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Research and Development

Final Project Report

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Project title	Trials to evaluate the effectiveness of subsoiling treatments on soil structure on mineral sites during the five year aftercare period.
MAFF project code	**LE0208**
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Executive summary (maximum 2 sides A4)

EXECUTIVE SUMMARY.

The objectives of this project were to:

1. Evaluate the effectiveness and longevity of different subsoil loosening treatments in improving soil structure and root development during the 5 year aftercare period following soil reinstatement
2. Identify the suitability of different subsoiler tines for use in different field situations, particularly with respect to their effective depth of operation and soil shattering abilities.
3. Develop a field procedure to allow rapid checks to be made on the soil loosening result achieved, so that any necessary implement adjustments can be made at the beginning of operations.
4. Provide guidance on subsoil selection and practice for different field situations.

Standard methods and measures such as soil penetration resistance, bulk density and moisture status commonly used to assess soil physical condition were found to be insensitive and on occasions gave faulty indications of soil conditions. A more effective and reliable method was developed and used, based on soil profile analysis to quantify the intensity, type and depth of root development and whether the soil structural units or clods were penetrable or not to roots. The method, whilst very suitable in a research context, is rather time consuming for use in routine field checks in aftercare situations. To overcome this time limitation, a method combining a quick soil profile check with replicated penetrometer transect measurements was developed and shows considerable promise for future use. The profile check allows the penetration resistance readings to be related to actual field conditions, allowing correct interpretation of the penetrometer information.

The investigations were carried out on 6 former opencast mineral extraction sites, on soils ranging from loamy sand to clay, some in arable cropping and others in grass, in different climatic situations. The experiments and observations continued over the 5 year aftercare period.

The subsoiler tines investigated included low and high-lift wing and no-wing tines, working at different depths under different soil density and soil moisture conditions. Comparisons between the tines were made in terms of the nature of the soil disturbance, effective working depth and the longevity of the loosening effect. The effective working depth of all the tines increased as the soil density increased, extending to depths of 0.8m and more under very compact conditions. With only moderate compaction, effective

working depth decreased to 0.4m in the case of no-wing tines. Winged tines had the greatest range of operating depths under all conditions, producing greater degrees of soil disruption and allowing, through control over wing lift height, more control over the degree of disturbance achieved. Considering all the performance factors, winged tines offer the greatest number of advantages for loosening compact restored soils

The experiments examining the longevity of the loosening treatments were carried out on 6 sites. The sites and loosening treatments were chosen to allow the influences of soil texture, soil aggregate stability, climate, drainage status, surface loading and land use to be identified. All treatments were installed using winged subsoilers, high-lift winged types being used for all the deep operations, (0.6-0.7m depth) and also for shallower operations (0.4-0.45m depth) on the arable sites. Low lift winged types were used in established grassland to avoid serious damage to the grassland sward. The effectiveness and longevity of the treatments were assessed in terms of the extent and degree of root development, the penetrability of the soil structural units and clods to roots and soil structure development within the soil profiles.

Subsoil loosening improved the initial condition of soils on all sites, but the effectiveness and longevity of the changes and need for further treatment varied between sites. The greatest improvement for the fewest mechanical inputs is most likely to occur as soil textures become finer, soil swelling and shrinkage behaviour increases, aggregates become more stable, subsoil wetness is reduced, and both surface loading and soil disturbance decrease. All sites benefited from an initial deep loosening and on the heavier soils under drier conditions with careful surface management, little further work was required, except perhaps for one further shallower loosening. As conditions became wetter a further deep operation was found to be beneficial to generate more cracks and fissures. The need for and the number of subsequent shallower operations depended upon the degree of soil slumping which occurred during wet periods or through bad drainage and the pressure from surface loadings. The sandy soils were the most unstable and regular loosening inputs were required to maintain satisfactory root development. Grassland cropping is to be preferred to arable where this can be fitted profitably into the farm system.

The nature and extent of loosening being achieved during subsoiling operations cannot be satisfactorily determined through surface observation. An excavation is required across the line of work at its commencement to check the work being done, so that modifications to working depth and/or tine spacing can be made where necessary. The loosened profile can be most easily identified by pulling away the loosened soil on the pit face on the side of the direction of subsoiler travel.

Guidelines are suggested for the different soils and situations likely to be encountered, with respect to the depth and number of loosening operations which may be necessary for successful soil profile development during the aftercare period. The guidelines are based upon site knowledge of soil texture, aggregate stability, likely soil moisture deficits, and the planned cropping whether grass or arable. It must be stressed that the operations suggested are only guidelines and actual requirements may differ significantly from them, depending upon weather conditions and final surface management. The recommended approach to determining the actual need for further loosening operations is to check the current stage of soil and root development within the profile and take decisions on that basis. Using the combined approach of interpreting penetrometer readings against rooting observations in a representative soil profile pit, the need for further work and if so, the required depth can be readily determined.

Scientific report (maximum 20 sides A4)

TRIALS TO EVALUATE THE EFFECTIVENESS OF SUBSOILING TREATMENTS ON SOIL STRUCTURE ON MINERAL SITES DURING THE FIVE YEAR AFTERCARE PERIOD.

M.A.F.F. CONTRACT NO. CTE 9406D

FINAL SCIENTIFIC REPORT, FEBRUARY 2000.

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CONTENTS.

1. INTRODUCTION.

This report presents the scientific results of work undertaken by Silsoe College on M.A.F.F. Contract CSA 2695 for the duration of the research contract from November 1994 to November 1999. Two sets of experiments were conducted. The first compared the performance of different subsoiler types on two restored sites in an experiment of one year duration. The second examined the longevity of subsoiling benefits to be attained by subsequent reloosening operations on six sites during the five year aftercare period. The objectives of the research were:

1. To evaluate the effectiveness of subsoiling treatments on maintaining and improving soil structure on restored mineral sites during the five year aftercare period. The performance of subsoilers were to be compared in terms of soil shattering, effective depth of operation, compatibility with aftercare objectives, longevity of benefit and effectiveness during aftercare in rehabilitating soil structure.
2. To develop a field procedure to enable subsoiler operators to quickly check the degree and depth of soil disturbance being achieved at the time of the operation. This will assist with implement adjustment to ensure the desired disturbance is being achieved.
3. To provide technical guidance on subsoiler selection and practice and highlight the potential pitfalls of the techniques investigated.

All these objectives have been met.

2. RESEARCH APPROACH.

Two experiments were conducted to identify the effectiveness of subsoil loosening treatments in producing a drained, aerated soil condition which would promote root establishment and sustained growth:

1. **An investigation into the effectiveness of different soil loosening equipment,** namely the level and types of initial subsoil disturbance produced by different subsoilers, compared with an undisturbed condition, measured over one year on two contrasting sites. The implements were selected to produce a range of soil disturbance levels. Quantitative observations of the breakout effectiveness of subsoiler tines were also conducted to examine the tine maximum effective working depth (critical depth), soil failure pattern and best-practice subsoiler operating conditions on compact sand and clay sites.
2. **A comparison of the longevity of soil loosening benefits**, relative to an unsubsoiled control treatment, to identify the required frequency of resubsoiling during the five year aftercare period on six contrasting sites. Loosening treatments were applied annually or as required to maintain structural condition.

Treatments were evaluated in relation to initial disturbance and heave produced, initial soil properties, drainage status, weather and improvements to soil physical condition. Assessments were made using improved techniques.

3. EXPERIMENTAL METHODOLOGY

3.1 SITE SELECTION

Six restored field sites were selected according to the following criteria:

1. Sites should comprise restored soils in extremely poor physical condition with compaction within 0.45m of the surface.
2. A range of contrasting soil and climatic conditions must be represented.
3. One site should receive above 1000 mm of rainfall per annum.
4. Both grassland and arable land uses should be represented.

The restored sites were all former opencast mineral extraction sites which entered aftercare between July 1994 and September 1995. Underdrainage was installed at all sites within one year of soil reinstatement. Restored soil samples were collected from each site between July and September 1997. Soil textural and swelling properties were determined using standard laboratory procedures. A slaking and dispersion test was used to determine soil stability. A comparative summary of site characteristics is given in Table 1.

