

Research and Development

Final Project Report

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Critical Levels of Soil Organic Matter

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Executive summary (maximum 2 sides A4)

It is widely known that amounts of a few per cent of soil organic matter (SOM) or soil organic carbon (SOC) confer desirable properties on many soils, e.g. better structure, better seed beds, improved water holding capacity, easier seed emergence, and so on. There has been increasing concern that increasingly intensive farming is causing the SOM contents of soils to fall to unacceptable levels. Again, there is a widespread belief that if SOM falls below a critical threshold, then there will be serious decline in crop yields, increased erosion, and general degradation of the soil resource sufficient to threaten the UK's ability to maintain acceptable levels of food production. There will also be environmental consequences of such degradation. The setting of such a critical threshold for all soils and land-use systems, or of different thresholds for different soils and land-use practices is a matter of much debate. A widely held view is that the lower limit for such a threshold should be 2 per cent organic carbon, which is equivalent, by convention, to c. 3.4 per cent organic matter.

This research has examined the evidence for such a threshold or thresholds. It set out to do this from a firm quantitative, i.e. numerical, standpoint. Anecdote was viewed as insufficient evidence. The requirement was for equations of state, properly replicated experiments with adequate statistical treatment, and evidence of wide applicability of the findings.

Approximately 1200 published papers and reports were examined initially - mostly in relation to temperate soils, in order to assess the opinions in the literature. This search revealed a surprisingly small number of published works which contained data and interpretations meeting the requirement for numerical robustness. There was limited evidence that a decline of c. 5 per cent might occur in cereal yields if SOC contents approached 1 per cent, and that this decline could not be corrected by the addition of greater amounts of inorganic N, P and K fertilisers. One or two papers suggested that soil structure - as measured by aggregate stability - would deteriorate to unacceptable levels if SOC approached 2 per cent. Such evidence as was found was often conflicting, e.g. some work showed marked change in soil properties above or below a particular threshold of SOM or SOC, whilst similar work from other groups failed to confirm such findings. There was almost no evidence from the literature that *thresholds* - if they existed - differed significantly between soil types, even though the amounts of SOC are known to differ between, for example, soil textural groups.

Investigation of data sets from England and Wales showed that SOC explained c. 10 per cent of the variation in the water holding capacity of topsoils, and that this contribution varied relatively little between soil types and land uses. SOC makes almost no contribution to the water holding capacity of subsoils.

In terms of soil structure - as expressed by dispersibility of soil aggregates - there is a marked decrease in stability of a wide range of soils under arable cultivation below c. 1.5 per cent SOC.

Soil organic carbon makes relatively little contribution to the plastic behaviour of agricultural soils in England and Wales, i.e. how readily they deform, and none at all to soil liquid limit, i.e. the point above which soils lose all mechanical strength.

SOM can be a considerable source of plant nutrients, especially nitrogen (N). Work on sandy, clayey and Chalk soils indicated a linear relationship between potentially soil mineralisable N (PMN) and SOC, but with no marked cut-offs. Sandy soils tend to contain less SOC so, as would be expected, they yield less PMN; usually $<100\text{kg N ha}^{-1}\text{ yr}^{-1}$. Chalk soils occupy an intermediate position, releasing roughly $100 - 150\text{ kg N ha}^{-1}\text{ yr}^{-1}$, whilst clayey soils can release almost $400\text{ kg N ha}^{-1}\text{ yr}^{-1}$ - although $150 - 250$ is more usual.

Mathematical modelling of SOC behaviour used the ROTH-C model from IACR-Rothamsted, and the CENTURY model, from N. America. Although both gave comparable results on sets of test data, CENTURY over-estimated SOC contents to a greater extent than ROTH-C. Further, ROTH-C was found easier to use with SSLRC data, and as help with the model was readily available in the UK, further modelling was confined to ROTH-C. The modelling showed that soils with <18 per cent clay, and Chalk soils, tended to an equilibrium SOC concentration of c. 1.3 per cent over periods of 100 years or more of continuous arable production. Soils with >18 per cent clay tended to an equilibrium value of c. 2.3 per cent SOC. These equilibrium values were independent of varying N inputs. Application of the medium-high climate change scenario (UK Climate Impacts Programme) as the climate input to ROTH-C caused these equilibrium SOC contents to decline further by c. 0.5 per cent.

It should be realised, however, that the modelling and the assessment of the output from it depends on the interpretation of changes in SOC that are small. There are many uncertainties in this, so the interpretations should be treated with due caution. It should also be noted that the modelling assumed only one kind of land use over these long periods of time. This is unlikely in practice, so the results of the modelling could be regarded as 'worst-case' scenarios.

The lack of clear thresholds for SOC/SOM in relation to soil properties, either from the literature, or from this work, made the derivation and application of SOC-related risk assessments difficult. However, by comparing the modelled data with the National Soil Inventory data, it can be seen that significant areas of Eastern England could suffer falls in SOC under long-term arable cultivation. The loss of SOC is unlikely to be made good by current returns of SOC from crop residues from arable agriculture. It seems, however, that the heavier soils, even though many of them have quite small SOC contents - 2 to 3 per cent is common, will remain at about these values provided that current crop residue returns do not decline. Clearly, however, the effect of climate change could alter both these positions.

Few data exist for crop returns under long-term managed grass. Modelling with these data indicated that SOC contents of permanent grass soils will increase in all soils in the long-term. This conflicts with the findings of the recent re-sampling of NSI sites, which showed that SOC contents in permanent grass soils were declining slightly after only c. 15 years. However, we found that the 'balance-point' between SOC increase or decline was very close to the currently assumed values of SOC inputs under grass (c. $2.8\text{ t C ha}^{-1}\text{ yr}^{-1}$ for the latter, compared to c. $2.6\text{ t C ha}^{-1}\text{ yr}^{-1}$ for the former). It remains a question, therefore, how representative the current permanent grass data are for large areas of the country. If this aspect is to be investigated further, then clearly a wider range of SOC input values under grass is required.

There are many papers in the literature which give better relationships between soil properties and 'active SOM', i.e. the relatively short-lived components of manures, crop residues, slurries and so on. We were unable to assess the importance of these 'active carbon' yr^{-1} in the soils of England and Wales because there are almost no data. This is clearly also an area for further research.

In conclusion, we found little clear evidence for critical thresholds of SOC in the soils of England and Wales. If such a value or values can be demonstrated, it - or they - might lie closer to 1 per cent SOC than the widely-proposed figure of 2 per cent. It might be that 2 per cent or more of SOC is seen as desirable from a precautionary point of view, but the *quantitative* evidence to support this is weak.

Scientific report (maximum 20 sides A4)

Note: all the Figures and Tables for this Report are in Annex 2.

1. Introduction

There is a widespread perception that the amount of organic matter¹ (SOM) or organic carbon (SOC) in soils needs to be kept above a minimum level in order to prevent, or at least minimise, irreversible decline in a range of soil properties. Soil structure, ease of cultivation, improved water retention, better seed-bed establishment, reduced erosion risk, more effective use of nutrients (especially N and P) have all been commented on (see, e.g., Carter and Stewart, 1996), although it is known that, in certain soils, other factors such as the 'free' iron content and exchangeable sodium content may have a marked effect on aspects of soil structural behaviour. Greenland *et al.* (1975) proposed a 'rule of thumb' that soils in England and Wales should be regarded as structurally unstable if the SOC content fell below 2%; conventionally this equals c. 3.4% SOM. This value seems to have become a reference point or benchmark in the soil science community. The UK Royal Commission on Environmental Pollution, in its Report on 'Sustainable Use of Soil' (RCEP, 1996), commented on the undesirability of allowing SOM to decline too far, although avoiding specific recommendation of limiting values. This report thus raised some fundamental questions in relation to SOM in the soils of England and Wales and the long-term sustainable use of UK soils for agricultural production, against a background of the need to manage soils in an environmentally sensitive manner. We sought to address three of these questions, *viz.* what is the *quantitative* evidence for critical levels of SOM in relation to specific soil properties; if such critical levels can be substantiated, how do they differ between soil types and management practices; what is the magnitude of any decline in soil properties if these critical levels are not maintained. It is against this background that project has been carried out.

2. The Project Objectives

These were:

1. To make a critical review of the literature on relationships between SOM, soil physical properties and crop production, including pedotransfer functions;
2. To identify those soil properties demonstrably related to soil structural stability and which are quantitatively related to SOM content;
3. To compile soil datasets for England and Wales which reflect the findings of (1) and (2).
4. To evaluate numerical relationships within these datasets, in the light of (1) and (2), and estimate the mathematical robustness of any relationships found.
5. To group soils in terms of SOM and textural class, and identify sites from which samples can be taken for the determination of aggregate stability and Lower Plastic Limit (LPL).
6. To determine aggregate stability and LPL for these samples, and analyse relationships with SOM and other soil properties.
7. To assess SOM mineralisation potential in relation to soil textural group and SOM content.
8. To identify relationships between SOM, mineralisation potential, and land use and cropping history for England and Wales.
9. To estimate returns of crop residues to soils under different land use and management practices.
10. To test the ability of current organic carbon turnover models to predict current SOM contents for sites for which historical data have been assembled.
11. To extend the use of organic carbon models from (10) to a range of soil types and cropping regimes.
12. To extend the work in (11) forward in time using current climate and accepted climate change scenarios.
13. To establish a risk matrix based on soil/cropping combinations under current and future climate.
14. To use this matrix to create maps of soil risk for England and Wales.

1. Critical Review of the literature on relationships between SOM, soil physical properties and crop production, including pedotransfer functions

¹ **NOTE:** There is great variation in the literature in the use of the terms soil organic matter (SOM) and soil organic carbon (SOC). The latter is most commonly measured, and SOM is derived conventionally as [SOC x 1.724], although many other factors exist (Howard & Howard, 1990). Many papers, especially in the earlier literature, use SOM and SOC interchangeably. We have endeavoured to use the most consistent terminology within the constraints of the information available. Thus, where we use SOM, we are quoting what we believe to be reliable figures which are [SOC x 1.724]. Where SOC is definitely given, we have not converted it to SOM, nor have we converted SOM to SOC.

Much of the literature surrounding the evidence for changes in soil properties with change in SOM content is based on observation and practice. However, we were interested in numerical (quantitative) relationships between variables, e.g. regression equations, equations of state, graphical relationships etc., supported by adequate statistical treatment. Our target was to identify threshold values for changes in SOC or SOM at which there was a demonstrable change in soil behaviour. Thus, we deliberately set out to avoid the anecdotal, qualitative or empirical literature. The search was initiated on the CABI database from 1984 to 1997 (when the search was carried out). The most productive keyword syntax was '*soil organic (and matter or carbon) and (structure or stability or nutr*)*', where, * was a wildcard which would encompass nutrient or nutrition. This identified c. 400 papers, the contents of which lead us on further searches until some 1200 or so papers had been scanned.

In general, the results of the search were surprising. Only c. 5% of the papers contained information which met our quantitative criteria, although almost all were very strong on assertion that SOM did improve a large number of soil properties, especially aggregate stability, although water retention, nutrient supply, and workability were also mentioned. The results of the review are summarised below, and the full document is attached as Annex 1.

a) **Crop nutrition:**

The role of SOC may be estimated either from comparison of soils of the same type, but of different SOC status, or from long-term studies in which crop yields are related to changes in SOC over time. Unambiguous identification of SOC effects is difficult due to confounding of changes in SOC with changes in other factors, although comparisons of soils of differing degrees of degradation are usually less equivocal. Studies of eroded soils, which provide a range of topsoil depths and hence SOC concentrations at adjacent locations, usually found that yields could be maintained if adequate fertilizers were added, although in some cases yields were reduced due to poor emergence due to the exposure of heavy clay subsoils. Results from long-term experiments usually indicate that yields are maintained, or increase over time despite continued reductions in SOM. For example, the Woburn experiment (sandy loam soil) was established in 1937, on a site that had been in an arable rotation since 1876 and had only 1% SOC. Despite a continued decrease in SOC over the next 30 years *there was no catastrophic reduction in yields*. In fact, provided fertilizer applications, particularly N, were appropriate, and the build-up of soil pathogens was avoided, yields tended to increase. In contrast, at IACR-Rothamsted, the SOC content of the unmanured plot in the Hoosfield continuous barley experiment has remained unchanged at c. 1.2% for 100 years. Similarly, the unmanured plot at Broadbalk also showed no decrease in SOC. Some of the other plots have been kept free of plants since 1870, and SOC has decreased further. This suggests that, in the cropped fields, SOC is maintained by crop-C inputs. The addition of straw for 6 years to the sandy soil at Woburn increased SOC from 0.7 to 0.9%. In a long-term experiment (begun 1925) in Australia, there was an overall decrease in SOC from 2.75 to 1.56%. This decrease in SOC was associated with consistent increases of arable crop yields over a range of fertilizer-N applications, the decrease being greater in rotations with a greater proportion of fallow. Yields have tended to decrease with time. Overall, the second largest yields (2.21 t/ha) were produced by a Wheat-Pasture-Fallow rotation, which experienced one of the greatest reductions in topsoil SOC (60%), suggesting a large release of nutrients (especially N) from the SOC pool, the only fertilizer input being P. Thus, in an unfertilized soil, *in which breakdown of SOC is necessary to maintain yields*, there may be a critical SOC. However, since the 1960s there has been a gradual *increase* in yields on the continuous wheat plot, which the authors attribute to a gradual build-up of light-fraction SOC, resulting from the greater C/N ratio of cereal residues. This light fraction is the more important in respect of aggregate formation and as a source of nutrients. Thus, from this study, and those at Rothamsted, there is evidence that, for cereal rotations at least, reductions in SOC can be arrested as returns from crop residues become equal to the annual breakdown of SOC.

