MINISTRY OF AGRICULTURE, FISHERIES AND FOOD

Date project completed:
31/03/1997

Research and Development

Final Project Report

(Not to be used for LINK projects)

Section 1 : Identification sheet

1. (a) MAFF Project Code: **SP0303**

(b) Project Title: To quantify the effects of cultivations on soil stability and on organic matter

(c) MAFF Project Officer: Dr. P. Costigan

(d) Name and address of contractor:
Silsoe Research Institute,
Wrest Park,
Silsoe,
Bedford
Postcode MK45 4HS

(e) Contractor's Project Officer: Prof. A.R. Dexter

(f) Project start date: 01/04/1992 Project end date: 31/03/1997

(g) Final year costs:

approved expenditure	£111,288
actual expenditure	£104,125

(h) Total project costs / total staff input:

approved project expenditure	£620,862
actual project expenditure	£589,249
***approved** staff input	9
***actual** staff input	10

(i) Date report sent to MAFF: 24/04/1997

(j) Is there any Intellectual Property arising from this project ? NO

***staff years of direct science effort**

Section 2 : Scientific objectives / Milestones

2. Please list the scientific objectives as set out in CSG 7 (ROAME B). If necessary these can be expressed in an abbreviated form. Indicate where amendments have been agreed with the MAFF Project Officer, giving the date of amendment.

1. To develop a laboratory apparatus for the rapid assessment of the effects of soil factors and machinery factors on the decomposition of soil organic matter.
2. To do further tests on the effects of mechanical energy inputs on the destabilisation of soil as measured by the increase in the content of readily-dispersible clay. In particular, soils with a range of organic matter contents will be examined.
3. To determine the effects of mechanical energy inputs on soil respiration (as a measure of the rate of depletion of soil organic matter) over a range of soil water conditions.
4. To test the hypotheses that depletion of soil organic matter is positively correlated with organic matter content, energy input and clay dispersibility.
5. To propose a simple model to account for the respiration rates measured for the limited range of soils which it will be possible to investigate.
6. To seek a link between the laboratory results obtained in this project and the results from existing and previous field experiments on mineralization of soil organic matter as influenced by tillage practices.

3. List the primary milestones for the final year.

It is the responsibility of the contractor to check fully that ALL primary milestones have been met and to provide a detailed explanation if this has not proved possible

Milestones		Target date	Milestones met?	
Number	Title		in full	on time
1	Determine the effects of mechanical energy inputs on soil respiration at different soil water contents (laboratory tests)	30/11/1996	YES	YES
2	Characterise soils used in (1)	30/11/1996	YES	YES
3	Comparison made between laboratory tests with energy inputs from different cultivation machinery and associated mineralization of organic matter	30/11/1996	YES	YES
4	Correlations sought between respiration, increase in dispersible clay, and the content of soil organic matter	30/11/1996	YES	YES
5	Preparation of papers presenting main scientific findings and environmental implications	28/02/1997	YES	YES

If any milestones have not been met in the final year, an explanation should be included in Section 5.

Section 3 : Declaration

4. I declare that the information I have given in this report is correct to the best of my knowledge and belief. I understand that the information contained in this form may be held on a computer system.

Signature: A.R. Dexter

Date: 25/04/1997

Name: A.R. DEXTER

Position in Organistation: Head of Soil Science Group

Section 4 : Executive summary

Rationale:
The maintenance of the soil resources is a key MAFF policy objective. Soil must be protected against long-term degradation which may compromise the ability of UK soils to provide a competitive agricultural industry into the future.

Main objectives:
To develop laboratory methods for the investigation of the effects of mechanical energy inputs (such as from tillage) on soil stability and on loss of organic matter through respiration.

To use these methods to quantify the effects of mechanical energy inputs on soil stability on loss of organic matter.

Methods:
Several new methodologies were developed because the work was completely novel, and no precedents were available. Additionally, the latest technical developments were exploited in turbidimetry (for measurement of dispersed clay), and in the data logging of alternating voltages (which enabled us to design and build conductimetric respirometers).

