)	4·14	1·33	1·58
12 July	W4 crop ridge	40·5	32·2	−26·4
	W4 crop flat	40·5	30·0	−31·6
	S.E. (4 D.F.)	3·23	2·49	0·88

by the NP was substantially less than irrigation (Fig. 3). On one such occasion the NP measured as little as 7 mm of the 18 mm applied. There was, therefore, no consistent relationship between the initial SMD and the amount of irrigation measured by the neutron probe. There was, however, a general trend for the NP to measure more of the applied irrigation in drier soils than in wetter soils. The NP never recorded a substantially greater increase in soil water storage than the irrigation amount; the maximum capture recorded was 110% of irrigation.

The intensive monitoring of soil water storage following irrigation to the flat and ridge bare soil plots also gave inconsistent results. Maximum capture in the flat plot was close to the applied irrigation, but was 15 mm less than the irrigation amount for the ridge plot. The exponential decrease in soil water storage recorded following maximum capture in both plots is typical of a drainage curve. This suggests that some of the irrigation input that was not measured by the NP 2–4 h after irrigation to soil with initially small SMDs might be attributed to drainage. However, it is unlikely that the 'missing' water could always be attributed to drainage, since this would imply that in the intensively monitored bare ridge plot there was 15 mm of drainage below 100 cm within 45 min of irrigation. The timing of movement of water down the profile is crucial in understanding whether the NP was capable of detecting all of the water present following irrigation. Since water had not reached 100 cm (the maximum measurement depth) at any access tube position within 12–34 min of irrigation, the water was in the soil within the measurement zone of the NP or sitting on the soil surface, since it did not move laterally out of the plot. However, no more than 19 mm of water was measured from the 34 mm applied to ridges, although in the flat plots the measured water input was much closer, 32 mm *v.* 34 mm applied. It is likely that the NP cannot measure the large quantities of water that remain close to the surface following irrigation, particularly where the surface profile is composed of ridges and furrows, but the ridge treatments demonstrate that over time it does not 'reappear' (Fig. 6).

The possibility of drainage beyond the maximum depth of measurement confounding the change in soil water storage measured by the NP was removed in the experiment using the soil tank. The validity of using a NP calibration derived from access tubes installed in the field for the soil tank experiment could be questioned, but, irrespective of any error that this may have introduced, the NP was still inconsistent in measuring the applied irrigation. The delay in accounting for all the water immediately after application might be attributed to the water being mainly close to the soil surface at this stage. The difficulty in obtaining reliable readings in the top 20 cm of soil is not new and arises from the extreme difference in NP reading between the air and moist soil resulting in a loss of fast neutrons from the soil when taking measurements within 20 cm of the soil surface (Bell 1987). However, the discrepancy between the water applied and measured at this stage was considerable (e.g. only 20 mm measured out of 40 mm applied). When water was distributed through the whole profile, there was much closer agreement between the NP measurements and the irrigation application (e.g. 62 mm measured out of 60 applied, 83 mm measured out of 80 mm applied). With further additions of water, the soil became saturated from the base of the tank upwards until further increases in water content were again confined to the soil surface. The NP was again unable to detect this water and could account for only *c*. 110 mm out of the total of 120 mm applied.

