# POROSITY AND HYDROLOGICAL CHANGES IN SURFACE MINE SOILS

*A.R.A. Marashi and J. Scullion*
Soil Science Unit, Institute of Biological Sciences, University of Wales Aberystwyth, UK.

## Abstract
Soils replaced after mining are subject to various treatments prior to revegetation and in the years following planting to promote their rehabilitation. Despite these treatments, compaction (bulk densities > 1.5 g $cm^{-3}$) and a complete loss of macro-pore systems are typical features of recently replaced substrates, whether these are topsoils or soil forming materials. The highly unstable nature of these substrates limits the effectiveness of mechanical treatments aimed at recreating these macro-pore systems. As a consequence, replaced soils shed rainfall with important implications for their ability to supply plants with water, for land management and for local hydrology. Over time, soil porosity and hydrologic characteristics change and the management of this process will largely determine whether there is a sustainable outcome to the land restoration process.

Results from studies into long-term changes in soil pore and moisture characteristics on land restored after surface mining in the UK will be presented. Recolonisation of soils by earthworms is a key factor in developing a new macro-pore system but in its early stages this can lead to waterlogging of surface soils and reduced surface bearing strength. During this transition phase the soils are particularly susceptible to damage by treading or wheel pressures and careless management can lead to a cycle of improvement and degradation.

The importance of ensuring a progressive transition from surface runoff to infiltration and through soil drainage, and the problems of achieving this objective, are emphasised. Implications for land management (both agricultural and woodland) during this transition period, and the need for informed long-term management, are discussed.

Additional Keywords: surface mining, soil, infiltration, runoff, drainage.

## Introduction
Surface mineral extraction in the UK has affected over 100000 ha of land that has been reclaimed following site working in accordance with planning requirements. Research into restoration and rehabilitation management has been undertaken for sand-gravel (e.g. Reeve *et al*., 1998), for other mineral extraction sites (e.g. Bradshaw and Chadwick, 1980) and for opencast coal sites (e.g. Harris *et al*., 1989; Stewart and Scullion, 1989; Younger, 1989: Malik and Scullion, 1998).

Soil handling practices during opencast coal mining typically involve different soil materials being stripped and stored separately. In most cases soil stripping and transfer to mounds is carried out using motor-scrapers and soil may remain in storage from 1-5 years. Soil replacement follows ripping, cultivation and stone-picking of underlying materials, with the motor-scraper again the most commonly used means of transport. Loose tipping of surface materials has been advocated for sites returned to forestry (Moffat and McNeill, 1994). Replaced topsoil is intensively cultivated, although often these soils are liable to recompaction (Spoor and Foot, 1998).

Fine-textured soils on restored land present particularly difficult and persistent problems of soil degradation, being typically compact and impermeable. Pore volumes in undisturbed soils can be reduced from > 50% (v/v) to < 40% (v/v) as a result of direct compaction by machinery and of a loss in natural aggregate stability leading to inter-packing of different sized particles. This latter process has been attributed to a disruption of the links between organic matter cycling, aggregation and biological activity in affected soils (Malik and Scullion, 1998). Earthworm abundance is drastically reduced by soil handling practices (Rushton, 1986) and full recovery in populations may take in excess of 20 years (Scullion, 1994). Malik and Scullion (2000) have shown that earthworms increase aggregation and affect the composition of organic matter in restored soils.

The loss of natural structure in restored soils results in increased surface runoff and wetness, reduced infiltration and water storage, and a tendency towards surface rooting in pasture and woodland. In addition, vegetation on restored land is more prone to drought, the management of restored land is less flexible and altered site hydrology can affect hydrological characteristics in catchments where mining activities are extensive. This paper describes how soil porosity and moisture characteristics of restored soils change with time. It also considers how different management practices and land uses affect the process of soil rehabilitation.

## Materials and Methods

Evidence of soil degradation and recovery was based largely on data from a series of investigations within a long-term research project on soil rehabilitation (Scullion, 1994) after opencast coal mining. Sites included in these studies were restored over the period 1967-1985 and site investigations were undertaken between 1977 and 2000. This range of restoration dates and the extended period of monitoring allowed for the investigation of long-term trends in soil properties. A previous study has described changes in aggregation and organic matter cycling in restored soils (Scullion and Malik, 2001). Here changes in porosity and soil hydrology were considered for the same sites. On all sites, topsoils and subsoils were stripped and stored separately, with soil transfers achieved using motorscrapers. Periods of soil storage ranged from 2 to five years. Each layer of replaced soil was ripped and cultivated before placement of the next layer.