Table 1: Characteristics of restored sites.

		Ripley	Woll Sand	Woll Clay	Hatfield	Iver	Broughton
Soil Type		Sandy loam to loamy sand	Sandy loam to sandy clay loam	Clay	Clay loam to silty clay loam	Clay loam to clay	Clay loam
Subsoil clay content (%)		5 - 7	16 - 24	43 - 63	17 - 22	26 - 38	29 - 36
Stability	**Slaking index**	0.02	0.04	0.26	0.13	0.09	0.17
Climate	**Av. Annual rainfall (mm)**	674	587	587	670	669	1068
	Excess winter rain (mm)	207	135	135	195	205	550
	Soil moisture deficit (end July)	99	95	95	102	99	39
Drainage		Moderate	Poor	Poor	Good	Mod to poor	Good
Field loading		High	Low	Low	Mod	High	Low
Land use		Arable	Grassland	Grassland	Arable	Arable	Grassland
Permission of		Hall Aggregates (South East) Ltd. Mr C. Rayner	St Albans Sand and Gravel Co. Ltd Mr I. Bowers		St Albans Sand and Gravel Co. Ltd. Mr B. Enever	Hall Aggregates (South East) Ltd. Mr C. Rayner	R.J. Budge (Mining) Ltd. Mr D. Harrison

3.2 EXPERIMENT 1: SUBSOILER TINE INVESTIGATIONS.

Two contrasting sites were selected for subsoiler tine comparisons to assess their loosening effects: Wollaston Clay, a silty clay loam grassland site and Ripley, a well-drained arable sandy loam site. Subsequent traffic loading on each site was dictated by normal farm practices. Table 2 indicates the treatments, established at each site using a replicated randomised block design. All treatments were installed in late August 1994 using subsoilers with rigid tines. Tines were arranged at recommended spacings (between 1 and 1.5 times the tine depth; Spoor and Godwin, 1990) in order to produce a uniform soil disturbance. Rapid profile checks were made at the time of subsoiling to ensure that the tines reached the required depth. Types and weights of equipment used during subsoiling, soil moisture content, initial bulk density and changes in soil surface elevation (heave) were recorded at the time of subsoiling.

Profile pits were excavated in the summer following the initial operations to identify the depth and uniformity of loosening, the resulting clod size distribution and the rooting distribution. Additional measurements included penetration resistance and gravimetric moisture content (April-May) in years 1, 3 and 5 after subsoiling, and dry bulk density by the replacement method (July). Penetration resistances were measured at 120 mm intervals across a 2.4 metre transect located perpendicular to the direction of subsoiling. The critical depth and loosening efficiency of different subsoiler tines were assessed on sandy loam and silty clay soils under hard, dry conditions. Table 3 indicates the tine configurations and working depths examined.

Table 2: Subsoil loosening treatments and methods.

Treatment	Nominal Working Depth (m)	Subsoiler Description	Tine spacing (m)	Passes
1. Untreated control	-	Not subsoiled	-	-
2. Moderate disturbance, shallow	0.4	Shallow, narrow pointed, low lift height (50 mm lift) winged grassland subsoiler with trailing roller	0.66	Single pass
3. Minimal disturbance, shallow	0.45	Shallow, heavy duty agricultural type multi-tined simple subsoiler with no wings	0.66	Single pass
4. High disturbance, shallow	0.45	Multi-tined shallow winged subsoiler (lift height 100 mm)with shallow leading tines	0.66	Single pass
5. Minimal disturbance, deep	0.8	Plane simple tines with no wings	1.0	Split double pass
6. High disturbance, deep	0.8	High lift height (100mm lift), rigid winged tines	1.0	Split double pass

Table 3: Subsoiler tine configuration for critical depth determination.

Soil type	Subsoiler type	Working depths (mm)	Tine width (mm)	Wing width (mm)	Wing lift height (mm)	Number of replicates
Sandy loam	No wing	300, 400, 550, 650	67	-	-	3
	Low-lift wing	300, 400, 550, 650	67	267	100	3
	Hi-lift wing	450, 550, 600	67	245	100	3
Silty clay	No wing	400, 550	67	-	-	3
	Hi-lift wing	400, 550, 650	67	245	100	3 (1 at 650)

Profiles were excavated across each tine slot and measurements taken included:
1. Core dry bulk density and gravimetric soil moisture content from the tine foot location,
2. Breakout profile depth at 20 mm intervals across the profile section,
3. Lateral limit (maximum width at the soil surface) of subsoiler disturbance,
4. Maximum height of soil surface heave across the disturbed profile
5. Draught force and disturbance area, recorded on an ad-hoc basis.

Further experiences of problems encountered during subsoiling operations and corrections made to improve loosening or facilitate subsoiling were recorded.

3.3 EXPERIMENT 2: EFFECTIVENESS AND LONGEVITY OF SUBSOIL LOOSENING

Loosened and control plots were installed, using a randomised design, at all sites listed in Table 4 in year 1 to identify the longevity of the best soil loosening treatments during the five year aftercare period. Plots were large (20 m wide) and sample replication within plots was high to ensure that site variability was represented. Further loosening was conducted on selected plots either annually or intermittently in response to the perceived need for re-loosening. Table 4 summarises the treatments applied. The same checks on tine depth were conducted and post-subsoiling information (equipment, soil moisture content, bulk density and heave) collected as in Experiment 1. Subsequent field management was determined by the farmer.

Profile pits were excavated each year between July and August and improvements in soil condition evaluated in terms of rooting, compaction, structure, porosity and fissuring, since these have the most fundamental effect on plant growth through rooting, drainage and aeration. Standard profile description methods were used in years 1 and 2. A new profile description technique was developed (see Section 3.4.2) and used in years 3 to 5. The following data were collected annually:
1. Penetration resistance and gravimetric moisture content to depth 0.5 m in spring at approximate field capacity condition and to 1 m depth at the time of maximum penetration resistance in summer.
2. Climatic data (rainfall totals, sunshine and potential evapotranspiration).
3. Records of crops, tillage operations, traffic and implement types provided by the farmer.

All penetration resistance measurements were recorded at 120mm intervals along a 3.6 metre transect located perpendicular to the direction of subsoiling.

Table 4: Long-term loosening treatments.

	Wollaston Sand and Clay				Ripley			Iver			Hatfield		Broughton Lodge			
Treatment	C	Sa	D	D Sg	C	Sa	D	C	D	D Sa	Sa	Sa Sa Sa	C	D	D D	D D Sg
Date of operations		94	94	94 97		94	94		94	94 97	95	95 96 97		95	95 96	95 96 97

Key to loosening treatments:
Sa - 0.45m shallow high lift height agricultural winged subsoiler
Sg - 0.45m shallow low-lift height grassland winged subsoiler
D - 0.75m deep, plane high lift height industrial winged subsoiler
C - Unloosened control

3.4 FIELD ASSESSMENT PROCEDURES.

3.4.1 STANDARD TECHNIQUES.

Comparison of existing field soil profile evaluation measures, including bulk density, shear strength, penetration resistance and profile description techniques, indicated that all had limitations for use in restored soil conditions. Bulk density or shear strength techniques using small cores or samples are unsuitable since a high number of replicate samples is required to account for field variability. Attempts to use the replacement method for bulk density (Avery and Bascombe, 1974) also produced inconsistent results reflecting the highly localised variability in soil condition resulting from reinstatement. Extreme compaction and high stone content prevented the installation of access holes for use of the gamma-ray density meter technique (Soane and Henshall, 1979). Soil loosening created fissures within a dense soil mass so bulk density was inappropriate for identifying the effects of subsoiling on soil structure and root development on restored sites. In soils with significant fissure development the relationship between root development and bulk density was also poor.