Findings:
We developed new, quantitative measures of the stability of soils, for the sensitivity of soils to mechanical damage, for soil friability, and for the effects of mechanical energy inputs on loss of soil organic matter through increased respiration.

All of these are powerful new measures of soil physical quality.
The measure of "sensitivity of soils to mechanical damage" provides a method for identifying soils at risk.

We have shown that for relatively dry soils, inputs of mechanical energy do not increase the amount of dispersible clay. However, for wet soils, the amount of dispersible clay increases with increasing water content and increasing energy input.

We have discovered that soil organic matter reduces the effects of mechanical energy input in destabilising soil and is also associated with increased values of soil friability. Both of these properties are measures of soil physical quality.

We have also found that mechanical energy input to soil can increase the rate of organic matter loss by microbial respiration - this effect is strongly related to clay dispersibility and indicates the key role of clay in protecting soil organic matter against microbial degradation.

The relative increase in respiration resulting from mechanical energy inputs was greater for degraded soils with low contents of organic matter. Respiration rates of soils with high levels of organic matter were little affected by mechanical energy inputs. This illustrates the key role of organic matter in protecting itself and shows that degraded soils are especially sensitive to further degradation.

Technology transfer:
The work has resulted in a series of major publications which are already attracting considerable international interest. An article is being prepared for an industry journal "The Furrow". Aspects of the work have been presented at several scientific meetings and to groups of people from industry.

Incorportation into codes of practice:
The findings could be incorporated into the Code of Good Agricultural Practice for the Protection of Soil. This could enable the boundaries between "good" and "bad" practices to be better defined.

Opportunities for further work:
The project has resulted in powerful new methodologies and several important new results. These can be used:-

(i) to determine minimum acceptable levels of organic matter in UK soils which are required to maintain soil physical quality,
(ii) to determine the relationship between the new laboratory tests and the susceptibility of soil to erode or to generate particulate transport in the environment,
(iii) to quantify the effects of cultivation practices on the increased release of nitrate through increased mineralization of organic matter and the consequences of this release for plant uptake or for pollution of waters.
(iv) to develop ways in which the amount of physically-protected organic matter in degraded agricultural soils can be increased to improve soil physical quality, and,
(v) to make surveys of UK soils to determine reference levels of soil physical quality.

Section 5 : Scientific report

Scientific Report

The overall objective of this project was to quantify the effects of cultivations on two principal measures of soil quality. The measures involved are clay dispersibility and soil respiration. Novel laboratory techniques have been devised in which the effects of mechanical energy inputs, such as occur during tillage, are applied to a range of soils and measurements are made of both soil stability and mineralization. These experiments are conducted over a wide range of soil water contents.

New Methodology (Objective 1)

A novel laboratory technique has been developed which has enabled us to study in the laboratory the effects of mechanical energy inputs to soil on soil stability and organic matter. The new method is of extreme simplicity and involves dropping a standard mass onto soil samples collected from a field. In spite of this simplicity, correlations between the effects of energy inputs on clay dispersibility in the laboratory using this device, and the effects of measured energy inputs to soil from different tillage implements in the field, show almost perfect agreement.

Soil Stability (Objective 2)

Soil stability was assessed by measuring the quantity of mechanically-dispersed clay, using a turbidimetric technique. Measurements were also made on a larger structural scale, on the quantity of water stable aggregates greater than 250 μm. Dry aggregate stability and friability were determined where appropriate using an indirect tension test.

The specific energy associated with different tillage practices ranging from zero input to intensive powered tillage was simulated using a simple falling weight apparatus (Watts *et al.*, 1996a). Results indicate that the sensitivity of soil to mechanical damage is essentially zero at water contents below the plastic limit. However, with increasing soil water contents, the sensitivity to destablisation increases sharply. A simple empirical model was devised to characterise these phenomena.

$$T = C + A_w + BEk^s, \qquad (1)$$

where T is turbidity (used to characterise mechanically dispersed clay), w, is gravimetric water content (g 100g^{-1}), E is specific energy (J kg^{-1}) with A, B, C empirical coefficients. K is a measure of the degree of plasticity of the soil.

