Water availability in a restored soil

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Abstract. The water contents of a restored and an undisturbed soil were monitored over two 'dry' growing seasons in order to examine the differences in crop water availability from different horizons. Bulk density was approximately 10% greater in the topsoil of restored land than in undisturbed land, and the water holding capacity was less, probably because there was less organic matter. In the subsoil a major problem was the inability of the soil to allow winter rainfall to recharge the water reserves. Bulk density and penetration resistance were greater in the restored subsoil than in the undisturbed subsoil. Increases in penetration resistance on drying may have restricted rooting activity, especially in the restored subsoil.

Ripping of the subsoil to a depth greater than the usual 0.5 m, possibly early in the year in a grass crop to allow new root growth to exploit the cracks, may increase water availability for future dry seasons.

INTRODUCTION

Soils restored after opencast coal mining can suffer from problems associated with compaction and decreased subsoil permeability (King, 1989). Decreased porosity and hydraulic conductivity can lead to decreased available water capacity (AWC: water volume held between −1500 and −5 kPa). Infiltration into the subsoil is impeded by destruction of fissures and pores (Jarvis *et al.*, 1984), so restored sites shed winter rainfall quickly and there is limited recharge of subsoil water reserves during the winter.

The purpose of this work was to compare the profiles of a restored and an undisturbed soil in terms of their abilities to provide plant available water. The soil properties which may have influenced water availability are discussed, and possible remedial measures suggested to improve water availability.

MATERIALS AND METHODS

Sites, climate and soils

Two sites were monitored, one on restored land and one on an undisturbed area, both at Acklington in Northumberland at an elevation of 30 m above sea level. The vegetation of both sites was a mixed grass/clover sward which received 200 kg N per hectare per year and was managed for silage production. Soils in the area around both sites were initially clay loam stagnogleys of the Dunkeswick series (Table 1), recorded as wetness class III in the undisturbed state but class IV/V in the restored state (Jarvis *et al.*, 1984).

Undisturbed soil profile description:

Ap, 0–0.25 m. Dark greyish brown (2.5Y 4/2) sandy clay loam; 5% sub-rounded stones up to 50 mm diameter; medium to fine angular blocky, moderate to weakly developed structure; moderately porous with many cracks; moderate/weak strength; slightly sticky; many roots throughout and rotting straw at 0.25 m; clear irregular boundary.

Eg, 0.25–0.45 m. Yellowish brown (10YR 5/6) sandy clay loam; few medium irregular mottles; 5% sub-rounded stones up to 60 mm diameter; medium to coarse sub-angular blocky, moderately to weakly developed structure; moderately firm to very weak in places; moderately sticky; fine roots throughout with pieces (< 2 mm) of coal; clear irregular boundary.

Btg, 0.45–1.0 m. Yellowish brown (10YR 5/8) and dark yellowish brown (10YR 3/3) with grey (N5) on ped faces, sandy clay loam; weak irregular mottles; up to 50% angular stones up to 200 mm diameter in layers; medium to coarse prismatic, strongly developed to massive structure below 0.8 m; moderately firm; sticky to non-sticky in pockets; few fine roots to 0.9 m.

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Restored soil profile description:

Topsoil, 0–0.25 m. Dark brown (10YR 3/2) clay loam with few (< 2%) fine mottles; 2–5% stones up to 50 mm diameter; medium/fine weakly developed sub-angular blocky structure; moderately weak strength; slightly sticky; many roots throughout; clear irregular boundary.

Subsoil, 0.25–1.2 m. Dark yellowish brown (10YR 4/4) clay loam with fine indistinct mottles; < 5% stones, angular up to 100 mm; massive structure with clods of varved clay originating from depths greater than 1 m before opencasting; very firm strength; moderately sticky; few fine roots to 0.5 m; small pieces of coal; sharp smooth boundary.

Overburden, >1.2 m. Grey shale and mudstone; angular slabs up to 0.25 m; massive structures; no pores or fissures; no roots; very strong.

The three horizons of the restored soil profile were a direct result of the restoration procedure. The topsoil and subsoil material, stripped from the original site, were stored in mounds for 7 years during the coal extraction period. After replacement, the subsoil was ripped (cracked and loosened with a subsoiler tine) before the topsoil was replaced, in an attempt to increase permeability. Below the subsoil the overburden consisted predominantly of impermeable grey shales and mudstones.