The most promising quantitative method involved use of the recording cone penetrometer to give a rapid and repeatable indication of field soil condition and soil penetration resistance. Averaged penetrometer data gave an indication of general trends in penetration resistance with depth in the profile and enabled direct comparison between treatments to be made. Much more information became available by collecting narrowly spaced readings along a 3 metre transect and plotting the individual penetrometer values for each depth. These transects showed the scale and location of variability within the soil profile. Relating penetration resistance to potential rooting without checking actual root development has to be treated with caution, however, since low moisture content with high penetration resistance could result from either water abstraction by roots or simply from lack of porosity due to compaction. It is therefore necessary to relate the observed penetration resistance values to actual soil profile conditions. This can only be achieved by using profile and root development observations at the location of penetrometer measurement. Once calibrated, the penetrometer can then be used to make rapid checks on soil condition over a larger area within a field.

Examination of current soil profile description methods indicated that none were completely suitable for evaluation of restored soils. Standard soil profile description methods (Hodgson, 1974) were of limited use in these soils since soil structures are very weakly developed and a many restored soil features are not easily interpreted, including extremely coarse and massive structures, discontinuous porosity and variability in soil condition. Comparison of profile descriptions across plots, sites and years is also difficult using the quantities of complex descriptive information generated. Therefore a new profile description technique was developed.

3.4.2 AN IMPROVED SOIL PROFILE EVALUATION PROCEDURE.

Examination of restored soil profiles over a number of years resulted in the observation that rooting provides the clearest visual indication of the soil physical state. Roots may occupy only 1% or less of the profile but their penetration into the soil profile is sensitive to soil physical conditions, namely soil structure and strength and, indirectly, moisture distribution, aeration and temperature. Roots may therefore delimit soil zones of different physical condition. The most readily observable rooting features are root density, rooting depth, ability of roots to penetrate into clods, root position and the spatial distribution of roots in relation to compact soil zones and fissures. These characteristics can be used to delimit areas of the soil profile with different levels of compaction, porosity and structural development.

A method of interpreting this spatially-referenced soil profile information was developed by identifying “zones” of uniform soil physical condition. Soil zone classes were defined using the following criteria:

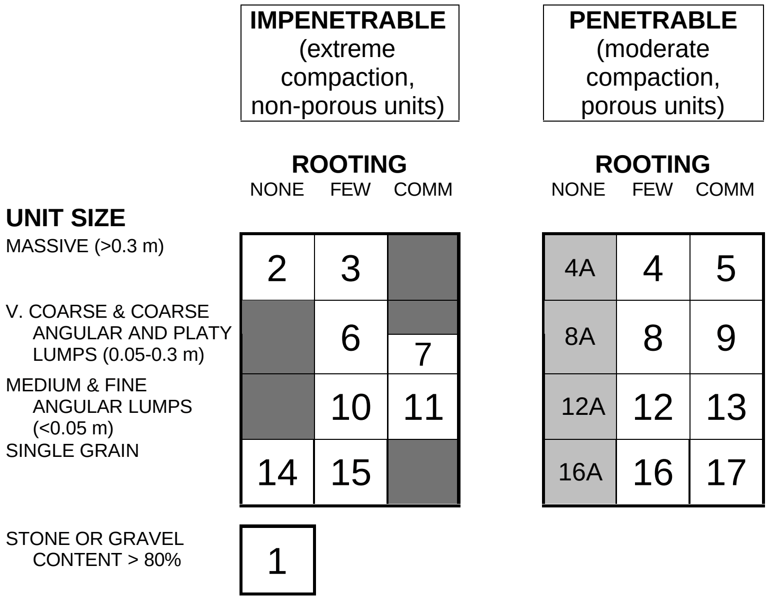
1. The degree of rooting:
   a. no roots (no observable roots within the section).
   b. few roots (between 400 and 0 roots/m^2),
   c. common roots (more than 400 roots/m^2),
2. Penetrability of soil units to roots:
   a. penetrability to roots, i.e. rooting inside clods, indicating porous conditions
   b. impenetrability to roots, i.e. roots absent from the clod and confined to fissures.
3. The size of soil units:
   a. Single grain (common in sandy soils with little cohesion)
   b. Medium and fine soil units (defined by unit size less than 0.05 m)
   c. Coarse soil units (size 0.05 to a maximum 0.3 m for angular or platy units)
   d. Massive (soil units greater than 0.3 m or unstructured soil).

The developed profile description procedure comprised the following steps:

1. Identify and map uniform soil “zones” according to rooting, penetrability and soil unit size, marking the respective boundaries between zones on the profile face using spray paint.
2. Assign each bounded area or soil “zone” of uniform structure, rooting and penetrability a class number based on the classification in Figure 1.

3. Overlay a grid onto the soil face as the spatial reference for mapping soil zones and draw, trace or photograph the profile.
4. Scan or plot the mapped soil profile image onto the computer.
5. Quantify profile features by determining the percentage of soil profile area covered by each soil zone or the depth to different soil profile boundaries.

An example of such an analysis is presented in Figure 5 to Figure 7.



A = Access restricted by other factors, i.e. penetrable zones with no roots where root access is restricted by anaerobicity, waterlogging or presence of impeding pans higher in the profile.

Figure 1: Classification of restored soil zones using rooting, penetrability and unit size.

The newly developed procedure is capable of:
1. Quantifying the main physical features and spatial variability of restored soil.
2. Identifying the effect and longevity of applied broad-scale mechanical treatments.
3. Providing information suitable for calibrating a penetrometer so that rapid assessment of field soil condition may be achieved.
4. Enabling the spatial patterning and location of soil treatments to be identified over the profile in relation to spatially-applied mechanical subsoil loosening treatments.

The profile description procedure was therefore used in combination with penetrometer transect and soil moisture information, to assess restored soil condition in this research.

4. RESULTS.

4.1 COMPARATIVE PERFORMANCE OF DIFFERENT SUBSOILER TINES

The comparative performance of different subsoiler tines, detailed in Table 2, was assessed over a range of depths (Table 3) on two soil types, with further investigation during the installation of five year aftercare treatments on 4 further sites. The performances of the different tines were compared using the following parameters:

- Limits of soil disturbance with single tines,
- Critical depth under different soil conditions,
- Degree of soil break-up,
- Surface heave,
- Degree and longevity of loosening effects,
- Draught requirements.

4.1.1 LIMITS OF SOIL DISTURBANCE.

The schematic diagram in Figure 1 illustrates the soil disturbance generated by both winged and no-wing tines. Examples of actual soil profile disturbances with these tines working at different depths in a moderately dense clay soil are shown in Figure 2 and Figure 3. The winged tine disturbance is always significantly wider than the no-wing but the disturbance area can also be significantly reduced if the tines work below their critical depth. This is occurring with the no-wing tine in Figure 2 below a working depth of 0.4m, where the tine cuts only a slot at depth, achieving little loosening. At similar working depths, the width of the disturbed area created by winged tines tends to be slightly narrower on the heavier more cohesive soils than on the more friable sands. This has implications when selecting the most appropriate tine spacing for mounting tines on a tool frame.

Figure 1: Influence of tine geometry on observed soil profile disturbance.

Figure 2: Breakout profiles using a no-wing subsoiler tine in clay restored soil.

Figure 3: Breakout profiles using a high-lift height winged subsoiler tine in clay restored soil.

4.1.2 CRITICAL DEPTH.

The critical or maximum effective working depth to achieve soil loosening was shown to be much more dependent upon the tine type, the initial soil density and the degree of moisture saturation than upon the soil type.

In the loamy sand soil, critical depth increased for no-wing tines from approximately 0.35m depth to approximately 0.7-0.8m depth as the soil density increased from 1.5 to 1.7/1.8kgm^{-3}. The degree of saturation varied between 80-98% at the higher densities and was of the order of 70% at 1.5kgm^{-3} density. In a sandy clay loam at 70% saturation with a density of 1.7kgm^{-3}, critical depth for the no-wing tine was at approximately 0.4m. Working under similar high density soil conditions, both the low and high lift winged tines continued to work above their critical depth to depths of 0.8m. Differences in critical depth between the two winged tines occurred at lower soil densities. At a density of 1.6 kgm^{-3} in the moist clay loam soil at Broughton Lodge, working depth with the low-lift winged tine was limited to 0.4m, compared to 0.5-0.6m with high-lift wings. Local differences in soil density are common on restored sites and can result in changes in the degree of soil disturbance achieved due to local differences in critical depth.