This model was evaluated under field conditions using different tillage implements, operating over a range of soil water contents (Watts *et al.*, 1996b). Tillage energy was measured directly. Good agreement was obtained between the levels of destabilisation measured in the field following cultivation and those obtained in the laboratory using simulated tillage, at similar specific energy values. These field experiments also showed that increased levels of dispersible clay following tillage were responsible for both stronger and less friable aggregates on subsequent drying.

As part of this work, a quantitative, physically-based stability index I, was developed in which

$$I = \left(1 - \frac{T}{T_r}\right)\left(1 - \frac{Y}{Y_r}\right), \qquad (2)$$

where T and T_r are the amount of mechanically-dispersible clay in natural and remoulded aggregates respectively, and Y and Y_r are the tensile strengths of dry natural and remoulded aggregates respectively. I ranks the soils on a scale from zero (a poor soil which is unstable when wet and strong when dry) and one (a good soil which is stable when wet and weak when dry). This index has been used to quantify a range of management regimes on soil physical quality (Watts *et al.*, 1996c). This work has quantified the adverse effects of wheel traffic, intensive tillage and monocropping in contrast with zero-traffic, direct drilling and rotational cropping.

Further experiments have been conducted to assess the long term impact of different management practices on soil structural condition. A range of soils was used, all with similar origins, but a subsequent 50 year history under differing management regimes. This has resulted in a set of soils with organic matter contents ranging from 1.1 to 3.2 g 100g^{-1}. We are thus able to refine our model further by linking clay dispersion, soil organic matter, and soil water content to energy of disruption (Watts *et al.*, 1997a). This work led to the development of a second index, S, which quantifies the sensitivity of soil to destabilisation by mechanical energy inputs, such as might be induced by tillage operations, wheel traffic and raindrop impacts. It is given by:

$$S = \frac{d}{dE}\left(1 - \frac{T}{T_r}\right), \qquad (3)$$

where E is the mechanical energy input per unit mass of soil. This index has been used to quantify the effects of organic matter and water potential in reducing the sensitivity of soil to mechanical damage (Fig. 1).

Other work has briefly studied the tendency of soils to recover from mechanical damage through the action of wetting/drying cycles (Grant *et al.*, 1995).

Soil Respiration (Objective 3)
Using the same laboratory-based techniques to simulate tillage as described above, we have been able to measure the effects of mechanical energy, on a range of soils and at different water contents, on the mineralization of organic matter (Watts *et al.*, 1997b). Mineralization is characterised by measuring soil respiration. For this purpose we have designed and built a set of data-logging conductimetric soil respirometers (Watts *et al.*, 1996d) which allow us to monitor continually the output of CO_2 from soil, following the application of different amounts of mechanical energy.

