IMPROVING LAND RESTORATION IN BRITAIN BY BETTER TIMING OF SOIL MOVEMENTS[1]

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Abstract: The soil moisture content at plastic limit is shown to be a suitable threshold below which there is likely to be less compaction and damage to soil structure when soils are being moved on surface mine and quarry sites. However, in wetter parts of England and Wales use of this threshold will result in a very short stripping season for stripping upper layers of soil and, in many years, deeper subsoil layers may never dry out sufficiently to resist damage. Direct use of plastic limit to control earthmoving involves continual on-site checking of soil moisture conditions, but it is feasible to predict suitable soil conditions from a remote location using models of soil moisture deficit. Maps of long-term moisture deficit can be used to define no-go periods and optimum soil stripping seasons, while real-time use of moisture deficit data in conjunction with rainfall measurements can aid the scheduling of site operations.

Additional Key Words: soil handling, plastic limit, soil strength.

Introduction

Effective revegetation of mining and quarrying sites is dependent upon the replacement of soils in the best possible physical condition. They are more likely to be in good condition if they have been stripped and handled in good condition. When soils are wet or very moist they are weak; handling inevitably results in smearing, compaction and loss of structure (i.e. deterioration of physical condition). As soils dry they develop greater strength and are more resistant to physical deterioration.

In England and Wales some 2,000 ha of land were restored each year of the 1980's after sand and gravel or clay workings and 700 ha after opencast coal mining. In total more than 20,000 ha of mineral workings were reclaimed between 1982 and 1988 (DoE 1991). Much of this land was in agricultural use prior to working and 90% was returned to a "green" afteruse (mainly for agriculture or amenity) which required careful attention to soil restoration. To achieve this, it was important that the most suitable soils were retained for restoration, that the most appropriate machinery was used to strip, store and respread them, and lastly (and perhaps most importantly) that soils were handled only when they were sufficiently dry to resist damage through compaction and smearing. Continuing examples of poor restoration show that these key criteria are not always being met, and this paper presents the results of research into improving the timing of soil handling.

Part of the work reported herein was carried out when the author was a senior research scientist with the Soil Survey and Land Research Centre.

Timing of Soil Handling

An early attempt at controlling the timing of soil handling was used in a series of agricultural land restoration experiments carried out in eastern England in the late 1970's (DoE 1982). Separate rules on soil movement, based on preceding rainfall, were given for soil stripping and direct reinstatement, reinstatement from storage heaps and restarting work after rain. An example is given in table 1.

There was a general proviso that soil-moving operations should normally only take place between May and October. However, as McRae (1989) points out, restricting soil handling to ordinarily dry times of the year takes no account of abnormally wet summers. Also, rainfall on its own is not a sufficient control as soil moisture

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Table 1. Impact of rainfall on stripping and direct reinstatement by earthscaper (after DoE 1982).

Rainfall, mm	For rainfall reading taken at: 0730 h	1800 h
0-1	May be ignored	May be ignored
1.1-3	Delay operations to midday	May be ignored
3.1-5	Delay to next day	Delay to midday next day
5.1-7.5	Delay to midday next day	Delay to day after next
7.6-10	Delay for 48 hours	Delay for 48 hours
>10	Delay for 3 days	Delay for 3 days

contents will vary with rainfall and evapotranspiration. Thus, rainfall in summer will normally be less restrictive than rainfall in early spring.

Because of the shortfalls of this system, criteria based on soil conditions were introduced during the 1980's and applied by local government through legal conditions attached to permissions to work minerals. Some site-specific planning conditions referred to the soil moisture content at plastic limit, either indirectly or directly. For example *"the stripping and movement of topsoil and subsoil shall only be carried out when the material to be moved is in a dry (and friable) condition"* (1991 planning condition for opencast coal mining in north-east England) and *"soil handling, cultivations and trafficking..... shall only take place when the moisture content of the soil is 5% or more below the lower plastic limit"* (1989 planning condition for sand quarrying in south-east England).

The use of plastic limit has some merits because it reflects the reaction of soil to specific forces. For example, above the plastic limit the compressibility of a soil increases rapidly and smearing occurs (Boekel 1979). The plastic limit has been reported as corresponding to a shear strength of about 170 kPa (Wood and Wroth 1978). This implies that at moisture contents near and below the plastic limit a soil will exhibit sufficient strength to resist the force exerted by the wheels of an agricultural tractor, bulldozer or small dumper truck, but may not have sufficient strength to bear the larger vehicles used for earthmoving without some deformation (table 2).