4.1.3 DEGREE OF SOIL BREAK-UP AND DISTURBANCE.

The degree of soil break-up during the soil loosening operations was soil-type dependent. Loosening operations tended to fracture the soil along relatively few failure planes and unless the soil within the larger soil units isolated was fairly friable in nature with little cohesion, the units were reluctant to break down further. The sandy soils, therefore, tended to fracture into much smaller units than the heavier soils, which were more cohesive in nature, see Figure 4.

Figure 4: Fissuring within the disturbed profile.

Winged tines created more soil break-up than no-wing tines. This was due to the bending action induced into the soil mass as it flowed off the back of the wings, see Figure 1 and Figure 4. This bending tended to generate tension cracks within weaker planes, thus reducing the size of the units. At any given depth, the fissuring and the degree of loosening tended to increase as wing lift height increased. To achieve greater soil fragmentation in the more cohesive clayey soils, it proved necessary to loosen the soil progressively deeper from the surface down. This was either achieved in one pass fitting shallow and deep working tines on the same tool frame, or by carrying out two passes, the second pass being at a greater depth than the first.

4.1.4 SURFACE HEAVE.

The amount of soil heave produced during the loosening operations depended upon the extent of soil loosening and the size of the units formed. The greater the degree of loosening and the larger the unit size, the greater the heave. This heave has implications for the under-frame subsoiler clearance required to allow the free flow of soil through the implement. The height of heave above the original surface level in situations where heave was great was approximately 0.1-0.15m at working depths between 0.4 and 0.5m, and 0.15-0.25m at depths of 0.6-0.7m.

4.1.5 DEGREE AND LONGEVITY OF LOOSENING EFFECTS.

Quantifying the degree and longevity of the loosening effect created by the different tines through penetration resistance measurements revealed more penetrable conditions at any given working depth following the use of a high-lift rather than a low-lift winged tine. The no-wing tine produced the greatest profile penetration resistance of the loosened treatments.

Soil properties had a greater influence on the longevity of the loosening effect than the type of tine used. On the more stable soils, the relative penetration resistances five years after the loosening operation remained lower than control values and were ranked in the same order as in the first year after loosening, the no-wing tines being highest and the high lift wing lowest.

4.1.6 DRAUGHT REQUIREMENTS.

Tine draught measurements indicated minimal differences between the different types of tine. The actual draught forces in these very compact restored soils were very high, being of the order of 40-50kN/single tine at a depth of approximately 0.5m.

4.1.7 CONCLUSIONS.

1. The maximum effective loosening depth, the critical depth, in any situation is controlled more by the tine type and soil condition than by the actual soil type. Under very compact soil conditions at moisture contents close to saturation, critical depths for all the tines tested were deep, extending to 0.8m in the case of no-wing tines and deeper with winged tines. Under less dense conditions, critical depths were considerably reduced. High-lift winged tines always had the greatest critical depth, followed by low lift wing tines and finally by no-wing tines.
2. Individual winged tines generated the widest extent of soil disturbance thus allowing tines to be fitted on tool frames at wider spacing, whilst still achieving complete soil break-out.
3. The degree of soil fragmentation upon loosening is greatest with high-lift winged tines and least with non-winged types and is strongly influenced by soil type and the degree of soil cohesion within the soil mass. Heavy clayey, cohesive soils break into the largest soil units.
4. Soil heave is greatest under conditions when the soil is breaking up into the largest units.
5. The longevity of any loosening effect is much more dependent upon the stability of the soil rather than on the type of tine used or the nature of the disturbance generated.
6. Draught forces of different tine types do not differ significantly at similar working depths. Winged tines have the highest draughts but also the greatest breakout efficiency.
7. Considering all the performance factors, winged tines offer the greatest number of advantages when loosening compact restored soils. Adjustments to wing lift-height provide the greatest control over the soil condition produced and adjustments can be made to suit the prevailing undisturbed soil condition and working depth requirement.

4.2 EFFECTIVENESS AND LONGEVITY OF LOOSENING TREATMENTS

The sites for these experiments were selected to encompass as wide a range of field situations as possible to examine the influences of soil texture, soil aggregate stability, climate, drainage status, surface loading and land use, on the effectiveness and longevity of different soil loosening treatments, see Table 1. The longevity treatments, Table 4, were selected to assess the potential benefits of loosening to different depths and of reloosening during the aftercare period. Based on the results of the initial work examining the performance and effectiveness of the different types of implement, winged subsoilers were used throughout these experiments. These implements have the widest operating depth range, give the greatest degree of control over the degree of loosening achieved and do not suffer any serious draught penalties compared with other subsoil types.

In reporting the results of the 5 year experiments, the following performance and behavioural parameters are used:

- Extent and degree of root development
- Penetrability of the soil units to roots
- Soil structure development and change in soil unit size

The results from each site are discussed in turn and comparisons are made between the different situations.

4.2.1 RIPLEY.

Penetration resistance profiles taken over the 5 year period indicated that in this arable cropped very weakly structured loamy sand soil, the loosening effects disappeared within 18 months (spring 1997) of the loosening operations. Nevertheless, small longer term differences were found between treatments in terms of root density, rooting depth and soil unit penetrability to roots. Table 1 indicates the average boundary depths with respect to root penetration within the different treatments from 1997 to 1999.

Table 1: Average soil boundary depths with subsoiling treatment at Ripley.

	Year	Subsoiling Treatment			LSD	P value
		C	D	S	(trt x year)	(trt x year)
Common / few roots (m)	1997	0.20 $_a$	0.14 $_a$	0.20 $_a$		
	1998	0.12 $_a$	0.17 $_a$	0.15 $_a$	0.073	<0.001
	1999	0.13	0.34 $_a$	0.35 $_a$		
Penetrable / impenetrable (m)	1997	0.36 $_a$	0.40 $_a$	0.38 $_a$		
	1998	0.34 $_a$	0.49	0.36 $_a$	0.062	<0.001
	1999	0.31 $_{a\ b}$	0.25 $_a$	0.33 $_b$		
Maximum rooting depth (m)	1997	0.44 $_a$	0.43 $_a$	0.50 $_a$		
	1998	0.46 $_a$	0.65	0.44 $_a$	0.077	<0.001
	1999	0.36	0.50 $_a$	0.48 $_a$		
Maximum subsoiling depth		-	0.75	0.45		

[a b c] All treatments significantly different except those labelled the same in any year.

The main differences are in the depth of common roots and the maximum depth of rooting. In both cases the loosening treatments improved rootability, although there was little difference between the loosening treatments themselves and minimal improvement after 1997. In the unloosened control the roots were largely confined to just below topsoil depth at approximately 0.3m, whereas in the shallow loosened, rooting ceased at about 0.4m and in the deep loosened they extended to 0.5m and beyond. Deeper rooting may have been limited due to chemical impedance at a depth of approximately 0.6m. The individual soil units remained impenetrable with no change in size throughout the five year period. Due to the inherent instability of this soil, frequent and regular reloosening operations (every 1 to 2 years) would be required to maintain the soil in a state suitable for good root penetration.