There is a growing body of evidence that the 'active' fraction of SOM is more important to soil properties than total SOM. This 'active' fraction consists mainly of recent additions of crop residues and organic manures. There is evidence that the majority of crop-available N comes from the 'active' fraction and hence N mineralisation is better related to this fraction than to total SOC or total N. Studies indicating the dependence of crop nutrition on nutrients from SOM were on largely unfertilized soils. The addition of N and/or P fertilizer usually produced yields similar to those on the greater SOM (undegraded) soils. In summary, there may be some suggestion that cereal yields may be reduced by up to c. 5% where SOC declines to c. 1%, and work at IACR-Rothamsted supports this view (Goulding, *pers. comm.*). However, insufficient work has been done to show whether this conclusion is robust, or how any apparent decrease in yield might be affected by changes management, choice of cultivar and other factors.

b) Aggregate stability:

- i) there is very considerable variation in the definition of what is meant by a soil aggregate in terms of size, although scales based on multiples of 0.25 mm are becoming increasingly widely used;
- ii) methods of measuring aggregate stability are equally diverse, and there is little evidence of standardisation or inter-laboratory comparisons of methods;
- iii) aggregate behaviour is very strongly influenced by pre-treatment, e.g. air-drying, wetting history (Haynes, 1993) or whether the measurements are made on field moist or air-dry soil (Haynes & Swift, 1990);
- iv) most numerical relationships between SOC or SOM and aggregate stability are linear (e.g. Stengel *et al.*, 1984), with only a few described by a power function (Kemper & Koch, 1966);
- v) a few studies have shown that small amounts of organically-bound iron (Douglas & Goss, 1982) can have an important effect on the stability of aggregates in non-calcareous soils, but this property is not measured in most studies;
- vi) exchangeable sodium content affects aggregate stability, but this factor is restricted to a small number of coastal soils in the UK (Hazelden *et al.*, 1986);
- vii) whilst most authors are agreed that minimum tillage (Douglas & Goss, 1982) and/or the introduction of green manures, grass breaks into rotations and similar land management practices increase aggregate stability in a wide range of soils, the literature shows that the improvements are difficult to quantify;
- viii) there is a considerable, although by no means unequivocal, body of research which shows better numerical relationships between the amounts of 'fresh' SOM (crop residues, green manures, FYM etc.) - and the associated biological factors, such as fungal and microbial activity - and aggregate stability, than with total SOM or SOC. The active components are believed to be mostly water-soluble polysaccharides, which have a relatively short (<9 months) residence time in the soil. Most studies, however, still only collect data for total SOM or SOC;
- ix) it is possible that many studies of the relationship between aggregate stability (and possible other soil properties) and SOM or SOC content are flawed because too great a depth of soil is examined, rather than the upper few centimetres where most of the benefits of SOM are concentrated (Unger, 1995). A similar point can be deduced from the Final Project Report of NT1014 (A systematic approach to national budgets of phosphorus loss through soil erosion and surface runoff at National Soil Inventory nodes; Fraser, *pers. comm.*).

c) Bulk Density (Db) and Shrinkage

- i) Williams (1971), Hamblin (1977) and Hamblin & Davies (1977) found that Db was relatively unaffected by change in SOC content once this had fallen below c. 2%. Shiel & Rimmer (1984), however, found no threshold in the relationship between SOC and Db at Cockle Park (Northumbria);
- ii) Unusually, Carter (1987) found a power function best described the relationship between Db and SOC irrespective of land use history, but again found that the relationships fitted a smooth curve with little sign of a critical threshold. Ekwue (1990) and Cannell *et al.* (1994) found linear relationships between Db and SOM irrespective of land use; neither study indicated a critical threshold.
- iii) Hamblin (1977) and Hamblin & Davies (1977) found that linear shrinkage was c. 5% less at pF2 (-10kPa tension) to <1% less at pF4.2 (-1500kPa tension) in soils with <2% SOC, than in soils with >2% SOC.

d) Porosity and water retention properties

- i) soils with <2% SOC had total porosities <1% lower at pF1 (-1kPa tension) to almost 10% lower at pF4.2 than soils with >2% SOC, possibly because the soils with >2% SOC had greater amounts of humified SOM in the 2-50 micrometre fractions than the low organic soils (Hamblin, 1977; Hamblin & Davies, 1977);
- ii) SOC generally explains only between c. 11% and 4% of the variance in the volumetric water content in the soils of England and Wales, the greatest influence being at smaller suctions (Thomasson & Carter, 1992; see also Pedotransfer Functions, below).

e) Other soil physical properties

- i) There has been a number of single studies investigating such diverse soil properties a cohesion (Kemper *et al.*, 1987), shear strength (Ekwue, 1990), the angle of friction (Bachmann & Zhang, 1991) and percolation and/or permeability properties (Greenland *et al.*, 1962). Although SOC or SOM were identified as factors controlling these properties, clay content was usually more important, and the studies are too few in number to draw general conclusions.
- ii) Evans (1988) made a comprehensive investigation of water-borne soil erosion under a range of land-uses and soil types in southern England, but made no link between SOC and soil loss volumes, rill and gully formation or the area affected by erosion. Project NT1014 (above) considered the factors affecting soil surface particulate transport, but again showed no link with SOC. The European Soil Erosion Model (EUROSEM) does not include SOC or SOM as a factor (Morgan *et al.*, 1998). In contrast, Benito & Diaz-Ferros (1992) did investigate the relationship between SOC and soil loss under different land uses in Spain, finding that whilst there was a reasonable relationship under pasture (soil loss in g/m²/month = -2.438logSOC% + 6.973; R² = 0.602), that under cereals was so weak as to be meaningless (soil loss in g/m²/month = -0.0279SOC% + 7.554; R² = 0.038). The figures for the pasture experiment showed a distinct rise in soil loss below c. 1.5% SOC, a threshold mirrored by work in Australia (Malinda, 1995). However, erosion conditions in southern Spain and Australia are difficult to interpret in terms of a UK climate, so these results need to be applied with caution.

f) Pedotransfer Functions (ptf)

These are mathematical relationships which allow prediction of an unmeasured soil property from one or more other measured soil properties, with a known degree of confidence, e.g. the prediction of bulk density from a knowledge of SOC and particle size distribution. The commonest forms of ptf are those used to derive soil hydrological properties, such as hydraulic conductivity or the soil water retention curve, which are difficult or time-consuming to measure. Wösten *et al.* (1998) used such an approach in relation to the map units of the 1:1 000 000 Soil Map of Europe. Simota & Mayr (1996) used data from England & Wales to parameterise the Arya-Paris model of the soil water retention curve (Arya & Paris, 1981) through calculation of the Mualem-van Genuchten parameters α (a parameter related to the pressure head of the point being fitted in the water retention curve) and n (a parameter which describes the rate of change in the slope of the water retention curve). Generally speaking, the most useful ptf are those known as continuous functions, of the form:

$$\Theta = a + b*\text{clay} + c*\text{SOM} + d*\text{dry Db} + \dots x*\text{variable}$$

where, Θ is a hydraulic function such as the soil volumetric water content (VWC) at a given tension, a , b , c , d and x are constants, and Db is dry bulk density. The resulting expressions can be complex, as the example from Wösten *et al.* (1998) shows:

$$\Theta_s = 0.7919 + 0.001691*C - 0.29619*Db - 0.000001491*S^2 + 0.0000821*\text{SOM}^2 + 0.02427*C^{-1} + 0.01113*S^{-1} + 0.01472*\ln(S) - 0.0000733*\text{SOM}*C - 0.000619*Db*C - 0.001183*Db*\text{SOM} - 0.0001664*\text{topsoil}*S \quad (R^2 = 76\%)$$

where, Θ_s is VWC at saturation, C is the clay content, Db is the soil dry bulk density, S is the *silt* content, *topsoil* is a qualitative variable with a value of 1, and \ln is the natural logarithm. The derivation of such equations is utterly dependent of the possession of a large database from which to derive the functions, and Wösten *et al.* (1998) discuss the problems of this in detail. Simota & Mayr (1996) make the point that generalised functions of this type, whilst they can be useful, inevitably degrade the ptf by 'lumping' the particle size classes together. They show that considerably better fits to moisture retention curves can be obtained if the ptf are derived for particle size groupings, especially for sandier soils. Both sets of authors fail to give an analysis of their ptf which would indicate the magnitude of the contribution from SOC or SOM, although it is known to be generally small in mineral soils (Mayr, *pers. comm.*). Thomasson & Carter (1992) derived multiple regression equations for VWC at different tensions in relation to particle size fractions, Db and SOC for soils in England & Wales. They found that SOC explained about 11% of the variance in VWC at -5kPa tension to <4% of the variance in VWC at -1500kPa in topsoils, but in subsoils SOC explained <2% of the variance at -5kPa and made no contribution to it at -1500kPa tension. Subsequent work has shown that the inclusion of Db in the

regression equations of Thomasson & Carter (1992) is mathematically unsound, as it is not an independent variable. Thus this work has been re-examined using a larger dataset, and is reported below.

g) Summary of the Literature Review

Only a small number of papers contained the kind of numerical data and relationships we were seeking. Whilst some of these suggested thresholds in soil behaviour at around 1 to 2% SOC, an equal number did not. Part of the problem may relate to the very great diversity in methods of investigation, especially of soil physical properties. Another part of the problem may be that too great a depth of soil is being investigated in relation to the distribution of SOC or SOM. Other papers suggest that it is the 'fresh' or 'active' fractions of SOM that are more important than total SOC. There is little information about the spatial distribution, proportions or chemical forms of such active fractions in UK soils, beyond making simplistic assumptions that there is likely to be more 'active' SOC under grass than under arable cultivation.

2. To identify those soil properties demonstrably related to soil structural stability and which are quantitatively related to SOM content.

The literature review did not clearly identify quantitative relationships between SOC or SOM and soil structural properties, either in general terms, or in relation to specific soil types or critical levels of SOM. It did, however, suggest that it was worth investigating further the relationships between SOC and aggregate stability, rheological properties, and soil water retention.

3. To compile soil datasets for England and Wales which reflect the findings of (1) and (2).

Data sets were derived from ADAS experimental sites and the SSLRC soil information system - LandIS.

4. To evaluate numerical relationships within these datasets, in the light of (1) and (2), and estimate the mathematical robustness of any relationships found.

5. To group soils in terms of SOM and textural class, and identify sites from which samples can be taken for the determination of aggregate stability and Lower Plastic Limit (LPL).

6. To determine aggregate stability and LPL for these samples, and analyse relationships with SOM and other soil properties.

The soil data and the relationships covered by these three objectives are intimately linked, and are described below in an integrated manner.

a) **General Relationships:** We undertook a general review of the soil property data held within LandIS. One of the more striking observations to emerge was that between soil clay content and SOC (Fig. 1) [all Figures are given in Annex 2]. The relationship is very similar whether one looks at soil profile or National Soil Inventory (NSI) data (the former are shown for clarity, as the NSI dataset contains over 5600 points, which tend to obscure each other). It is uncertain whether the lower boundary to the scatter of data represents an absolute limit to soil SOC content, controlled by the protection of a proportion of the SOC by the soil clay, or whether it represents an equilibrium condition which reflects land-use within England & Wales over the last few decades. A crude test was made by comparing the SOC value for the Broadbalk exhaustion plots at IACR-Rothamsted (SOC c. 1%) with that predicted from the slope in Fig 1., using the measured clay contents of representative A horizons of Broadbalk soils of 24.6% and 26.6% (Avery & Bullock, 1969). The calculation gives SOC contents of 1.01% and 1.09%, respectively, for these clay contents. These values are intriguingly close to the measured value, although they cannot be regarded as proof that the relationship is in anyway permanent or universal. This relationship is considered further under 'Modelling'. Although there is some general clustering of the data according to land use, there is clearly considerable overlap between the classes, and thus land use is not particularly well separated by SOC.

b) **Aggregate stability:** All methods of measuring the stability of aggregates rely to a greater or lesser degree on their behaviour in water, e.g. the amount of water-dispersible clay, the reduction in size of the aggregates when immersed in water, the strength of the aggregate at some given water content and so on. Methods exist which involve measurements of static systems, involve stirring or shaking, with or without an electrolyte in the system, use comparisons between wet and dry aggregates and many, many more. In order to make comparisons with previous work in the UK (as in MAFF Project OC9403: The impact of

farming practice on the sustainable use of soil), we continued with the use of the Dispersion Ratio (DR) method (MAFF, 1982). Preliminary work on a small number of samples had indicated a poor relationship between SOC and DR, but we widened the analysis until we had 365 sets of data covering a wider range of SOC. All the samples were taken from arable sites, as these are at greatest risk of surface structural breakdown, and most are at the finer end of the particle size spectrum (clayey, fine silty, fine loamy). The results are shown in Fig. 2. Above c. 1.5 % SOC, only c. 7% of the samples have DR >20%, but below c. 1.5% SOC, the latter has little or no effect on DR. The interpretation of DR has always been uncertain as the method was originally designed to investigate stability in clayey soils and its extension outside this particle size class has never been thoroughly investigated. Hazelden *et al.* (1986) proposed that soils with DR<15 are slightly unstable, those with DR 15-30 are moderately unstable, and those with DR>30 are very to very/extremely unstable. On this basis, most soils with SOC <1.5% are moderately to extremely unstable.

- c) **Soil Rheology:** The response of soils to an applied stress e.g. during cultivation, the passage of machinery, animal movements, or during restoration, is generally known as deformation. It is a function of the load itself, the rate at which it is applied, and the properties of the soil, especially of particle size distribution and water content. The latter is often expressed through the concept of the Upper Liquid Limit (LL) - the water content above which the soil behaves effectively as a liquid, and the Lower Plastic Limit (PL), the water content below which the soil ceases to deform in a plastic manner. Although civil engineers have long made the distinction between organic soils, i.e. peats, and other soils in terms of these rheological properties (e.g. BSI, 1999), there have been few quantitative investigations of the contribution of SOC to LL and PL in agricultural soils since the work of Soane *et al.* (1972). They found good correlations ($r = 0.569$ for SOC vs LL; $r = 0.708$ for SOC vs PL; $p < 0.001$ for both) for 59 agricultural soils from Scotland, but showed no graphical relationships which might indicate threshold values in their data. In view of the findings for DR (above), we were particularly interested in the SOC range around 1% SOC to 2% SOC. Table 1 gives the linear correlation coefficients between silt, clay and SOC contents and LL and PL for 184 samples [all Tables are given in Annex 2]. The findings are not so different from those of Soane *et al.* (1972). The relationship with SOC is poor for Liquid Limit ($r = 0.269$), but stronger for Plastic Limit ($r = 0.683$). It can be seen from Fig. 3 that there is no threshold similar to that seen in Fig. 2. There is more clustering where values of SOC and PL are small, but there is no evidence of *marked* change in the relationship in this part of the graph, the number of points being roughly equal above and below the fitted curve where SOC <1.5%.
- d) **Soil Water Retention Properties:** We re-investigated the findings of Thomasson & Carter (1992) (above), using a larger dataset than was available in the late-1980s, when they did their work. Initially, we included Db in the analysis. However, it became clear that Db is strongly correlated with clay and SOC contents, so it was omitted from the final analysis. We also normalised the parameters, as we know that clay contents, sand contents and SOC contents of soils are not normally distributed. The resulting regression equations are given in Table 2. The improvement in the variance explained, compared with that of Thomasson & Carter (1992) - using the larger dataset, omitting Db from the regressions, and using transformed data - was about 3% to 5%. Table 3 shows the cumulative variance explained *for topsoils only* using the revised approach. Clay content is clearly the dominant factor. It can be seen that SOC generally explains between c. 20% and 3% of the variance, the contribution declining as the tension increases. SOC makes an increasingly small contribution to the regressions as the soil water tension increases from -5kPa to -1500kPa, making no detectable contribution at tensions ≥ -200 kPa under permanent grass or 'Other Land Uses' - this being mostly woodland. This contrasts greatly to the contribution of almost 27% at *low* tensions for the 'Other land use' class. This undoubtedly reflects the higher topsoil SOC contents of the woodland soils in this class. Given the importance of soil clay content to VWC, we stratified the topsoil data by clay content and land use (Table 4). Again, clay content tends to be an important factor, but by no means universally so. We have not shown the data for subsoils as SOC explained <2% of the variance at any tension and for any stratification.