Table 2. Static contact pressures exerted on soil by earthmoving and cultivation equipment.

Vehicle	Maximum static tire/ soil normal stress, kPa[1]	Reference
Wheeled agricultural tractor	54-95	Blackwell et al. 1985.
Medium tracked-bulldozer	45-70	Manufacturer's literature.
Low-ground-pressure bulldozer	30-45	Manufacturer's literature.
23-mt 3-axle dumper truck	[2]145-170	Manufacturer's literature.
40-mt 2-axle dumper truck	[2]220-250	Manufacturer's literature.
330-HP wheeled tractor-scraper	[2]160-185	Manufacturer's literature.
550-HP wheeled tractor-scraper	[2]260-300	Manufacturer's literature.

[1]Dynamic stresses can be much larger than static stresses as a result of slewing (tracked vehicles) and bouncing (wheeled vehicles).

[2]Calculated as 50% to 60% of tire/hard surface stress.

Exclusive use of the plastic limit (or a moisture content related to it) to control soil movements on mineral sites has caused problems, however. Subsoils on clayey substrates or in wet parts of England and Wales may never dry sufficiently to reach the plastic limit, in effect precluding continued working of the site or, more likely, resulting in a default of the planning condition because it is too stringent.

For this reason a research program was undertaken to study changes in soil moisture and plasticity in specific soils over an 18-month period. The aims were to see whether it is realistic in practice to use a plastic limit-related threshold to control earthmoving, to investigate the use of meteorological soil moisture deficit data as a partial control of earthmoving, and to develop a Code of Practice that would ensure that a consistent and practicable approach is adopted in future permissions to work minerals.

Site Monitoring

A range of agricultural sites were monitored for a 15-month period from July 1990 to January 1992. Soils ranged from fluvic ustochrepts and haplaquepts (typical of sites from which alluvial gravels are quarried) to ochric and mollic haplaquepts on boulder clay (typical of open pit coal mining areas). Soils were divided into three main textural categories:

- Sandy loams and sandy clay loams (12% to 24% clay in topsoils, 10% to 23% in subsoils)
- Clay loams and silty clay loams (26% to 35% clay in topsoils, 26% to 37% in subsoils)
- Clays (32% to 49% clay in topsoils, 41% to 51% in subsoils)

In each category 25 m x 25 m monitoring plots were established under grassland and replicated between three climatic regions defined by the magnitude of the average annual potential soil moisture deficit. Some of the soil and climate combinations were replicated under a wheat crop or left unvegetated. Moisture contents and shear strengths were measured weekly (twice weekly during the spring period of rapid drying) at 10-cm intervals to a depth of 0.5 m and at depths of 0.75 and 1 m. The measurement method involved augering a 6-cm diameter vertical hole in stages, measuring shear strength with a vane tester 5 cm below the base of the hole, and then taking a loose soil sample by soil auger from the same zone. Moisture contents of the samples were determined gravimetrically in the laboratory. On any visit, measurements were taken from three auger holes distributed across each plot and the results for any depth averaged. The soils of each site were fully characterized physically, including analysis of the bulk density and plastic limit moisture content at each monitoring depth.

Results

Soil Strength and Plastic Limit

Some results of this study are presented by Reeve and Davies (in press) and show that the plastic limit of remoulded soil is an approximation to an undisturbed shear strength of 100 to 200 kPa, dense soils having a greater strength than others. This range can be compared with the equipment ground pressures in table 2 and suggests that at the plastic limit careful use of the lighter items of earthmoving equipment will result in little damage to soils.

Opportunities for Soil Stripping Using a Plastic Limit Threshold

The opportunities that are provided by the use of a plastic limit threshold for soil stripping can be seen in figure 1. In this, data are presented for a zone in the upper subsoil (Bw or Bg horizon at 40-cm depth) in each soil. This is a soil layer that often has a better structure than layers below but one that is very vulnerable to damage while topsoils are being stripped from above it. The main year of the study, 1991, was unremarkable climatically but had a drier than average autumn. Figure 1 shows that a long soil-stripping period would be obtained by using the plastic limit as a threshold in the drier parts of eastern England (right column of graphs). Stripping of loamy soils could continue from early spring to late autumn and of clayey soils from June to late autumn (with the exception of a wet spell in early July). In any texture, however, the stripping season shortens markedly from the drier climatic zones to the moist ones (right to left in figure 1). In the moister areas of western and northern England an