It would not have been possible to predict at any stage when sufficient time had elapsed to ensure the applied water had distributed through the profile to allow the NP to record the irrigation input with acceptable accuracy. It is, therefore, not possible to interpret the change in water storage measured with a NP before and after irrigation using a single post-irrigation measurement. For example, in Fig. 5, 4 h after 34 mm irrigation was applied to the bare flat plot only 17 mm of the irrigation was recorded by the NP. If this had been the only reading, it would not have been possible to state if the 'missing' water was confined to the surface (and not 'visible' to the NP), or if it had already drained beyond the maximum depth of measurement. In this particular situation, because readings had been taken closer to the start of irrigation and 32 mm of the applied water had been measured 30 min after irrigation, the missing water 4 h after irrigation was assumed to have drained. However, there is no justification for attributing drainage to every occasion when the NP did not measure all the input, or, conversely, to attribute all unmeasured water to being confined to the soil surface and not detectable by the neutron probe. Any intermediate interpretation (e.g. some missing water was drainage, some not detectable) would be based on conjecture and could not be quantified. This only leaves the conclusion that the NP is inconsistent in its ability to measure inputs of water and, therefore, its utility for determining changes in soil water storage where there are substantial inputs of water has to be questioned. In practice, these are exactly the conditions in which the use of the NP was thought to be most helpful in providing an accurate instantaneous measurement of SWC. If the changes in water storage measured using the NP (following water input) cannot be trusted then no reliance can be placed on values of SMD derived using the NP. The tendency for the increase in soil water storage recorded by the NP to be less than the input recorded in rain gauges will result in the NP tending to overestimate SMD. Consequently, irrigation scheduling advice based on SMDs derived from the NP will tend to recommend more irrigation than is required, despite using a field-specific calibration.

Field-specific calibrations for the NP are generally not available for growers' fields. Obtaining a field-specific calibration so that the NP can be used to schedule irrigation is too costly for most growers. Consequently, a general calibration equation is typically used by the NP operator. Gardner (1981) collated NP calibration results from across the UK for the IH probe. Within the sandy loam textural class the gradient of the calibration line determined in field calibrations ranged from 0·529 to 0·922. For an actual SMD of 40 mm, a typical limiting deficit for potatoes on sandy loam soils, the SMD predicted by using the extreme gradients above would range from 24·9 to 49·5 mm, irrespective of uncertainties associated with accounting for irrigation inputs. Gardner (1981) was sufficiently mistrustful of the quality of some of the calibrations that she applied a standard calibration to all her collated data. From analysis of our experiments, it was not possible to identify why the 1999 calibration data were offset from those of previous years, but the consistency of the gradient between years gave some confidence in the calibration of the NP at CUF for measuring changes in water stored in the soil profile. The excellent fit of the data around a linear regression (mean percentage variance accounted for was 93·8 %), and the slope, which was close to the 'standard' loam soil of Bell (1987) for the majority of the data at depths $\geqslant 20$ cm, gives confidence in the accuracy and validity of our calibrations. The discrepancy in estimating SMD caused by using Bell's (1987) standard loam line compared with our calibration would amount to an error of only 2·5 mm at a typical SMD of 40 mm. The exception to this confidence would be a number of very low count ratios observed in 1999 where the calibration line was much shallower than Bell (1987), but nevertheless within the range found by Gardner (1981). For scheduling irrigation, where a measure of the SMD is required in real time, failure to use an accurate calibration alone could lead to unacceptable errors in the timing and amounts of irrigation applied.

The conclusion that the NP cannot measure reliably irrigation and rainfall input, with or without a field-specific calibration, also has major implications for testing irrigation scheduling and water use models. The NP has provided many data sets against which models have been tested and refined (Francis & Pidgeon 1982; Hamer *et al.* 1994; Bailey *et al.* 1996; Ejieji & Gowing 2000), the assumption being that if the model and measured SMDs do not agree, the measured are correct and the model needs modifying. The tendency for the NP to record a smaller increase in SWC than the input recorded in rain gauges, reported in this paper, may explain some of the discrepancies between published comparisons of measured and modelled data. Whilst authors of these papers have generally stated that their modelled data fitted measured data closely when regression techniques have been used as a comparison, there exist large discrepancies between measured and modelled

SWC or SMD, particularly when the soil is wet. For example in irrigated treatments where SWC was measured using a NP, Siddig (1982) and Prestt (1983) had maximum modelled – measured differences in SMD of +18 to +20 mm, Singh *et al.* (1993) −38 mm, Hamer *et al.* (1994) −29 mm, Bailey *et al.* (1996)+13 to −12 mm and Ejieji & Gowing (2000) +21 to −26 mm. These differences, where negative, are similar to, or in excess of, the differences between measured inputs of irrigation and measured changes in SWC observed in our experiments. Some of these published differences between measured and modelled could, therefore, be partially or completely explained by the inability of the NP to measure all of the water in the soil following irrigation.