*Field sites*

Detailed data reported here were obtained from a complex of sites (UK Grid Ref. SN259214) in South Wales. Initial soil conditions and management regimes were carefully recorded as part of a long-term research programme. The region had annual high rainfall (1400-1600 mm), with both undisturbed and restored soils having poor to imperfect drainage. Soils on all of the study sites had clay loam texture.

Cultivation and ripping operations are frequently advocated (Spoor and Foot, 1998) as a means of alleviating compaction in replaced soils. Data from two studies underline the limitation of these approaches. In the first study, soils compacted during their replacement (Glyn Glas site) were disc-cultivated to a depth of 10 cm and seeded; intact cores (0-5 cm depth) were taken from control and cultivated soils 3 days and 4 weeks after cultivation. During the period following cultivation, there was heavy rain and the second sampling coincided with the stage when sward germination was well established. Four replicate samples were taken within each of the sampled areas. In the second study, pasture (Rockcastle site) recently subsoiled to a depth of 35 cm using a McConnel ‘Shakaerator’ was compared with untreated controls in two fields to determine whether this operation had any effect on soil pore characteristics and moisture contents. Here samples were taken at 6 points within each plot and at several different depths on a field capacity day – the third dry day following heavy rain (Stewart and Adams, 1968).

On the Glyn Glas site the influence of earthworms on soil porosity and moisture regimes was evaluated by comparison of control and earthworm input plots (Scullion, 1994). Four 'blocks', including one control and one earthworm input plot (each 400 $m^2$), were designated prior to the introduction of earthworms; control and input plots within a ‘block’ were located 40 m apart. Earthworm inoculations were carried out during the second year after soil replacement and aimed to create a population typical of undisturbed pasture. Inputs were equivalent to almost 70 individuals $m^{-2}$ (for details see Scullion, 1994) and were representative of the full range of species in local pastures. Field drainage and general management were considered (Scullion, 1994) to favour earthworms. In the fourth year after soil replacement, populations on input plots were similar to those on adjacent, undisturbed pasture (Marashi, 1995) and included a high proportion of the deep burrowing species *Lumbricus terrestris* (L.) and *Aporrectodea longa* (Ude). Prior to the final earthworm survey 6 years after earthworm inoculation, populations on control plots were markedly lower than those of input plots and were dominated by the surface dwelling, early colonising species *Lumbricus rubellus* Hoff. and *Allolobophora chlorotica* Sav.. Intact cores were taken at 4 points in each plot and at several sampling depths.

In a further study, a number of sites were sampled to investigate long-term soil development either under grass-clover leys (Malik and Scullion, 1998) or mixed species amenity woodland (Scullion and Malik, 2001). Woodland areas had been planted to a mixture of tree species, mainly *Alnus glutinosa, Betula pendula, Salix* spp and *Quercus* spp. Soil samples were taken (6-8 points within each area), with woodland samples located under *Alnus glutinosa*, the fastest growing of the tree species.

*Field measurements and soil analysis*

Field drain flows and surface runoff were recorded using pre-calibrated V-notch flow gauges (Scullion and Mohammed, 1986). Rainfall was recorded on site using a tilting siphon rain gauge as part of a regular recording of meteorological conditions. Surface infiltration was measured using the double ring infiltrometer method of Bertrand (1965).

Intact soil cores (6 cm diameter metal rings) were driven into the soil, then weighed at sampling and after equilibration on a centrifuge (Piper, 1950) at -10 kPa moisture potential. Total pore space was calculated from the difference between bulk and particle density. Bulk density was obtained by direct measurement from core dimensions whilst particle density was estimated from the relative proportions of mineral and organic matter (Adams, 1973). Organic matter was estimated by loss on ignition at 300°C; this ignition temperature avoided losses from coal fragments present in some soils and was equivalent to <85% of loss on ignition values at 400°C (Scullion, 1994). Percentage waterlogged pore space was calculated from moisture contents and pore volumes as sampled on field capacity days (3 days after heavy rain) and at -10 kPa.

Comparisons of different soil groups were made by one-way or two-way analysis of variance, using the Statgraphics version 7 (Statistical Graphics Corporation, 1993) statistical package.