7. To assess SOM mineralisation potential in relation to soil textural group and SOM content.

8. To identify relationships between SOM, mineralisation potential, and land use and cropping history for England and Wales.

The amount of nitrogen mineralized from soil organic matter (SOM) is an indicator of the inherent fertility of a soils and hence of its sustainability. A range of methods are used to estimate the rate of, or potential for, N mineralization. Laboratory methods measure the rate of mineralization of SOM under standard conditions, to elucidate the process. However, results obtained often bear little relation to measurements of crop uptake from SOM made in the field. Two methods commonly used to estimate mineralization potential are: potentially mineralizable N (PMN) under anaerobic conditions; readily mineralizable N (RMN) extracted by a hot solution of potassium chloride (KCl). The estimates obtained by the two methods differ by a factor of $c 2$ since they do not measure the same material. In this study, topsoils (0-15cm) from 60 arable fields across England were collected in late January 1998 (prior to N fertilizer application) and analyzed (fresh) for potentially mineralizable N (PMN) by anaerobic incubation, SMN (given as part of the PMN analysis), total N and SOC. Soils were largely taken from fields growing cereal crops, with a few samples taken from fields growing sugarbeet, oilseed rape, peas, beans or setaside: 27 of the samples had a sandy texture (<18% clay); 23 had a clay texture (>18% clay) and 10 were from shallow soils over Chalk. The relationship is shown in Fig. 4.

The total SOC of the topsoils ranged from 0.71% to 7.0% (1.2-12.1% SOM) and total nitrogen from 0.07% to 0.83%. The greatest contents were found in the Durrington soil series, a shallow silty clay loam over Chalk. The potentially mineralizable N content of the topsoils was highly related to the organic C contents (Fig. 4). The Durrington soil series exerted a strong influence on these relationships. However, when removed, the relationships were still highly significant with non-significant intercepts and mineralizable-N equivalent (in kg ha^{-1}) to $c. 53$ times the organic C content ($R^2 = 0.60$; $P < 0.001$) and 505 times the total N content, expressed as percentage of soil mass ($R^2 = 0.67$; $P < 0.001$) of the topsoil. The greatest organic C and hence mineralizable N contents were observed on the clay soils, possibly resulting from physical protection of organic matter within soil aggregates. However, the best relationship between organic C and mineralizable N was observed in the shallow soils over chalk, possibly due to the range of organic matter contents present. Shepherd (1998) estimated N mineralization as the N balance between spring and harvest soil N supply (SNS) from 56 sites. There was no correlation between SNS and total SOM, even though the soil N concentration was well correlated with SOC ($R^2 = 88\%$). Further examination of each soil type/previous crop subset produced only one significant relationship between net N mineralization and SOM. From the measurements of PMN made over a wide range of British arable soils some trends emerge:

- Clayey soils tend to maintain more SOM, and thereby greater potentially mineralizable nitrogen concentrations, when compared with sandy soils.
- Clayey soils tend to have more potentially mineralizable nitrogen at any given SOM concentration, than sandy soils. (not tested statistically)
- Shallow silt soils over chalk maintain the same SOM and PMN levels as clayey soils.

We can only speculate as to the reason for the above conclusions, but it is likely that clays maintain more SOM because of the greater specific surface area available for retention and physical protection in micro-aggregates. The physical protection argument runs into difficulty, however, with the second observation, as protection from microbial invasion and degradation would militate against there being a larger readily mineralizable component. This effect may be a feature of less leaching of soluble organic components compared with sandy soils, which are also likely to be part of the potentially available pool. It is presumed that the retention of SOM in the shallow soils is a feature of the chalk rather than the silt, and maybe the effects of calcium divalent-ion bridging increase the relative retention capacity of silt. In none of the datasets is there any suggestion that there is a "critical point" for mineralization processes or potential nitrogen supply. Only a fairly narrow range of SOM contents (1.5 - 6.5 %) was sampled, though this is typical of most arable and grassland soils in lowland Britain. However, there may conceivably be a critical point within any one soil type below which the mineralizing potential alters dramatically, but that the soils sampled were all above this point and mineralized N from their component pools *pro-rata*. Using the model of Matus and Rodriguez (1994), it is estimated that it would take 81 years in a continuous wheat rotation for the organic N pool in the soil to stabilise (Table 8). Assuming that the yield of straw and chaff is equal to the yield of grain and that the %N of straw and chaff is 0.39% of that in grain then using the Sundial model (Bradbury *et al.*, 1993) the amount of mineralisation following addition of straw and chaff residues from a continuous wheat rotation can be calculated (Table 9).

9. To estimate returns of crop residues to soils under different land use and management practices.

The object of this part of the Project was to estimate the impact of changes in fertilizer-N use on the equilibrium SOC in arable soils. Reductions in fertilizer-N applications from current practice, whether a consequence of Policies to reduce N pollution or because of decreasing commodity prices, are likely to lead to reductions in crop yields and also reductions in the amounts of crop residues returned to the soil. Reductions in additions of organic matter to soil would be expected to effect the equilibrium SOC. Changes in SOC may be expressed as:

$$\Delta\text{SOC} = \text{Annual mineralization of SOC} - \text{stabilised residue from annual addition of OM}$$

In arable soils annual ΔSOC will usually be negative since most of the fresh OM is mineralized within the season of application and the stabilised addition will be less than the mineralization of SOC. The decrease in SOC is exponential and may be expressed as:

$$C_e = C - (C_0 - C_e)e^{-rt}$$

where, C_e = equilibrium SOC; C = current SOC; C_0 = initial SOC, r = decomposition constant, and t = time. Thus as the decrease in SOC becomes smaller over time providing crop yields are maintained the stabilised additions of C from crop residues etc will eventually balance the annual loss of SOC and a stable equilibrium will be reached. In arable rotations the majority of OM returns are as crop residues and hence may be estimated from fertilizer-N additions. To estimate the effects of changing fertilizer-N use an equilibrium SOC an all-cereal rotation was assumed. Data on the effect of fertilizer-N use on crop residue returns was taken from the ADAS NITRIC database which contains cereal N response data from 261 sites. Residue return was calculated from:

- 1) Yield response parameters
- 2) %N response parameters
- 3) Yield calculated for specified fertilizer-N rates.
- 4) %N in grain calculated from 3 and 4
- 5) Grain N offtake calculated from 5 and assumed harvest indices of 0.73 for sandy soils and 0.80 for other soil types.

These estimates of N returns were converted to C using a C:N ratio of 44. The effects of fertilizer-N reductions were estimated by calculating residue-C returns at current fertilizer-N application rates from the survey of Fertilizer Practice (SFP) and SFP-50 and SFP-100 kg N ha⁻¹. Separate estimates of crop C returns were made for the main soil groups clay, silt, sand, shallow over chalk and other mineral soils. At current and reduced fertilizer-N applications, crop C returns were significantly ($p < 0.05$) greater for clay and silt soils than for the other soil groups.

10. To test the ability of current organic carbon turnover models to predict current SOM contents for sites for which historical data have been assembled.

11. To extend the use of organic carbon models from (10) to a range of soil types and cropping regimes.

12. To extend the work in (11) forward in time using current climate and accepted climate change scenarios.

These three milestones are intimately linked, so we have considered them together.

a) **Choice of Model:** The two models widely available in the UK are CENTURY (Parton, 1996) and RothC (Smith, *et al.*, 1996).

i) **CENTURY:** This simulation model was developed in the Great Plains area of N. America. It analyses interactions between existing SOM, fertiliser and SOM additions and crop productivity as they affect changes in SOM, nitrogen, phosphorus and sulphur pools in soil, under various land uses. The grassland, crop and forest system models have different plant production sub-models linked to a common SOM sub-model, with the ability to specify temperature-driven production curves representing the site-specific plant community. The model was validated in the United States by simulating steady-state soil C and N levels and above-ground plant-production for 24 sites in the Great Plains, and comparing the simulated values with mapped plant-production and soil C and N levels for fine, medium and sandy textured soils at these sites. Five organic matter

pools are defined in the model, two representing litter and three representing SOM, which in turn is partitioned into three fractions:

- an active fraction consisting of microbial biomass and metabolites and having the most rapid turnover rate of 1.5 years;
- a slow (intermediate or protected) fraction, representing stabilised decomposition products with an intermediate turnover rate of 25 years;
- a passive fraction, representing highly stabilised, recalcitrant SOM with a turnover of 1000 years.

The CENTURYM program is a FORTRAN representation of the CENTURY SOM model (Parton, *et al.*, 1992; Metherell *et al.*, 1993). The program runs using a one, six or twelve month time step and the essential input variables are:

- monthly maximum and minimum air temperature,
- monthly precipitation,
- soil pH, texture (per cent sand, silt and clay), bulk density and water holding capacity,
- initial SOM, and organic N, P and S contents.

These parameters, together with other 'desirable' data are available for many natural and agricultural ecosystems, or can be estimated from existing literature.

ii) ROTHC: is a model of the turnover of SOC in non-waterlogged soils that allows for the effects of soil type (*via* clay content), temperature, soil moisture content (derived from meteorological data) and plant cover on the turnover process. It was written by IACR-Rothamsted and uses a monthly timestep to calculate total SOC (t C ha⁻¹), microbial biomass carbon (t C ha⁻¹) and $\Delta^{14}\text{C}$ (change in the radio-active carbon content) on a years-to-centuries timescale. The data required to run the model are:

- average monthly rainfall (mm),
- average monthly air temperature (°C),
- average monthly open pan evaporation (mm),
- soil clay content (as %), the depth of the soil layer modelled (cm),
- an estimate of the decomposability of the incoming plant material,
- soil cover for each month (between 0 and 1),
- monthly input of plant residues (t C ha⁻¹),
- monthly input of farmyard manure (t C ha⁻¹),
- the SOC content (t C ha⁻¹) at the start of the model run, divided into decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO), humified organic matter (HUM) and inert organic matter (IOM).

iii) Model Comparison: It is clear that many of the inputs are essentially similar in both models. Many of these variables are supplied as default values, or they can be changed by the user. Preliminary work on some Fen Silt soils (Bradley, *pers. comm.*) showed that CENTURY tended to predict increases in SOC in UK soils which were greater than those found (Table 6; Fig. 5 - note that most points lie above the 1:1 line). A comparison of CENTURY and ROTH-C using standard soil data showed that ROTH-C gave slightly lower estimates than CENTURY (Fig. 6). Our ultimate objective was to run CENTURY and ROTHC on a wider range of soils. This would test both the wider effectiveness of the models and whether one or the other was easier to use on a day-to-day basis. An important factor was also the ability to obtain advice should we run into difficulties. For testing the models, we used data supplied by ADAS for a number of sites with contrasting soil types (Table 7) (note that we have, for the purposes of this report called these the *modal soils*, as they represent a wide range of soil types in England and Wales). Crop-residue returns were set at zero, i.e. fallow in UK terminology, although this does not exist as a specified long-term land use in the options available within CENTURY. The latter model was run for 100 years (the maximum run-time within the model). In ROTHC, it was first necessary to run the model to produce a starting SOC content the same as that originally present in that soil type (Tables 5 and 7). This was done by assuming that SOC had reached equilibrium, and running the model iteratively over 10000 years, with different annual inputs of plant C from permanent grass and different amounts of inert organic matter (IOM) (all other components of carbon were set to zero to start the equilibrium run), until the required value of SOC was obtained. Once this equilibrium was achieved, the model was run with no input plant residues for each soil type for 100 years, starting with the initial values estimated. Fig. 6 shows the fit between the values produced by CENTURY and ROTHC for the different soils, and Table 6 gives the statistics of the goodness-of-fit for each curve. It is clear that up to about 60 years, the two models give very comparable values for SOC. Thereafter, CENTURY always predicts a higher value of SOC, most noticeably in the clay and Chalk soils. It is not immediately obvious why this should be so, but we believe that it might be

due to the higher retained water contents of these soils in comparison to the others. However, we found that RothC is much easier to use, in terms of setting up and altering the parameter files, and makes no pre-judgements about what is meant by land-use types or land use systems for the simple reason that it does not use them to drive the model. Although we had little need to seek assistance for either model, it is easier to contact the RothC team at IACR-Rothamsted than it is to contact the CENTURY team in the USA. For these reasons, we chose to continue with RothC.

a) Application of RothC to a range of soils and cropping regimes:

i) Data used

Throughout the initial and subsequent model runs using RothC, the baseline data were chosen as follows (although almost everything can be re-set by the user if alternative data are available). The climate data were for Lincolnshire (taken to be representative of the median climate for large areas of eastern England used for arable cropping) and obtained from the MAFF publication, *Agricultural Climate of England and Wales* (Smith, 1976). This gives the average monthly rainfall and the average monthly temperature, but not the open pan evaporation. Potential evapotranspiration (given by Smith, *loc. cit.*) was converted into open pan evaporation by dividing by 1.33. The range of values of soil clay content of soil were those of the modal soils (Table 5). The depth of soil was taken as 20cm. The estimate of the decomposability of the incoming plant material used was the default given in the model for most agricultural and improved grassland (a DPM/RPM ratio of 1.44). The soil cover for each month, and monthly input of plant residues were varied for different runs of the model (below). No farmyard manure was used.

ii) Model runs

Although we chose 100 years as the model run-time when comparing CENTURY and RothC, we chose the longest possible equilibrium run-time (140 years) after we opted for RothC. This was because the initial runs suggested that the curves showing change in SOC would in fact flatten, i.e. reach equilibrium, somewhere between 100 and 140 years. In the event, each soil type reached a different 'end-point', and none reached a constant (equilibrium) value, although the difference between the values after 140 years is very small (this needs to be judged against an analytical, i.e. laboratory, precision of c. +/- 0.1% in the determination of SOC). It is interesting that the modelled values for SOC after 140 years are much smaller for the higher clay content soils than those which might be estimated from Fig. 1, but of about the right order for the soils with c. 10% clay.