The soil was replaced early in 1986, field drains were installed in August of that year and the first grass was sown in May 1987. The drainage scheme consisted of 60-mm PVC pipes at 10 m spacing and a depth of 750 mm, covered with permeable fill to within 150 mm of ground level. The undisturbed site had an old drainage system of clay pipes backfilled with subsoil.

The average annual (previous 10 years) rainfall is approximately 750 mm and average potential evapotranspiration is 430 mm.

Soil properties

Soil properties which directly affect the water holding and transmitting properties of the soil were determined. For water holding capacity these were particle size distribution, bulk density and organic matter content. The saturated hydraulic conductivity (K_{sat}) of the subsoil was determined by the falling head method (Black, 1965) on 4 cores from each site.

Penetration resistance. Soil penetration resistance was measured at both sites over a period of 4 months from the end of February to the end of May during a period of prolific root growth. The first measurement was taken when the soil profile was at field capacity (moisture status after gravitational drainage from the completely saturated state), and subsequent determinations were made at monthly intervals until the end of May. Ten measurements were made at each site using a Bush penetrometer recording every 3.5 cm down to 52.5 cm.

Meteorological data

Rainfall for 1989 and 1990 was recorded using a Campbell Scientific tipping raingauge, and potential evapotranspiration (PET) was obtained for Cockle Park (10 miles south of Acklington) from the MORECS data base (Thompson *et al.*, 1981) as not all data necessary to calculate PET could be obtained from the site weather station.

Soil moisture monitoring

Soil moisture was monitored on a two-weekly basis from February 1989 to September 1990 using two neutron probe access tubes at each site. On each occasion readings were taken at four depths in both tubes:

1. 10 cm was the closest to the surface that readings could reliably be taken (Bell, 1976).
2. 20 cm provided a reading for the base of the topsoil with little influence from moisture in the subsoil mainly below 30 cm.
3. 40 cm was a reading taken well into the subsoil and therefore little influenced by moisture in the topsoil.
4. 70 cm was where most of the roots reach their maximum depth.

The readings were converted into volumetric soil moisture content from a calibration curve determined for each site and each depth. This involved determining the volumetric soil moisture content on four occasions throughout the year so spanning a range of neutron probe readings. Soil core samples were taken near to neutron probe tubes inserted specifically for calibration. The relationship between neutron probe reading and soil moisture was linear; however, the slope of the line varied according to soil density.

To convert the volumetric soil moisture content into the soil matric potential, a soil moisture characteristic curve was first obtained. Four 20-cm^3 undisturbed cores were taken from the topsoil at 10 cm depth and from the subsoil at 50 cm depth at both sites. Previous studies had shown no difference in moisture release within the topsoil and subsoil horizons used for our neutron probe readings. These were allowed to saturate for 48 h before being transferred to tension tables and later to pressure plate equipment to determine the moisture release curves from −1500 to −10 kPa. The volumetric moisture content was converted to matric potential using the relationship developed by Williams *et al.* (1983):

$$\ln \Psi_m = a - b \times \ln \theta_v \qquad (1)$$

where:

ln = natural logarithm
Ψ_m = soil matric potential (kPa)
a = constant for each curve
b = constant for each curve
θ_v = volumetric soil moisture content.

Table 1. The physical properties of soil at the restored and undisturbed sites (Dunkeswick series). Standard errors in parenthesis

	Restored		Undisturbed	
	Topsoil	Subsoil	Topsoil	Subsoil
Particle sizes				
< 2 μm	28.2 (0.76)	28.3 (1.19)	27.5 (1.13)	28.7 (0.57)
60–2000 μm	17.4 (0.35)	25.3 (0.81)	16.8 (0.42)	26.0 (0.20)
> 2000 μm	49.5 (0.74)	43.3 (1.69)	49.4 (1.43)	40.2 (0.76)
Dry bulk density (Mg/m^3)	1.49 (0.07)	1.80 (0.09)	1.29 (0.09)	1.76 (0.04)
AWC volume %	14.4 (1.1)	6.5 (0.5)	16.0 (0.6)	12.0 (0.7)
K_{sat}* ($\times 10^{-2}$) (m/day)	—	0.03 (0.01)	—	9.37 (0.84)
K_{sat}* class	—	very slow	—	slow/mod slow
Organic matter %	3.76 (0.17)	3.17 (0.19)	5.13 (0.16)	2.80 (0.08)
Plastic limit†	23.8 (0.69)	21.7 (0.87)	28.2 (1.04)	21.9 (0.22)