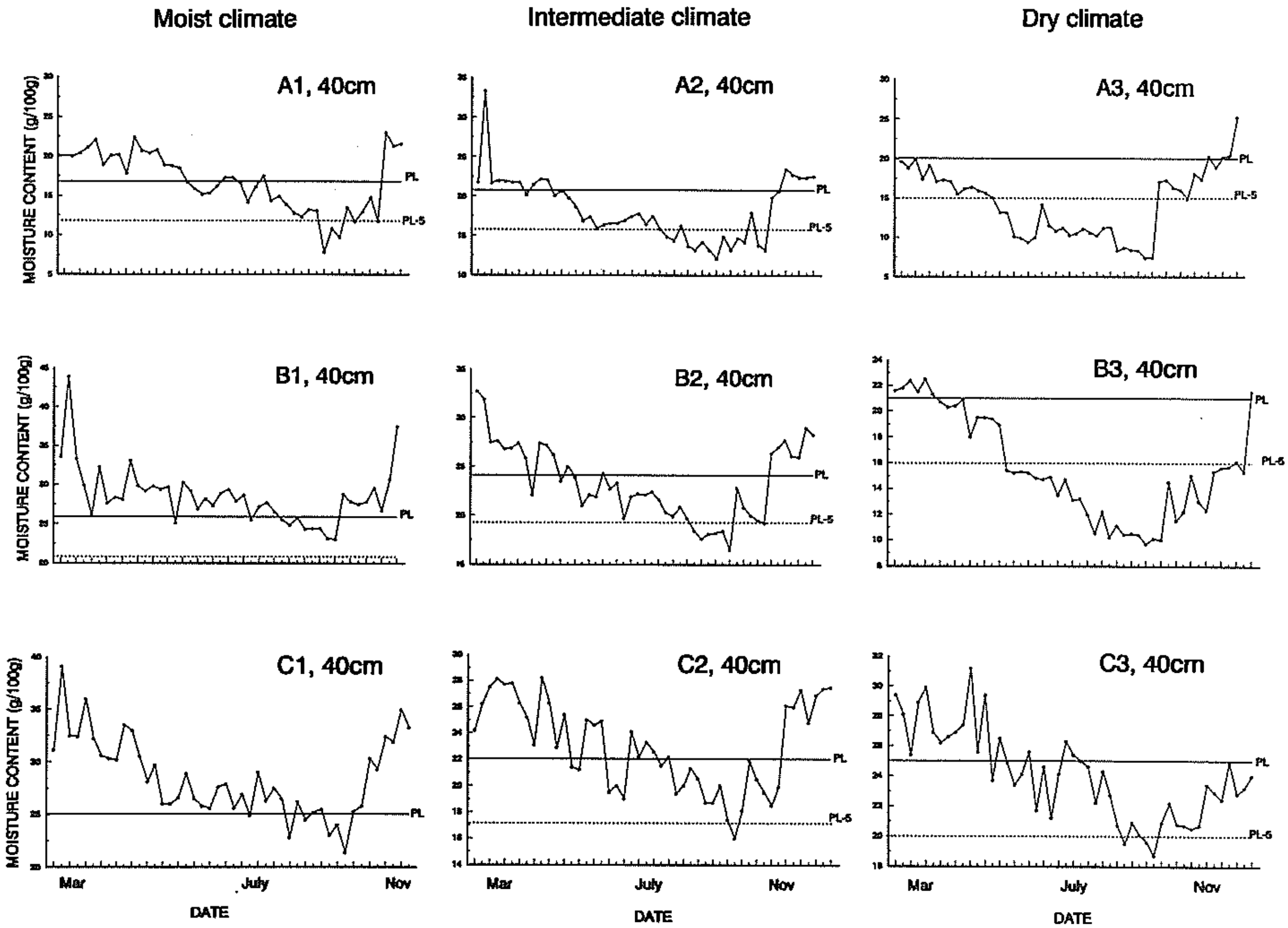


Figure 1. Changes in moisture content and consistency during 1991 for upper subsoils at 40-cm depth. Sites A1-A3 are light loams, sites B1-B3 heavy loams and sites C1-C3 dense clays. (PL = plastic limit moisture content; dotted line = plastic limit moisture content minus 5 g/100g)

acceptable period would exist for the stripping of the lighter loamy soils, but suitable conditions for stripping the clay loams and clays would have been confined to the months of August and September in 1991. A wetter-than-average year would thus completely preclude the stripping of certain soil textures if earthmoving was legally controlled by use of the plastic limit moisture content. The graphs also show that while it may be desirable to delay soil-stripping operations to await a moisture content of 2% to 5% lower than the plastic limit, during which time bearing capacity will have increased further, this is only likely to be practicable in the drier parts of England and for loamy soils.