ADAS calculated the annual return of SOC for each modal soil type for different yields of winter wheat, winter barley and spring barley, against yields estimated for ADAS standard N-application rates (called 'std yield', '50kg', i.e. 50 kg N ha⁻¹ below standard-N, and '100kg', i.e. 100 kg N ha⁻¹ below standard-N). (Table 7). Using the SOC from this Table as a starting value, the model was run to generate starting values for each of the components as before. The model was then run for 140 years using the ADAS-derived plant residue inputs to show the effect of the different N-applications. (Fig. 7). This graph shows very little effect in the change in SOC for the different N-applications. However, it is interesting to note that those soils with the lower clay content ('sand' and 'light') appear to heading for a different equilibrium point to those with higher clay contents. To examine this further, the initial value of SOC for the sandy soil was increased by 1% - shown as 'high start sands', but the SOC continued to fall towards the same equilibrium level as when starting from a lower SOC content. We assume that this is a reflection of surface area, in that soils with little clay have less surface to which SOC can be associated. Thus, if we take the arguably extreme view that soils with SOC contents representative of a wide range of arable soils are used for continuous cereals for the next century, AND that N-inputs are reduced significantly, then crop-residue returns will keep SOC contents on heavier soils at c. 2.2% and at c. 1.3% on lighter soils. The latter figure approaches that at which others have identified the possibilities of reduced yields (above). We recognise that this modelling takes no account of changes in crop varieties and management practices, but we are unable to model these at present. Further, this modelling does not take into account climate change scenarios, which we address below.

iii) Effect of climate change

The climate data for Lincolnshire were varied using the *medium-high scenario* for the Climate Change Scenarios for the United Kingdom (Hulme & Jenkins, 1999). The effect is shown in Fig. 8 for the standard-N regime. The curves do, of course, represent an extreme, in that the climate change impact is applied from the present day (neither CENTURY nor RothC can accommodate incremental changes in the climate input file). Thus the sharp falls in the SOC contents in all soils after 60 years and more are not necessarily a true representation of what would happen with gradual climate change; the real picture lies somewhere in between. Nonetheless, climate change will clearly cause carbon stocks to fall in all soil types under arable agriculture.

iv) Effect of using SSLRC definitions of soil types

The 'modal soils', for which data were supplied by ADAS, do not exactly match the definitions of soil types used within LandIS. For that reason, we investigated the effect of modelling with average soil property values for similar soil classes taken from the National Soil Inventory. The RothC model was then run as before using the different N scenarios. Table 7 contains the starting values estimated as before. Fig. Shows the results, from which it can be seen that the equilibrium SOC contents are slightly higher, but the grouping of the texture classes is comparable.

v) Extreme initial SOC values from NSI data

Fig. 1 shows the relationship between clay content and SOC, and implies either some fundamental relationship which controls the SOC content whatever the circumstances, or represents current equilibrium conditions across a range of soil types and land uses. We wished to know whether, under the appropriate conditions, RothC would predict the SOC values for a given clay content, whatever the starting SOC content. Soils with little clay would have to 'lose' a lot of carbon, those with more clay would have to lose less. To this end, we chose a starting SOC content of 11% (very much the upper end of the spectrum) at clay contents of 15%, 30%, and 45%. Following initial equilibration of the model, it was run as fallow (no inputs) and also with a 'standard-N' scenario, i.e. a crop return of $2.37 \text{ t C ha}^{-1} \text{ yr}^{-1}$. Fig. 10 shows the modelled SOC contents for these soils. According to Fig. 1, soils with 15%, 30% and 45% clay, should sustain SOC values of c. 0.65%, 1.25% and 1.85% SOC. However, it can be seen that whatever the clay content, the soils behave in a similar way. After 100 years of fallow, they all contain c. 2% SOC and this continues to fall to c. 1% SOC after 140 years (an apparently still declining slowly). With standard crop-residue returns, the SOC contents are close to 6% and 5% for the two time-slices, respectively. The implications of this exercise are difficult to assess. If the model is correct, then the apparent equilibrium suggested in Fig. 1 is not in fact so. It simply represents the situation at the present day. There may well be a baseline SOC content, but it may not be strongly controlled by clay content.

vi) Permanent grass

RothC was developed for use on non-waterlogged soils under arable cultivation and that is the situation for which it has been tested most often. However, there is no reason why it should not work for permanent grass. P. Smith (IACR-Rothamsted) (*pers. comm.*) supplied model parameters based on work at Park Grass, Rothamsted. The most crucial figure is the annual input of carbon which, for improved and cut grass, was set at $2.76 \text{ t C ha}^{-1} \text{ yr}^{-1}$. We then re-ran RothC for the basic soil types as identified by ADAS, but using starting SOC values for grass plots on such soils. The results are shown in Fig. 11, from which it can be seen that SOC increases in all soils. This conflicts with the findings from the re-sampled permanent grass NSI sites, which show a small decrease in SOC over c. 15 years. However, the 'turn-over' value for SOC, i.e. the annual SOC input at which one sees a long-term decline in SOC under permanent grass is c. $2.6 \text{ t ha}^{-1} \text{ yr}^{-1}$. This is very close to the value used here. This implies that the Park Grass value is not representative of large parts of permanent grassland in England and Wales. This is an area clearly in need of further investigation.

13. To establish a risk matrix based on soil /cropping combinations under current and future climate.

14. To use this matrix to create maps of soil risk for England and Wales.

It is clear from the foregoing sections that we have been unable to establish two central tenets of this research:

- Robust numerical (quantitative) relationships between various soil properties, crop yields and SOC;
- Clear thresholds for SOC, either generally or by soil type, below which it can be stated unequivocally that soil properties or crop yields will change markedly.

This clearly presents a considerable problem in the establishment of risk classes. There is some suggestion in our work and that of others, that yields of cereals might fall by c. 5 per cent if SOC concentrations fall to c. 1%. There is also some suggestion that finer textured soils become structurally unstable at similar values of SOC. This may be nearer to the critical threshold than the 2 per cent commonly assumed, as mentioned at the beginning of this report. The modelling with RothC suggests that arable soils fall into two classes of SOC behaviour - light soils (<18 per cent clay) and heavier soils (>18 per cent clay). The former tend, over long time scales, towards an equilibrium SOC content of c. 1.3 per cent, whilst the heavier soils tend to c. 2.3 per cent SOC. Although there are many assumptions in this scenario, perhaps the greatest being that no-one is likely to keep their land in cereal production for 140 years, we have mapped this effect (Fig. 12). The effect is not entirely what one would expect. Certainly the light land in Eastern England shows a decline, but much of the relatively low carbon land identified by the National Soil Inventory (Fig. 13) does not decline much further. This is in accord with the findings of the re-sampling of the arable/ley grassland NSI sites, where the change in the

lower quartile value for SOC was a decline of only c. 0.1 per cent in 15 years. This contrasts with a decline of c. 0.3 per SOC in the lower quartile value for permanent grass over the same time interval. In addition, we have compared the measured SOC contents for the original NSI samples with the values predicted by the modelling at those sites under **arable** cultivation (given that the permanent grass modelling was based on only one set of input data, we decided not to pursue this further), and have drawn a difference map, i.e. to show where the soils are already above or below the long-term predicted values (Fig. 14). Where the values are above those predicted by the model, one might reasonably assume that these soils are at a lower risk of degradation. Where the SOC contents are already below those predicted by the model, the implication is that current land management on those soils is already inadequate to maintain SOC contents at a reasonable level. There are clear uncertainties in this approach, e.g. is it reasonable to take such coarse texture classes as a basis for risk assessment, what is the precision of the modelled values, what would be the effects of different cropping regimes, and so on. However, if the precautionary principle is to be followed, then this approach identifies that land under greatest risk of decline in SOC content under long-term arable cultivation.

16. Conclusions from the research

1. There was little evidence in the literature for robust numerical relationships between SOC contents and a wide range of soil properties. There is almost no evidence for differences in such relationships in relation to soil type.
2. There is little evidence to support the proposition that there is a critical level at c. 2 per cent SOC, below which major changes in soil properties and crop yields will occur.
3. There is some evidence from the literature that cereal yields will decline by c. 5 per cent on soils where SOC falls to c. 1 per cent. This fall in yields cannot be reversed by greater additions of inorganic N, P or K.
4. There is a growing body of evidence that the 'active' fractions or forms of SOC, i.e. those derived from 'fresh' organic wastes such as crop residues, manures and - possibly - digested sewage sludge have a greater effect on soil behaviour that can be shown through measurements of, and relationships with, 'total' SOC.
5. Investigation of relevant data for England and Wales showed that:
 - a) For a given soil clay content there appears to be a value below which SOC will not fall, irrespective of land use. The carbon involved in this relationship could be protected by the soil clay.
 - b) Total SOC makes a small contribution to the magnitude of volumetric soil water content at low tensions in topsoils, and that this contribution differs only slightly between agricultural land uses and soil texture groups. The contribution at higher tensions is negligible. SOC makes an insignificant contribution to the volumetric soil water content in sub-soils.
 - c) There is a marked change in soil aggregate stability at c. 1 per cent SOC in a wide-range of arable soils.
 - d) There is a poor relationship between SOC and soil Plastic Limit (Lower Liquid Limit). The data indicate that SOC exercises little control over PL below c. 1 to 1.5 per cent SOC.
 - e) There is a linear relationship between soil mineralisable N and SOC for a range of soils under arable cultivation. There is no sign of a major change in the slope of this relationship at any SOC content.
6. In modelling the behaviour of SOC we found that:
 - a) Both ROTH-C and CENTURY performed equally well in predicting the change in SOC contents of some Fen silt soils. However, ROTH-C was easier to set-up and use than CENTURY and has the additional advantage that help with the model is readily available within the UK. Thus, our efforts concentrated on using ROTH-C.
 - b) Under arable cropping, the behaviour of SOC fell into two classes: (i) 'light' soils, which we define as those with <18 per cent clay, and Chalk soils, both tending to an equilibrium SOC content of c. 1.3 per cent over a century or more; (ii) 'heavy' soils, i.e. those with >18 per cent clay tended to an equilibrium SOC content of c. 2.3 per cent over the same period.
 - c) Changes in N-application rates had little effect on SOC behaviour in the long-term, either in terms of absolute amounts of SOC or the equilibrium SOC content reached.
 - d) Climate change, as represented by the UKCIP 'medium-high' scenario caused the equilibrium SOC contents to fall by up to 0.5 per cent compared with the estimates using current climate data.

- e) Comparison of the modelled SOC contents and the measured SOC contents from the NSI data, showed that many of the lighter and Chalk soils in Eastern England would continue to lose SOC if kept in continuous arable cropping, but few of the heavier soils would fall below 2 per cent SOC in the long term (>100 years). These results must be judged against the rather unlikely scenario of continuous arable cultivation for a century or more.
- f) Comparison of the modelled SOC contents with those measured during the NSI showed that some soils - particularly in Eastern England - are already at or below their long-term predicted equilibrium SOC contents. This is believed to reflect both the difficulties of predicting very small changes in SOC content accurately, and the uncertainties inherent in applying simple SOC change scenarios based on soil texture.

In summary, therefore, the research has shown that there is little firm evidence for critical thresholds in relationships between SOC and other soil properties and crop yields in the soils of England and Wales. There may be some evidence that, if such a threshold or thresholds exist, then it or they would be nearer to 1 per cent SOC than the widely quoted 2 per cent SOC. Over periods of a century or more of arable cropping, light and Chalk soils tend to an SOC equilibrium content of c. 1.3 per cent and other soils tend to a value of 2.3 per cent. Current arable crop returns, under the current climate, seem adequate to maintain these SOC contents on heavier soils, but possibly not for lighter and Chalk soils.

17. Further Research

The literature gives many references to the greater importance of 'active' SOC or SOM rather than 'total' SOC/SOM. There is almost no spatial information about active SOC in England and Wales, and we suggest that this should be the subject of further investigation. It would also be useful if the modelling of SOC could be run both spatially, and for crop rotations/other land uses within the time frame chosen.

18. Publications

Loveland, P.J., Webb, J & Bellamy. In Press. Critical Levels of soil organic matter: the evidence for England and Wales. Proceedings of the Conference: *Sustainable Management of Soil Organic Matter*, British Society of Soil Science, Edinburgh, September, 1999.

Loveland, P.J. & Webb, J. In press. Is there a critical level for soil organic matter: a review. *Soil Use and Management*.

19. Contractors

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Annex 1 to CSG15_SP0306

**CRITICAL LEVELS OF SOIL
ORGANIC MATTER**

(MAFF PROJECT CODE SP0306)

LITERATURE REVIEW

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EXECUTIVE SUMMARY

Soil Organic Matter (SOM) has long been regarded as a source of plant nutrients, principally N, with subsidiary P, S and micro-nutrients, as well as being beneficial to a range of soil physical characteristics. Many studies have concluded that N is generated mainly by mineralisation of recent additions of organic matter (OM) in crop residues and organic manures, i.e. the 'young' or 'active' fraction of SOM, whilst the older, more humified material is largely inert. This same active fraction of SOM has also been implicated in improvements in soil physical properties. The components of this active fraction are variously described as polysaccharides, gums, fungal components of various kinds, root and/or microbial exudates, and 'readily-oxidisable' fractions; many are ill-defined mixtures which change in composition both with time and source. Several studies point to the short-term nature of their effects - no more than a year in most cases, and often much less. Under arable cropping, annual returns of crop residues to the soil are the major source of these active substances, whereas under grass they are produced almost continuously. This difference is quoted again and again as the reason for better soil physical properties, especially aggregate stability, under grass compared with arable soils. Thus, the literature strongly implies that measurements of **total** SOM can be a poor guide to the function of the latter as both a source of plant nutrition and of soil physical behaviour. There are cases where decrease in total SOM is matched by improvement in soil structure because the remaining SOM, although small in amount, is composed almost entirely of active SOM.

Unequivocal studies of the influence of SOM on plant nutrition have often been confounded by climatic effects and differences in other soil properties. However, studies on differentially eroded sites suggest that loss of SOM does cause reduced crop yields, which could be made good by addition of fertilisers. However, about 50% of the N taken up by crops is derived from mineralisation of SOM, although microbes associated with the SOM can immobilise ca 30-50% of added fertiliser N. Thus SOM may both provide and deny N to crops. No threshold value has been identified for SOM content at which this effect can be discounted. Similarly, there is little **direct** evidence of the amounts of P, S and micronutrients released to crops from SOM.