## Results and Discussion

*Initial soil physical and hydrological conditions*

On each of the sites investigated, soil conditions were assessed several months after establishment of vegetation. In all cases, replaced soils showed high bulk densities and low porosity compared with adjacent undisturbed soils (Table 1). In addition, the surface soils sampled on field capacity days showed very high levels of waterlogged pore space that generally exceeded those at -10 kPa. The converse was the case for samples taken at depth. These data were consistent with measured rates of surface infiltration that were negligible. The failure of restored soils to wet up at depth may be attributed to the presence of air trapped in pores beneath a saturated surface layer.

**Table 1. Selected physical properties of recently replaced soils for two of the study sites.**

| Site-Depth (cm) | Total pore space (%v/v) | Bulk density ($g/cm^3$) | %Waterlogged pores - field | %Waterlogged pores -10 kPa |
|---|---|---|---|---|
| **Rockcastle E** | | | | |
| 0-5 | 40.6 | 1.51 | 102.0 | 97.2 |
| 5-10 | 37.9 | 1.57 | 90.3 | 92.4 |
| 10-15 | 38.1 | 1.53 | 88.7 | 96.9 |
| 15-20 | 34.2 | 1.66 | 84.4 | 94.7 |
| **Glyn Glas** | | | | |
| 0-5 | 44.5 | 1.45 | 88.6 | 85.5 |
| 5-10 | 41.5 | 1.54 | 93.8 | 93.3 |
| 10-15 | 39.5 | 1.59 | 84.6 | 95.6 |
| 15-20 | 38.6 | 1.61 | 87.2 | 97.2 |
| **Undisturbed** | | | | |
| 0-5 | 64.2 | 0.95 | 74.8 | 75.4 |
| 5-10 | 61.5 | 1.01 | 76.2 | 77.3 |
| 10-15 | 58.6 | 1.09 | 83.9 | 81.6 |
| 15-20 | 55.4 | 1.16 | 87.3 | 82.7 |

As a consequence of the degraded soil physical conditions, restored land consistently shed in excess of 90% (Scullion, 1994) of incident rainfall during winter and early spring; maximum runoff rates were similar to preceding average hourly rainfall rates and frequently exceeded 5mm $h^{-1}$ (Scullion and Mohammed, 1986). The runoff hydrograph was consistent with rapid surface flow and negligible temporary storage of water within the soil profile. Land management problems included excessive surface wetness and ponding, rapidly changing surface conditions with changes in weather conditions and extreme susceptibility to drought because of shallow rooting depths exacerbated by poor retention of moisture in replaced soils.

*Mechanical treatments to improve soils*

Comparing porosity and bulk density values (Table 2), it is clear that cultivation resulted in a significant ($p< 0.01$) initial improvement in these parameters. However, this improvement was short-lived and by the time that the newly seed sward had germinated any improvement had been lost. The transient effect of cultivation on soil porosity has been recognised in similar studies of normal agricultural soils (e.g. Finney and Knight, 1973). However, cultivation effects persisted for several months in these soils and their reconsolidation was more gradual. The rapid change in conditions in replaced soils can be attributed to a lack of any water stability (Scullion, 1994) resulting in a rapid collapse and slaking of tillage units.

Subsoiling reduced surface runoff and wetness in these experiments (Scullion and Mohammed, 1986). However, these changes were not always apparent in bulk soil properties two months after the operation (Table 3). Although there was a tendency for soil on subsoiled plots to have higher porosity this difference was significant only at the

15-20 cm depth. Differences in waterlogged pore space were generally not significant, although subsoiling reduced waterlogging in the surface layer. Other studies (Scullion and Mohammed, 1991; Spoor and Foot, 1998) have shown that the effects of subsoiling operations on restored land can be localised and short-lived.

**Table 2. Transient effect of cultivation on soil properties (for each property, means with a common letter suffix do not differ at P<0.05 Duncan's multiple range test)**

| Property | Control - Initial | Cultivated - Initial | Control – 4 weeks | Cultivated – 4 weeks |
|---|---|---|---|---|
| **Total pore space (%v/v)** | 43.6b | 56.1a | 44.7b | 43.8b |
| **Bulk density (g cm$^{-3}$)** | 1.48a | 1.10b | 1.46a | 1.49a |

**Table 3. Effects of subsoiling on soil conditions after 3 months (for each depth, means with a common letter suffix do not differ at P< 0.05 Tukeys LSD test)**

| Depth (cm) | 0-5 | 5-10 | 15-20 | 25-30 |
|---|---|---|---|---|
| **% pore space (v/v)** | | | | |
| Control | 42.7a | 37.8a | 33.9b | 34.3a |
| Subsoiling | 45.0a | 36.4a | 39.3a | 35.1a |
| **% waterlogged pores – field capacity day** | | | | |
| Control | 98.3a | 90.4a | 88.7a | 86.3a |
| Subsoiling | 94.1b | 89.6a | 90.2a | 88.5a |