* SATURATED HYDRAULIC CONDUCTIVITY † BS 1377

RESULTS AND DISCUSSION

Soil properties
Texturally, the restored soils were similar to the Dunkeswick series at the undisturbed site (Table 1). However, organic matter content of the topsoil was significantly less than at the undisturbed site and bulk density was greater in both horizons at the restored site, particularly in the topsoil. Subsoil K_{sat} and AWC for topsoil and subsoil were less at the restored site.

Penetration resistance. Soil penetration resistance reflected soil density and was generally greater at the restored site. When measured at field capacity, soil penetration resistance for the topsoil was 30% greater ($P < 0.001$) at the restored site (Fig. 1a). However, in a zone about 7 cm thick from 28 to 35 cm, the resistance was greater at the undisturbed site. This may have resulted from greater organic matter contents and increased lower plastic limits (Table 1) at the bottom of the topsoil or top of the subsoil. At both sites an increase in resistance was recorded with depth in the subsoil. Both sites had a resistance of 22 N at 38.5 cm, but at 52.5 cm it was 26 N at the undisturbed site compared with 40 N at the same depth at the restored site.

When penetration resistance was measured in February 1990, the soil at both sites was at 'field capacity'. This corresponded to gravimetric moisture contents of 24.8% at the restored site and 31.8% at the undisturbed site. Soil at the restored site therefore had a gravimetric moisture content 1% greater than the lower plastic limit, and at the undisturbed site it was 3% greater than the lower plastic limit (Table 1). Increased penetration resistance at the restored site could therefore have been a product of increased density and lower plasticity in February.

By 21 March, penetration resistance at both sites had increased markedly in the topsoil (Fig. 1b) and slightly in the top of the subsoil. Differences in topsoil penetration resistance between sites were similar to those measured in

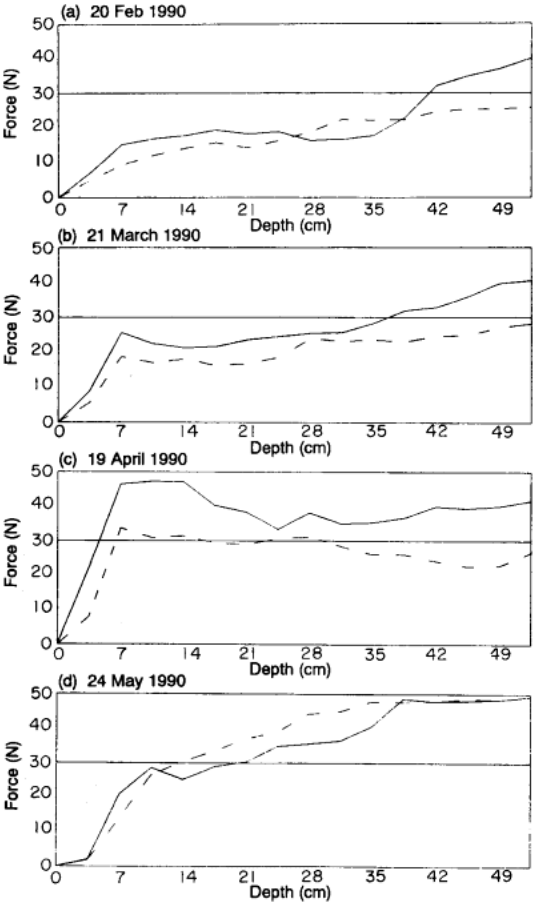


Fig. 1. Soil penetration resistance measured on four occasions during 1990: —, restored; ---, undisturbed. The horizontal line at 30 N indicates the penetration resistance above which root growth is prevented or severely impeded.