The literature on SOM and soil physical properties is predominantly concerned with aggregate stability. Although a few papers indicate that a total SOM content of ca 2% may indicate a point at which soil physical properties may change, there are far more papers which fail to demonstrate such a threshold. One problem identified in this literature search is that there is little consistency in the methods used to measure soil aggregate properties, and this makes comparison of results difficult.

Soil water holding capacity (WHC) at various suctions is influenced by SOM, but often only contributes <10% to the known variance of this property, especially at large suctions. Again, much of the improvement in WHC is attributed to young SOM. Such improvement can indirectly increase crop yields by making water more readily available to the growing crop.

Cation exchange properties, soil bulk density, consistency and permeability have all been shown to be affected by SOM, but the number of quantitative studies is so small that it seems unwise to draw wide-ranging conclusions.

In most of the papers from which graphical or graphable data could be extracted, relationships were linear between SOM and the soil variable under study. In some cases, however, curvilinear relationships were found. Land use history was often cited as a bigger factor than any other, when investigating the effects of SOM on soil properties.

The overall conclusion is that as long as returns of fresh or active OM to the soil are adequate, then soil sustainability will not be compromised by a reduction of **total** SOM below <2%. The next phase of this project will be to assess what are the adequate returns of crop residues to provide adequate buffering of nutrient supply, and to maintain soil structural stability.

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Review of Critical Levels of Soil Organic Matter (SOM) in Relation to Soil Properties

Preamble

It has long been known that additions of, or increases in, SOM can benefit soil properties. Improved plant nutrition (N, P, S, micronutrients), ease of cultivation, penetration and seed-bed preparation, greater aggregate stability, lower bulk density, improved water holding capacity at low suctions, enhanced porosity and earlier warming in Spring have all been commented upon. Many of these properties are clearly linked, and there is a large literature around these topics (see, for example, Carter & Stewart, 1996). It follows from this that a decline in SOM content will adversely affect most, if not all, of these properties. This thinking has led to statements that there is some inherent threshold below which the benefits of SOM to soil will be effectively lost, a situation which will then limit the ability of the UK to maintain its agricultural productivity (see, for example, RCEP, 1996).

This concept of a critical threshold for organic carbon appears to have been bolstered in recent times by the conclusion of Greenland *et al.* (1975) that soils with < 2% organic carbon were prone to structural deterioration. However, this 2% threshold was a 'rule of thumb' (*sic*) to indicate soil structural stability. It was not intended to be a measure of soil physical properties in the field, but an indication of the soil response to stress.

Part 1: Crop Production

Introduction

The role of SOM in crop production was thoroughly reviewed by Allison (1973). SOM was considered vital because it was the main source of N for crop production. It was also considered to increase the availability to plants of many essential micronutrients, as well as substantial amounts of P and S.

The source of N for crop growth was identified as the 'active' pool of SOM comprised of plant and animal residues added to the soil in the previous 5, or at most, 25 years. Older humic material was considered to make almost no direct contribution to crop nutrition. This concept of 'young' OM has subsequently been developed by many workers e.g. Matus and Rodriguez (1994). Previous evidence for the dependence of crop yields in SOM were provided by studies such as those of Uhland (1949), in which the major factor controlling crop yields was N. However, humic acids, by increasing the solubility of micronutrients, were considered essential to enable crops to recover sufficient of those nutrients for normal growth.

The direct effect on soil moisture supply was considered to be limited. With the exception of sandy soils, increases in SOM do not greatly increase the capacity of soils to store available water. Much of the water associated with SOM is held too tightly for plant use.

Allison (1973) reported that chelating and buffering were considered by many to be the most important properties of soils. Without the soil's buffering capacity, agriculture would require constant management, as do hydroponic systems. Humus may account for 30-60 % of cation Exchange Capacity (CEC), more on sandy soils. For mineral soils CEC is typically 2-50 meq 100g⁻¹. Values below 3-4 meq 100g⁻¹ may be found in sandy soils, but such soils are not likely to be suitable for agricultural use. Soil CEC is not a constant, it may increase with increasing pH, and treatment of the absorption complex by phosphate (Tan & Dowling 1984). Hence CEC comprises a permanent (CEC_p) and variable (pH dependent) fraction (CEC_v). The CEC_p has been regarded as derived mainly from the clay fraction, while CEC_v is mainly located in the soil OC.

Reference was made by Allison (1973) to virgin soils in Arizona which contain only 0.1-1.0% SOM. The small concentrations did not seriously limit crop yields under irrigated conditions, providing adequate fertilizer-N was supplied.

It therefore appears appropriate to review subsequent work on the direct effect of SOM on crop nutrition under 4 headings; crop nutrition, soil available water, soil buffering capacity and micronutrient availability.

Crop Nutrition

Bauer & Black (1994) carried out a field study to quantify the effect of increments of SOM on crop production. They found large seasonal differences (by a factor of 2.5) and concluded that a major contribution is available N mineralized during the growing season. However in 2 of the 4 years application of fertilizer-N masked the differences in grain yield caused by differences in SOM.

Zhukov *et al.* (1993) found that, for a loamy sand podzol, unfertilized grain yield was directly dependent upon humus concentration. With fertilizer-N application the role of humus decreased markedly. There was some evidence of slightly greater maximum yields as SOM increased from 0.7-2.4 % (0.4-1.4 % C), but not above.

Verity & Anderson (1990) studied the degree of soil erosion on crop yields. Decrease in topsoil depth reduced organic C and P and both total and mineralized N and S. Cereal yields were greater at the foot of slopes than on the eroded parts. There was no assessment of the role of fertilizer additions in ameliorating the effects of soil erosion.

Tanaka & Aase (1989), attempted to quantify the effect of SOM on crop yield by systematically removing topsoil. Treatments were : control; 50 % of A horizon removed; all of A horizon removed; and all of A horizon and some of the subsoil removed. In three out of five years crop yields were reduced by topsoil removal. In the other two years yields were limited by water supply and there were no treatment effects. Mean organic C in the top 30 cm of soil were 1.27, 1.18, 0.98 and 0.96 %. In the years when treatments reduced yields, the addition of N and P fertilizers brought yields of treated soils up to those of the control. In these experiments P appeared to be limiting nutrient with mean Olsen-extractable P of 9, 5, 2 and 1 mg l⁻¹ in the top 30 cm of soil.

These results were consistent with the earlier observations of Krause and Allmaras (1982) that despite topsoil loss, yields have continued to increase due to improved cultivars, weed control and use of fertilizers. Although those workers concluded that while fertilizers increased yields on eroded soils, yields were generally less than on soils that had not been eroded.

These studies suggest that loss of organic C, usually as a result of soil erosion, reduced crop yields. This was mainly a consequence of reduced nutrient supply. The addition of N, or N and P fertilizers frequently, but not always, produced yields on eroded soils as great as an uneroded soils. Moreover in most studies additions of N and P were only moderate (c. 40-125 kg nutrient ha⁻¹), and no S fertilizers were applied. Hence nutrient supply may have remained limited. Shepherd et al. (1996) observed that even on UK soils receiving large annual fertilizer-N applications, a significant proportion of crop N uptake was mineralized from SOM. It is also possible that the inability of fertilizer-N and P to fully maintain crop yields was in consequence of better buffering of nutrient supply in soils with greater SOM. It should be noted that in some of these studies satisfactory crop yields were nevertheless obtained from soils of organic C concentration much less than 2 %.

Available Water Capacity

Bauer & Black (1992) found that available water capacity (AWC) remained essentially constant in sandy soils as organic C increased from 0.74 to 1.49 %. They concluded that the decline in productivity from soil erosion was not caused by a reduction in AWC, but by a decline in nutrients and biological activity.

Cation Exchange Capacity

Thompson *et al.* (1989) estimated the contribution of OC to soil CEC by means of an orthogonal comparison of soils, one cultivated after prairie, another cultivated after deciduous woodland. Each was paired with an uncultivated prairie or deciduous woodland soil. Soils were of a common parent material and landscape position.

Soil OC was estimated to be responsible for c. 50 % of total CEC. However in the fine clay fraction, in contrast to the coarse and fine silt and coarse clay fractions, inorganic soil compounds dominated CEC. This was considered due to organic colloids coating inorganic surfaces, holding particles together, and making net CEC *less* than would be expected from an additive estimate.

McGrath *et al.* (1988) reported CEC of a sandy soil to increase from 75 to 158 meq/kg as soil OC increased from 0.46 to 1.39 %.

Tan and Dowling (1984) investigated the role of OC in CEC_v and CEC_p by destroying soil OC with H₂O₂. Of the 5 soils studied, total CEC was greatest in a soil with montmorillonitic clays. In this soil removal of OC *increased* CEC_p, due to removal of blocking of exchange sites by OC. In other soils reduction in OC decreased CEC_p. Variable CEC was >40 % of the total in all soils and c. 50 % or more in 4 soils. However the study did not confirm OC as the major site of CEC_v. Martel *et al.* (1978) in a study of 11 clay soil, (40-51 %, mean 3.1 OC) concluded that

only c. 10-15 % total CEC was associated with OC. These soils were poorly drained and undecomposed OM accumulated on the surface. Thus materials such as fulvic acids, with many carboxyl groups, were only a small proportion of the total OC.

Curtin & Smillie (1976) studied 51 soils, with mean OC of 1.9 % (range 0.1-8.9 %), mean clay 26.2 % (range 0.4-56 %) and pH 6.2 (range 3.8-8.3) and found OC accounted for a mean of 43 % of CEC.

Wright & Foss (1972) looked at 3 groups of soils (57 in total), with mean OC of 0.9, 1.4 and 1.8 %, mean clay content of 10, 18 and 18 %, and pH 5.7, 6.0 and 6.2. The overall mean CEC due to OC was c. 56 %.

McLean and Owen (1969) quantified the influence of pH on the contribution of OC to CEC. Twelve soils were used of 21 % mean clay content (8-64 %), 1.9 % mean OC (0.7-3.5 %). Above pH 6.0 there was a large increase in CEC associated with OC.

Wilding & Rutledge (1966) studied 3 soils of 17-37 % clay and 1.6 - 3.0% OC and found 21-52 % of CEC associated with OC.

Helling *et al.* (1964) also investigated the effect of pH on the proportion of CEC associated with OC. Using 60 soils with mean clay content of 13 %, OC 1.9 % they found the proportion of CEC due to OC increased from 19 % at pH 2.5 to 45 % at pH 8.0.

Thus from these studies it may be concluded that in agricultural soils, maintained at pH of c. 6.0 to 8.0, c. 40 - 50 % of CEC may be associated with OC. However the proportion is likely to be much less in poorly - drained clay soils. There is also an interaction with clay mineralogy. Soils containing montmorillonite clays may have their CEC *reduced* by OC reducing surface area.

Micronutrient Availability

Figliola *et al.* (1993) added Cu and Zn to soil of contrasting OC status. Availability of Zn increased with increasing OC, but this was not accompanied by an increase in plant (*Avena sativa*) uptake of Zn. Availability of Cu was reduced by increasing OC, but there was no effect on plant uptake.

Tagwira *et al.* (1992) found that on sandy soils of low Zn status, addition of OC may reduce Zn availability.

McGrath *et al.* (1988) added solutions containing a range of concentrations of Mn, Zn and Cu to five samples of a sandy loam soil with OC concentrations ranging from 0.46 to 1.39 %. After a 3 week incubation the total concentrations of Mn, Zn and Cu in displaced solutions was almost independent of OC, although the concentrations of Cu^{2+} was smaller with greatest OC. When EDTA and acetic acids were used as single extractants, of samples to which no metals had been added, available metal concentrations were unaffected by soil OC. However where Zn and Cu had been added to the soils acetic acid - soluble metals decreased as OM increased. This decrease in soluble Zn and Cu at the greatest OC concentration was noted at all pH's.

Part 2: Soil Physical Properties

Introduction

Much of the evidence surrounding claims for improvement in soil physical properties with increase in SOM content (SOM) is based on observation and practice. For *prediction* of soil behaviour under different or changing amounts of SOM, numerical relationships between the variables are needed. Alternatively, clear and consistent experimental evidence of measurable and significant change in a given property at or close to a threshold value (or values) of SOM is desirable.

The Literature

The literature search which underpins this review was aimed at finding those papers, reports etc., which contain such numerical data, equations of state and/or threshold values which express the required relationships. A review of the qualitative, empirical or anecdotal literature is not given, except in a few cases where it helps explain the development of research.

The literature search was run initially across the CABI database from 1984 to the latest version available. The most productive keyword expression was:

soil organic and (matter or carbon) and (structure or stability)

This yielded 357 hits. Cross-checks substituting such terms as:

bulk density, aggregate, penetration, workability

reduced the number of hits, and did not appear to locate any which did not appear in the first list.

All of these papers were scanned for evidence of numerical relationships between SOM and soil physical properties, in the form of equations, graphs, tables of data, class limits and so on. Additional papers for the earlier literature were traced from the bibliographies of the CABI search items. More recent papers were found by scanning publications such as '*Soil and Tillage Research*'. In all, about 1000 papers were examined, albeit most were found to lack the kind of information sought. The vast bulk of the papers found deal with aggregate stability, with few other soil properties being investigated. This is reflected in the review.

In reading this review, it should be noted that the earlier literature used 'humus', 'organic matter' and 'organic carbon' interchangeably, often within the same report. It is not always clear, therefore, on what basis the results were discussed.

Aggregate stability

Aggregates

Numerous early papers refer to aggregates or ‘crumbs’ obtained in very diverse ways, ranging from simple manual separation from field soils, to products obtained of complete ‘puddling’ of the soil followed by several ‘conditioning’ cycles (*sic*) of wetting and drying, or by the mixing of, e.g. clay, with peat in various proportions. Similarly, whilst sizing of aggregates was commonly by sieving, the range of sieve apertures used to separate the aggregates into classes has been very wide. This variety of approach makes it difficult to compare much of the literature, especially that before the late 1950s and early 1960s. McHenry (1945) seems to have been the first to suggest that aggregates should be ‘defined’ on a scale of multiples of 0.25 mm, which is now widespread (but not universal) practice. Another common practice is to quote the ‘mean weight diameter’ (MWD) of aggregates. This is the mass of aggregates retained on a sieve of particular aperture, multiplied by the difference in the aperture size of adjacent sieves. This makes it impossible to derive any information about aggregate size, unless one knows the sieve apertures used, and the mass of material retained. All too often one or both of these is missing.