Under conditions of minimal water input, the changes in soil water storage measured by the NP were acceptably close to those predicted by Penman–Monteith estimates of ET adjusted for crop cover and canopy resistance. This gives some confidence in using the NP in drying conditions (providing drainage is negligible). Experiments where there is negligible water input may provide useful information on growing crops under drought conditions. In a temperate climate with an irrigated crop, the problems of accounting for irrigation and rainfall inputs cannot be avoided or ignored.

If the NP cannot be used to test and improve water use models, an alternative independent test of water uptake in a range of soil conditions needs to be identified. Current alternative methods for measuring SWCs include manual gravimetric sampling, capacitance-based probes and TDR-based instruments. Gravimetric sampling is destructive and time consuming and is not a viable option. Capacitance and TDR-based instruments only sample a very small volume of soil within a few cm of the probes. Their use in widely spaced row-crops such as potatoes is, therefore, prohibitively expensive because of the number of measurement sites required to quantify the soil water status across the row-width. Few studies on potatoes have considered whether the NP is capable of measuring across the entire row-width, and those that have done so mainly confine themselves to comparing the results of ridge- and furrow-installed access tubes. It has been recognized that differences in water uptake between ridge and furrow positions are likely to be observed until the root system becomes homogeneously distributed across the row width (MacKerron & Jefferies 1987), and that intense precipitation events cause water to shed from leaves into the furrow beyond the range of detection of a single access tube in the ridge (French *et al.* 1973*a*, *b*, *c*). Loss of accuracy from ridge-installed tubes is a problem owing to neutron escape, so some researchers have used furrow-located tubes on their own (Jefferies & MacKerron 1987, 1989). Prestt (1983) placed tubes in different positions in beds 1·8 m wide, but no two tubes were closer than 45 cm apart. There appears no reference in the literature that has adopted such a wide areal sampling arrangement as the experiments reported here, and given the lack of observed accuracy in estimating SMD despite the confidence of measuring an entire transect of the rooting volume (both width and depth), it cannot be expected that data from single access tubes installed in ridge centres will result in accurate measurement of water use and scheduling of irrigation of potatoes.

Where comparisons have been made between dielectric-type probes (e.g. capacitance and TDR) and NPs, some studies have concluded that they offer a suitable alternative to the NP in the measurement of SWC (Bell *et al.* 1987; Ayars *et al.* 1995; Payne & Brück 1996; Roberson *et al.* 1996; Ould Mohamed *et al.* 1997; Vandiver & Kirsch 1997) whilst other studies have shown them to be unsatisfactory in measuring SWC across all soil types (Evett & Steiner 1995; Waugh *et al.* 1996; Gaze *et al.* 2000; Hanson & Peters 2000; Hanson *et al.* 2000). Where comparisons with NPs were not favourable, air gaps around the access tubes and/or soil heterogeneity (bulk density, salinity, texture) have been suggested as possible explanations. Whilst capacitance probes do give a greater resolution in terms of detail of soil water profile, they are much more prone to air gaps and soil heterogeneity because of their greater resolution. Identifying a reliable and affordable method for measuring crop water use under a range of conditions is critical if progress is to be made in understanding the relationship between crop water demand and soil supply, particularly in irrigated crops with wide row-spacing.

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REFERENCES

ALLEN, R. G., JENSEN, M. E., WRIGHT, J. L. & BURMAN, R. D. (1989). Operational estimates of reference evapotranspiration. *Agronomy Journal* **81**, 650–662.

ANON. (1983). *Soils of England and Wales. Sheet 4 Eastern England.* Soil Survey of England and Wales. Southampton: Ordnance Survey.

AYARS, J. E., MEAD, R. M., PALTINEANU, I. C. & LIU, J. (1995). Radioactive versus capacitance techniques for measuring soil water. In *Nuclear Techniques in Soil–Plant Studies for Sustainable Agriculture and Environmental Preservation*, pp. 419–428. Vienna: IAEA/FAO.