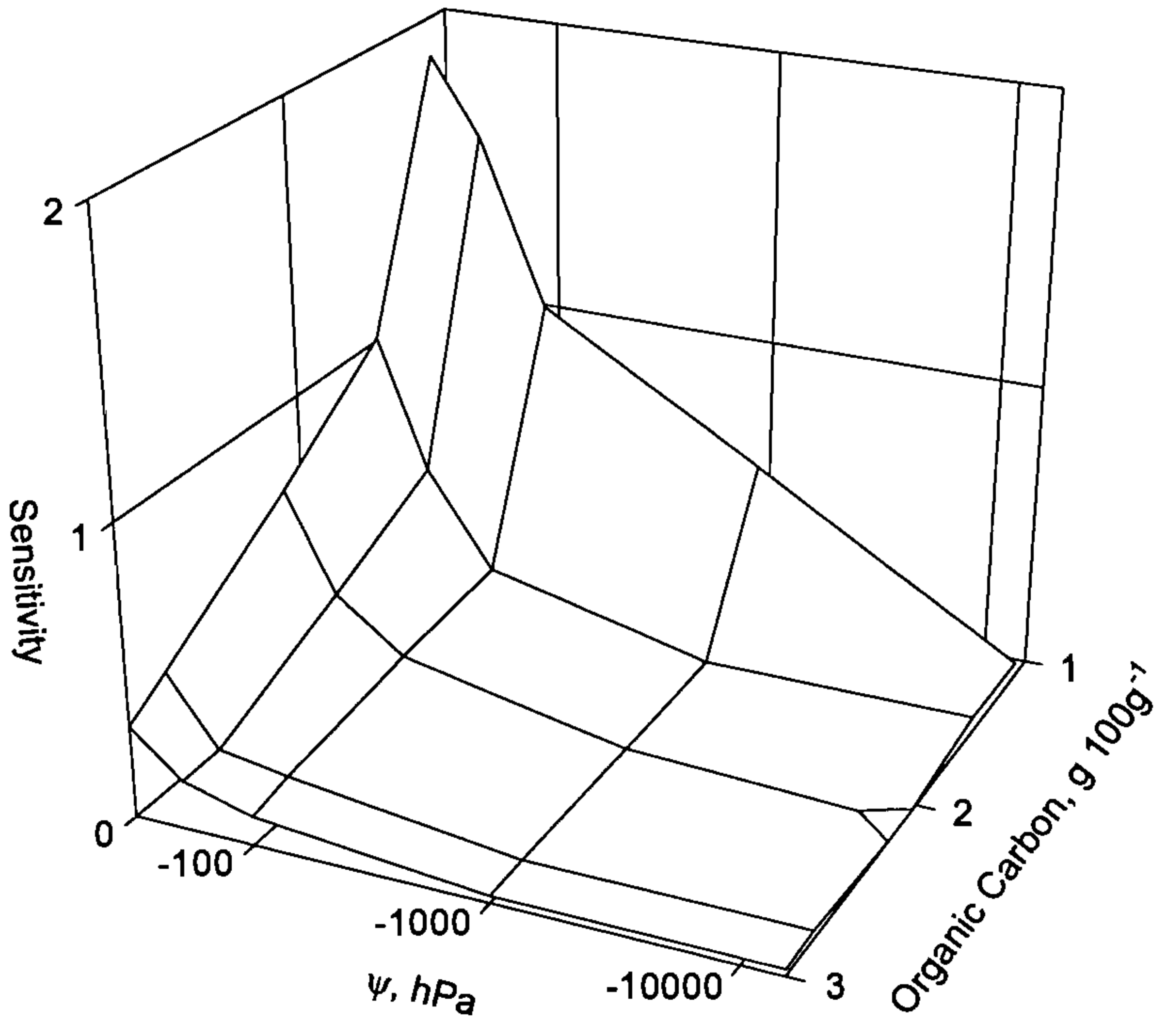

Fig. 1 Sensitivity, *S*, of soil to mechanical damage during simulated tillage as influenced by organic carbon (SOC) and water potential (ψ)

Factors which cause increased respiration (Objective 4)
Increased levels of soil respiration have been measured on soils with higher organic carbon contents, and increased levels of CO_2 are also associated with soils as they move from relatively dry to increasingly moist. By contrast, reduced CO_2 outputs are associated with soils low in organic matter and soils as they become very wet and approach saturation.

The application of energy has been shown to increase levels of soil respiration which we have characterised by a respiration ratio *R*, where

$$R = \left(\frac{R_E}{R_O}\right), \qquad (4)$$

where R_E and R_O are respiration rates measured following the application of, and in the absence of, external energy, respectively. Higher values of R are associated with increasing energy levels, particularly on soils with lower-soil organic matter contents, which were previously shown to be susceptible to destabilisation. However, the application of increased energy levels at very high soil water contents has resulted in a reduction in the value of R to below 1. We believe that under these conditions, the soil has become puddled, closing many of the pores to the outside, and that as a consequence, anaerobic conditions exist within aggregates.