4.2.2 WOLLASTON SAND.

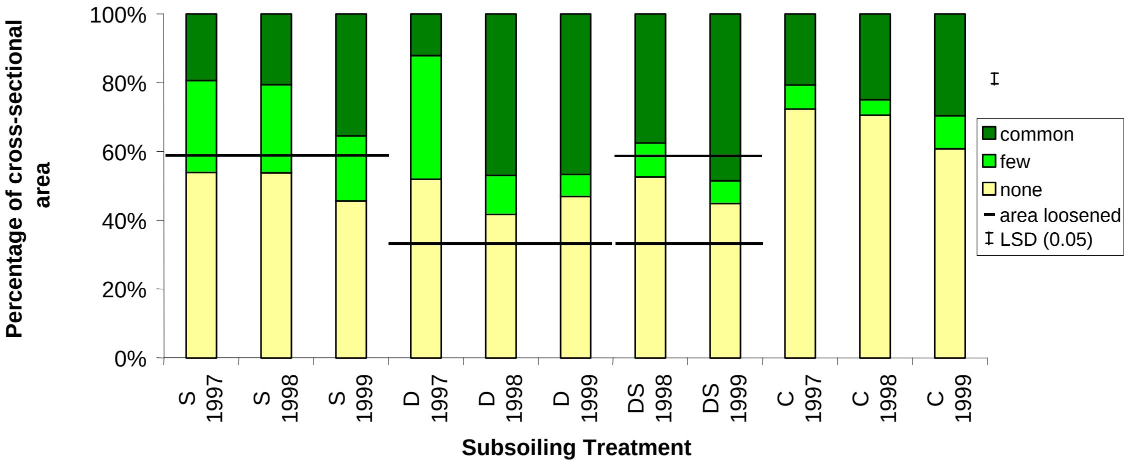


Figure 5: Effect of loosening on soil rooting zones at Wollaston Sand.

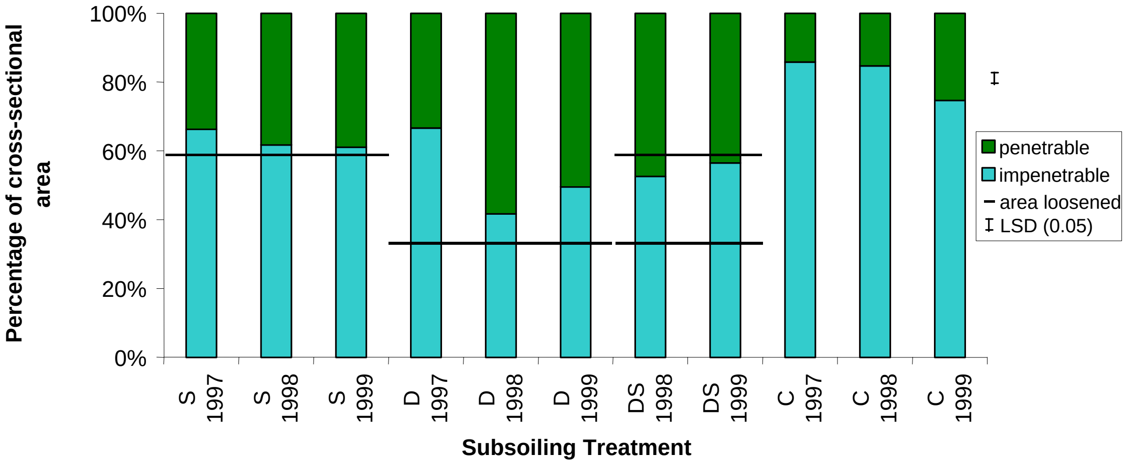


Figure 6: Effect of loosening on soil penetrability at Wollaston Sand.

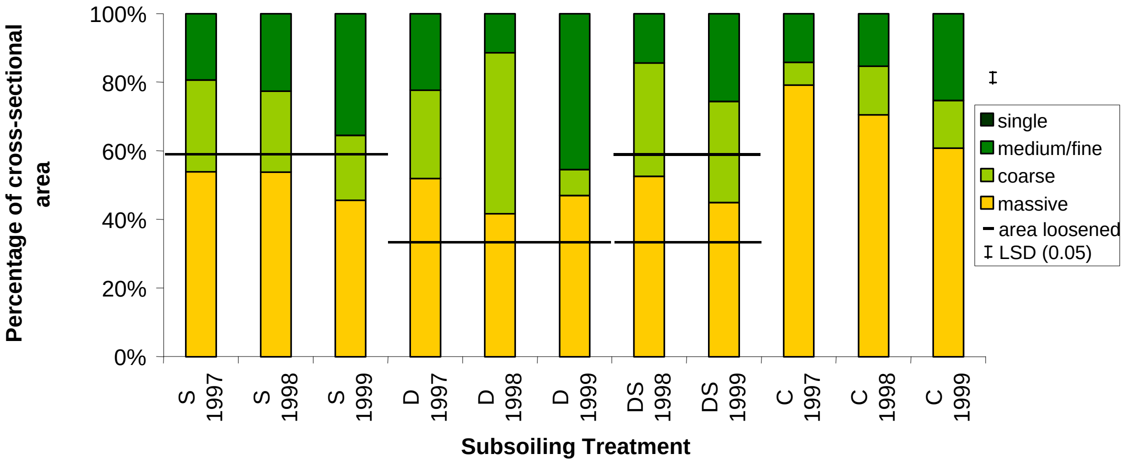


Figure 7: Effect of loosening on soil structural zones at Wollaston Sand.

The slightly more stable, sandy loam at Wollaston Sand was in grassland and subjected to fewer and lighter loadings. The loosening effects, in terms of reduced penetration resistance, persisted over the 5 year period and produced differences in root development, see Figure 5 and Table 2. Rooting was related to loosening depth, the deep loosening treatment significantly increasing the depth of potentially rootable soil. The full potential of this loosened depth was, however, not realised by the roots, due to poor drainage holding up water tables during winter and spring. Figures 7-21—7-23 indicate the effects of the treatments on the percentages of the different rooting zones, the penetrability of the soil units to roots and the structural zones respectively, between 1997 and 1999. A slow increase in rootability with time took place in the undisturbed control area but this was very limited. The loosening treatments generated a much greater response, limited in the deeper case by the high water table. The effect of the shallow reloosening operation in 1997 was to significantly increase the depth and density of common roots and increase soil structural development. Increases in rooting depth were expected but were inhibited, probably by water table depth. The longevity of the loosening effect allowed a progressive improvement in rooting and soil structure over the period of the experiment.

Table 2: Average soil boundary depths with subsoiling treatment at Wollaston Sand.

Boundary	Year	Subsoiling Treatment				LSD	P value
		C	D	S	DS	(trt x year)	(trt x year)
Common / few roots (m)	1997	0.12 $_{a b}$	0.09 $_{a}$	0.17 $_{b}$	-		
	1998	0.23	0.41	0.15	0.12	0.052	<0.001
	1999	0.27 $_{a}$	0.43	0.32 $_{a}$	0.44		
Penetrable / impenetrable (m)	1997	0.14	0.30 $_{a}$	0.31 $_{a}$	-		
	1998	0.14	0.52	0.36 $_{a}$	0.43 $_{a}$	0.088	<0.001
	1999	0.23	0.46 $_{a}$	0.35 $_{b}$	0.40 $_{a b}$		
Maximum rooting depth (m)	1997	0.25	0.43 $_{a}$	0.41 $_{a}$	-		
	1998	0.27	0.52	0.44 $_{a}$	0.43 $_{a}$	0.051	<0.001
	1999	0.36	0.49 $_{a}$	0.49 $_{a}$	0.50 $_{a}$		
Maximum subsoiling depth		-	0.65	0.45	0.65 0.45		

[a b c] All treatments significantly different except those labelled the same in any year.

Comparing the Ripley and Wollaston sandy soils, it is apparent that a combination of higher clay content (16-24%), the lack of soil disturbance (grass) and much lighter and fewer loadings at Wollaston Sand were responsible for the more effective and prolonged loosening benefits. Whilst the clay content was higher at Wollaston, the soil structural stability was extremely low and similar to that of Ripley. The improved and satisfactory response at Wollaston must, therefore, be due largely to much better surface management, with zero soil disturbance after loosening and only light loading on the surface.

4.2.3 WOLLASTON CLAY.

This clay soil exhibited significant shrink-swell capability and the aggregates had higher stabilities on wetting. Differences in penetration resistance between the treatments persisted throughout the 5 year period, in this light-loading, grassland situation. Improvements in root development took place with time in the undisturbed control treatment due to the cracking qualities of this soil, but at a considerably slower rate than in the loosened plots, see Table 3.