BAILEY, R. J. & SPACKMAN, E. (1996). A model for estimating soil moisture changes as an aid to irrigation scheduling and crop water-use studies: I. Operational details and description. *Soil Use and Management* **12**, 122–128.

BAILEY, R. J., GROVES, S. J. & SPACKMAN, E. (1996). A model for estimating soil moisture changes as an aid to irrigation scheduling and crop water-use studies: II. Field test of the model. *Soil Use and Management* **12**, 129–133.

BELL, J. P. (1987). *Neutron Probe Practice*. Report No. 19 (3rd Edn). Wallingford, UK: Institute of Hydrology.

BELL, J. P., DEAN, T. J. & HODNETT, M. G. (1987). Soil moisture measurement by an improved capacitance technique. Part II. Field techniques, evaluation and calibration. *Journal of Hydrology* **93**, 79–90.

BROWN, K. F. & BISCOE, P. V. (1985). Fibrous root growth and water use of sugar beet. *Journal of Agricultural Science, Cambridge* **105**, 679–691.

BROWN, K. F., MESSEM, A. B., DUNHAM, R. J. & BISCOE, P. V. (1987). Effect of drought on growth and water use of sugar beet. *Journal of Agricultural Science, Cambridge* **109**, 421–435.

CHANASYK, D. S. & NAETH, M. A. (1996). Field measurement of soil moisture using neutron probes. *Canadian Journal of Soil Science* **76**, 317–323.

EJIEJI, C. J. & GOWING, J. W. (2000). A dynamic model for responsive scheduling of potato irrigation based on simulated water-use and yield. *Journal of Agricultural Science, Cambridge* **135**, 161–171.

EVETT, S. R. & STEINER, J. L. (1995). Precision of neutron scattering and capacitance type soil water content gauges from field calibration. *Soil Science Society of America Journal* **59**, 961–968.

FERNANDEZ, J. E., CLOTHIER, B. E. & VAN NOORDWIJK, M. (2000). Water uptake. In *Root Methods: A Handbook* (Eds A. L. Smit, A. G. Bengough, C. Engels, M. van Noordwijk, S. Pellerin & S. D. van de Geijn), pp. 461–507. Berlin: Springer-Verlag.

FRANCIS, P. E. & PIDGEON, J. D. (1982). A model for estimating soil moisture deficits under cereal crops in Britain. 2. Performance. *Journal of Agricultural Science, Cambridge* **98**, 663–678.

FRENCH, B. K., LONG, I. F. & PENMAN, H. L. (1973*a*). Water use by farm crops. I. Test of the neutron meter on barley, beans and sugar beet. In *Rothamsted Report for 1972, Part 2*, pp. 5–42, Harpenden, UK: Rothamsted Experimental Station.

FRENCH, B. K., LONG, I. F. & PENMAN, H. L. (1973*b*). Water use by farm crops. II. Spring wheat, barley, potatoes (1969); potatoes, beans and kale (1968). In *Rothamsted Report for 1972, Part 2*, pp. 43–61, Harpenden, UK: Rothamsted Experimental Station.

FRENCH, B. K., LONG, I. F. & PENMAN, H. L. (1973*c*). Water use by farm crops. III. Bar soil, short truf and crops in rotation, 1962 to 1967, 1971. In *Rothamsted Report for 1972, Part 2*, pp. 62–85, Harpenden, UK: Rothamsted Experimental Station.

GARDNER, C. M. K. (1981). *The soil moisture database: Moisture Content Data from some British Soils*. Report No. 76, Wallingford, UK: Institute of Hydrology.

GAZE, S. R. (1996). *Water Balance of Farmer-managed Millet and Fallow–Savannah on Sandy Soils in South West Niger*. Ph.D. thesis, University of Reading.

GAZE, S. R., SIMMONDS, L. P., BROUWER, J. & BOUMA, J. (1997). Measurement of surface redistribution of rainfall and modelling its effect on water balance calculations for a millet field on sandy soil in Niger. *Journal of Hydrology* **188–189**, 267–284.