The main problem with using plastic limit as a controlling moisture threshold for soil movements is that it involves regular site measurements of moisture conditions. For the quarrying operator wanting to plan his next season's soil stripping or the earthmoving contractor wishing to make best use of manpower and equipment, there is a need for a system to better define normal soil stripping periods for specific soils in specific climatic regions.

Soil Moisture Deficit and Attainment of Plastic Limit

The research was extended to develop relationships between plastic limit attainment dates and soil moisture deficits. Modeled soil moisture deficits throughout the year are available in Britain from a service run by the Meteorological Office. Actual soil moisture deficits were calculated for all sites and compared with the modeled estimates and with the dates at which individual soil layers reached plastic limit. Using this approach, a model was derived that gave target soil moisture deficits for attaining plastic limit for specific layers of the soil (table 3).

Soil-Stripping Seasons

Through applying this model to long-term average moisture deficit data for England and Wales it is possible to produce a series of maps defining the soil-stripping season. An example is given in figure 2, in which median dates for attainment of a specified deficit (in the case of figure 2A, a deficit of 50 mm) are used to indicate the average start to the soil-stripping season for different parts of England and Wales. Because rewetting of soils does not necessarily occur evenly, or from the surface, a poor correlation was found between whole-profile deficits and the return of individual soil layers to plasticity in the autumn. For this reason a date related to the return to meteorological field capacity is used to define the average end of the soil stripping season (figure 2B).

Table 3. Soil moisture deficits for attaining plastic limit during soil drying

Soil layer	Deficit mm
All topsoils	25
Subsoils above 50-cm depth:	
Light and medium loams (10% to 27% clay)	25
Heavy loams and clay (>27% clay)	50
Subsoils below 50-cm depth[1]:	
Light loams (<18% clay)	25
Medium loams (18% to 27% clay) and dense heavy loams and clays (>1.5 g/cm^3)	50
Heavy loams and clays (>27% clay)	100

[1] layers at 100 cm may never become friable except in dry climatic zones or in very dry years

Use of the whole suite of maps generated by this study has enabled England and Wales to be divided into three climatic zones (figure 3) for which the best periods for stripping soil layers of various texture and depth below the surface can be derived (table 4).