February when the soil was at field capacity. However, the restored site had developed a greater penetration resistance in the top of the subsoil than the undisturbed site.

On 19 April topsoil penetration resistance had increased to a maximum of approximately 30 N at the undisturbed site and nearly 50 N at the restored site. Taylor *et al.* (1966) and Cockroft *et al.* (1969) reported that roots generally do not grow in soil with a penetration resistance exceeding 30 N. The increase in resistance in the top of the subsoil was greater at the restored site (Fig. 1c). Up until the end of April root growth may have become increasingly restricted in the restored subsoil, though it was still possible at the undisturbed site. On 24 May soil penetration resistance at both sites was great enough to prevent root growth. The slightly lower resistance at the restored site was probably related to numerous cracks in the subsoil.

The plastic limit of the subsoil was similar for both sites and so the lower moisture content reached earlier in the year at the restored site indicated the soil to be in a friable state (soil fails by brittle fracture rather than by plastic flow as its moisture content is less than that at the lower plastic limit) about 2 months earlier than at the undisturbed site. Soil shear strength is greatest near the lower plastic limit; thereafter as soil dries and becomes friable, compressive strength increases (Baver *et al.*, 1972). The rate of increase in penetration resistance as the soil dried was greatest at the restored site because of the increase in compressive strength. Penetration resistance, although partially dependent on soil density, is particularly dependent on soil moisture content, which in turn has large influences on soil consistence, shear strength and compressive strength. Ehlers *et al.* (1983) showed that soil bulk density and water content influence cone resistance. Soil at 70 cm at the restored site seemed to have remained friable throughout the year and at 40 cm a moisture content just below the plastic limit was reached on 24 May. This led to the increased penetration resistance at the restored site and may have resulted in poor root growth at depth. However, there was a combined effect of soil consistence (friable, plastic or liquid) and density on soil penetration resistance. For a given gravimetric soil moisture content within the range from the plastic limit to 5% below the plastic limit, resistance was greater at the restored site.

Weather factors

During 1989 and 1990 the average rainfall for the two years was approximately 60% of the 10-year average (Fig. 2). Monthly PET was greater than usual early in 1990 (Fig. 3) and consequently provided greater opportunity for drying the soil.

Soil moisture monitoring

Matric potentials at both sites and in both years fluctuated between approximate field capacity during the winter months and values well below the permanent wilting point (PWP) during the summer. All differences discussed below were statistically significant at the 99.9% level. In both horizons there were also significant differences between sites in the water holding capacity of the soil. This was clearly shown by the difference between the moisture release curves for topsoil (Fig. 4a) and subsoil (Fig. 4b). The difference in volumetric moisture content was nearly 5% at saturation (0 kPa) and nearly 2% at PWP (−1500 kPa).

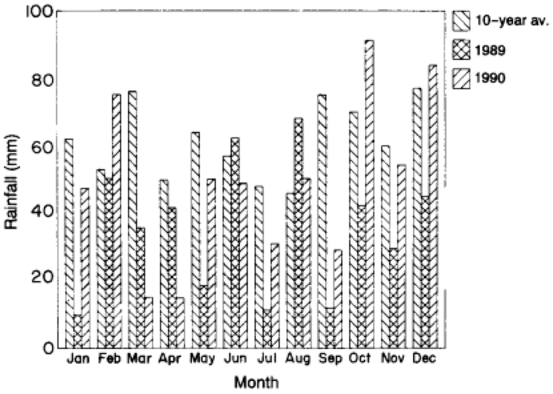


Fig. 2. Monthly rainfall at Acklington for 1989 and 1990.