Table 3: Average soil boundary depths with subsoiling treatment at Wollaston Clay.

Boundary	Year	Subsoiling Treatment				LSD	P value
		C	D	S	DS	(trt x year)	(trt x year)
Common / few roots (m)	1997	0.11	0.2 $_{a}$	0.21 $_{a}$	-		
	1998	0.31	0.41 $_{a}$	0.41 $_{a}$	0.45 $_{a}$	0.052	<0.001
	1999	0.35	0.47 $_{a}$	0.47 $_{a}$	0.53		
Penetrable / impenetrable (m)	1997	0.11	0.24 $_{a}$	0.24 $_{a}$	-		
	1998	0.15	0.46	0.36	0.66	0.088	<0.001
	1999	0.16	0.51 $_{a}$	0.56 $_{a b}$	0.64 $_{b}$		
Maximum rooting depth (m)	1997	0.72	0.63	0.57	-		
	1998	0.7 $_{a}$	0.52 $_{b}$	0.52 $_{b}$	0.66 $_{b}$	0.051	<0.001
	1999	0.7 $_{a b}$	0.57	0.66 $_{a}$	0.73 $_{b}$		
Maximum subsoiling depth		-	0.65	0.45	0.65 0.45		

[a b c] All treatments significantly different except those labelled the same in any year.

Root development was similar in both the shallow and deep loosened treatments, the shallower loosened plot exhibiting deeper rooting due to fissure development generated on drying. A further shallow loosening 3 years after the initial disturbance produced a large improvement in rooting within the shallow loosened zone and this appeared to increase the chances of roots finding small fissures and planes of weakness below, allowing root entry and further development at depth. These deep, rooted fissures occurred at fairly regular spacings and hence were most likely to be relics of fissures developed during the initial deep loosening operations.

Comparing root development in this clay with the sandy soil under similar management on the same site, it was apparent that maximum development occurred under rather different soil moisture conditions. Most rapid root development occurred in the sandy soil, which had little structure and few fissures, under moist conditions when the soil was weaker. Little improvement was observed in dry years when the penetration resistance was high. On the clay, however, root development was good in both moist and dry years, fissures opening up through shrinkage in the dry periods, allowing roots to extend to depth.

4.2.4 HATFIELD.

Treatments on this clay loam site did not include a deep loosening, rather they explored the improvements that would be possible with shallower working farm type equipment where loosening depth was restricted to 0.4m. The annually loosened plots always had a lower penetration resistance than the once loosened but this was not translated into further improvement in root development, see Table 4. Steady improvement in root development was observed in all treatments with time, rooting depth limits being considerably greater than loosening depths. This deeper rooting occurred due to the shrinking properties of this soil on drying; the deeper soil layers shrank and developed into very large massive soil units which remained impenetrable to roots within but encouraged root development in the fissures between. Deeper rooting was also assisted considerably on this site following a crop of hemp, which developed very large vertical roots to depth. The main rooted area was, however, restricted to loosening depth, deeper rooting being limited to the few larger fissures. Deeper loosening to fracture the lower layers would have stimulated much deeper rooting on this site.

Table 4: Average soil boundary depths with subsoiling treatment at Hatfield.

Boundary	Year	Subsoiling Treatment		LSD	P value
		S	SSS	(trt x year)	(trt x year)
Common / few roots (m)	1997	0.22	0.08		
	1998	0.38_{a}	0.39_{a}	0.06	<0.001
	1999	0.40_{a}	0.41_{a}		
Penetrable / impenetrable (m)	1997	0.43_{a}	0.45_{a}		
	1998	0.35_{a}	0.39_{a}	0.066	<0.001
	1999	0.38_{b}	$0.32_{a\,b}$		
Maximum rooting depth (m)	1997	0.62_{a}	0.58_{a}		
	1998	0.79_{a}	0.79_{a}	0.085	<0.001
	1999	0.77_{a}	0.77_{a}		
Maximum subsoiling depth		0.40	0.40		

[a b c] All treatments significantly different except those labelled the same in any year.

In comparison with Wollaston Clay, which had similar shrink-swell properties, rooting was much deeper at Hatfield and this was attributed to root depth restrictions at Wollaston arising from the high groundwater table during the spring and winter periods. A further difference was that repeated shallower loosening at Hatfield did not improve the density of rooting between 0.4 and 0.7m depth, as occurred at Wollaston, roots remaining confined to widely spaced shrinkage cracks. This is thought to be due to the absence of an initial deep loosening at Hatfield and hence more closely spaced root-accessible fracture planes were not initiated.

4.2.5 IVER.

The clay fraction in this clay loam soil exhibited only minor shrink-swell tendencies, its aggregate stability was very low when subjected to long periods of wetting, and management subjected it to fairly high loadings in an arable cropping regime. The results of the loosening treatments clearly reflect this situation.

Some differences in penetration resistance due to loosening persisted throughout the 5 year period but they were slight. The loosening treatments gave a considerable improvement over the control, although rooting was restricted to loosening depth, see Table 5. Root development was slow on the unloosened plots and suffered a reversal following a very wet period during the winter of 1998. The soil slumped badly during this wet period on all plots, but its adverse influence on rooting and soil structure was greatest on the control. Despite the apparent major improvement in root development in 1999 in the shallow reloosening treatment, indicated in Table 5, this result is considered to be atypical of the conditions in general. In the previous year, the year following reloosening, the response had been very minimal and the set-aside in 1999 was highly unlikely to have produced such a major improvement. It must be concluded, therefore, that reloosening benefits were minimal due to the loss, through slumping, of many of the deeper fissures generated at the time of the first deep loosening. Soil drying also failed to open up deeper fissures for roots to exploit, due to the limited shrinkage properties.

Table 5: Average soil boundary depths with subsoiling treatment at Iver.

Boundary	Year	Subsoiling Treatment			LSD	P value
		C	D	DS	(trt x year)	(trt x year)
Common / few roots	1997	0.00	0.20 $_{a}$	-		
	1998	0.15 $_{a}$	0.22 $_{a}$	0.17 $_{a}$	0.111	0.003
	1999	0.36	0.18	0.53		
Penetrable / impenetrable	1997	0.64	0.47	-		
	1998	0.57 $_{a}$	0.54 $_{a}$	0.56 $_{a}$	0.061	<0.001
	1999	0.55	0.41	0.9		
Maximum rooting depth	1997	0.59	0.66	-		
	1998	0.57 $_{a\,b}$	0.54 $_{a}$	0.63 $_{b}$	0.066	<0.001
	1999	0.55	0.43	0.90		
Maximum subsoiling depth		-	0.60	0.60		
				0.45		

[a b c] All treatments significantly different except those labelled the same in any year.

The shallow reloosening treatment at both Iver and Hatfield, in contrast to Wollaston Clay, failed to give a response. It would appear, therefore, that unless there are residual fissures or weak planes present below reloosening depth for the roots to exploit, benefits in terms of deeper rooting from this further operation will be minimal. Only very few weak planes were present at Hatfield through lack of an initial deep operation, they collapsed at Iver due to soil slumping, but remained following deep loosening under the more stable conditions at Wollaston and were significantly exploited.

4.2.6 BROUGHTON LODGE.

Reductions in penetration resistance arising from the loosening treatments were retained throughout the 4 year period, see Table 6. The control treatment itself showed continuing improvement in rooting with time and, by the second year, rooting was not markedly different to that under the single deep loosening treatment. Greatest improvements in rooting occurred on the plots which were deep loosened twice, a shallow third loosening giving no further benefit. All plots experienced a deterioration in soil structure following the very wet winter of 1998 and this produced a set-back in root development both on the control and once loosened plots. No deterioration in rooting occurred, however, on the plots deep loosened twice. This was thought to be due to the second operation helping maintain good drainage, thus reducing soil wetness. The loosening operations on this site were carried out at relatively close tine spacings and the resulting uniform loosened zone allowed more uniform rooting at depth.

Table 6: Average soil boundary depths with subsoiling treatment at Broughton Lodge.