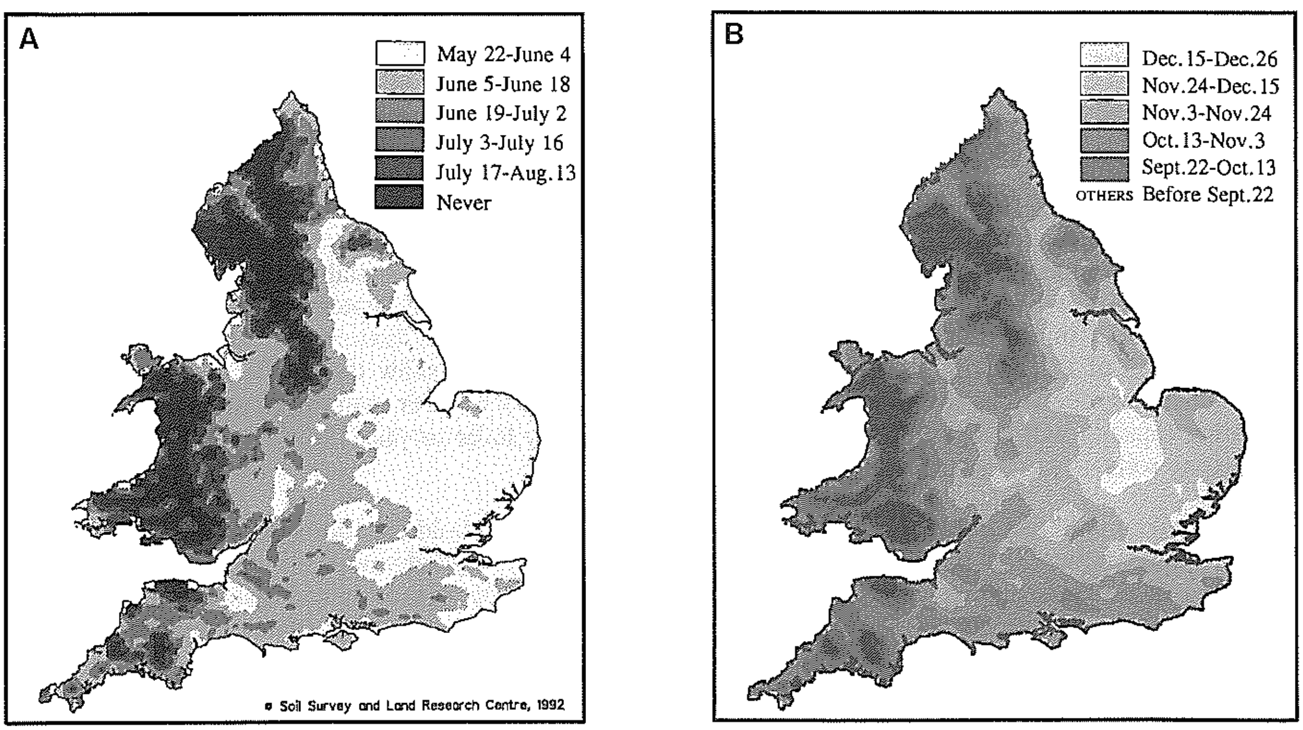


Figure 2. Maps showing in an average year (A) the dates of attainment of a 50-mm soil moisture deficit under grass and (B) the date of return to field capacity.

Soils with <10% clay that do not have a plastic limit are assigned a provisional moisture deficit threshold of 5 mm for the start of stripping. A date of 2 weeks before the return to meteorological field capacity is used to define the average end date of the stripping season for all soils except those having groundwater within 1-m depth during some part of the growing season; a date of 4 weeks before the return to field capacity is used for these.

No-Go Periods for Soil Stripping

While information on the best periods for stripping in a year of average climate is generally useful in defining normal earthmoving periods, it does not allow the optimum use of "shoulder" seasons in drier than average years. Using data for the driest standard deviation, it is possible to define no-go periods, though accepting that rigorous use of such might preclude earthmoving at certain times in exceptionally dry years. Figure 4 presents two of the maps used to derive the start and end of the no-go periods shown in table 5. The start is defined in relation to the dry standard deviation date for the end of field capacity (one week after for most soils, but 3 weeks before for difficult soils) and the end by the dry standard deviation date for the attainment of the moisture deficits in table 3.

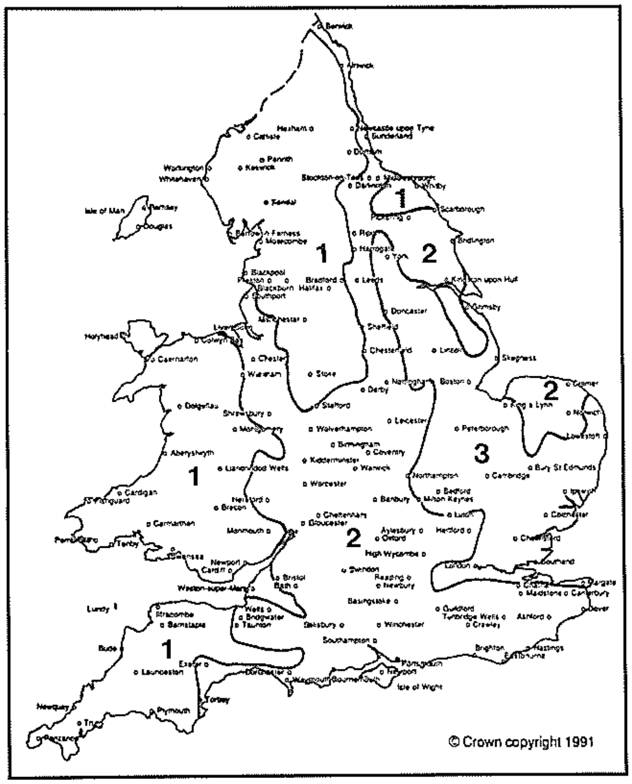


Figure 3. Climatic zones for soil stripping in England and Wales.

Table 4. Best periods for stripping vegetated soils in an average year

Strip depth[1]	Soil[2]	Climatic zone 1 [3]	Climatic zone 2 [3]	Climatic zone 3 [3]
<30 cm	VL[4]	Mid Apr.-early Oct.	Late Mar.-early Nov.	Late Mar.-early Dec.
	L,M,H,D	Late May-early Oct.	Early May-early Nov.	Early Apr.-early Dec.
30 to 60 cm	VL[4]	Late Apr.-early Oct.	Mid Apr-early Nov.	Early Apr.-early Dec.
	L,M	Late May-early Oct.	Early May-early Nov.	Early Apr.- early Dec.
	H,D	Late June-early Oct.	Early June-early Nov.	Late May-early Dec.
>60 cm	VL[4]	Late Apr.-early Oct.	Mid Apr.-early Nov.	Early Apr.-early Dec.
	L	Late May-early Oct.	Early May-early Nov.	Early Apr.-early Dec.
	M, H	Late June-early Oct.	Early June-early Nov.	Late May-early Dec.
	D	Mid July-mid Sept.	Early July-mid Oct.	Late June-mid Oct.