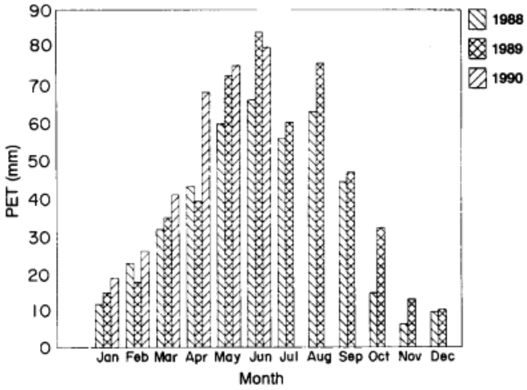
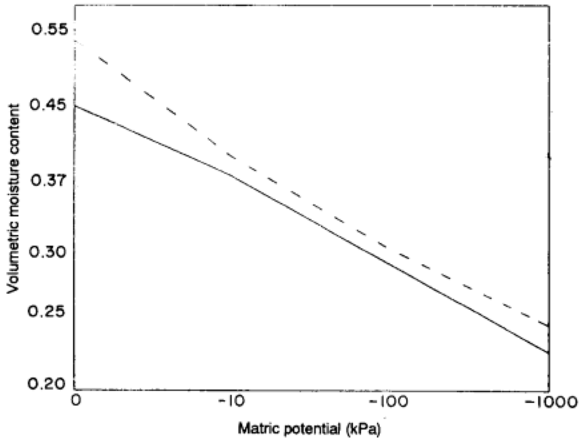


Fig. 3. Monthly potential evapotranspiration at Cockle Park for 1988, 1989 and 1990.

Topsoil (10 and 20 cm readings). In February 1989 'field capacity' (−5 kPa) in the topsoil had been reached at both sites at 10 cm depth (Fig. 5a). By the end of May 1989, however, the matric potential at 20 cm in the restored topsoil had reached −1500 kPa (PWP), whereas it was only −148 kPa at the undisturbed site. Although both sites were at or near 'field capacity' during the 1988/89 winter, the restored site held considerably less available water (Table 2). High PET in spring 1989 (Fig. 3) suggested that all available water would be used quickly from the topsoil at the restored site by the end of May. Matric potentials at the undisturbed site did not reach the permanent wilting point until the end

(a) Topsoil



(b) Subsoil

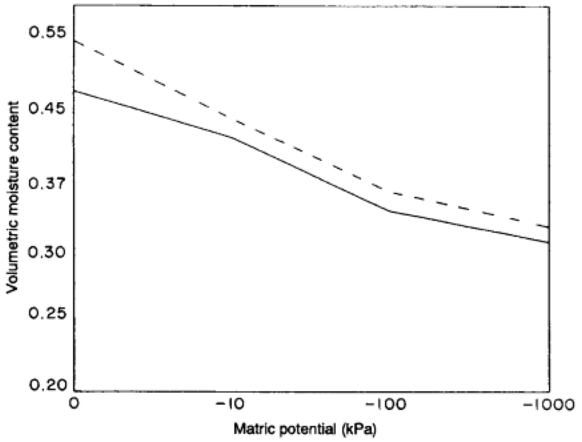
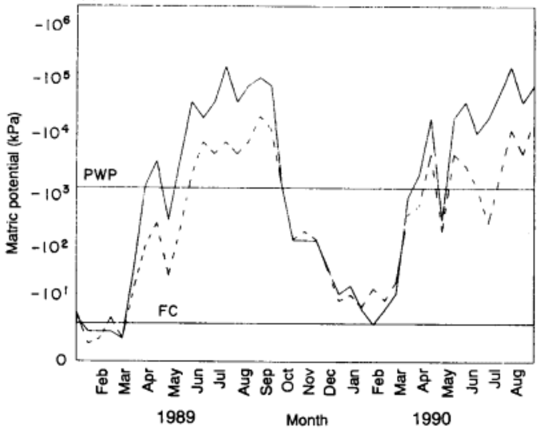


Fig. 4. Moisture release from undisturbed soil cores: —, restored; ---, undisturbed.

(a) 10 cm



(b) 20 cm

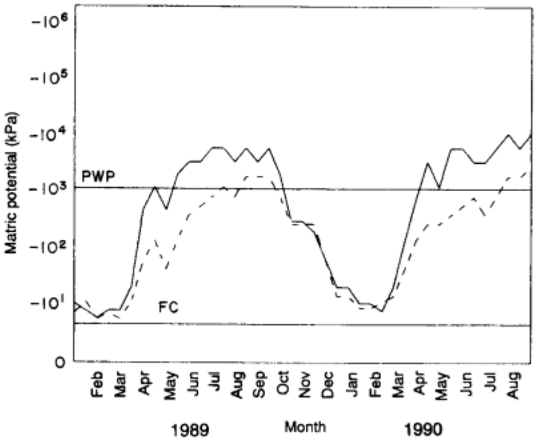


Fig. 5. Topsoil matric potentials measured at two depths every two weeks during 1989 and 1990: —, restored; ---, undisturbed; PWP, permanent wilting point; FC, field capacity.

of July or August. A similar trend was detected for 1990, although both sites reached PWP about a month earlier than in 1989, because PET was greater during the first quarter of 1990 than in 1989 (Fig. 3), and the topsoil had failed to reach 'field capacity' during the 1989/90 winter (Fig. 5).