GAZE, S. R., STALHAM, M. A., ALLEN, E. J. & NEWBERY, R. M. (2000). *Effect of Soil Water Status and Soil Physical Conditions on Potato Growth, Yield and Tuber Dry Matter Concentration*. Final Report to the British Potato Council, Project No. 807/182. Oxford: British Potato Council.

GRANT, D. R. (1975). Comparison of evaporation from barley with Penman estimates. *Agricultural Meteorology* **15**, 49–60.

GREGORY, P. J., MCGOWAN, M. & BISCOE, P. V. (1978). Water relations of winter wheat. 2. Soil water relations. *Journal of Agricultural Science, Cambridge* **91**, 103–116.

HALL, S. M. & JONES, R. J. A. (1983). Soil moisture changes under grassland as measured by neutron probe in midland England. *Journal of Agricultural Science, Cambridge* **101**, 481–493.

HAMER, P. J. C., CARR, M. K. V. & WRIGHT, E. (1994). Crop production and water-use. III. The development and validation of a water-use model for potatoes. *Journal of Agricultural Science, Cambridge* **123**, 299–311.

HANSON, B. R. & PETERS, D. (2000). Soil type affects accuracy of dielectric moisture sensors. *California Agriculture* **54**, 43–47.

HANSON, B. R., ORLOFF, S. & PETERS, D. (2000). Monitoring soil moisture helps refine irrigation management. *California Agriculture* **54**, 38–42.

HAVERKAMP, R., VAUCLIN, M. & VACHAUD, G. (1984). Error analysis in estimating soil water content from neutron probe measurements: 1. Local standpoint. *Soil Science* **137**, 78–90.

HEBBLETHWAITE, P. D. & MCGOWAN, M. (1977). Irrigation and nitrogen studies in S. 23 ryegrass grown for seed. 2. Crop transpiration and soil-water status. *Journal of Agricultural Science, Cambridge* **88**, 615–624.

ISARD, S. A., WELFORD, M. R. & HOLLINGER, S. E. (1995). A simple soil moisture index to forecast crop yields. *Physical Geography* **16**, 524–538.

JEFFERIES, R. A., HEILBRONN, T. D. & MACKERRON, D. K. L. (1991). Water stress as a constraint on growth in the potato crop. 2. Validation of the model. *Agricultural and Forest Meteorology* **53**, 197–205.

JEFFERIES, R. A. & MACKERRON, D. K. L. (1987). Aspects of the physiological basis of cultivar differences in yield of potato under droughted and irrigated conditions. *Potato Research* **30**, 201–217.

JEFFERIES, R. A. & MACKERRON, D. K. L. (1989). Radiation interception and growth of irrigated and droughted potato (*Solanum tuberosum*). *Field Crops Research* **22**, 101–112.

MACKERRON, D. K. L. & JEFFERIES, R. A. (1987). Access tube location within a simulated potato crop and the measurement of soil moisture with a neutron probe. *Plant and Soil* **102**, 253–255.

MARSHALL, T. J. & HOLMES, J. W. (1988). *Soil Physics*. 2nd edition. Cambridge: Cambridge University Press.

MCGOWAN, M. & WILLIAMS, J. B. (1980). The water balance of an agricultural catchment. I. Estimation of evaporation from soil water records. *Journal of Soil Science* **31**, 217–230.

MARTIN, R. J., JAMIESON, P. D., WILSON, D. R. & FRANCIS, G. S. (1992). Effects of soil moisture deficits on yield and quality of 'Russet Burbank' potatoes. *New Zealand Journal of Crop and Horticultural Science* **20**, 1–9.

MONTEITH, J. L. (1965). Evaporation and environment. In *The State and Movement of Water in Living Organisms. XIXth Symposium, Society for Experimental Biology, Swansea*, pp. 205–234. Cambridge: Cambridge University Press.

MONTEITH, J. L. (1981). Evaporation and surface temperature. *Quarterly Journal of the Royal Meteorological Society* **107**, 1–27.

MONTEITH, J. L. (1986). How do crops manipulate water supply and demand? *Philosophical Transactions of the Royal Society, London, Series A* **316**, 245–259.