Boundary	Year	Subsoiling Treatment				LSD (trt x year)	P value (trt x year)
		C	D	DD	DDS		
Common / few roots (m)	1997	0.19	0.30	0.38	-		
	1998	0.35 $_{a}$	0.34	0.36 $_{a}$	0.31 $_{a}$	0.06	<0.001
	1999	0.26	0.29	0.52	-		
Penetrable / impenetrable (m)	1997	0.24	0.42 $_{a}$	0.5 $_{a}$	-		
	1998	0.44 $_{a}$	0.53 $_{a}$	0.64 $_{b}$	0.65 $_{b}$	0.092	<0.001
	1999	0.53 $_{a}$	0.54 $_{a}$	0.7	-		
Maximum rooting depth (m)	1997	0.45 $_{a}$	0.50 $_{a\,b}$	0.60 $_{b}$	-		
	1998	0.58 $_{a}$	0.63 $_{a\,b}$	0.71 $_{b}$	0.69 $_{b}$	0.108	0.02
	1999	0.66 $_{a}$	0.60 $_{a}$	0.86	-		
Maximum subsoiling depth		-	0.60	0.60	0.60		
					0.45		

[a b c] All treatments significantly different except those labelled the same in any year.

Comparing the responses at Broughton with those at Hatfield and Wollaston Clay, all sites exhibiting reasonable swelling and shrinkage properties, highlights the effect of differences in climate on soil improvement and root development. At both Hatfield and Wollaston, with considerably more drying and cracking, roots developed well below loosening depth. This did not occur under the much wetter conditions at Broughton, where little or no cracking occurred below loosening depth in poorly drained plots. Improvements at Broughton were achieved through the second deep loosening, which effectively reopened fissures created during the first loosening, as well as generating more. Like the sandy soil at Wollaston Sand and the minimal swell/shrink soil at Iver, root development at Broughton benefited from moist conditions for root penetration and development, in the absence of natural fissuring on drying.

4.2.7 CONCLUSIONS.

1. Subsoil loosening improved the initial condition of soils on all sites, but the effectiveness and longevity of the changes varied between sites.
2. The main factors controlling the effectiveness and longevity of loosening were soil texture, clay type, aggregate stability, climate, drainage status, loading and land use.
3. The greatest improvement for the fewest mechanical inputs is most likely as soil textures become finer, shrink-swell behaviour increases, aggregates become more stable, subsoil wetness is reduced, and both surface loading and soil disturbance decrease.
4. Short and long-term benefits from loosening were greater with an initial deep loosening than a shallow one, since this produced planes of weakness which in later years facilitated soil development, drainage and penetration of roots to greater depths, particularly in the more stable clay soils.
5. Only moderately stable soils containing expansive clays exhibited the ability to self regenerate from a compact state, but the rate of improvement was slow.
6. On extremely compact very dry soils of low stability, the effectiveness of subsoil loosening was limited to the actual depth of loosening.
7. Extension of rooting and soil profile improvements beyond the depth of loosening may be expected on soils with moderate clay content which are moist in spring and/or which exhibit shrink/swell activity.
8. Deep loosening was of only minimal benefit in soils which suffered from poor subsoil drainage and in weak structured soils prone to slaking or slumping.
9. A single deep loosening operation in the first year produced a significant improvement in soil physical condition, but the full significance of the treatment in the more stable soils was not fully realised until later years, roots needing time to exploit the deeper layers.
10. On wetter sites and in soils exhibiting little swelling and shrinkage, natural regeneration was minimal after the initial loosening. In these situations, with reasonable structural stability, a second deep loosening was particularly beneficial, reopening fissures and improving drainage.
11. On the more stable soils where weak planes created during the initial deep loosening remained intact, a subsequent shallower loosening encouraged root proliferation in the reloosened zone and this stimulated rapid root development to depth below, exploiting weak planes within the lower subsoil. In the absence of such weak planes, the main effect of the shallower operation was limited mainly to improved root development in the reloosened zone itself.
12. The longevity of the loosening effect on coarse textured, very weakly structured soils was only of the order of 1 to 2 years. On the more stable soils under moderately dry conditions, the loosening benefits were retained over the 5 year period.
13. Sites under grass and subjected to only light loading were more likely to experience rapid and sustained improvement in soil condition than highly loaded arable situations.
14. A run of dry years was particularly helpful in establishing a good rooting situation and this provided insurance against deterioration during periods of prolonged wet weather.

5. RECOMMENDATIONS FOR MANAGEMENT.

5.1 SUITABLE LOOSENING EQUIPMENT AND TINE SPACINGS.

Single tine studies showed that winged tines produce the most effective break up of compact restored soil under all studied site and soil conditions and offer the most control over the size of soil units produced. The greater the level of disturbance applied, corresponding to the lift height of the wings, the greater the chance of soil fissuring. High lift height winged tines are therefore recommended for all deep loosening operations and for subsequent reloosening on arable sites. On grassland, low-lift height wings may be used to reduce the degree of surface disturbance and risk of grass kill. The rate of soil structural improvement should not be reduced providing that adequate fissuring occurs.

Guideline tine spacings to achieve relatively uniform soil breakout at working depth are given in Table 1. As working depth needs increase on these restored soils, tine spacings need to be reduced, particularly on the more cohesive soils. At working depths approaching 0.7m or more, winged tine spacings may need to approach almost 1.0 times working depth. At these spacings, to avoid blockage, tines need to be suitably staggered on the tool frame to allow the free flow of soil through the implement.

Table 1: Tine spacings for complete loosening at depth and level surface conditions.

Subsoiler type	Depth (m)	Tine spacing [a]
Narrow (no-wing) tine	0.0 – 0.4	1.0 – 1.5 d
Winged tine	0.0 – 0.5	1.5 – 2.0 d
	0.55 – 0.6	1.5 – 1.8 d [b]
	0.65 – 0.75	1.0 – 1.5 d [b]

[a] d = working depth of deepest tine; [b] check the breakout pattern to ensure uniform disturbance

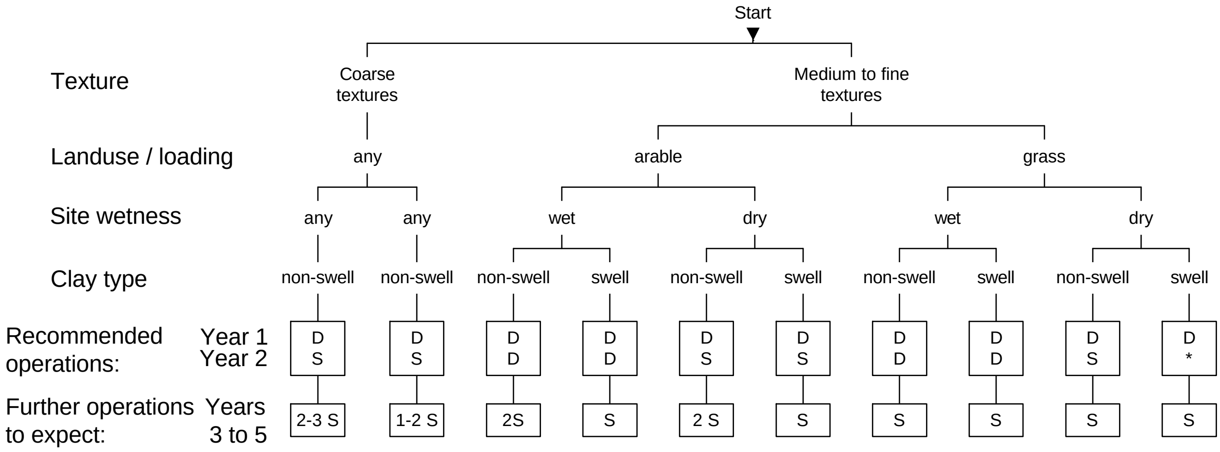
5.2 FIELD PROCEDURE FOR CHECKING THE WORK BEING ACHIEVED DURING SUBSOILING OPERATIONS

It is critical at the commencement of any subsoiling operation that checks be made to ensure the desired soil conditions are being achieved. This cannot be achieved through surface observation alone, checks must be made on the actual disturbed soil profile at depth. Following a short trial run, a profile pit needs to be excavated across the line of travel for profile observation. The pit should be excavated deeper than subsoiling depth, so that soil disturbed in the process of identifying the boundaries of the loosened zone can fall into the pit bottom without obscuring the loosened profile. To delineate the limits of the disturbed zone, loosened soil should be pulled away from the side of the pit. This can be most readily observed by investigating the pit face which lies in the direction of subsoiler travel. This process allows the uniformity of soil breakout at depth to be determined as well as the degree of soil break-up within the loosened zone. If disturbance at depth is very irregular, either tine spacings are to great or the tines are working below their critical depth. Necessary adjustments can be made to tine spacings in the first situation, but if the latter, working depth needs to be reduced or a shallower loosening operation carried out before the final deep one, to ensure satisfactory loosening is achieved.