*Earthworms and soil rehabilitation*

The re-colonisation of restored sites by earthworm populations is an inevitable part of the soil recovery process. When this process is accelerated by the artificial establishment of populations, marked changes occur in soil conditions (Table 4). Earthworm activity resulted in a significant increase in soil porosity at all sampled depths. Indeed porosity values at the lowest depth on control plots had changed little over a 7-year period since soil replacement (by comparison with Table 1). Changes attributable to earthworms resulted in increased rooting at depth and improved productivity (Marashi and Scullion, 2003). However, this increase in porosity was associated with greater soil waterlogging, despite the site having been drained and subsoiled. Earthworm activity encouraged water infiltration and artificial drainage was not effective in removing excess water from the soil profile.

**Table 4. Differences in soil properties 6 years after inoculation with earthworms (for each depth, means with a common letter suffix do not differ at P< 0.05 Tukeys LSD test)**

| Depth (cm) | 0-5 | 5-10 | 10-15 | 15-20 |
|---|---|---|---|---|
| **Pore space (% v/v)** | | | | |
| Control | 59.8b | 43.3b | 40.8b | 39.5b |
| Inoculation | 61.8a | 49.7a | 43.9a | 41.7a |
| **% Waterlogged pores – field capacity day** | | | | |
| Control | 98.1b | 96.5b | 95.2b | 93.1b |
| Inoculation | 103.2a | 99.8a | 99.3a | 98.6a |

*Changes in soil conditions with time*

Changes in soil porosity over time under different land uses are illustrated in Table 5. For the sites sampled, grassland and woodland soils did not have significantly different porosity values in the year following soil replacement. After 21 years, surface soils under both systems had improved to a similar extent but below 5 cm the improvement in soil porosity was more marked in grassland soils. Mackenzie *et al*. (1998) also found that soil development under trees was limited other than in layers close to the soil surface. There may be several reasons for this diverging trend in soil rehabilitation under the two land uses. Woodland soils are not affected by compaction due to trafficking by animals or machinery. On the other hand, field drains are not installed in woodland areas and these areas are not subjected to subsoiling operations, other than at soil replacement. In addition, earthworm populations in woodland soils tend to develop more slowly (Scullion and Malinovszky, 1995). This combination of factors may explain the slower rate of soil improvement at depth under woodland.

## Conclusions

The loss of structure in replaced soils and associated impermeability has implications for land use and off-site hydrology. Rehabilitation of these soils requires several decades and involves a shift from surface shedding to

**Table 5. Changes in soil porosity (% v/v) under different management over 20 years since soil replacement (for each depth, means with a common letter suffix do not differ at P< 0.05 Duncan's multiple range test)**

| Depth (cm) | 0-5 | 5-10 | 10-15 | 15-20 |
|---|---|---|---|---|
| Grassland – year 1 | 42.5b | 38.3c | 37.4c | 34.6c |
| Woodland – year 1 | 40.6b | 37.9c | 38.1c | 34.2c |
| Grassland – year 21 | 60.2a | 51.5a | 48.4a | 46.8a |
| Woodland – year 21 | 59.1a | 44.7b | 43.2b | 43.6b |

water infiltration and soil drainage. During the transition, agricultural soils are very susceptible to damage and require careful management. This susceptibility is only partially alleviated by field drainage. In woodland, the process of soil improvement is very slow at depth, underlining the value of avoiding soil damage to these soils by adopting practices such as loose tipping of replaced soils (Moffat and McNeil, 1994).