Emerson (1954) was particularly critical of this diversity of approach, especially of ‘conditioning’, because most of the methods subjected the aggregates obtained to hydraulic stresses far in excess of any likely to be found in the field under a temperate climate. Not surprisingly, Emerson was able to show that very different aggregate behaviour could be demonstrated for the same soil depending entirely on the pre-treatment to which it has been subjected (something confirmed yet again by Haynes (1993), who found that the aggregate stability measured depended almost entirely on the wetting-history of the sample). Another feature of the tests then available, which Emerson also criticised, was their inability to distinguish between slaking and dispersion. Emerson’s paper of 1954 was important because it eventually led to far-reaching changes in the way in which aggregate stability tests were carried out. He also showed that soil electrolyte concentration could have a profound effect. However, in the absence of the latter, soil aggregates with a soil organic carbon content <0.7 %, failed as much by deflocculation as dispersion, and this effect was completely reversible.

‘Fresh’ OM

A common finding, even in the early literature, was that *total* SOM was usually less-well correlated with aggregate stability than was ‘*fresh*’ material.

For example, Sideri (1938), using a combination of microscopy and selective extraction, showed convincing evidence that soil particles bond in the presence of ‘fresh humates’. Ackerman & Myers (1943) found, for soils under grass, strong correlation ($r > 0.95$; $p < 0.001$) between the stability of aggregates ($d > 0.106$ mm) in water and soil organic carbon content and soil N content. Similar correlation for soils under cultivation was poor ($r < 0.3$; $p < 0.05$). In the grassland group, soil organic carbon content was >2 % in 5 of the 6 soils (1.6 % in the other), but <1.9 % in the arable

soils. Aggregate stability was reported as greater in soils in which lucerne had formed part of the treatment, and 'fresh' residues were abundant.

This apparent importance of younger organic components or 'active components' of 'humus' in conferring stability on soil aggregates was emphasised by Swaby (1950), who reviewed much of the earlier chemical work. The nature of this 'active fraction' was investigated by several workers and, on balance, it was believed that polysaccharides were the most important group of compounds involved, although proteins/amino-acids and lignins were also thought to be involved.

Chesters *et al.* (1957) found that 'microbial gum' (extracted with 0.5M NaOH, followed by precipitation with acetone) was generally the single most important factor in soil aggregation in 75 samples of four silty soils in the central USA. Total soil organic carbon correlated very poorly with aggregate stability, except in one soil in which several samples had SOC > 2 %, where the correlation was described as 'significant' ($r=0.345$). Correlation with soil microbial gum content was generally >0.35, with values >0.7 being the norm. The authors gave the following equation for a silt loam (clay content ca 31 %) derived from reddish, dolomitic till (probably comparable to an Argillic Brown Earth in England and Wales):

$$\begin{aligned} \text{\% aggregation (>0.1 mm aggregates)} \\ = 2.6 \times \text{\%OC} + 326 \times \text{\%microbial gum} + 0.57 \times \text{\%clay} + 11.8 \times \text{\% iron} \\ \text{oxide} + 0.1 \times \text{pH} + 6.1 \end{aligned}$$

Although the relationship between measured and predicted values was shown graphically, no measure of goodness-of-fit was shown between the two.

The question of 'fresh' or less-degraded components of SOM was further examined by Greenland *et al.* (1962), who found a 'considerable increase' in permeability ratio (a measure of aggregate stability expressed as inter-aggregate pore space) as soil organic carbon (SOC) rose from 1.2 % to 2 % in a Red Brown Earth (Urrbrae Soil; 19 % clay) in Australia. From a study of the effects of selective chemical treatments, they postulated that polysaccharides were the main factor in maintaining aggregate stability in this soil.

Griffiths & Jones (1965), found that incubation of soils from Aberystwyth and Lincoln (the latter almost certainly Kirton from remarks made in this and subsequent papers) with polysaccharide-excreting bacteria gave considerable, but different, increases in aggregate stability in the two soils, but that this increase was unrelated to the initial OC content of the soils (ca 5 %). Griffiths & Burns (1972) confirmed these earlier findings about microbially-produced polysaccharides with further work on the Kirton soil, and also found that subsequent treatment of the polysaccharide-enriched soil with tannins greatly increased aggregate strength. Although they could not suggest a mechanism to explain this behaviour, they postulated that it could be important in field soils receiving additions of fresh - especially woody -OM.

Reid & Goss (1980) also examined the nature of the OM in a study of aggregate stability under perennial ryegrass, and concluded that root exudates were the most important factor in such stability, but did not further specify their composition.

An extensive review of the relationship between soil organic carbon and aggregates by Tisdall & Oades (1982) made a number of points, which reflect the findings of these earlier workers:

- a) only part of OM stabilises aggregates, and this is generally the 'fresher' material, with a relatively large content of polysaccharides, roots and fungal hyphae;
- b) above a certain content of OM there is no further increase in the stabilising effect;
- c) OM is not a major binding agent;
- d) disposition of OM is more important than the amount;
- e) particle arrangement is more important in some soils than is the amount of OM.

The authors also comment on the wide variations in the type and content of OM between aggregates of different sizes, and that aggregate stability can vary widely within the same soil depending in part when OM was added, what type of OM it is, and when the aggregates were subsequently taken for examination. All these factors were seen as part of the difficulty in coming to a consensus about the role of OM in aggregate stability, especially in relation to attempts to derive equations of state from the data available. In general terms, Tisdall & Oades (1982) ranked OM components, in terms of the time-scale over which they exert an influence on aggregate stability and/or formation, as follows:

- 1). glucose-like compounds (which they equate to 'transient polysaccharides'): act strongly after 2-3 weeks, and decline over the next 4-6 months;
- 2). cellulose achieves its maximum effect after 6-9 months, but is never as effective as transient polysaccharides;
- 3). ryegrass residues increase in effect over ca 3 months, persist for another 4-6 months, then decline in effectiveness over the next 3-4 months.

In effect, the most important components of OM in relation to soil aggregation exert their effect over no more than ca 1 year, which matches the observation that aggregate stability is greatest under grass (near continual production of such components), but decreases rapidly under arable cultivation. However, Tisdall & Oades (1982) do not give any threshold values above or below which soil properties are more or less dependent on a particular level of OM.

Chaney & Swift (1984) also found that soil carbohydrate content is slightly more strongly related to MWD than total OM ($r = 0.711$ vs $r = 0.663$, respectively; $p < 0.001$).

Total OM

Strickling (1950) studied wet aggregate stability in 46 silt loams from the western United States. Although he found the relationship:

$$\% \text{ aggregate stability} = 16.9(\text{SOM}) - 13 \quad (r = 0.87)$$

He, somewhat surprisingly, concluded that total SOM did not have an important effect on aggregate stability.

Clement & Williams (1958) found 'evidence of soil structural instability in 'Hurley soils' when organic carbon fell below ca 1.5 %, irrespective of sward type. Reported soil clay contents were 7 - 10 %, which indicates coarse loamy soils of the Hurley Series (modern correlative = Wick Series) (Osmond, *unpublished*; Jarvis *et al.*, 1979).

Boekel (1963) used a visual scoring system for soil structure, and related this to clay content (somewhat unusually defined as material <0.016 mm), SOM and the upper and lower plastic limits. His overall conclusion was that 'good' soil structure could only be obtained - for soils with >10 % 'clay', if SOM>2%, and the latter had to increase by ca 1 % for every 10 % increase in 'clay' content to maintain good soil structure. Thus a soil with ca 20 % 'clay' (<0.002 mm + fine silt - not an uncommon situation in the UK) would need a minimum SOM content of ca 3 % to have 'good' soil structure. This equates with ca 2 % soil organic carbon.

Kemper & Koch (1966) investigated the properties of 519 samples of soils from across the whole of the United States. Their most fundamental conclusion was that, overall, there was a sharp inflection point in the curve relating the amount of water stable aggregates to total organic carbon. Above 2% OC little increase in aggregate stability occurred, whereas below 2% a marked decrease could be seen, with an even more marked decline in stability below 1% OC. Small amounts of iron oxides improved aggregate stability whereas an increase in soil exchangeable sodium content caused a decrease. However, neither of these effects was particularly significant. Kemper & Koch (1966) derived a number of regression equations from their data, the most useful of which they gave to be:

$$\% \text{ stable aggregates (all soils)} = 49.7 + 13.7\log(\text{OM}\%) + 0.61(\text{Clay}\%) - 0.0045(\text{Clay}\%)^2 + 9.0(\text{Fe}_2\text{O}_3) - 1.6(\text{Fe}_2\text{O}_3)^2 - 0.28(\text{ES}\%) - 0.06(\text{ES}\%)^2$$

$$\% \text{ stable aggregates (arable topsoils)} = 40.8 + 17.6\log(\text{OM}\%) + 0.73(\text{Clay}\%) - 0.0045(\text{Clay}\%)^2 + 3.2(\text{Fe}_2\text{O}_3\%) \quad [44\% \text{ of variance explained}]$$

$$\% \text{ stable aggregates (grass topsoils)} = 45.1 + 22.6\log(\text{OM}\%) + 0.28(\text{Clay}\%) - 0.0021(\text{Clay}\%)^2 + 1.55(\text{Fe}_2\text{O}_3\%) \quad [38\% \text{ of variance explained}]$$

There is some uncertainty in these equations as Kemper & Koch (1966) move between organic carbon and OM without necessarily stating that the change is intended or that the appropriate conversion has been made. The equations are given as in the paper. It is also interesting that the authors state that the exchangeable sodium (ES) and iron oxide factors contribute very little to the explanation of the variance, and could be omitted without serious error. Even with this amount of data, the amount of variance explained is not great.

In a study of 189 British soils, Williams (1971) made an equally wide range of measurements of physical properties, and attempted to relate these to organic carbon,

total N and to each other. He found that the amount of 'coarse particles - 6mm to 0.02 mm', had a marked effect on the percentage of water slaking aggregates, as expressed by:

$\% \text{ water slaking} = 2.47 + 0.47(\% \text{ coarse particles}) - 5.95 (\text{OC}\%)$ [49% variance explained]

Greenland *et al.* (1975) used a method developed by Emerson (1967) to test the aggregate stability of 180 samples of English and Welsh soils. Although many factors were examined, and the samples subsequently divided into seven classes on the basis of their physical behaviour, the general conclusion was:

soils <2 % organic carbon: unstable
 soils 2 - 2.5 % organic carbon: moderately stable
 soils >2.5 % organic carbon : very stable

Douglas & Goss (1982) investigated the effect of different cultivation practices, over a 5-year period, on the physical properties of Hamble, Andover, Lawford and Denchworth soils in southern England. Correlations of OC with wet-sieving aggregate stability for individual treatments were generally significant ($p < 0.001$), but not especially strong ($r \sim 0.6$ to 0.7). Pooling of data from all treatments improved the correlations for the Lawford, Hamble and Denchworth soils to $r = 0.727$, 0.858 and 0.945 (all $p < 0.001$), respectively. Minimum cultivation tended to lead to greater aggregate stability compared to deep ploughing, although the most stable aggregates were again found under grass. Differences between the cultivation treatments often did not become significant until the 5th year of treatment. Although Douglas & Goss fitted curves to their data, they gave no equations for them. It is clear, however, from their graphs, that relationships are different for each soil, and that no useful numerical relationship between soil organic carbon and aggregate stability exists within their pooled data, nor are there any obvious inflection points in their graphs which would indicate a marked change in behaviour above or below a particular value of organic carbon.

Stengel *et al.* (1984) looked at the relationship between OC and wet sieve aggregate stability (WSA) in Ashley, Hamble, Wothersome (now Tickerton), Fincham (now Maxted), Hanslope, Wicken, Denchworth, Lawford, Newchurch, Newport and Andover soils. They found (Figure 1) that:

$$\text{WSA}\% = 11.57 (\text{OC}\%) + 12.75 \quad (r = 0.61; p < 0.001)$$

Chaney & Swift (1984), in a study of more than 120 UK soils, found that total SOC could help to identify soils at risk of structural degradation. They give the mean weight diameter of wet-stable soil aggregates as:

$$\text{MWD} = (\text{OM} + 24) \times 31 \quad (p < 0.01)$$

Note again the switch from OC to OM without explanation.

Figure 1. Relationship between soil organic carbon content (OC%) and mass of water stable aggregates (WSA w/w) (after Stengel *et al.*, 1984).

On previous evidence, green manuring should improve soil structural properties because of the greater proportion of 'fresh' OM returned to the soil. However, MacRae & Mehuys (1985, 1987) were unable to show any much benefit in an 8x3yr experiment involving clover/vetch intercropped with maize on a clay soil and a gravelly sandy loam in Canada. Dry bulk density (Db) decreased in the green-manured plots, but the effect was not especially significant ($p < 0.05$).

King and Evans (1989) show a linear relationship graphically between the mass of water stable aggregates and OM for a range of restored and unmined (*sic*) soils in northern England. From the graph it can be estimated that an increase of ca 1% OM gives an increase of ca 8% by mass of water stable aggregates, irrespective of land use.

In contrast to many of the above studies, Perfect & Kay (1990) found no relationship between aggregate stability and OC content in a Canadian silt loam subject to a number of land uses.

Ekwue (1990) looked at the amount of water stable aggregates (WSA) in sandy soils under grass from Woburn in relation to organic carbon content, and found that:

$$\text{WSA (\%>0.5mm)} = 3.32(\text{OC\%}) - 1.44 \quad (n = 14; r = 0.873; p < 0.001)$$

By examining soil data from long-term experiments at Woburn, Saxmundham and Rothamsted, Rose (1990) found that farmyard manure (FYM) increased available water capacity and aggregate stability by up to 20% in all soils. On sandy soils, however, Db and macroporosity decreased with increasing use of FYM, but changed relatively little on other soils (mostly clay loams and silt loams).

Land use and soil water content were found to influence aggregate stability more than total OC content or polysaccharide content in New Zealand silty and silty clay soils of the same mineralogy, in the sequence (Haynes & Swift, 1990; Swift, 1990):

arable < pasture (<2 yrs) < pasture (>2yrs)

There was considerably more scatter in the data obtained from air-dried samples, than those from field-moist samples of the same soils (Fig. 2).

Fig. 2. Relationship between soil organic carbon content (OC%) and mean weight diameter (MWD) of aggregates for air-dried (ad) and field moist (fm) samples of some New Zealand soils (derived from Haynes & Swift, 1990).