[1] Total depth from surface of all soils to be stripped and retained for reuse as a growing medium in restoration.
[2] The texture of the heaviest layer to be stripped for reuse. VL=very light (<10% clay), L=light (10% to 18% clay), M=medium (18% to 27% clay), H=heavy (>27% clay), and D=difficult (heavy soils affected by groundwater during the growing season).
[3] From figure 3.
[4] Opportunities for stripping very light soils occur during dry weather throughout the year but are best during the periods indicated.

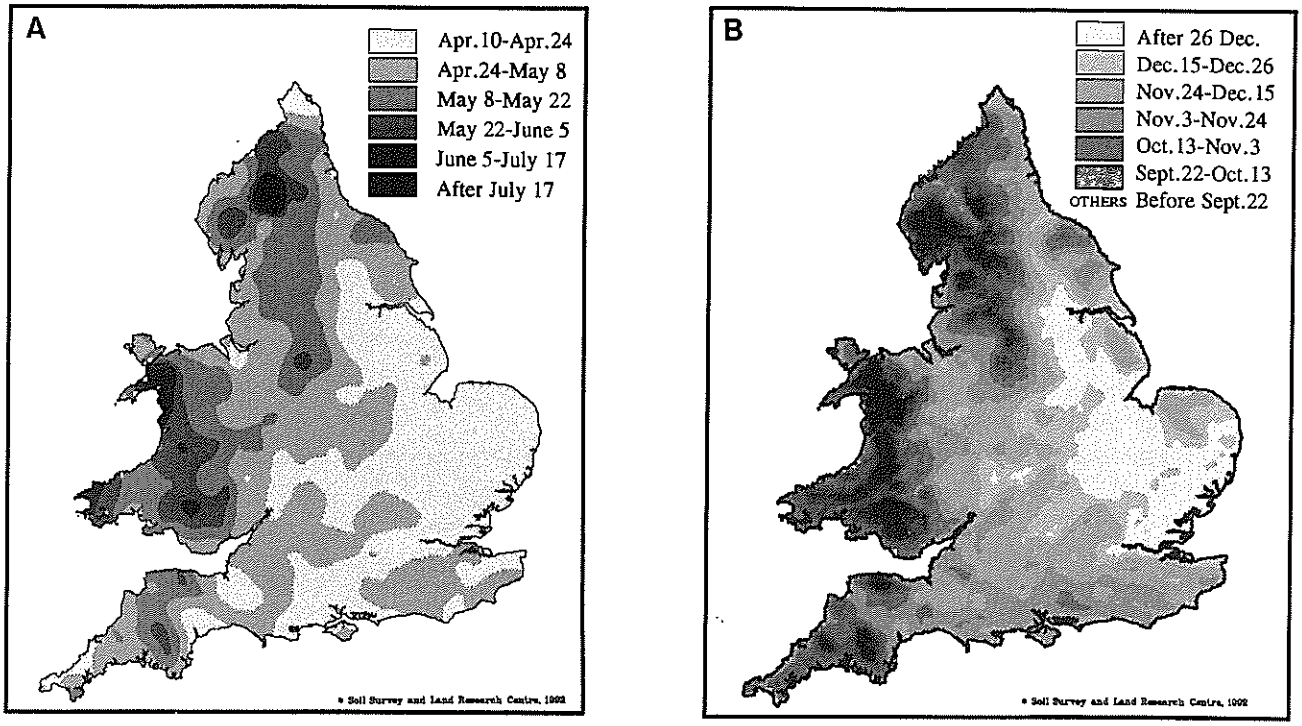


Figure 4. Maps showing in a dry year (A) the dates of attainment of a 25-mm deficit under grass and (B) the date of return to field capacity