A field experiment showed that increased soil respiration could be measured following tillage particularly from high energy intensive tillage. Differences could still be measured several weeks after cultivation. (Watts *et al.*, 1997b).
Using soil mechanics techniques, we were also able to measure changes in respiration following both direct shear, and compression of soil cores, collected from sites with contrasting management regimes (Watts *et al.*, 1996e). A sharp rise in R was noted during the elastic phase of shearing, the rate of increase of which diminished after yielding. During the initial phase, particle bonds were being broken, but following yielding, particles were just being rearranged. At the onset of compressive loading, there was also an increase in R, but this was soon offset by diminishing porosity associated with increasing compressive strain. Values of R in excess of 2 were recorded following direct shearing. This work has shown that soil mechanics can provide a powerful tool for the study of organic matter and microbial activity in soil.

Soil quality as influenced by tillage (Objective 5)
As mentioned previously, the overall objective of this work was to quantify the effects of cultivations on two principal measures of soil quality. To that end, we have developed the sensitivity index, S, which quantifies the ease by which soils can be destabilised during tillage. Secondly, we have devised the respiration ratio, a measure of increased mineralization of organic carbon, following mechanical energy inputs, such as those resulting from tillage. We have sought a link between these two measures of soil quality, (Watts *et al.*, 1997c). The principal parameters found to be influencing S and R are: soil organic carbon (SOC) and soil water content, or potential (Ψ), which we have used to establish the following empirical relationships.

$$\begin{array}{l} S = \underset{(\pm 0.266)}{2.288} - \underset{(\pm 0.152)}{0.527} \log(-\psi) - \underset{(\pm 0.192)}{0.747}(SOC) + \underset{(\pm 0.067)}{0.172}(SOC)(\log(-\psi)) \end{array} \quad (5)$$

with r^2 (coefficient of determination) = 0.686

Similarly,

$$R = \underset{(\pm 0.068)}{1.700} - \underset{(\pm 0.046)}{0.160} \log(-\psi) - \underset{(\pm 0.058)}{0.188}(SOC) + \underset{(\pm 0.020)}{0.042}(SOC)(\log(-\psi)) \quad (6)$$

with r^2 (coefficient of determination) = 0.707

The coefficients have been derived using experimental data in the following ranges E (0 - 150J kg^{-1}); SOC (1.1 to 3.2) and Ψ (-50hPa to -1.5MPa). Soils at and wetter then -50hPa become puddled and are probably anaerobic. Using these data we have obtained the following correlation:

$$R = \underset{(\pm 0.019)}{0.308}S + \underset{(\pm 0.025)}{1.021} \quad (r^2 = 0.935) \quad (7)$$

(Numbers in brackets, below equations 5, 6 and 7 represent the standard error of coefficients and r^2 is the coefficient of determination based on 23 degrees of freedom.)

This result supports the hypothesis that organic matter, physically protected from microbial attack by stable soil structures, can become exposed to mineralization when the structure is destabilised during tillage. Increased levels of soil organic matter and soil water contents below the soil plastic limit, in conjunction with reduced tillage energy inputs provide the best approach to maintaining soil quality.

Link with other work (Objective 6)
The results from this project are consistent with previous published research, but have extended it considerably. The new research methodologies developed have enabled us to make very rapid progress in understanding and quantifying the effects of mechanical energy inputs, such as through tillage, to soil.

The new findings will be discussed in relation to previous work in Watts and Dexter, 1997c.

Additional work

In parallel with this project, some other work was done. It is mentioned briefly here because the work used some of the same soils as SP0303, and because the findings complement SP0303.

A re-examination of the statistical theory of brittle fracture (Watts and Dexter, 1997d) has shown that soil friability, F, can be quantified by

$$F = \frac{\sigma_y}{\overline{Y}}, \qquad (8)$$

where $\overline{Y}$ is the mean tensile strength of a batch of soil aggregates and σ_y is the standard deviation of Y. This simple measure is formally related to the statistical theory of brittle fracture. We have found that F increases with soil organic carbon content, goes through a maximum at the optimal water content for tillage, and is reduced if tillage is done when soil is too wet. Friability, F, is a powerful, theoretically-based index of soil physical quality.