## Acknowledgements
This work was funded initially by a British Coal Opencast Executive grant.

## References
Abdul-Kareem, A.W. and McCrae, S.G. (1984). The effects on topsoil of long-term storage in stockpiles. *Plant and Soil* 76, 357-363.
Adams, W.A.A. (1973). The effect of organic matter on bulk and true densities of some uncultivated podsolic soils. *Journal of Soil Science* 24, 10-17.
Armstrong, M.J. and Bragg, N.C. (1984). Soil physical parameters and earthworm populations associated with opencast coal working and land restoration. *Agriculture Ecosystems and Environment* 11, 131-143
Bertrand A.R. (1965). Rate of water uptake in the field. In 'Methods of Soil Analysis Part 1', (Ed C.A. Black) pp 197-209. America Society of Agronomy, Wisconsin USA.
Bradshaw, A.D. and Chadwick, M.J. (1980). *The Restoration of Land*. Oxford, Blackwell.
Finney, J.R. and Knight, B.A.G. (1973). The effect of physical conditions produced by various cultivation systems on the root development of winter wheat. *Journal of Agricultural Science, Camb* 80, 435-442.
Harris, J.A., Birch, P. and Roberts, G. (1989) Changes in the microbial community and physio-chemical characteristics of topsoils stockpiled during opencast mining. *Soil Use and Management* 5, 161-168.
MacKenzie, A.J., Weilmot, A., Fox, H.R. and Moore, H. (1998). The restoration of soils in opencast coal plantations in Derbyshire. In 'Land Reclamation. Achieving Sustainable Benefits', (eds. Fox, H.R., Moore H.M. and McIntosh, A.D. ), pp287-295. AA Balkema, Rotterdam.
MAFF (1986). *The Analysis of Agricultural Materials*, Third Edition. HMSO, London.
Malik A. and Scullion, J. (1998). Soil development on restored opencast coal sites with particular reference to organic matter and aggregate stability. *Soil Use and Management* 14, 234-239.
Marashi A.R.A. (1995). *Earthworm, Soil Structure and Opencast Mining for Coal*. PhD Thesis, University of Wales Aberystwyth.
Moffat A.J. and McNeill, J. (1994) *Reclaiming Disturbed Land to Forestry*. Forestry Commission Bulletin 110. London, HMSO.
Piper C.J. (1950). *Soil and Plant Analysis*. University of Adelaide, Adelaide.
Reeve, M.J., Heaven F.W. and Duncan, N.A. (1998) The Bush Farm experiment 15 years on: Recovery in soil and agricultural quality. In 'Land Reclamation. Achieving Sustainable Benefits' (eds. Fox, H.R., Moore H.M. and McIntosh, A.D.), pp13-20. AA Balkema, Rotterdam.
Rushton, S. P. (1986) Development of earthworm populations on pasture land reclaimed from opencast coal mining. *Pedobiologia* 29, 27-32
Scullion, J. and Mohammed, A.R.A. (1986). Field drainage experiments and design on former opencast coal mining land. *Journal of Agricultural Science, Camb*. 107, 521-528.
Scullion, J. and Mohammed A.R.A. (1991). Effects of subsoiling and associated incorporation of fertilizer on soil rehabilitation after opencast mining for coal. *Journal of Agricultural Science, Camb.* 116, 265-273.
Scullion, J. (1994). *Restoring Farmland after Coal*. British Coal Opencast-University of Wales, Aberystwyth.
Scullion, J. and Malinovszky, K.M. (1995). Soil factors affecting tree growth on former opencast coal land. *Land Degradation and Rehabilitation* 6, 239-249.
Scullion, J. and Malik, A. (2000). Earthworm activity affecting organic matter, aggregation and microbial activity in soils restored after opencast mining for coal. *Soil Biology Biochem*istry 32, 119 – 126.
Scullion, J. and Malik, A. (2001). The influence of land use and earthworm activity on organic matter dynamics in soils restored after opencast coal mining. In 'Sustainable Management of Soil Organic Matter'(eds R.M. Rees, B.C. Ball, C.D. Campbell and C.A. Watson) pp377-385. CABI Publishing Wallingford.
Marashi, A.R.A. and Scullion, J. (2003). Earthworm casts form stable aggregates in physically degraded soils. *Biology and Fertility Soil* 37, 375-380.
Spoor, G. and Foot, K.J. (1998). Soil compaction alleviation on restored sites. In 'Land Reclamation. Achieving Sustainable Benefits', (eds. Fox, H.R., Moore H.M. and McIntosh, A.D. ), pp277-286. AA Balkema, Rotterdam.
Statistical Graphics Corporation (1993). Statgraphics - Statistical Graphics System: version 5. Statistical Graphics Corporation, (Rockville, Md.).
Stewart V.I. and Adams W.A.A. (1968). The quantitative description of moisture states in natural habitats with special reference to moist soils. In 'The Measurement of Environmental Factors in Terrestrial Ecology' (R.M. Wadsworth ed.), pp161-173. Blackwell Scientific, Oxford.
Stewart V.I. and Scullion, J. (1989) Principles of managing man-made soils. *Soil Use and Management* 5, 109-116.
Younger A (1989). Factors affecting the cropping potential of reinstated soils. *Soil Use and Management* 5, 150-154.