OLESEN, J. E., MORTENSEN, J. V., JORGENSEN, L. N. & ANDERSON, M. N. (2000). Irrigation strategy, nitrogen application and fungicide control in winter wheat on sandy soil. I. Yield, yield components and nitrogen uptake. *Journal of Agricultural Science, Cambridge* **134**, 1–11.

OULD MOHAMED, S., BETUZZI, P., BRUAND, A., RAISON, L. & BRUCKLER, L. (1997). Field evaluation and error analysis of soil water content measurement using the capacitance probe method. *Science Society of America Journal* **61**, 399–408.

PAYNE, R. W., LANE, P. W., DIGBY, P. G. N., HARDING, S. A., LEECH, P. K., MORGAN, G. W., TODD, A. D., THOMPSON, R., TUNNICLIFFE WILSON, G., WELHAM, S. J. & WHITE, R. P. (1993). *Genstat™ 5 Release 3 Reference Manual*. Oxford: Clarendon Press.

PAYNE, W. A. & BRÜCK, H. (1996). Evaporation and other soil water balance terms estimated from neutron and capacitance probe measurements. In *Evaporation and irrigation scheduling* (Eds C. R. Camp, E. J. Sadler & R. E. Yoder), *Proceedings of the International Conference 3–6 November, 1996, San Antonio, Texas*, pp. 455–462. St Joseph, MI, USA: ASAE.

PRESTT, A. J. (1983). *Soil Management and the Water Use of Potatoes*. Ph.D. thesis, National College of Agricultural Engineering, Cranfield Institute of Technology, Silsoe, Bedfordshire.

RAMADAN, M. H. A. E. (1986). *Modelling for Irrigation Scheduling with Particular Reference to the Potato Crop*. Ph.D. thesis, University of London.

ROBERSON, M., FULTON, A., WU, L., HANDLEY, D., BUSS, P. & OSTER, J. (1996). Capacitance probe used for cotton irrigation scheduling. In *Evaporation and Irrigation Scheduling* (Eds C. R. Camp, E. J. Sadler & R. E. Yoder), pp. 1109–1114. *Proceedings of the International Conference 3–6 November, 1996, San Antonio, Texas*. St Joseph, MI, USA: ASAE.

SIDDIG, A. A. (1982). *Computer Aided Irrigation Scheduling*. Ph.D. thesis, National College of Agricultural Engineering, Cranfield Institute of Technology, Silsoe, Bedfordshire.

SINGH, G., BROWN, D. M., BARR, A. G. & JUNG, R. (1993). Modeling soil-water status for irrigation scheduling in potatoes. 2. Validation. *Agricultural Water Management* **23**, 343–358.

SMITH M. (1992). *CROPWAT. A Computer Program for Irrigation and Planning and Management*, Irrigation and Drainage Paper, **46**. Rome: FAO.

THOM, A. S. & OLIVER, H. R. (1977). On Penman's equation of estimating regional evaporation. *Journal of the Royal Meteorological Society* **103**, 345–357.

VACHAUD, G., ROYER, J. M. & COOPER, J. D. (1977). Comparison of methods of calibration of a neutron probe by gravimetry or neutron-capture model. *Journal of Hydrology* **34**, 343–356.

VANDIVER, D. W. & KIRSCH, S. W. (1997). A field test of an electrical-capacitance method for measuring soil-water content. *Physical Geography* **18**, 80–87.

VISVALINGHAM, M. & TANDY, J. D. (1972). The neutron method for measuring soil moisture content – a review. *Journal of Soil Science* **23**, 499–511.

WILLIAMS, J., HOLMES, J. W., WILLIAMS, B. G. & WINKWORTH, R. E. (1981). Application in agriculture, forestry and environmental science. In *Soil water Assessment by the Neutron Method* (Ed. E. L. Greacen), pp. 3–15. Melbourne, Australia: CSIRO.

WAUGH, W. J., BAKER, D. A., KASTENS, M. K. & ABRAHAM, J. A. (1996). Calibration precision of capacitance and neutron soil water content gauges in arid soils. *Arid Soil Research and Rehabilitation* **10**, 391–401.