This contrasts with the work of Haynes *et al.* (1991) in a sandy loam, silt loam and a clay loam in New Zealand, which showed that the best predictor of MWD of aggregates was the length of time under grass **and** the amount of hot-water soluble polysaccharide. This was especially true in soils under pasture for more than 4 years. The data showed considerable scatter, and no inflections suggestive of thresholds in OC values. The best fits within the data were given by:

$$\text{MWD} = 0.60(\text{OC}\%) + 0.65: \text{sandy loam}$$

$$\text{MWD} = 1.09(\text{OC}\%) - 0.86: \text{silt loam}$$

$$\text{MWD} = 0.62(\text{OC}\%) + 0.27: \text{clay loam}$$

MWD of water stable aggregates in the 0-5 cm layer of a number of Canadian soils under a range of tillage was found to be linearly related to OC by the following expression (Carter, 1992):

$$\text{MWD}\% = 127 (\text{OC}\%) - 63.4 \quad (r = 0.942; p < 0.001)$$

The maximum 'value' of soil structure, as expressed by MWD was found at 4.5% organic carbon content.

Polysaccharides were again reported to be the prime cause of improvements in aggregate stability in an irrigated coarse loamy soil receiving additions of various amendments (Martens & Frankenberger, 1992). The amendments were most effective in the order:

barley straw>poultry manure>sewage sludge>alfalfa

Statistical treatment of the data, however, gave weak correlations between the properties measured, although $p < 0.001$ in all cases.

Seasonal variation in aggregate stability under different cropping regimes was studied by Chan *et al.* (1993) in Australia, who compared zero tillage (ZT) and conventional tillage (CT) for wheat, with and without a lupin (L) break-crop. Lupins improved aggregate stability under CT, but made no difference under ZT. There was no statistically significant difference between ZT and CT without L ($n = 6$):

$$\begin{aligned} \% \text{Aggregates (50um, CT+L)} &= 0.376 + 0.163 (\% \text{OC}) \quad (r = 0.97; p < 0.1) \\ \text{ditto (250um, CT+L)} &= -0.107 + 0.303 (\% \text{OC}) \quad (r = 0.95; p < 0.1) \end{aligned}$$

Also in relation to CT vs ZT, Beare *et al.* (1994) found that the OM content of the aggregates, rather than of the whole soil, gave a better ranking of aggregate stability, irrespective of tillage practice. However, they gave no numerical data to support this claim (see, also, Franzluebbers & Arshad, 1996, below).

This contrasts with the conclusions of Carter *et al.* (1994) who found no correlation between amounts of SOM, either on a whole soil basis or fractionated, and aggregate stability in a range of soils under long-term cool-temperate *Fescue* grassland in Canada.

Rasiah (1994) and Rasiah & Kay (1994) attempted to calculate the half-life for water-stable aggregates in soils under forage, and arrived at 4.5yrs for a clay loam, and 7.75yrs for a sandy loam. However, they gave no data to show the uncertainty of these modelled results.

Data from long-term continuous wheat experiments in Australia (Grace *et al.*, 1995) showed that between 1925 and 1993, mean soil OC content dropped from 2.75% to 1.56%. In the 0-10 cm soil layer, aggregate stability and AWC increased, despite the drop in OC due, it was thought, to the continual return of 'fresh' crop residues to the soil. Similarly, yields of wheat gradually increased from 1.53 t ha⁻¹ to 1.87 t ha⁻¹ as the effect of the 'fresh' OM had an increasing effect on AWC.

The effect of OC from different sources on aggregate stability was examined by Puget *et al.* (1995) for a silty soil under conventional and zero tillage in the Paris Basin. Young C4-carbon from <6 to 23 years in age, and located in the aggregates rather than dispersed through the soil, was responsible for most of the stability of soil aggregates >1 mm in size. OC contents of this soil ranged from $\approx 1\%$ to 2.5%.

In long-term (38 yr) experimental plots at Ultuna, Sweden, Gerzabek *et al.* (1995) reported that SOM which encouraged greater production of soil microbial biomass (SMB) gave greater aggregate stability. Thus, fallow plots had the least aggregate stability, and plots receiving farmyard manure, the greatest, which accords with the findings of Rose (1990). Peat additions to soils were found to give relatively little increase in SMB, and thus improved aggregate stability relatively little. This is

paralleled by the work of Friedel *et al.* (1996), who also found that the amount of young 'microbially-active' SOM was closely related to water stable aggregation ($r = 0.936$).

Unger (1995) made the point that many studies of the interaction between SOM and aggregate stability could be flawed, because too great a depth of soil was examined. In a study of ridge-tilling, he found that most benefit from SOM was confined to the top 4 cm of the soil. Sampling from greater depths obscured this benefit.

Also in Canada, ZT increased the amount of OC sequestered in aggregates $>0.25\text{mm}$ in the upper 125mm of a Gray Luvisol (clay content = 18%) from 0.16 kg m^{-2} to 0.34 kg m^{-2} over a period of up to 16 years, as compared to the same soil under conventional tillage (Franzluebbers & Arshad, 1996). The length of time under grass was found by Jastrow (1996) to influence strongly the amount of organic carbon in the aggregates themselves, as expressed by:

$$\text{aggregate OC\%} = 96.6(1 - 0.637^{-0.012 \text{ yrs since cultivation}})$$

The effect of other soil components

Kemper & Koch (1966) included exchangeable sodium, iron and aluminium in the regression equations used to predict aggregate stability, but noted that these contributed little to the explanation of the variance, and could probably be omitted without meaningful loss of precision.

This seems to fit with the work of Hamblin & Greenland (1977), who noted that removal of the organically-bound iron and aluminium from East Anglian silty soils greatly decreased aggregate stability, but were unable to show a quantitative relationship between this decrease and the amounts of Fe, Al and C extracted.

Douglas & Goss (1982) also noted that the amount of organically-bound iron and aluminium (although very small: generally $<0.2\%$) in the Hamble, Lawford and Denchworth soils contributed to aggregate stability, but not so in the calcareous Andover soil. Similarly, both Bartoli & Philippy (1990) and Goldberg *et al.* (1990) reported that removal of Fe and Al from soils by acetylacetone (a known extractant for organically-bound Fe and Al) greatly increased the amount of water-dispersible clay. Wierzchos *et al.* (1992) showed that as little as 0.02M organically-bound Al or Fe kg^{-1} soil was enough to give a measurable degree of aggregate stability. Gu & Doner (1993) calculated that that 0.15M Al kg^{-1} soil, in association with 1% SOM, could give rise to similar effects.

Bulk Density (Db) and shrinkage

In his study of UK soils, Williams (1971) found that:

$$\begin{aligned} \text{Db (arable)} &= 1.42 - 0.78(\text{Total N\%}) \text{ [38\% variance explained]} \\ \text{Db (grass)} &= 1.37 - 0.76(\text{OC\%}) \text{ [69\% variance explained]} \end{aligned}$$

Graphs presented by Williams (1971) showed an inflection at ca 2% OC, below which little change in Db occurs (note, however, that the number of points on this graph is remarkably small for a dataset drawn from 189 soils- no explanation is given for this). Williams did not fit a curve to these data, so it is not possible to say that the inflection point could be justified mathematically.

Hamblin (1977) and Hamblin & Davies (1977) investigated the influence of soil organic carbon content on the Liquid and Plastic Limits, air-filled porosity ($pF < 5.0$), pore size distribution ($pF 1.0$ to 5.0), shrinkage (assumed to be linear) and Db of silty soils in Eastern England (Beccles, Newchurch, Agney, Romney and Sheringham Series). Although they present their findings in terms of 'high organic' and 'low organic' soils, they somewhat frustratingly do not state explicitly the numerical criterion which they use to form the two groups. Internal evidence in Hamblin (1977) suggests that this might have been 2% organic carbon, but this cannot be confirmed. Values of Db between ca $pF 2$ and $pF 5$ are consistently 0.2 g/cm^3 higher in the 'low organic' soils. Hamblin & Davies (1977) give the following regression equations:

$$\text{Low organic soils: } Db (\text{g/cm}^3) = 1.31 + 0.12pF$$

$$\text{High organic soils: } Db (\text{g/cm}^3) = 1.07 + 0.13pF$$

Shiel & Rimmer (1984) also carried out a study of the relationship between OC and Db at Cockle Park, and gave the relationship:

$$Db (\text{g/cm}^3) = 1.62 \times 0.134(\text{OC}\%) \quad (r = -0.99)$$

In a rather similar study to that of Douglas & Goss (1982), Carter (1987) studied the influence of tillage practices on the relationship between Db and soil organic carbon content, and found:

$$Db \text{ max} = 1.62(\text{OC}\%)^{-0.079} \quad (r^2 = 0.90; n = 16)$$

Although the magnitudes of the components of the equation are not so very different to those of Shiel & Rimmer (1984), Carter (1987) found a distinctly curvi-linear relationship, and not the straight line shown or implied by most other workers. There are no inflections in this curve over the range of carbon values shown (ca 0.3% to 2.1%).

Ekwue (1990) gives the following relationship for Db in sandy soils under grass from Woburn:

$$Db = 1.61 - 0.09(\text{OC}\%) \quad (n = 29; r = -0.977; p < 0.001)$$

Cannell *et al.* (1994) also found a linear relationship between Db and SOM in soils in a cultivation experiment extending over 18 years of different tillage practices:

$$Db = -0.102(\% \text{OM}) + 2.07 \quad (r^2 = 0.93; p < 0.001)$$

Porosity and water retention properties

Hamblin (1977) and Hamblin & Davies (1977) found that all the 'low organic' soils had lower total porosities at all suctions than the 'high organic' soils. From the graphs presented in their papers, these differences were <1% at pF1 to almost 10% at pF4, although most are <5%. Shrinkage is ca 5% less at pF2 to <1% less at pF4 in the low organic soils, and was described by the following equations:

$$\text{Low organic soils: Shrinkage} = 27.63 - 5.04pF$$

$$\text{High organic soils: Shrinkage} = 31.8 - 5.88pF$$

Water content at pF2 correlated strongly with total organic carbon ($r = 0.91$; $p < 0.001$), as did Db at pF2.5 ($r = -0.94$; $p < 0.001$) and maximum compaction density ($r = -0.93$; $p < 0.001$). Some of these differences in behaviour (and also for Db, above) were attributed by Hamblin (1977) to the fact that the high organic soils contained greater amounts of humified OM in the 2-50 micrometre fractions than the low organic soils, whilst the latter contained more humified OM in the <2 micrometre fractions.

There have been numerous attempts to relate soil water retention properties to SOC or SOM. Hollis *et al.* (1977) examined the relationships between SOC and both water held at -5kPa ($-5Q_{vf}$), and available water (A_{vf}) (both on a volumetric basis in <2mm soil) within 77 soil profiles from the West Midlands. The curvi-linear relationship between OC and $-5Q_{vf}$ in the surface horizons was described by:

$$-5Q_{vf} = 23.88 + 7.85(OC) - 0.43(OC)^2 \quad (\% \text{ variance explained} = 73.5)$$

The plotted curve is smooth with no apparent clustering of the data. The authors make the point that where OC is the same in different soils, then differences in $5Q_{vf}$ and (A_{vf}) can be due to different amounts of clay and silt.

Thomasson & Carter (1989) also examined the relationship between water retention properties and factors such as SOC by stepwise regression, using the data in LandIS. It can be seen from Table 1 that SOC generally explains only between ca 11% and 4% of the variance in Q_{vf} , the greatest influence being at smaller suctions.

Carter (1992) found a linear relationship between Q_{vf} (-1500kPa) and OC in the soil layer 0-5 cm depth under a range of tillage practices in Canada:

$$Q_{vf}(-1500kPa) = 7.2 + 2.3(\% OC) \quad (r = 0.97; p < 0.001)$$

Table 1. Factors explaining variation in water retention in topsoils in England & Wales (after Thomasson & Carter, 1989).

Factor	% Clay <2µm	+ % Silt (2-63µm)	+ % Organic carbon	% from Organic carbon	+ Bulk density	n
% Variance explained						
$Q_{vf}(-5kPa)$	44.2	50.8	62.0	11.2	70.2	516
$Q_{vf}(-10kPa)$	50.2	58.0	67.0	9.0	71.8	473
$Q_{vf}(-40kPa)$	57.7	65.3	71.7	6.4	73.4	463
$Q_{vf}(-200kPa)$	63.7	68.7	75.1	6.4	75.1	341
$Q_{vf}(-1500kPa)$	65.4	66.9	70.7	3.8	70.7	520

Other soil physical properties

Kemper *et al.* (1987) found that, in a series of reconstituted soils (5% to 40% clay; <0.6% to 1.2% OC), recovery of cohesion was ca 100x faster in soils with >35% clay and <0.6% OC, than in the other soils. It was assumed that this reflected the ability of clay particles to form stable inter-particle bonds more quickly in the absence of OC.

In sandy soils from Woburn, Ekwue (1990) found that shear strength was related to OC by:

$$\text{shear strength} = 20.61 + 0.67(\%OC) \quad (n = 29; r = 0.52; p < 0.001)$$

Cohesion and the angle of friction were found to be controlled by both SOM content, but only in amounts >5%, and water held at suctions <-50kPa in sandy soils in North Germany (Bachmann & Zhang, 1991).

Auerswald (1995) found a linear relationship between 'percolation stability' (PS) (see, also Greenland *et al.*, 1962), pH and SOM content in aggregates 1-2 mm diameter from arable topsoils:

$$PS = (14 - pH) \times \%SOM \quad (r^2 = 0.72; p < 0.001; n = 113)$$

Soil erosion is one aspect of soil physical behaviour in which organic carbon content is regarded as a factor. Data for the UK appear to be lacking, but Bernito & Diaz-Fierros (1992) presented data from Spain, from which Figure 3 is derived. The relationship for soils under cereals is, effectively, non-existent, whilst that for soils under pasture is more definite. From the graph, it would seem that soil loss decreases markedly above a soil organic carbon content greater than about 3% to 4%.

Fig.3. Relationship between soil organic carbon content (OC%) and soil loss ($\text{g m}^{-2} \text{ month}^{-1}$) under different land-uses in Spain (derived from Bernito & Diaz-Fierros, 1992).

Under Australian conditions, Malinda (1995) found that soil loss from 10yr plots under wheat, was strongly controlled by soil OC content, with a steep increase in amounts of soil loss at OC contents <1.6%:

$$\text{soil loss (t/ha/yr)} = 31 + 16(\% \text{OC}) - 45(\sqrt{\% \text{OC}}) \quad (r = 0.87)$$

Part 3: Further Work

1. Around 50% of the N taken up by fertilized crops is derived from mineralization of SOM. However, microbes associated with SOM also immobilise ca 30-50% of fertiliser N additions. Thus SOM may both provide and deny N to crops. Some recent studies suggest that fertiliser recovery may increase as SOM decreases, and hence as the supply of soil N decreases so the uptake of N-fertiliser may increase. This interaction needs further investigation, initially through the literature.
2. To assess the magnitude of the returns of fresh OM to soils to maintain adequate buffering of soil nutrient reserves and structural properties.
3. To examine ways in which the current data held within England and Wales can be further stratified, e.g. in terms of land use, soil group, range of SOM contents as to better understand the contribution of SOM to other measured properties - especially WHC.
4. To consider the feasibility of measuring the active fraction of SOM on a routine basis and the correlation of this with other soil properties, including total SOM.