5.3 GUIDELINES FOR THE FREQUENCY OF LOOSENING OPERATIONS.

Figure 8 presents a guideline to determine the type and frequency of loosening operations that are likely to be necessary during the five year aftercare period on restored sites according to site and soil condition. Sites are classed according to broad soil textural category, land use (or loading risk), site wetness, soil shrink-swell capability and aggregate stability. The research has established that unloosened soils will not self-regenerate unless they comprise stable, shrink-swell soils under low-loaded, grassland conditions in relatively high soil moisture deficit areas. Regeneration rates even then would be very low. The loosening recommendations are designed to bring the soil to a minimum acceptable condition for rooting during the five year aftercare period, aiming to generate a sustainable improvement which might allow the farmer to return to “normal agricultural operations” in later years. All soils exhibiting low soil stability should be treated as “wet” soils in the guidelines, since more loosening operations will be required.

An initial deep loosening operation below 0.7m is recommended for all sites to establish fissures deep in the profile and to increase the immediate drainage capability. The maximum depth of loosening in restored soils often limits the total potential rooting that can be achieved in the profile in the aftercare period, with greater benefit achieved by maximising the loosening depth in the initial operation. On lighter sandy soils, regular and frequent shallow loosening operations are required after the initial deep loosening. These soils slump readily on wetting or loading and little further benefit is to be gained from deep reloosening. Shallow reloosening is required to maintain a minimum condition suitable for rooting. It is important to note that following the five year aftercare period, sandy sites with extremely unstable and heavily loaded soils did not generate a self-sustaining improvement in soil condition and regular reloosening would be required for the foreseeable future. On medium to heavier soils, the required frequency of reloosening following the initial deep operation is dependent upon the degree of subsequent site loading and wetness. On predominantly wet sites (regardless of loading condition), a second deep loosening (to within 0.15m of the underdrainage) is recommended in the second year of aftercare to reopen fissures and enhance the movement of water to the drains. On drier sites under heavy loading, a shallow loosening operation (0.45 to 0.7m deep) is encouraged in the second year of aftercare to reduce compaction. This operation may not be required in the second year on dry, low-loaded (grassland) sites but should be conducted as soon as possible if abnormally wet weather occurred following the first deep loosening.



NB: Extremely low soil stability is equivalent to the "wet" site class.
All operations subject to prevalence of dry conditions at expected time of subsoiling.

KEY:
D deep (>0.7m) loosening
S shallow (0.45-0.7m) loosening
* shallow loosen only following adverse wetness / loading conditions
Wet site is > 800mm p.a. rainfall
Coarse textures include sand, sandy loam, loamy sand and sandy silt loam
Medium and fine textures include silty and sandy clays to clay loams and clay.

Figure 8: Guidelines for determining required soil loosening treatments.

Further shallow loosening operations will be required in years 2 and 3 to 5 of aftercare to reduce compaction resulting from loading and to gently break up coarse structures into progressively smaller fragments. Sites under heavy loading or arable cultivation will require more regular reloosening operations than low-loaded, grassland sites since the longevity of loosening benefits is considerably reduced. Shallow loosening is necessary to encourage and maintain rooting to full profile depth, especially under cyclical arable rooting conditions. Grassland sites which receive high annual field loading should be classed as arable. Soils of medium texture will gain extra benefit from root development and increased water-holding capacity if shallow loosening operations are performed at successively greater depths (progressively loosened). The timing of the operations in years 3 to 5 will depend upon site management and the prevalence of suitable weather and ground conditions for loosening to take place. Loosening operations should be conducted, wherever possible, in the autumn following extremely wet or heavily loaded conditions and may be brought forward by a year to achieve this. If ground conditions are too hard or too wet then the subsoiling operation can also be delayed by a year.

The recommendations in Figure 8 represent good loosening regimes for different types of restored site, to return the soil to good condition in a reasonably short period of time. They must, however, only be considered a guide. A check on soil condition by excavating a pit in a representative area of the field and calibrating and using a penetrometer to identify compaction over a wider area would, however, ensure the optimum soil management and, in good conditions, may reduce the total number of loosening operations required.

Three key soil profile features should be observed and related to the penetration resistance readings. These are maximum rooting depth, depth to common rooting (defined in 3.4.2) and penetrable depth (corresponding to a large increase in penetration resistance above 3 to 4Mpa using a 30°, 12.5mm diameter cone, depending on soil type). The maximum depth of subsoiling will be determined by the maximum rooting depth required. If uniform rooting extends to or below the depth of underdrainage then deep loosening will not be necessary. The distribution and depth of rooting will however, dictate the requisite maximum depth of shallower operations. In non-expansive soils or under wet conditions where drying is limited or where the soil is extremely compact, it is necessary to create deep subsoil fissures by loosening since roots will not extend below loosening depth. The depth of rooting required (relative to available soil moisture conditions) will therefore dictate the required depth of loosening.

In expansive swelling soils where the soil can dry to reasonable moisture deficits, deeper loosening will not normally be required unless the roots are shallow, since roots can exploit and extend natural fissures present. A shallow loosening operation may be necessary, however, to alleviate surface compaction and boost rooting in the surface layers, encouraging roots to reach the deeper fissures. The soil penetrability and depth of common roots will determine the most appropriate subsoiling depth. This will lie at a depth of approximately 0.15m below the penetrable depth or depth of common rooting (i.e. where the number of roots falls below 4 in 0.1m^2 and roots become confined to fissures) up to a maximum limit of 0.15m above the drains. The penetrometer can be calibrated to identify and establish this boundary between well-rooted and poorly rooted soil to determine the required loosening depth over the entire field.

6. SUMMARY / IMPLICATIONS.

The project has been able to provide guidelines for determining:

- The maximum effective working depth of different subsoiler tines under different conditions
- Tine spacing requirements for uniform soil breakout at depth
- The likely required frequency of loosening operations in different situations

These aim to restore the soil to a “normal” condition during the five year aftercare period.

Winged tine subsoilers have been shown to offer many advantages over no-wing types for use on restored soils. Improved, more reliable techniques for checking the work of subsoilers and for assessing soil condition and rootability, have been developed to assist with subsoiler adjustments and in determining the need for further loosening operations, respectively. Whilst guidelines are helpful, for effective and efficient restoration every effort should be made to check the actual prevailing conditions in the field before final decisions are taken.

7. REFERENCES.

AVERY, B.W. & BASCOMBE, C.L. (1974) Soil Survey laboratory methods. Harpenden.

HODGSON, J.M. (1974) Soil Survey Field Handbook: Describing and Sampling Soil Profiles. Soil Survey of England and Wales, Technical Monograph No. 3: 99pp.

SOANE, B.D. & HENSHALL, J.K. (1979) Spatial resolution and calibration characteristics of two narrow probe gamma-ray transmission systems for the measurement of soil bulk density in situ. Journal of Soil Science, 30: 517-528.

SPOOR, G. & GODWIN, R.J. (1990) Soil loosening: requirements, implements and techniques. Report to the Home Grown Cereals Authority. Research Review No. 19: 52pp.

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