Table 5. No-go periods for stripping light, medium, heavy and difficult soils

Strip depth[1]	Soil[2]	Climatic zone 1 [3]	Climatic zone 2 [3]	Climatic zone 3 [3]
<30 cm	L,M,H,D	Nov.10-Apr.10	Dec.1-Apr.1	Jan.1-Mar.20
30 to 60 cm	L,M	Nov.10-Apr.10	Dec.1-Apr.1	Jan.1-Mar.20
	H,D	Nov.10-May 1	Dec.1-Apr.20	Jan.1-Apr.20
>60 cm	L	Nov.10-Apr.10	Dec.1-Apr.1	Jan.1-Mar.20
	M,H	Nov.10-May 1	Dec.1-Apr.20	Jan.1-Apr.20
	D	Oct.10-June 10	Nov.1-May 20	Nov.1-May 20

[1] Total depth from surface of all soils to be stripped and retained for reuse as a growing medium in restoration.
[2] The texture of the heaviest layer to be stripped for reuse. L=light (10% to 18% clay), M=medium (18% to 27% clay), H=heavy (>27% clay), and D=difficult (heavy soils affected by groundwater during the growing season).
[3] From figure 3.
NOTE: Opportunities for stripping very light soils (<10% clay) occur during dry weather throughout the year and can occur in winter.

Day-to-day Control of Soil Stripping

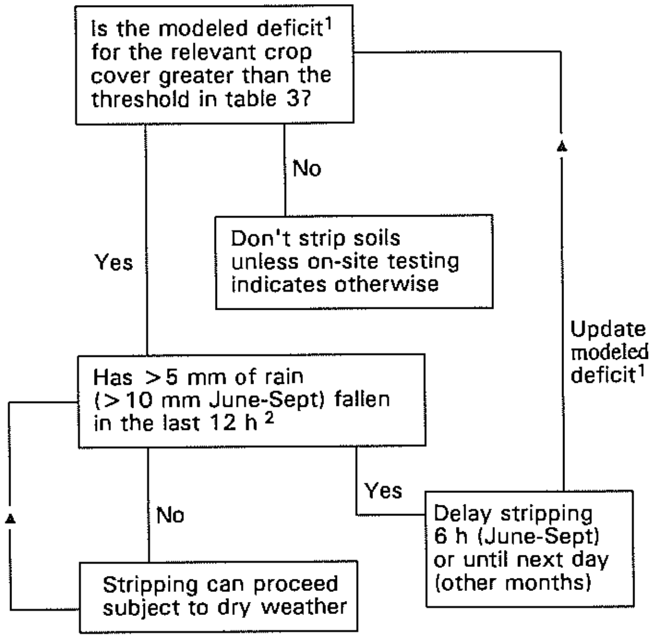
While it is clearly useful to be able to plan in advance the opportunities for soil stripping, once earthmoving equipment is on-site it is important that soil stripping should continue only while soil conditions are suitable. Information on dry or average years is of little relevance in this situation and it is necessary either to directly check soil consistency with a plastic limit test or to run a moisture-deficit model interactively with daily information on rainfall in the same way as irrigation might be scheduled. Figure 5 gives an example of the decision processes that might be incorporated in such a model.

The approach in figure 5 brings rainfall into the equation. As a general rule soil stripping and handling should not be started during wet weather and should be suspended if rain starts during operations. However, there is the need for some flexibility as steady rain on a dry soil is likely to have less immediate effect on soil strength and plasticity than light rain on a very moist soil. After rainfall ceases there will always be surplus water in the surface layers of soil. If earthmoving continues immediately, the surface layer will become compacted, ruts will be formed, and any further rain will tend to lie on the surface and drain away far more slowly than previously. Conditions will then continue to deteriorate during earthmoving. Suspending earthmoving for a period of hours after rain stops enables surplus water to drain away and there is a consequent lessening of the risk to soil structure when earthmoving recommences. The amount of rain that has fallen is important. Less than 5 mm over 12 hours will increase the moisture content of the surface 100 mm of an average soil by <4g/100g. Amounts of >5 mm in spring and autumn are likely to return the upper 100 mm of soil (which may have a moisture content only a few percent below plastic limit) to plasticity but, in summer, larger amounts of rainfall (up to 10 mm) are likely to be accommodated by the soil without this occurring.

<u>**Influence of Vegetation**</u>

While the foregoing has emphasised the importance of building up a significant soil moisture deficit before soil stripping commences, the part played by a good vegetative cover has not been addressed. It may be obvious to soil scientists that in a temperate climate subsoil layers will not dry significantly without the moisture demand of a plant root system, but it has been common practice not to crop agricultural land in the months preceding the start of mineral working and soil stripping.