Three major factors may have influenced the topsoil water regimes. First, organic matter contributes to the retention of water (Holliday *et al.*, 1965), and there was 36% less organic matter in the topsoil at the restored site. Second, there was a 15% increase in bulk density at the restored site. These two factors together may have contributed to the 7% decrease in AWC. Therefore, before any extraction of water began, the restored site held significantly less water in the topsoil. A third factor which may have restricted the supply of water to the plant at the restored site was a 30% increase in the penetration resistance in the subsoil. It is possible that the relative impenetrability of the subsoil at the restored site resulted in a greater proliferation of roots in the topsoil and a greater extraction of water from this horizon. This increased use of water from the topsoil may have contributed to the restored site reaching the PWP approximately 2 to 3 months earlier than the undisturbed site.

Further rainfall occurred during the period (February to August) that the stored winter water was used. Although this was the same at both sites, the flow of water into the profile, the movement within the profile and then extraction at different rates from different horizons all affected the demand on stored water and therefore the matric potential regimes. It was assumed that all rainfall after April was quickly transpired or evaporated and did not affect the soil water reserves. It was also assumed that there was little difference in the rate at which water was transpired from the two sites.

However, evapotranspiration was probably greater at the undisturbed site because of the visibly more vigorous growth. Despite this, water at the undisturbed site was more easily available for longer in the year than at the restored site.

Table 2. Stored winter rainfall in the soil profile at field capacity which was available in February (a) and then used by August (u) from each horizon. Data are the average for 1989 and 1990

Horizon		mm of water per horizon	
		Restored site	Undisturbed site
0–150 mm	a	20.1	25.7
	u	31.5	31.2
150–300 mm	a	20.1	25.7
	u	24.8	28.1
300–550 mm	a	23.3	26.3
	u	28.8	32.3
550–1000 mm	a	29.3	53.5
	u	29.3	35.6
Total	a	92.8	131.3
0–1000 mm	u	114.4	127.2

Subsoil (40 and 70 cm readings). Cyclical fluctuations of matric potential in the subsoil were smaller than in the topsoil; they did not rise to the same value as the topsoil 'field capacity' and did not fall as far below the PWP (Fig. 6). Differences in the matric potential between sites were considerably less in the top part of the subsoil at 40 cm (Fig. 6a) than in the topsoil (Fig. 5). Both sites reached a similar field capacity over the winter period. By mid-June 1989 and early May 1990, soil at 40 cm depth at the restored site reached PWP approximately 2 weeks earlier than at the undisturbed site.

At 70 cm matric potentials were greater at the restored site throughout most of the experimental period. Over the winter period, when the subsoils (70 cm) at both sites reached their respective 'field capacities', the matric potential at 70 cm at the restored site was considerably greater than that of the subsoil at the undisturbed site (Fig. 6b). The subsoils at each site clearly had different matric potentials for field capacity; during the winter they were approximately −66 kPa at the restored site and −12.5 kPa at the undisturbed site. A soil matric potential of −12 kPa at field capacity is considered more realistic than −5 kPa in a slowly permeable subsoil (Reid & Parkinson, 1987). Soil at the undisturbed site therefore did reach what is generally considered a 'realistic' potential for field capacity. At the restored site during 1989 matric potentials reached −1500 kPa (PWP) and in 1990 were less than this potential, so that all water in the rooting zone was unavailable.

After the soil water had been recharged over the winter period, the plant available water at 'field capacity' in the profile (to 1 m) was 92.8 mm at the restored site and 131.3 mm at the undisturbed site (Table 2). Both sites had the same opportunity to collect water over the winter period and throughout the growing season, and so subsequent differences in availability of water reflect differences in water movement into and retention by the profile and also in evapotranspiration.