Publications arising from the project

Watts, C.W., Dexter, A.R., Dumitru, E. and Arvidsson, J. 1996a An assessment of the vulnerability of soil structure to destabilisation by tillage. Part I. A laboratory test. *Soil and Tillage Research*, **37**: 161-174

Watts, C.W., Dexter, A.R. and Longstaff, D.J. 1996b An assessment of the vulnerability of soil structure to destabilisation by tillage. Part II. Field trials. *Soil and Tillage Research*, **37**: 175-190

Watts, C.W., Dexter, A.R., Dumitru, E. and Canarache, A. 1996c Structural stability of two Romanian soils as influenced by management practices. *Land Degradation and Development*, **7**: 217-238

Watts, C.W. and Dexter, A.R. 1997a The influence of organic matter in reducing the destabilisation of soil by simulated tillage. *Soil and Tillage Research* (in press)

Grant, C.D., Watts, C.W., Dexter, A.R. and Frahn, B.S. 1995 An analysis of the fragmentation of remoulded soils with regard to self-mulching behaviour. *Australian Journal of Soil Research*, **33**: 569-583

Watts, C.W., Eich, S. and Dexter, A.R. 1997b Effects of mechanical energy inputs on soil respiration. *Soil and Tillage Research* (submitted)

Watts, C.W. and Dexter, A.R. 1996d Data logging respirometers. Proc. 2nd International Symposium, ISMOM96, Nancy, France

Watts, C.W., Hallett, P.D. and Dexter, A.R. 1996e The effects of mechanical stresses and strains on soil respiration. Proc. 2nd International Symposium, ISMOM96, Nancy, France

Watts, C.W. and Dexter, A.R. 1997c Influences of tillage on soil quality. (in preparation)

Watts, C.W. and Dexter, A.R. 1997d Soil friability: theory, measurement, and the effects of soil management practices and organic carbon content. Eur. J. Soil Science (in preparation)

Technology Transfer

The work has resulted in the above series of major publications which are already attracting considerable international interest. An article is being prepared for an industry journal "The Furrow" (60,000 copies in UK alone). Aspects of the work have been presented at several scientific meetings and to groups of people from industry.

Incorporation into codes of practice:

The findings could be incorporated into the Code of Good Agricultural Practice for the Protection of Soil. This could enable the boundaries between "good" and "bad" practices to be better defined.

Principal conclusions

We have shown that for relatively dry soils, inputs of mechanical energy do not increase the amount of dispersible clay. However, for wet soils, the amount of dispersible clay increases with increasing water content and increasing energy input.

We have discovered that soil organic matter reduces the effects of mechanical energy input in destabilising soil and is also associated with increased values of soil friability. Both of these properties are measures of soil physical quality.

We have also found that mechanical energy input to soil can increase the rate of organic matter loss by microbial respiration - this effect is strongly related to clay dispersibility and indicates the key role of clay in protecting soil organic matter against microbial degradation.

The relative increase in respiration resulting from mechanical energy inputs was greater for degraded soils with low contents of organic matter. Respiration rates of soils with high levels of organic matter were little affected by mechanical energy inputs. This illustrates the key role of organic matter in protecting itself and shows that degraded soils are especially sensitive to further degradation.

Opportunities for further work:

The project has resulted in powerful new methodologies and several important new results. This work can now be built upon to answer a range of questions relating to soil physical quality and the consequences of soil management practices for soil behaviour in the environment.

(i) to determine minimum acceptable levels of organic matter in UK soils which are required to maintain soil physical quality,

(ii) to determine the relationship between the new laboratory tests and the susceptibility of soil to erode or to generate particulate transport in the environment,

(iii) to quantify the effects of cultivation practices on the increased release of nitrate through increased mineralization of organic matter and the consequences of this release for plant uptake or for pollution of waters,

(iv) to develop ways in which the amount of physically-protected organic matter in degraded agricultural soils can be increased to improve soil physical quality, and,

(v) to make surveys of UK soils to determine reference levels of soil physical quality.

These suggestions for further work would help MAFF to meet its policy requirements of maintaining, protecting and sustaining the soil resource.