The disadvantages of this are seen in figure 6, which compares the data for some of the bare soil and wheat plots with that for the grass plots in our study. While



[1] weekly modeled deficits can be updated daily by adding 2 mm and subtracting the daily rainfall.
[2] rain-gauge readings at 07.00 or 17.00 h.

Figure 5. Flow chart for scheduling soil stripping using moisture deficit and rainfall data.

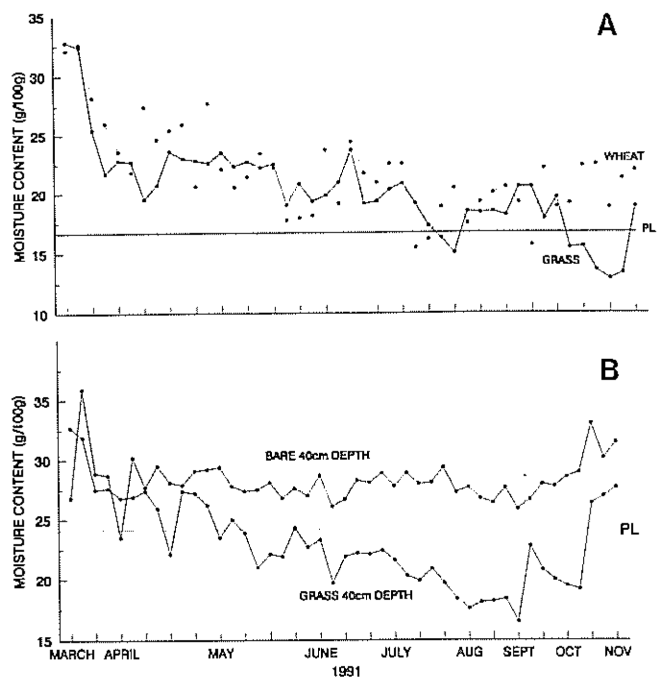


Figure 6. Extent of soil drying in relation to crop: (A) light loam subsoil at 100 cm depth; (B) heavy loam soil at 40 cm depth. PL = plastic limit moisture content.

the wheat crop (fig. 6A) extracts moisture at depth as efficiently as grass up to mid summer, once it senesces prior to harvest it ceases to use soil moisture. The grass crop thus has a distinct advantage in continuing to dry deep soil layers, particularly when the autumn is relatively dry but there is a flush of autumn grass growth. Without any vegetation, evaporative drying seldom extends below a depth of 30 cm, so while the topsoil may dry to a friable state, the major part of the subsoil will remain plastic throughout the year, especially when heavy-textured (Fig. 6C).

Conclusions

The study has shown that the season for stripping soil resources from surface mine and quarry sites can be defined in relation to the attainment and duration of moisture contents below the plastic limit. Defining the soil-stripping season using such criteria is acceptable in the drier parts of England and Wales but less so in the wetter parts, where heavy-textured subsoils may seldom dry to the plastic limit. One option for testing for suitable soil moisture conditions is to regularly monitor soil moisture contents and plasticity at key depths in the soil profile to be stripped. However, soil moisture deficit and agrometeorological data could be used to identify no-go periods and best periods for stripping soils and could also be used for day-to-day scheduling of soil stripping. The assumption that critical soil deficits increase in relation to the clay content of a soil layer (as a result of an increasing difference between the moisture contents at field capacity and plastic limit) only holds true for soils of comparable mineralogy. There is evidence that the plastic limits of ferruginous and calcareous soils are closer to field capacity moisture content than in other similarly textured soils. Use of the critical soil moisture deficits presented in table 3 for such soils would thus overestimate the amount of soil drying necessary prior to stripping, but at least the error would be on the safe side.

Code of Practice

The results of this research are to be integrated into a Code of Practice for Soil Handling to be prepared by the Ministry of Agriculture, Fisheries and Food for public consultation in 1994. Soil stripping is, of course, only one element of soil handling and the Code must consider re-spreading of soils from stockpiles. Although the old adage "soil which enters a stockpile in good condition is more likely to be removed from it in good condition" is largely true, it is important to ensure that stockpiles are kept vegetated, that a soil moisture deficit exists during removal of soils from them and that the respreading season allows enough time for a ground cover crop to be established before the end of the growing season. For this reason the season for respreading soils is likely to be shorter than the season for stripping them. While the Code will seek to minimize the damage to soils that can occur during conventional earthmoving systems, there is considerable opportunity for mineral extraction companies to further reduce the chance of damaging soil through adopting systems that avoid the trafficking of soils (e.g. Bransden 1991).

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