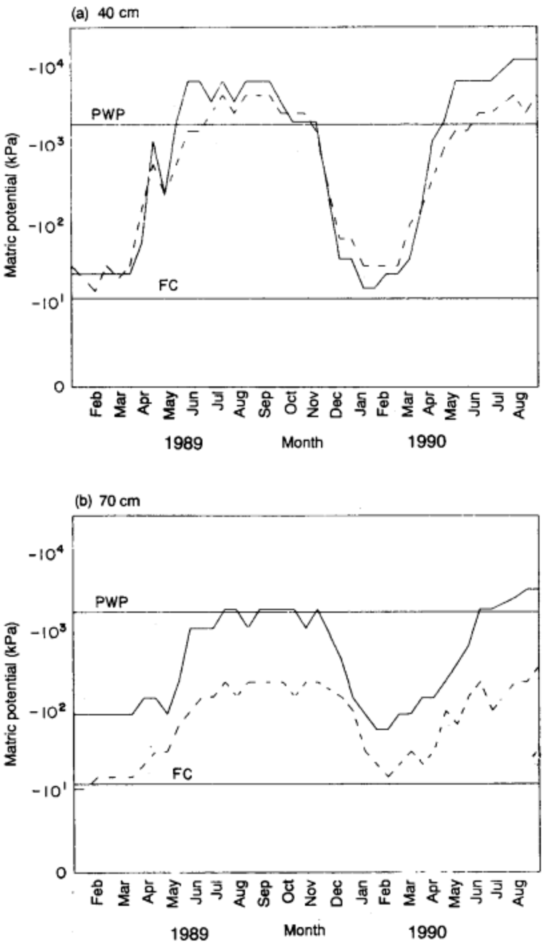


Fig. 6. Subsoil matric potentials measured at two depths every two weeks during 1989 and 1990: —, restored; ---, undisturbed; PWP, permanent wilting point; FC, field capacity.

During the growing season, the restored site lost more water from the profile than the plant available water in the profile (114.4 mm, Table 2). This additional loss beyond the water available to the plant was probably caused by evaporation from soil not fully covered by the cut grass but intermittently wetted, thus aiding the capillary rise of water from horizons below. Ultimately the soil matric potential reached or exceeded −1500 kPa (PWP) to a depth of 70 cm for much of the summer, as little or no recharge took place over this period. However, the undisturbed site lost only 127.2 of the 131.3 mm of available water. Examination of the amounts of water used and available indicated proportionally less water use at the restored site at depth (Table 2).

Soil at the restored site at 70 cm depth was friable throughout the year, and below 50 cm had a penetration resistance greater than 30 N. Therefore few roots could have penetrated to this depth. Water use from 70 cm may have been mainly by capillary rise. The availability of water to the crop at this depth must therefore have been very small.

CONCLUSIONS

Our work established differences between the soil physical properties which may account for variations in the availability of water between the sites. The restored site seems to have had a limited water movement into the subsoil during the winter and also a smaller AWC.

For crop growth it is particularly important that the subsoil allows water to infiltrate during the winter and then retains this water for use in the summer. Periodic subsoiling to 0.5 m or possibly deeper after reinstatement might assist water penetration to a greater depth and allow the subsoil to recharge its water reserves during the winter.

The soil penetration resistance suggested that timing of subsoiling is important. On a recently restored site, initial subsoiling should be done early in spring, as water may not have entered the subsoil which would then be in a friable state. Subsoiling in spring would allow grass roots to establish at depth before the possibility of slumping (collapse of the system of cracks and fissures produced by subsoiling) over the winter period. The timing of subsequent subsoiling would need to be considered in relation to the consistence of the subsoil. Subsoiling would not decrease clod density in the short term, but could provide cracks and allow water and roots to penetrate deeply.

Compaction of subsoil in restored land after opencast coal mining is one of the major restoration problems with medium to heavy soils. If soil was moved when friable or near to the lower plastic limit, improved soil conditions may result after restoration. The soil would resist deformation better than when wet and plastic. Earth moving operations should be restricted to periods when the soil is dry, as it may then require less post restoration attention.

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