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Critical Levels of Soil Organic Matter

MAFF Project SP0306

Annex 2 to CSG15_SP0306: Figures and Tables

Fig. 1. The relationship between land use category and SOC (soil profile topsoil data; n=1261).

Fig. 2. The relationship between soil organic carbon content (SOC %) and dispersion ratio (DR %) (n=365)

Fig. 3. Relationship between soil organic carbon content (SOC) and plastic limit (PL) (n=365).

Fig. 4. Relationship between topsoil organic carbon content and potentially mineralisable N, all soils.

Fig. 5. Change in SOC modelled by CENTURY compared with change in measured SOC in some Fen Silt soils (solid line is fitted to data; dashed line is 1:1).

Fig. 6. Comparison of CENTURY and RothC for modal soils under fallow

Fig. 7. Change in SOC in modal soils using C returns at 3 N levels (see text) (ROTHC).

Fig. 8. Effect of climate change on SOC for modal soils (standard N input) (ROTHC).

Fig. 9. Effect of using modal NSI soil texture groups for soils (standard N input) (ROTHC)

Fig. 10. Behaviour of high SOC soils (from the NSI database) in relation to clay content (standard N input and no inputs) (ROTHC).

Fig. 11. Change in SOC for cut and grazed (improved) grass according to RothC.

Fig. 12. Distribution of soils in England and Wales according to their possible equilibrium topsoil SOC contents predicted from texture class (see text). Soils with more than 18 per SOC were not modelled as they are primarily peat soils.

Fig. 13. Soil organic carbon contents (%) - original NSI data.

Fig. 14. Distribution of soils in England and Wales according to the difference in their topsoil SOC contents predicted from texture class (see Fig. 12) and the amounts of SOC measured during the NSI.

Table 1. Linear correlation coefficients (r) between Liquid Limit (LL), Plastic Limit (PL) and other soil properties.

	SILT(%)	CLAY(%)	LL(%)	SOC(%)	PL (%)
SILT (%)	1				
CLAY (%)	-0.483	1			
LL (%)	-0.403	0.733	1		
SOC (%)	0.059	-0.008	0.269	1	
PL (%)	-0.019	0.392	0.593	0.683	1

Table 2. Relationships between volumetric water content of topsoils and various factors: Clay (C), Silt (Z), Organic Carbon (SOC)).

Regression Equations	Variance accounted for (%)
Topsoils – all landuses	
$\theta(-5\text{kPa})=22.44+0.28\text{C}+0.14\text{Z}+1.63\text{SOC}$	66
$\theta(-10\text{kPa})=19.45+0.33\text{C}+0.15\text{Z}+1.33\text{SOC}$	69
$\theta(-40\text{kPa})= 15.25+0.39\text{C}+0.15\text{Z}+0.82\text{SOC}$	74
$\theta(-200\text{kPa})= 10.07+0.43\text{C}+0.11\text{Z}+0.52\text{SOC}$	72
$\theta(-1500\text{kPa})=6.14+0.39\text{C}+0.06\text{Z}+0.38\text{SOC}$	75
Topsoils - arable	
$\theta(-5\text{kPa})=20.11+0.39\text{C}+0.12\text{Z}+1.25\text{SOC}$	75
$\theta(-10\text{kPa})=17.36+0.43\text{C}+0.14\text{Z}+0.95\text{SOC}$	79
$\theta(-40\text{kPa})= 13.82+0.45\text{C}+0.13\text{Z}+0.79\text{SOC}$	80
$\theta(-200\text{kPa})= 9.47+0.44\text{C}+0.10\text{Z}+0.66\text{SOC}$	80
$\theta(-1500\text{kPa})=4.94+0.42\text{C}+0.06\text{Z}+0.47\text{SOC}$	83
Topsoils – Ley grassland	
$\theta(-5\text{kPa})=21.1+0.25\text{C}+0.15\text{Z}+2.12\text{SOC}$	63
$\theta(-10\text{kPa})=17.94+0.32\text{C}+0.16\text{Z}+1.93\text{SOC}$	70
$\theta(-40\text{kPa})= 13.28+0.37\text{C}+0.16\text{Z}+1.72\text{SOC}$	76
$\theta(-200\text{kPa})= 8.63+0.46\text{C}+0.10\text{Z}+1.30\text{SOC}$	78
$\theta(-1500\text{kPa})=3.79+0.45\text{C}+0.05\text{Z}+0.92\text{SOC}$	82
Topsoils – Permanent grassland	
$\theta(-5\text{kPa})=29.57+0.91\text{C}+0.11\text{Z}+1.13\text{SOC}$	50
$\theta(-10\text{kPa})=25.53+0.24\text{C}+0.14\text{Z}+0.97\text{SOC}$	56
$\theta(-40\text{kPa})= 19.68+0.31\text{C}+0.15\text{Z}+0.61\text{SOC}$	64
$\theta(-200\text{kPa})= 14.71+0.38\text{C}+0.12\text{Z}$	55
$\theta(-1500\text{kPa})=9.74+0.35\text{C}+0.06\text{Z}$	60
Topsoils – other landuses	
$\theta(-5\text{kPa})=18.96+0.27\text{C}+0.16\text{Z}+2.13\text{SOC}$	74
$\theta(-10\text{kPa})=15.61+0.41\text{C}+0.15\text{Z}+1.84\text{SOC}$	76
$\theta(-40\text{kPa})= 12.30+0.54\text{C}+0.10\text{Z}+0.97\text{SOC}$	80
$\theta(-200\text{kPa})= 8.01+0.57\text{C}+0.11\text{Z}$	80
$\theta(-1500\text{kPa})=7.57+0.44\text{C}$	73

Table 3. Cumulative percent variance in volumetric water content explained by various factors.

Factor	Sqrt Clay (<2mm)	+ Silt (2-60mm)	+ ln(Organic Carbon)	No. of Samples
	%Variance explained			
All Topsoils				
$\theta(-5\text{kPa})$	47.1	51.7	70.8	652
$\theta(-10\text{kPa})$	55.0	60.3	74.1	597
$\theta(-40\text{kPa})$	65.4	70.6	77.4	597
$\theta(-200\text{kPa})$	68.9	71.9	75.5	516
$\theta(-1500\text{kPa})$	74.4	74.9	77.8	652
Topsoils - Arable				
$\theta(-5\text{kPa})$	62.8	66.2	76.4	248
$\theta(-10\text{kPa})$	67.9	71.7	78.8	222
$\theta(-40\text{kPa})$	70.5	74.2	79.4	222
$\theta(-200\text{kPa})$	72.8	74.9	79.7	208
$\theta(-1500\text{kPa})$	79.0	79.0	82.1	248
Topsoils – Ley grass				
$\theta(-5\text{kPa})$	43.8	53.5	61.5	106
$\theta(-10\text{kPa})$	53.7	63.1	68.9	94
$\theta(-40\text{kPa})$	63.6	72.0	75.8	94
$\theta(-200\text{kPa})$	72.6	75.4	77.8	81
$\theta(-1500\text{kPa})$	79.5	79.5	80.4	106
Topsoils – perm. grass				
$\theta(-5\text{kPa})$	38.7	42.3	55.7	238
$\theta(-10\text{kPa})$	46.2	51.8	61.6	227
$\theta(-40\text{kPa})$	56.7	64.1	68.8	227
$\theta(-200\text{kPa})$	54.6	59.3	61.8	178
$\theta(-1500\text{kPa})$	64.7	65.5	67.8	238
Topsoils – other landuses				
$\theta(-5\text{kPa})$	36.4	48.1	74.9	58
$\theta(-10\text{kPa})$	46.1	55.8	76.6	52
$\theta(-40\text{kPa})$	67.5	67.5	79.7	52
$\theta(-200\text{kPa})$	75.9	75.9	75.9	47
$\theta(-1500\text{kPa})$	72.2	72.2	72.2	58

Table 4. Effect of clay content and land use stratification.

Landuse	Clay content	Equation	% variance explained	No. of observations
Arable	>35%	$\theta(-5\text{kPa})=17.40+3.72\sqrt{C}+4.19\ln\text{SOC}$	48	45
	Between 18 and 35%	$\theta(-5\text{kPa})=20.34 +1.84\sqrt{C} +0.10Z +5.98\ln\text{SOC}$	43	109
	<18%	$\theta(-5\text{kPa})=20.81 +1.08\sqrt{C} +0.13Z +4.80\ln\text{SOC}$	56	101
Ley grassland	>35%	$\theta(-5\text{kPa})=-15.71 +7.09\sqrt{C} +0.33Z$	61	14
	Between 18 and 35%	$\theta(-5\text{kPa})=13.60+5.05\sqrt{C}$	16	44
	<18%	$\theta(-5\text{kPa})=23.86 + 0.20Z+5.50\ln\text{SOC}$	58	48
Permanent grass	>35%	$\theta(-5\text{kPa})=36.36+2.06\sqrt{C}$	9	55
	Between 18 and 35	$\theta(-5\text{kPa})=28.83 + 0.11Z + 8.69\ln\text{SOC}$	34	125
	<18%	$\theta(-5\text{kPa})=19.9+3.18\sqrt{C}+0.07Z +4.70\ln\text{SOC}$	31	58
Other landuses	>35%	No significant relationship		7
	Between 18 and 35	$\theta(-5\text{kPa})=24.75 +12.7\ln\text{SOC}$	43	17
	<18%	$\theta(-5\text{kPa})=20.36 +0.14Z+8.55\ln\text{SOC}$	70	33

soil type	%clay	initial%C	Bulkdensity	initial tonnes/ha	C initial DPM	Initial RPM	Initial BIO	Initial HUM	Initial IOM	radioage DPM	radioage RPM	radioage BIO	radioage HUM
sands	7	1.27	1.5	38.1	0.3538	6.2046	0.6841	26.2059	4.65	0.24	10.93	29.38	188.9
light(other soils)	loams 10	0.94	1.4	26.32	0.1915	4.1035	0.4901	18.7836	2.77	0.28	11.02	30.88	190.37
shallow chalk	25	2.61	1.2	62.64	0.4871	8.5101	1.2542	48.0093	4.4	0.25	10.92	35.96	195.46
clay	30	1.85	1.1	40.7	0.2994	5.4217	0.8291	31.7714	2.4	0.25	10.78	36.38	193.39
silt	30	1.28	1.2	30.72	0.1912	4.0417	0.6216	23.8283	2.04	0.28	10.85	36.4	193.39
ADAS data													
sands	7	1.33	1.5	39.9	0.4079	6.9049	0.7602	29.1178	2.71	0.24	10.91	29.38	188.9
light(other soils)	loams 10	1.1	1.4	30.8	0.2456	4.8039	0.5719	21.9144	3.26	0.26	10.98	30.87	190.37
shallow chalk	25	2.66	1.2	63.84	0.5056	8.7442	1.2881	49.3069	4	0.24	10.92	35.96	195.46
clay	30	1.62	1.1	35.64	0.2453	4.7317	0.7254	27.7998	2.14	0.26	10.81	36.39	193.39
silt	30	1.62	1.2	38.88	0.2668	5.0968	0.7811	29.9184	2.78	0.26	10.8	36.36	193.38
extra sand	7	2.33	1.5	69.9	0.762	12.4566	1.3694	52.4131	2.9	0.23	10.89	29.36	188.9
NSI data													
sand	11.6	1.8	1.45	52.2	0.4375	8.2545	1.0153	38.867	3.63	0.26	10.96	31.57	191.09
shallow chalk	25	2.77	1.26	69.804	0.5457	9.6552	1.4236	54.497	3.68	0.25	10.93	35.96	195.46
clay	25.9	2.7	1.21	65.34	0.4912	8.9291	1.3277	50.8299	3.8	0.25	10.91	36.05	195.08
silt	14.2	2	1.28	51.2	0.4284	7.8057	1.0068	38.5449	3.42	0.25	10.94	32.66	192.17
Extreme NSI points													
15% clay	15	11	1.3	286	2.73	45.6645	5.9492	227.5354	3.8	0.24	10.89	32.94	192.48
30% clay	30	11	1.15	253	2.3654	35.5797	5.3971	206.5221	3.2	0.22	10.68	36.33	193.38
45% clay	45	11	1.1	242	2.1743	32.3089	5.1666	197.7594	4.6	0.22	10.5	37.18	191.6

Table 5. Parameters used in the RothC model runs.

Table 7. Average yield and SOC returns based on ADAS field experiments (std = yield or return, as appropriate, under standard fertiliser-N recommendation; -50kg = standard minus 50 kg N ha⁻¹; -100kg = standard minus 100 kg N ha⁻¹).

Average data from ADAS winter wheat, winter barley and spring barley experiments								
soil type	SOM%	SOC%	grain yld t ha ⁻¹ at 85%DM			annual return of C t ha ⁻¹ including root exudates		
			std	-50kg	-100kg	std	-50kg	-100kg
shallow	4.6	2.66	6.64	6.11	5.03	2.33	2.28	2.19
clay	2.8	1.62	8.79	8.50	7.89	2.45	2.43	2.40
silt	2.8	1.62	8.09	7.97	7.60	2.41	2.41	2.39
sand	2.3	1.33	6.80	6.56	5.79	2.34	2.32	2.26
other	1.9	1.10	6.63	6.24	5.36	2.32	2.30	2.22

Table 8. Effect of nitrogen application on amount of organic N stabilised (kg N ha⁻¹).

soil type	N applied 0 kg/ha	N applied 50 kg/ha	N applied 100 kg/ha	N applied 150 kg/ha	N applied 200 kg/ha	N applied 250 kg/ha
sand	405	544	610	641	657	661
clay	285	492	682	867	1001	1071

Table 9. Effect of nitrogen application on amount of mineralisation (kg N ha⁻¹).

soil type	Time	N applied 0 kg/ha	N applied 50 kg/ha	N applied 100 kg/ha	N applied 150 kg/ha	N applied 200 kg/ha	N applied 250 kg/ha
sand	after 1 wk	-7.4	-12.5	-13.4	-11.9	-10.0	-8.6
sand	after 1 yr	-15.9	-26.0	-25.0	-17.2	-9.4	-4.1
clay	after 1 wk	-13.7	-22.8	-28.0	-30.0	-30.5	-30.2
clay	after 1 yr	-30.4	-49.9	-59.3	-59.9	-57.6	-55.0